RESEARCH & DEVELOPMENT

Final Report

Work Zone Monitoring and Assessment for TIP I-5311/I-5338

Behzad Aghdashi, Ph.D.[1)]
Bastian J. Schroeder Ph.D., P.E.[2)]
Thomas Chase[1)]
Nabaruna Karmakar[1)]
Nagui M. Rouphail, Ph.D. [1)]
Billy Williams, Ph.D. [1)]

1) Institute for Transportation Research and Education
North Carolina State University
2) Kittelson and Associates, Inc.

NCDOT Project 2014-33

FHWA/NC/2014-33

February 2017

NCDOT Project 2014-33

Work Zone Monitoring and Assessment for TIP I-5311/I-5338

Final Project Report

Prepared for:

North Carolina Department of Transportation

Prepared by:

Behzad Aghdashi, Ph.D.[1)]
Bastian J. Schroeder Ph.D., P.E.[2)]
Thomas Chase[1)]
Nabaruna Karmakar[1)]
Nagui M. Rouphail, Ph.D. [1)]
Billy Williams, Ph.D. [1)]

1) Institute for Transportation Research and Education, North Carolina State University
2) Kittelson and Associates, Inc.

February 14, 2017

Technical Report Documentation Page

1. Report No. FHWA/NC/2014-33	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Work Zone Monitoring and Assessment for TIP I-5311/I-5338		5. Report Date February 14, 2017 6. Performing Organization Code
7. Author(s) Behzad Aghdashi, Ph.D., Bastian J. Schroeder Ph.D., P.E., Thomas Chase, Nabaruna Karmakar, Nagui M. Rouphail, Ph.D., Billy Williams, Ph.D		8. Performing Organization Report No.
9. Performing Organization Name and Address Institute for Transportation Research and Education, North Carolina State University, Centennial Campus Box 8601, Raleigh, NC		10. Work Unit No. (TRAIS) 11. Contract or Grant No.
12. Sponsoring Agency Name and Address North Carolina Department of Transportation Research and Development Unit 104 Fayetteville Street Raleigh, North Carolina 27601		13. Type of Report and Period Covered Final Report October 2013 to August 2016 14. Sponsoring Agency Code *2014-33*
Supplementary Notes:		

16. Abstract

This document is the final project report for NCDOT project 2014-33: Work Zone Monitoring and Assessment for TIP I-5311/I-5338. This multi-year research project focused on enhanced modeling, continued monitoring, and assessment of a large work zone project in Raleigh, North Carolina. The project encompassed a significant amount of predictive modeling work of expected work zone impacts, using a variety of software tools. The project also included a broad data monitoring effort, capturing operational performance data of the work zone using a variety of data sources. In addition to these modeling and monitoring activities, the project produced a work zone operations guide for NCDOT. All deliverables are contained in this report.

17. Key Words *Fortify, Work Zone, Monitoring, Modeling*	18. Distribution Statement		
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 197 Pages	22. Price

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

DISCLAIMER

The contents of this report reflect the views of the author(s) and not necessarily the views of the University. The author(s) are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of either the North Carolina Department of Transportation or the Federal Highway Administration at the time of publication. This report does not constitute a standard, specification, or regulation.

Acknowledgements

The research team acknowledges the North Carolina Department of Transportation for supporting and funding of this project. We extend our thanks to the project Steering and Implementation Committee members:

Stuart Bourne (Chair)
Joseph Ishak
Jennifer Portanova
Michael Reese
Shawn Troy
A. Whitley IV
J. Bowman
Chad Hinnant
Terry Hopkins
Kevin Lacy
Meredith McDiarmid
Ernest Morrison (Project Manager)

The authors would like to thank all members of the Steering and Implementation Committee for their continued guidance and support throughout this project. We would like to express special gratitude to the committee chair Mr. Stuart Bourne for his time in overseeing this project. Special thanks also goes to Mr. Ernest Morrison of the research unit, who continues to help guide the project along and offered assistance with meeting scheduling and contractual questions.

The authors also would like to thank all project team members for their efforts in conducting this research project including Shams Tanvir, Martin Hartmann, Ali Hajbabaie, Katy Salamati, Brian Narron, Xingyu Xuan, Briana Philips.

Without the help of all the above individuals, the project would not be able to be completed in a successful and timely manner.

Executive Summary

This document is the final project report for NCDOT project 2014-33: Work Zone Monitoring and Assessment for TIP I-5311/I-5338. This multi-year research project focused on enhanced modeling, continued monitoring, and assessment of a large work zone project in Raleigh, North Carolina. The project encompassed a significant amount of predictive modeling work of expected work zone impacts, using a variety of software tools. The project also included a broad data monitoring effort, capturing operational performance data of the work zone using a variety of data sources. In addition to these modeling and monitoring activities, the project produced a work zone operations guide for NCDOT. All deliverables are contained in this report.

The work zone project covered construction work conducted under TIP numbers I-5311/I-5338: I-40 and I-440 Re-Construction Work from Exit 293 to I-40 Exit 301 and I-440 Exit 14. The ITRE team was previously involved in a prior NCDOT research project to predict operational impacts of this work zone using network-wide and corridor-level evaluations tools to estimate the congestion and traffic diversion impacts of the eleven-mile work zone. This project expanded on that work and included a significant data monitoring component.

This project had five major objectives that were accomplished:

(1) Provide assistance to NCDOT in Evaluating traffic management strategies for this work zone,
(2) Evaluate the performance of the transportation network during actual construction activities,
(3) Calibrate and validate mesoscopic and macroscopic models based on observed conditions,
(4) Assist in real-time revisions to the traffic management plans to help mitigate observed congestion patterns and choke points, and
(5) Generate guidance for modeling and monitoring future work zones in North Carolina

The final report is broken down into five major sections. Part I focuses on the introduction and organization, while the major monitoring and monitoring tasks are documented in Part II for the first Fortify Work Zone stage (called Area 3 by contractor) and in Part III for the second Work Zone stage (called Areas 1&2). Based on the findings and lessons learned in work on the Fortify work zone, a Guidance Document was developed and is presented in Part IV along with an informational brief in Part V.

Key findings and results included in this report include the modeling performed on the work zone based on sensor and probe data of actual traffic conditions, traffic diversion rates which varied throughout the work zone timeline ranging from 2% to 15%, and development of simplified planning level capacity charts which can be used to quickly identify work zone configurations which may cause congestion.

Table of Contents

CHAPTER I - INTRODUCTION

1 Introduction

This document is the final project report for NCDOT project 2014-33: Work Zone Monitoring and Assessment for TIP I-5311/I-5338. This multi-year research project focused on enhanced modeling, continued monitoring, and assessment of a large work zone project in Raleigh, North Carolina. The project encompassed a significant amount of predictive modeling work of expected work zone impacts, using a variety of software tools. The project also included a broad data monitoring effort, capturing operational performance data of the work zone using a variety of data sources. In addition to these modeling and monitoring activities, the project produced a work zone operations guide for NCDOT. All deliverables are contained in this report.

1.1 Overview and Objectives

The work zone project covered construction work conducted under TIP numbers I-5311/I-5338: I-40 and I-440 Re-Construction Work from Exit 293 to I-40 Exit 301 and I-440 Exit 14. The ITRE team was previously involved in a prior NCDOT research project to predict operational impacts of this work zone using network-wide and corridor-level evaluations tools to estimate the congestion and traffic diversion impacts of the eleven-mile work zone. This project expanded on that work and included a significant data monitoring component.

With this project, ITRE and the NCDOT had the unique opportunity to conduct a real-time evaluation of the work zone while under construction. With the use of high-density traffic sensors and cameras already deployed in the work zone and surrounding areas, and with probe-based travel time readily available, the team was able to validate the model predictions of queuing and congestion impacts, as well as verify predicted diversion impacts. The latter were critical assumptions going into the initial modeling effort, and the ability to field-verify these diversion impacts represented an exceptional opportunity that also benefits future modeling efforts. In addition, the enhanced modeling work supported NCDOT's outreach effort for this work zone, to provide timely and useful information on impacted areas to citizens as well as public and private organizations in the Triangle Region.

The specific objectives of this project were as follows:

(6) Provide assistance to NCDOT in Evaluating traffic management strategies for this work zone,
(7) Evaluate the performance of the transportation network during actual construction activities,
(8) Calibrate and validate mesoscopic and macroscopic models based on observed conditions,
(9) Assist in real-time revisions to the traffic management plans to help mitigate observed congestion patterns and choke points, and
(10) Generate guidance for modeling and monitoring future work zones in North Carolina

1.2 Organization of Document

Due to the length and complexity of this research project, the report is broken out into several distinct parts, corresponding to different stages of the project (and the Fortify work zone). Specifically, the report is broken out into five separate parts:

- Part I: Introduction,
- Part II: Performance Report for Work Zone Stage 1 (Construction in Area 3),
- Part III: Performance Report for Work Zone Stage 2 (Construction in Areas 1&2),
- Part IV: Guidance Document for Work Zone Operational Modeling and Monitoring, and
- Part V: Informational Brief Summary of Work Zone Guidance.

Part I of the document (this section) provides a general overview of the project, a brief background and objectives, and the general organization of the document.

Part II presents the performance report for the first stage of construction in the Fortify project. In this first phase, the contractor worked primarily in "Area 3" of the work zone, which is the stretch on Interstate I-440 on the southeast quadrant of Raleigh, between I-40 Exit 301 and I-440 Exit 14. Work in Area 3 commenced approximately in February 2014, and continued for about one year until February 2015. The Area 3 report summarizes all modeling and monitoring activities related to that stage of construction.

Part III presents the performance report for the second stage of construction in the Fortify project. In the second phase of construction, the contractor shifted work to "Areas 1 and 2" of the work zone, which is the stretch on Interstate I-44 south of Raleigh, between I-40 Exit 293 and I-40 Exit 301. Work in Areas 1 and 2 commenced approximately in February 2015, but no lane closure were in effect until the summer of 2015. Work in areas 1 and 2 continues through the present day and is expected to finish in 2017. The scope of the project report ends in December 2015. The Area 1 and 2 report summarizes all modeling and monitoring activities related to that stage of construction, and mirrors the content of the previously-submitted Area 3 report.

Part IV of this document represents a summary guidance document for modeling and monitoring the operational performance of work zones in North Carolina. The guidance document is intended for analysts in the work zone and congestion management groups within the North Carolina Department of Transportation, to help NCDOT properly scope work zone studies. The focus is on operational analysis and monitoring, which is one of the critical dimensions of work zone performance assessment. But other considerations, including safety performance, economic impacts, etc. should be considered as well, even if they are beyond the scope of this document.

> In the context of the document, *Modeling* refers to predicting the operational effects and impacts of a work zone prior to construction starting. Modeling is performed prior to the construction activity to predict work zone operations, compare and contrast alternatives, and support decision-making for work zone staging. The guidance discusses types of models, and presents guidance for applying different levels of analysis tools to estimate work zone effects.

Monitoring refers to evaluating and tracking performance of a work zones once it is in effect. Work zone monitoring is conducted during active construction, and captures data collection, data analytics, and opportunities for providing real-time decision-support. The guidance discusses types of sensing and data collection approaches to quantify operational characteristics of a work zone, and makes recommendations for what level of monitoring is appropriate for a given work zone. In the context of the guidance, modeling refers to

Finally, Part V of the document contains a four-page informational brief, summarizing the information contained in the Part IV guidance document. The info brief is intended to provide highlights of the information contained in the guide, and encourages analysts to take a closer look at the guide for their next work zone analysis. As such, the informational brief serves as a summary and marketing piece supplementing the actual guide. It can easily printed for a readily accessible reference on work zone modeling and monitoring in NC.

1.3 Implementation and Technology Transfer

1.3.1 Overview of Research Products

The main product of this research is this final report project report, summarizing the research and providing guidance to NCDOT about the impacts of the proposed work zone on the freeway mainline, as well as the surrounding traffic network. These contained parts of this report quantify queues, travel time, and delay for critical links and serve to inform the NCDOT and stakeholders about the severity of construction impacts for the Fortify project.

The reports further provides a comparison and assessment of model predictions versus actual performance, and verifies the accuracy of the various assumptions feeding the model development.

A key deliverable of this project, and part of this report in Parts IV and V, is a set of analysis guidelines in the form of a step-by-step work flow of how to evaluate large-scale freeway work zones. These guidelines are useful for future assessment of similar projects in North Carolina and beyond.

1.3.2 How NCDOT Will Use Research Product

The products of this research will be used by the NCDOT Safety and Mobility Division to better understand the impacts of the proposed construction activity, and inform future modeling of similar work zones in North Carolina. A quantitative understanding of congestion impacts will facilitate effective planning to help mitigate the impacts of the work zone. Through the research, the NCDOT will gain estimates of key measures of effectiveness, which will be used to predict mobility and safety impacts during construction. With knowledge of the estimated performance, NCDOT will be able to develop a well-targeted traffic management plan for the work zone, which effectively focuses NCDOT resources on critical areas. Overall, the results of this research will help improve the management and scheduling of the construction activities, as well as NCDOT traffic management resources.

1.3.3 Suggested Plan for Implementation and Technology Transfer for NCDOT

The key to successfully transferring the results of this research into practice is an active outreach effort internal to NCDOT, including both central office staff, as well as division offices. While this final project report is quite lengthy and technical, the modeling and monitoring guidance document in Part IV is geared to be directly and readily useable by practitioners across North Carolina.

To further facilitate technology transfer, the team has created a four-page informational brief that summarizes core messages and key points of the guidance document. This info brief can be readily printed and disseminated to division staff, as well as consultants to NCDOT.

Finally, NCDOT is encouraged to develop a training program covering the contents of this report, and specifically the guidance document. This training could take the form of a half to full-day workshop with NCDOT staff presenting an overview of the guidance, and working through real-world and hands-on examples. Potentially, this training could also be conducted through a series of webinar and web-based training efforts.

CHAPTER II -

PERFORMANCE REPORT FOR WORK ZONE STAGE 1 (CONSTRUCTION IN AREA 3)

TABLE OF CONTENTS

1.0 INTRODUCTION

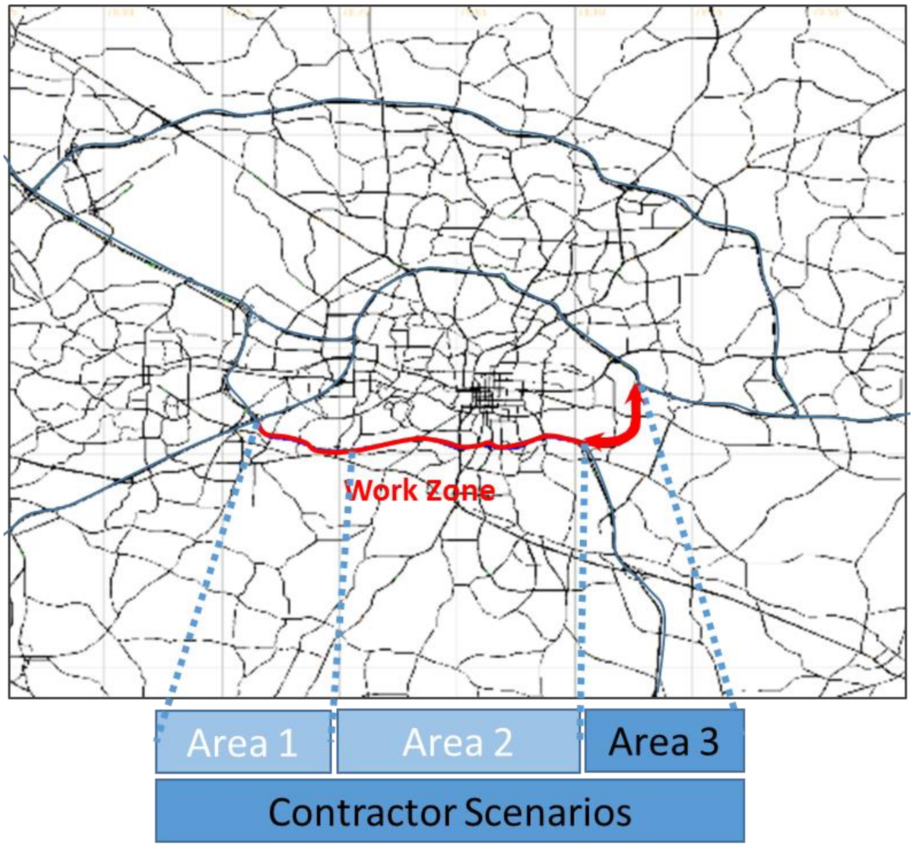
This report presents initial results for an NCDOT research project focused on continued monitoring and assessment of a large work zone project in North Carolina. The work zone project covers work to be completed under TIP numbers I-5311/I-5338: I-40 and I-440 Re-Construction Work from Exit 293 to I-40 Exit 301 and I-440 Exit 14. In a previous project to the team was focused on predicting operational impacts of this work zone using network-wide and corridor-level evaluations tool to estimate the congestion and traffic diversion impacts of the eleven-mile work zone. With this project, ITRE and the NCDOT have a unique opportunity to conduct a real-time evaluation of the eleven-mile work zone under construction and network impacts, to develop public outreach material, and to develop future analysis and calibration guidance for similar projects in North Carolina.

The work zone project, also referred to as the *Fortify* project, is constructed in two primary operational stages. This report focuses on the evaluation of what has been labeled *Area 3*, which is the section of the work zone on I-440 from the I-40/440 split at exit 301 to the US264 interchange on I-440. This report presents a corridor and network-level analysis of this phase in FREEVAL and DTALite. Future work will summarize results for the second major work zone stage, with construction between the I-40/440 split at exit 301 and the US1/64 interchange at exit 293 on I-40.

1.1 Project Overview

The results presented in this report represent the first construction stage as part of the "Fortify" work zone project under TIP I-5338 and I-5311. The work area in this stage, referred to as "Area 3", is constrained to a roughly three-mile stretch on I-440 between the I-40/440 split (Exit 301) and the I-440/US264 interchange on I-440. In the scenario, traffic in both directions is reduced to two lanes at a lane width of 11 feet in the work zone area. An additional auxiliary lane is maintained between Poole Road (Exit 15) and the US264 interchange (Exit 16) in both directions. In addition, the on-ramps and off-ramps in both directions of travel are reduced to a single lane. A map of the study area is shown in Exhibit II - 1.

Exhibit II - 1: Map of Study Area



For the system interchange at Exit 301 in the northbound/eastbound (I-40) and eastbound/northbound (I-440), the approach ramps are dropped to two lanes and a single lane respectively prior to the merge point, and then merge with 3-to-2 lanes to enter I-440.

The ITRE team monitored the work zone using three different types of sensors and technology:

1. HERE.Com (previously Traffic.com) side-fire radar sensors deployed throughout the triangle, which provide traffic volume and (spot) speed estimates on the freeway network.
2. INRIX probe-based data that is available for all freeways and major arterials in North Carolina, and provides travel time and (segment) speed estimates. By looking at speed estimates over multiple segments, it is further possible to estimate queue lengths. It is noted that INRIX data can be unreliable for arterial performance, especially over short segments.
3. Video observations from overhead-mounted NCDOT traffic cameras. These video stream are used to provide a visual of work zone performance, as well as confirm traffic volumes and queue lengths if needed.

The lessons learned from this activity will be available for this and future research, to offer more North Carolina-specific modeling and calibration guidance for freeway work zones. This project is a long-term monitoring and assessment effort conducted in parallel to the construction activities. The project builds on an available calibrated mesoscopic network simulation model in DTALite, as well as corridor-level macroscopic models in the FREEVAL tool. Both the mesoscopic and macroscopic tools will be continuously refined in this project.

This report is focused on performance assessment of the work zone in the initial phase of construction, which is estimated to occur in “Area 3” as defined by the contractor. The task will allow the team to collect detailed data on opening day, week, and month traffic characteristics, and develop an estimate of traffic congestion and diversion impacts over time. This performance assessment stage will also serve as feedback to NCDOT in the early construction stages, and provide recommendations for potential improvements to the network-wide traffic management plan and the network model calibration. This stage also provides invaluable information on the traffic patterns that are expected at the onset of other phases of the construction.

1.2 Facility Geometry

To further illustrate the geometric configuration of the work zone, the team divided the facility into analysis segments following guidance in the Highway Capacity Manual, HCM (TRB, 2010). While the mesoscopic simulation analysis that is a big focus of this report doesn’t use the same convention for segments, the geometry is presented this way for two reasons: First, to illustrate the varying cross-section (number of lanes) on the facility in the eastbound (EB) and westbound (WB) direction; and second, in preparation for the macroscopic analysis in FREEVAL-WZ, which uses the HCM convention and which will be presented in the final project report. Exhibit II - 2 and Exhibit II - 3 show the EB and WB geometries, respectively. The Exhibit II -s give general information about segment type, segment length, segment number of lanes, as well as reference to mile-postings and freeway interchanges to assist with interpretation.

In the eastbound direction (Exhibit II - 2) the facility spans a length of 20.3 miles, with a spatial extent of the work-zone of approximately 10.6 miles between mile markers 293 on I-40/440 and mile marker 14 on I-440. The work zone directly impacts nine interchanges, including US1 (Exit 293), Gorman Street (Exit 295), Lake Wheeler Road (Exit 297), South Saunders Street (Exit 298), Hammond Road (Exit 299), Rock Quarry Road (Exit 300), I-40/440 Split (Exit 301), Poole Road (I-440 Exit 15), and US264 (I-440 Exit 14). Along this nearly eleven-mile stretch, the cross-section of the study facility varies between two lanes (north/east of I-40/I-440 split) and five lanes. It should be noted that the two-lane section around I-40 Exit 301 features a very wide shoulder, which is assumed to be usable as a full-lane during construction. In addition to this choke point, an extended three-lane section between Exit 293 and Exit 297 is expected to act as the critical bottleneck in this direction. Recurring congestion is also evident due to the I-40/440 split at Exit 301, with I-40 southbound traffic being reduced from four to two lanes. The peak travel in the EB direction typically occurs in the PM peak hour, as traffic leaves Raleigh heading to residential communities south of town.

In the westbound direction, Exhibit II - 3 shows a total length of 20.2 miles with the total work zone (Areas 1, 2, and 3) spanning approximately 10.2 miles. All measurements were taken of Google Earth, which may explain some of the rounding difference between eastbound and westbound directions. Similar to the EB direction, a total of nine interchanges are impacted, but the cross-section varies only from three to five lanes (no two-lane section in the WB direction). Known bottlenecks in the WB directions are a lane drop just past Exit 297 and spillback from the US1 interchange at Exit 293. Both are predominant in the AM peak hour.

Exhibit II - 2: Eastbound Lane Geometry and Work Zone Extents

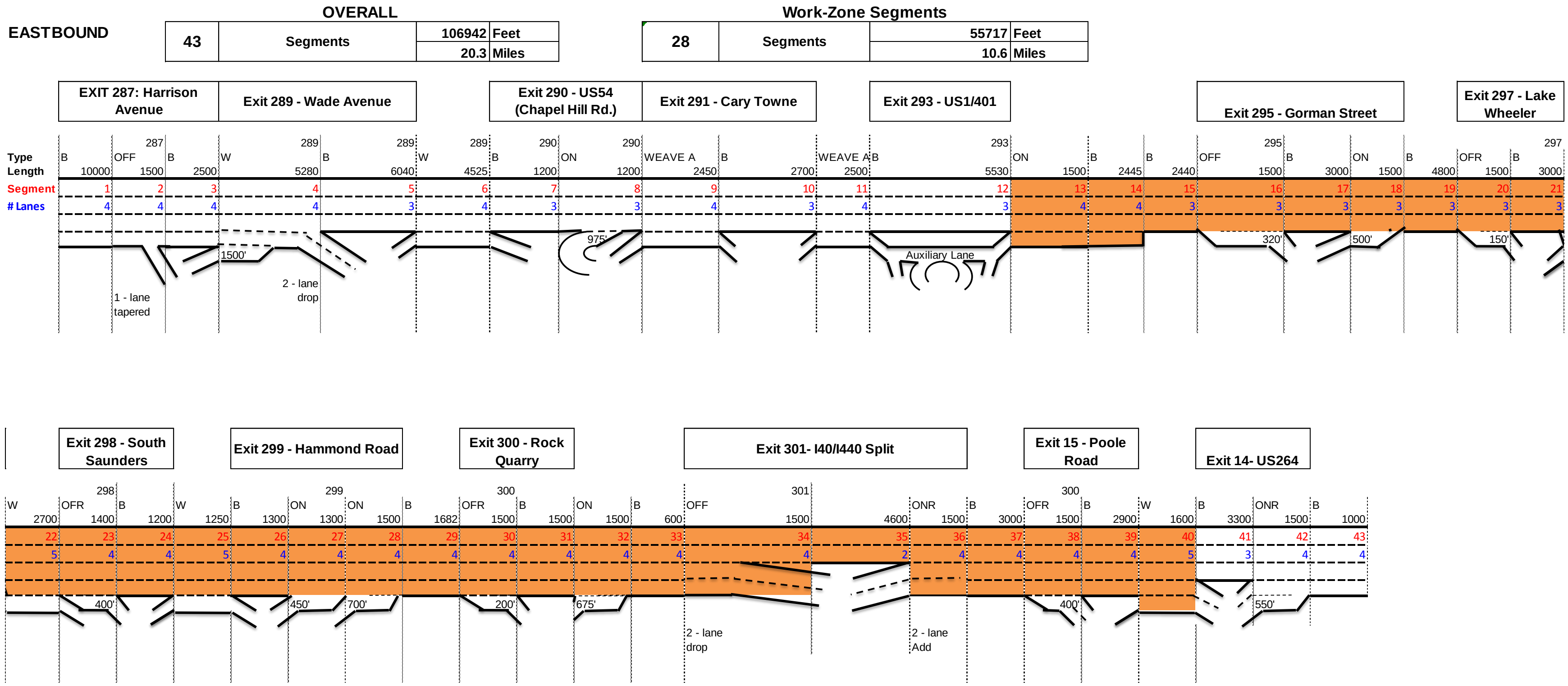
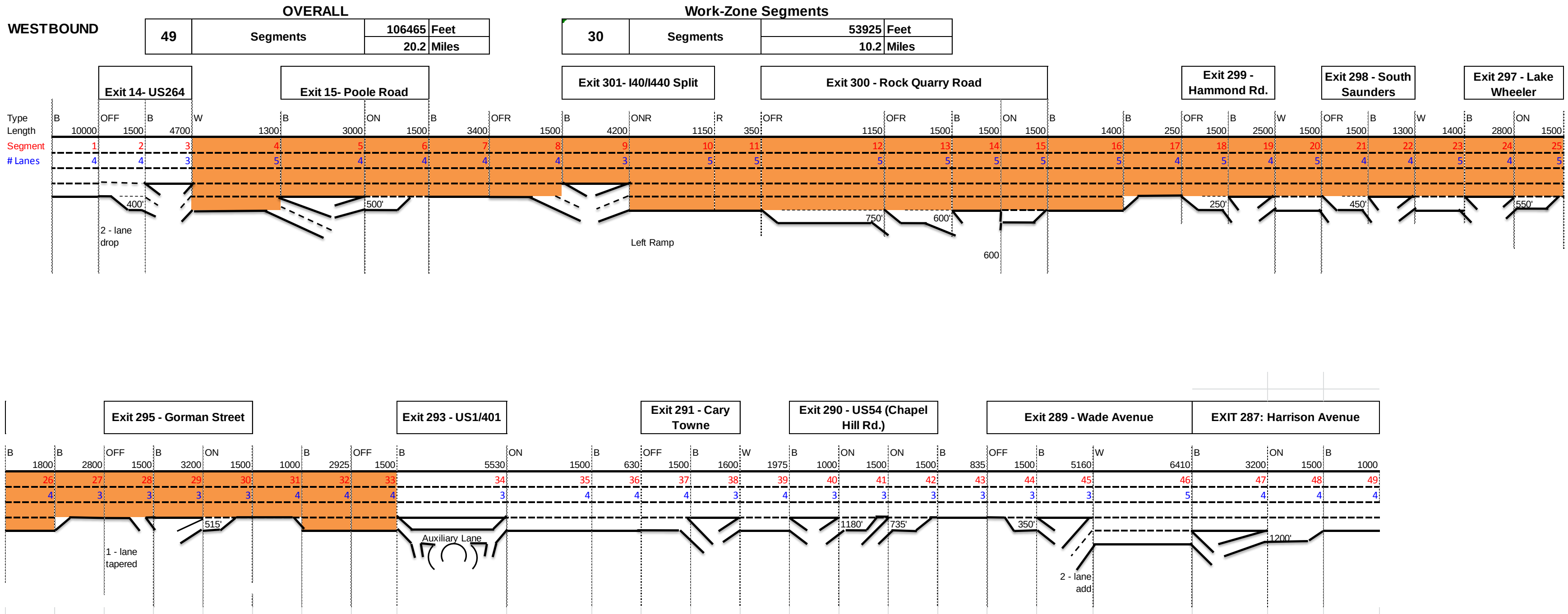


Exhibit II - 3: Westbound Lane Geometry and Work Zone Extents



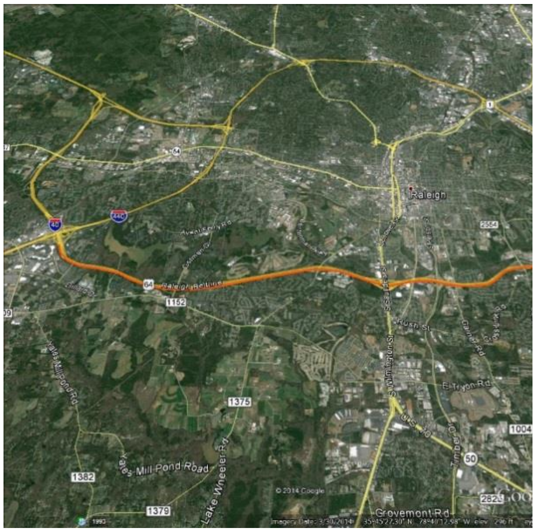
1.3 Description of Analysis Routes

The results presented in this report focused on the analysis of four key routes in the triangle area:

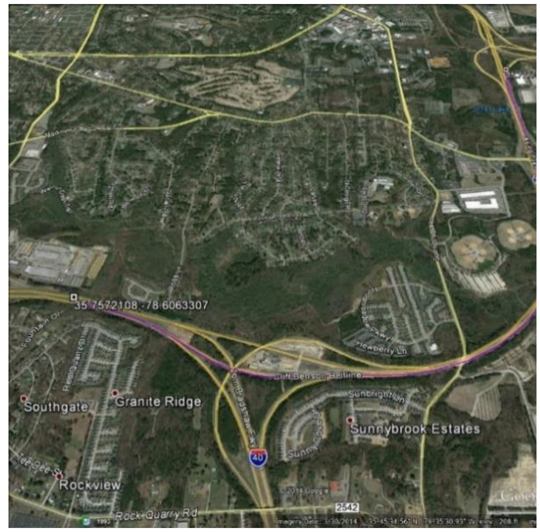
- **Route A:** An 8 mile section of I-40 between the I-40 and US1 interchange (Exit 293) and the I-40/440 split (Exit 301). This route combines areas 1 and 2 of the Fortify project, which is a key diversion route to the construction in Area 3.
- **Route B**: A 3-mile section of I-440 between the I-40/440 split (Exit 301) and the I-440 and US264 interchange (Exit 16 on I-440). This route represents area 3 of the Fortify project, which contains the construction activity focused on in this analysis.
- **Route C**: An approximately 28-mile section from Exit 312 on I-40 and Exit 284 on I-40, with a path along I-40 (southern loop). This route includes areas 1 and 2 of the Fortify project, and represents a primary diversion route to the construction activity in Area 3, but may also be impacted by queue spillback resulting from the construction.
- **Route D:** An approximately 28-mile section from Exit 312 on I-40 and Exit 284 on I-40, with a path along I-440 (northern loop). This route includes the construction activity in area 3, as well as upstream and downstream sections that are likely impacted by queue spillback from the construction.

The routes are shown in Exhibit II - 4.

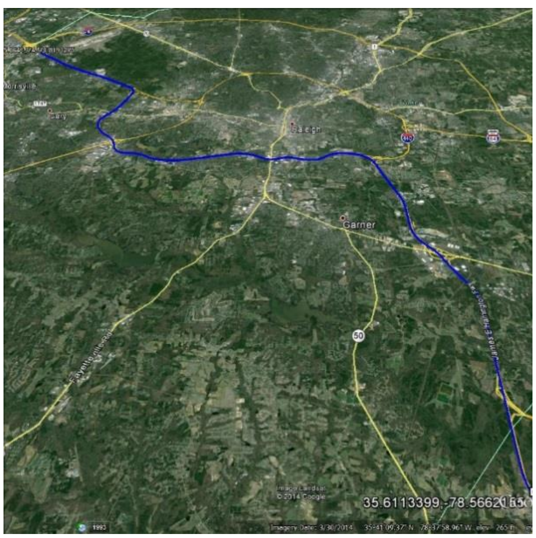
Exhibit II - 4 Major routes selected for work zone analysis: (a) Route A (b) Route B (c) Route C and (d) Route D



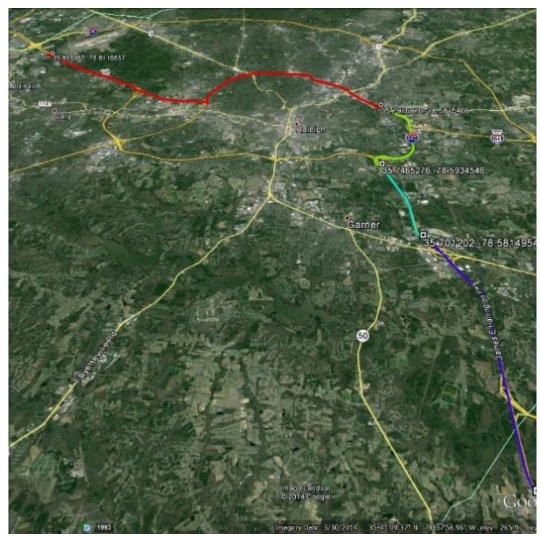
(a)



(b)



(c)



(d)

2.0 METHODS OF ANALYSIS

The team employed three primary methods of analysis: (1) Field data obtained during construction, (2) macroscopic modeling data from the FREEVAL tool, and (3) mesoscopic modeling data from the DTALite tool. The following sections summarize the analysis and data collection methodologies for these three study approaches.

2.1 Field Data

The ITRE team monitored the Area 3 work zone using three different types of sensors and technology:

1. HERE® (previously known as Traffic.com) side-fire radar sensors deployed throughout the Triangle region, which provide traffic volume and (spot) speed estimates on the freeway network.
2. INRIX probe-based data that is available for all freeways and major arterials in North Carolina, and provides travel time and (segment) speed estimates. By looking at speed estimates over multiple segments, it is further possible to estimate queue lengths. It is noted that INRIX data can be unreliable for arterial performance, especially over short segments.
3. Video observations from overhead-mounted NCDOT traffic cameras. These video streams are used to provide a visual of work zone performance, as well as confirm traffic volumes and queue lengths if needed.

For travel time analysis, INRIX probe technology was the primary source for data collection. The Vehicle Probe Project Suite through the Regional Integrated Transportation Information System (RITIS) was used to download travel time data that was collected through the INRIX probe technology. Peak period data was gathered for each weekday between January 27, 2014 and October 2014, where the peaks are between 6:00 AM and 10:00 AM and between 3:30 PM and 7:30 PM. The team focused on Routes A through D both eastbound and westbound as previously defined, covering the extent of the Area 3 work zone and much of I-40/440 in the Triangle Region. Data from NCDOT was also obtained for the westbound AM peak between I-40 at NC 42 and the I-440 Split (Exit 301) extending until I-440 at Poole Road (Exit 15).

All of these data allowed the team to determine the extent of the effects of the work zone on various traffic patterns and routes. Once these data were collected, they were organized into Excel spreadsheets for analysis. By statistical analysis, days with unusual travel times were removed from the data set and an "average" day was generated. Outliers were considered to be days that had a travel time outside of plus or minus two standard deviations of average travel time for the entire data set. After the outlier days were removed, these were then classified as days with incidents, holidays, inclement weather, or another cause for unusual travel times. Incident data provided by NCDOT was utilized in this step, along with archival weather data to help explain outlier events. The effects of various lane configurations, seasons, and the day of week were also determined. The findings were then summarized and compared to modeling data.

Speed data was also collected from RITIS for Routes A through D during the specified peak periods in a similar manner to travel time data, with outliers filtered out of the analysis. Speed analysis was generally not as in depth as travel time analysis, as travel time does help to give an estimate of how fast vehicles in the Area 3 work zone were traveling. In this analysis, speed data were more useful in comparison against traffic volume for the various routes. Factors considered in analyzing speed were capacity of the lanes and the speed limit or free flow speed in the segment of travel.

Volume analysis utilized HERE® sensors deployed throughout the specified routes. Data was collected for a number of sensors along the work zone and upstream and downstream of the work zone to assess its impacts, with a focus on three key sensors. Data was also collected for similar time periods one year prior to construction to assess the impacts of the work zone in specific areas. Similar to travel time data analysis, data was collected for each weekday throughout the study period during the peak periods between 6:00 AM and 10:00 AM and between 3:30 PM and 7:30 PM. The data was filtered for outliers due to inclement weather, incidents, or other valid reasons to develop average volumes.

2.2 Macroscopic Analysis: FREEVAL

In addition to the two mesoscopic tools, the team used the macroscopic tool FREEVAL to explore the operational impacts of the various work zone scenarios. While DTALite is a simulation tool that models movements of individual vehicles, FREEVAL is an analytical tool based on the Highway Capacity Manual (HCM) that estimates performance in 15-minute intervals. The motivations for including FREEVAL in this evaluation include (1) a verification of the mesoscopic results from HCM theory, (2) a comparison of the application and results of both tools, and (3) understanding trade-offs between tools as guidance for future work zone evaluations.

The FREEVAL tool was previously applied for work zone evaluation in North Carolina, and resulted in close matches with field-observed work zone performance data. The tool is further more quickly applied, and allows for straightforward sensitivity analysis of for example volume inputs. Being a macroscopic tool, it does not allow for estimation of network impacts, nor does it estimate diversion percentages. FREEVAL focuses on the evaluation of a single facility (pipe), but with consideration of all merge, diverge, and weaving segments. The methodological steps for a FREEVAL analysis are as follows:

1. Gather geometric and volume input data
2. Code baseline facility
3. Estimate baseline performance and adjust inputs as necessary
4. Identify work zone segments and capacity adjustments
5. Estimate work zone scenario performance
6. Perform sensitivity analysis on work zone results.

For the first step, the team developed the FREEVAL segmentation for key routes through the work zone from aerial imagery. The volume input was obtained directly from the previously calibrated mesoscopic model baseline files for the AM and PM peak period. The use of calibrated mesoscopic model volumes was justified because the intent was to offer a direct comparison of the two tools. Steps 2 and 3 were completed using standard guidance in the Highway Capacity Manual.

In Step 4, a general work zone free-flow speed of 55mph was assumed for all work zone segments. Additionally, each lane closure segment was coded with a capacity adjustment factor (CAF) of 0.63. The CAF was selected consistent with guidance for the FREEVAL-based evaluation of work zones in North Carolina based on a prior NCDOT research effort.

The FREEVAL analysis in Step 5 initially focused on the evaluation of work zone impacts using the mesoscopic base volume inputs. Conceptually, these results are similar to the *one shot* results from the calibrated model, without any consideration of diversion. Rather than relying on the user equilibrium results, Step 6 then performed a sensitivity analysis for potential diversion results, by reducing the modeled demands by fixed percentages between 0% and 30% diversion across the modeled facility.

The FREEVAL tool generates a host of performance measures at the individual segment and facility levels, and aggregates these results for each 15-minute time period, as well as the overall multi-hour study period. For the purpose of this analysis, the primary performance measures are as follows:

- **Maximum Queue Length**, measured along the entire facility and estimated as the longest queue in the study period;
- **Speed Contour Plots,** are generated by FREEVAL automatically to get a sense of the distribution of space mean speed over space (segments) and time (multiple analysis periods). The speed contours are a valuable tool to assess "size" of congestion across the time-space domain;
- **Travel Time Index,** or TTI is defined as the ratio of the prevailing travel time divided by the free-flow travel time. The TTI is increasingly used in reliability analysis, and is particularly useful here as it allows the comparison of different routes using one common metric. The analysis reports the average TTI across the study period, as well as the maximum TTI within any 15-minute period.

In addition to these three performance measures, many other outputs are available, including density contours, levels of service (LOS) contours, and various other measures. Many of these outputs are made available in the appendix, but are not reported in the body of the report.

For the purpose of this study, four base conditions in each direction and peak period were coded as shown below:

1. Route C - EB PM Base
2. Route C - WB AM Base
3. Route D - EB PM Base
4. Route D - WB AM Base

The geometric information was obtained using online mapping tools. An important input for the FREEVAL computational engine are traffic demand values for mainline and all on-ramps and off-ramps, for the entire analysis period. These were obtained from the previously calibrated model used in this research. Exhibit II - 5 summarizes the geometric information for the base conditions. Although both Route C and Route D have the same start and end points, Route D is slightly longer since it covers the I-440 facility, which is slightly longer than the I-40 facility between the two end points. Routes A and B were not included in the FREEVAL analysis, as queuing impacts are typically found upstream of the work-zone bottleneck, in which case the analysis of the work zone segments only would not result in a reasonable assessment of work zone congestion.

Exhibit II - 5 Basic Geometric Information for FREEVAL scenario files

oute	Direction/Period	Start Point	End Point	Length (miles)	# HCM Segments
	EB/PM	Airport Blvd and I-40 MP 284	I-40 MP 312	27.9	56
	WB/AM	I-40 MP 312	Airport Blvd and I-40 MP 284	27.8	68
	EB/PM	Airport Blvd and I-40 MP 284	I-40 MP 312	30.9	70
	WB/AM	I-40 MP 312	Airport Blvd and I-40 MP 284	31.0	70

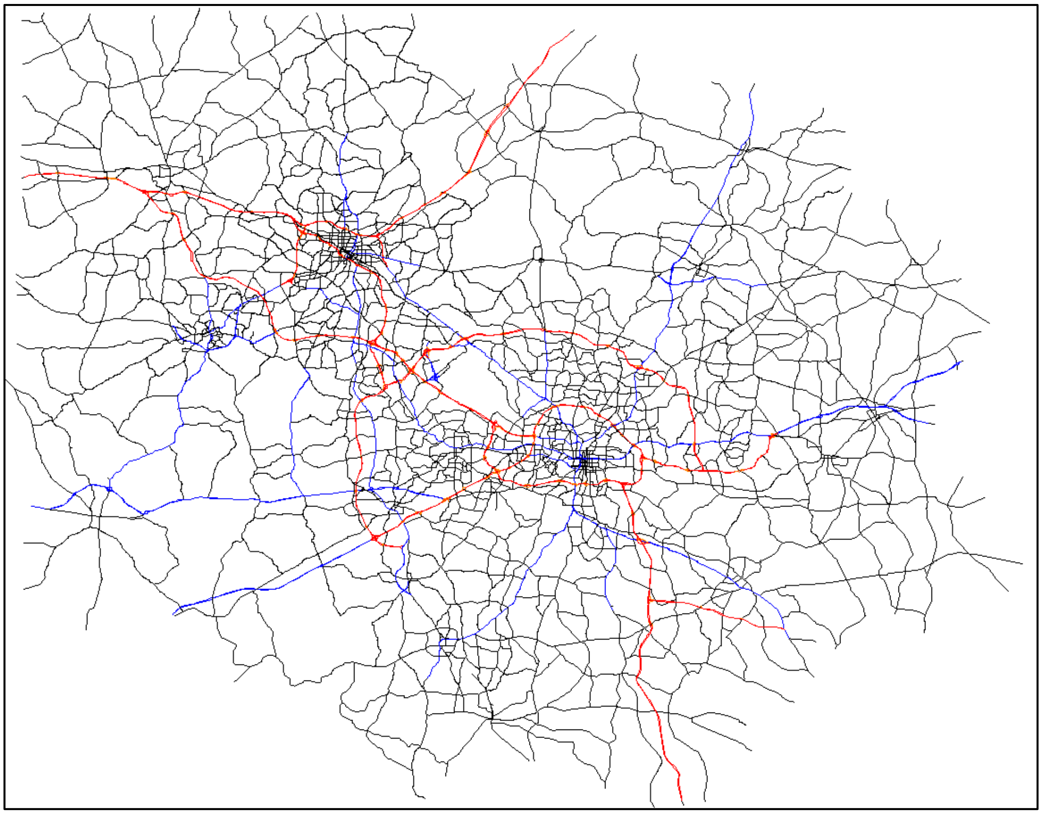
The free-flow speed in the work zone area was assumed to be 55 mph and a Capacity Adjustment Factor of 0.63 was used to account for capacity reduction due to the presence of the work zone. The work zone models are conceptually similar to "one-shot" results from the mesoscopic model. The analysis focused on Travel Time, Denied Entry Queue Length (DEQL), Queue Length, maximum demand/capacity (d/c) ratio, and Speed Contours.

2.3 Mesoscopic Simulation Analysis: DTALite

2.3.1 Model Overview

The mesoscopic network used in this project was initially obtained from NCDOT project HWY-2009-05 (Williams et al., 2001), and then updated significantly in NCDOT project HWY-2012-36 (Schroeder et al., 2013). The original network was converted from the TRM (Triangle Regional Model), which was developed in 2010 for the planning year 2015. Exhibit II - 6 illustrates the original network. Red lines represent freeway facilities with a total of 1,165 links and 649 on and off ramps. These include I-40, I-85, I-440, and I-540 as the major interstate freeways in the network. Blue lines represent highway facilities (principal arterials, 2,644 links) and black lines represent arterial roads (minor arterials and collectors, 15,792 links). The mesoscopic network comprises 2389 traffic analysis zones, 9527 nodes, and 20,250 links.

Exhibit II - 6: Mesoscopic Simulation Base Network



In the prior project (NCDOT HWY-2012-36), two separate models were set up to include the four-hour AM peak period, and the four-hour PM peak period. The total travel demand for AM and PM peak periods corresponds to 1,092,648 vehicles and 2,124,827 vehicles, respectively. It is noted that the model includes Triangle Express Toll Road.

The mesoscopic DynusT tool was applied in two different approaches in this project: (1) One-shot simulation, and (2) User Equilibrium Modeling.

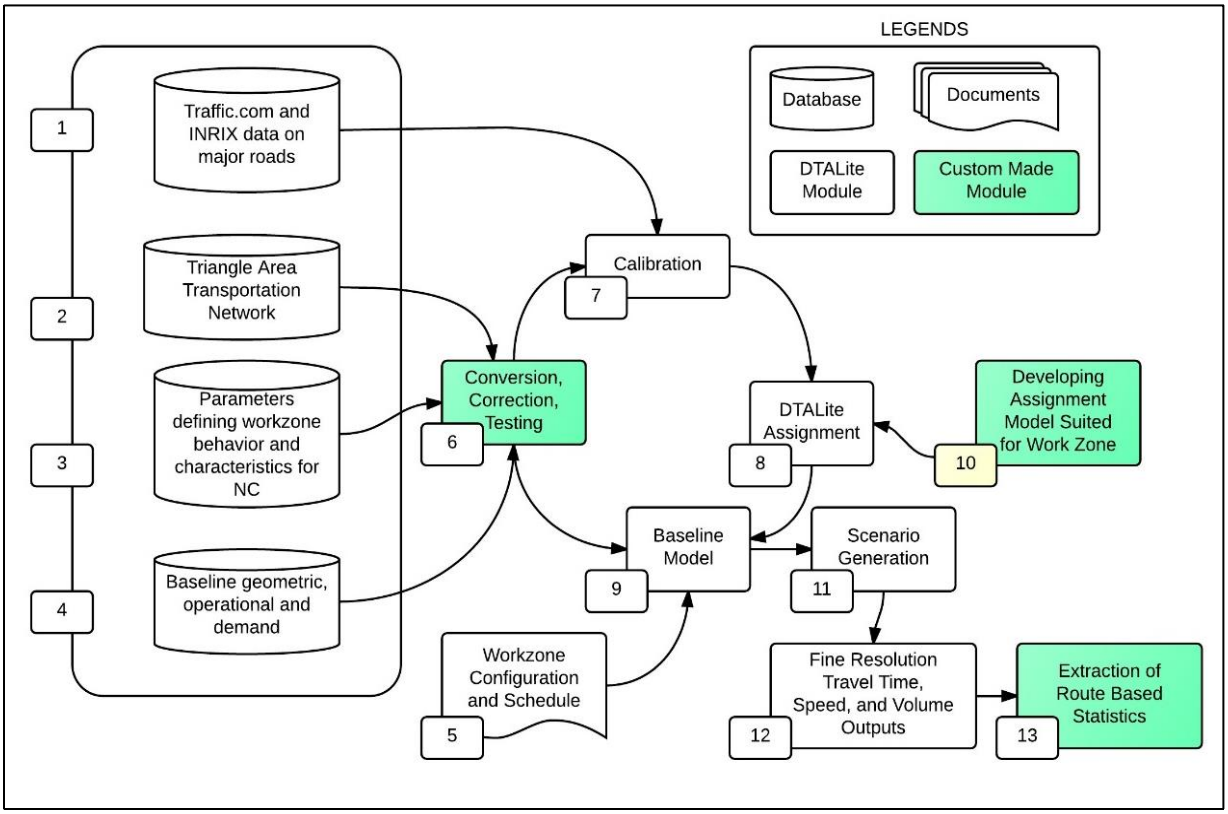
The *one-shot* modeling approach assumes that the origin-destination (O/D) matrix and the path assignment from the calibrated base network are unchanged when the work zone is put in place. The one-shot results therefore assume no diversion due to the work zone, with all traffic maintaining its optimum path from the base network. The one-shot results conceptually represent the *worst-case* conditions for the I-40 work zone facility, while representing low expected impacts on diversion routes and the surrounding network.

The *user-equilibrium (UE)* model, accounts for traffic diversion as modeled vehicles "try" different routes until an optimum path is reached. The UE model requires multiple iterations of the simulation model, until all drivers have settled to a path. The final user equilibrium run corresponds to a *steady-state* solution, where additional iterations would not results in significant further changes in the path file. It is emphasized that even with the UE model, the overall O/D matrix is left in place, and no peak spreading, car-pooling, or trip reduction effects are considered. Between different UE iterations a vehicle will switch to an alternate route if it can identify a path with a lower travel time than its original route.

2.3.2 Simulation Process

The simulation process adopted for the mesoscopic model application used in this project is described in Exhibit II - 7.

Exhibit II - 7 Workflow of Mesoscopic Model- DTALite



The first step to begin a network simulation is to identify data requirements and establish a data collection, correction, and testing protocol. Network and demand information for the mesoscopic model is transcribed from the Triangle Regional Model (TRM), which is the prime planning tool for the Raleigh-Durham-Chapel Hill region. The baseline demand information is calibrated using traffic volumes from roadside sensors at major freeway locations. Various options regarding scheduling, staging, lane closure, ramp closure in developing the scenarios are figured out from the contractor documents. Boxes colored blue in Exhibit II - 7, are custom made modules for this project.

The first custom made process was to determine how a link affected by work zone should be represented in the model. Information from previous work zones constructed in North Carolina is used to determine parameters for links that falls within a work zone. The second custom made process was to determine the assignment procedure. Our team determined that instead of getting a fixed diversion sensitivity we will try to model two extremes for the impacted scenario: no-diversion (ND) assignment method and user-equilibrium (UE) assignment method. As we are validating our model results with the field-observed information for the work zone at area 3, the ultimate goal would be to identify the factors that influence differing levels of diversion sensitivity and select the appropriate assignment method to adequately model similar work zones. The third custom made process for mesoscopic simulation process was in the extraction of results. As mentioned earlier it was difficult to observe and identify reasons behind the traffic impacts from a work zone on a network level. We have therefore selected four major freeway routes and fifteen other alternative arterial routes to analyze, explain and validate our model. Travel time statistic is a major tool of comparing the system- or route-level performance between the baseline and the work zone models. Also, volumes and speeds at particular locations of the network can provide us insight into the diversion and level of service within the network.

The base model was calibrated using traffic volume information from roadside traffic sensors. It was done to ensure the initial demand matrix adequately represent the condition of “before work zone” scenario. However, initially calibrated baseline model can become backdated due to the time-consuming process of mesoscopic modelling and delays in start date of actual construction work. Therefore, our team updated the baseline demand model routinely to capture the differences that can be attributed to the work zone. The recalibration process includes identification of sensors that represent the network flow adequately and creating a repository with average traffic volumes at these sensors.

3.0 WORK ZONE MONITORING: FIELD DATA ANALYSIS

3.1 Travel Time Data Analysis

The majority of the travel time analysis focused on Routes A through D both eastbound and westbound and in AM and PM peak periods. NCDOT also supplied data for two routes in the AM peak, one on I-40 westbound from NC 42 to I-40/I-440 split and the second on I-40 westbound from NC 42 to Poole Road Exit (Exit 15) on I-440, which were also used for travel time analysis. The first NCDOT route focuses on upstream analysis of the Area 3 work zone, while the second includes the Area 3 work zone.

On July 18, 2014, a new work zone configuration was introduced with traffic in Area 3 shifting from the inside lanes to the outside lanes. Part of the travel time analysis was completed to evaluate the effects of the two work zone configurations. Results through mid-July 2014 are presented separately for some routes to clearly distinguish the effects of the two work zone configurations on travel time. Configuration 1 has construction on the inside with open travel lanes on the outside, with work on the inside travel lanes completed in mid-July 2014. In Configuration 2, traffic shifted to the inside lanes with construction occurring on the outside. Two traffic camera images of Configuration 2 are shown in Exhibit II - 8 and Exhibit II - 9 below.

Along with examination of effects due to work zone configuration, the team also examined effects due to inclement weather or incidents. These factors combined with construction work can have severe impacts on travel times.

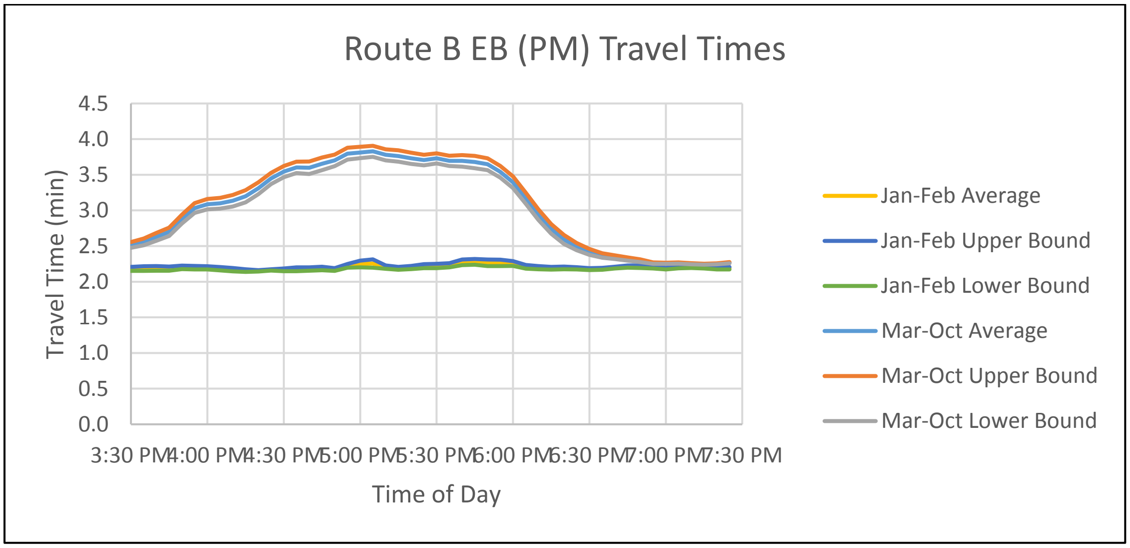
Exhibit II - 8 Camera view at Walnut Creek crossing on I-40 East of I-40/I-440 split

Exhibit II - 9 Camera view just north/east of I-40/I-440 split

3.1.1 In the Work Zone

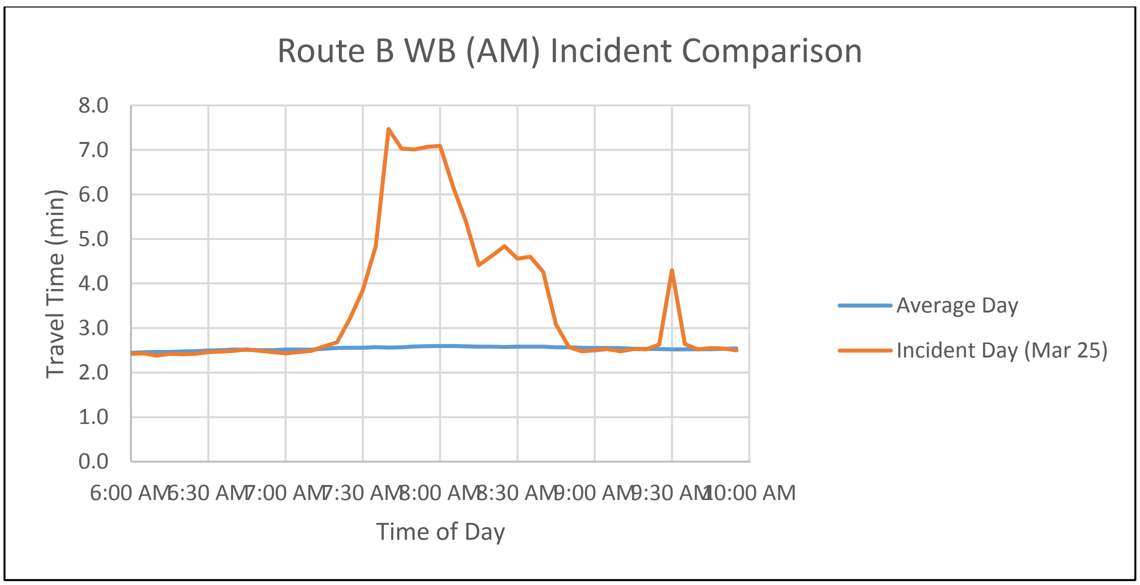
Route B as previously defined encompasses the Area 3 focus and was the primary focus for several areas of travel time analysis. After determining the average day for the route, outliers could be examined and compared against the average day to assess the effect of inclement weather or incidents. Data by day of week was also examined along with average travel times by month. Specific changes within the work zone were also considered for their impacts. For example, in early March 2014, installation of lane closures on I-440E was completed. This resulted in a near doubling of the average travel time in the work zone during the PM peak period, as shown in Exhibit II - 10.

Exhibit II - 10 Route B EB (PM) Travel Times



Incidents were also shown to have significant impacts in the work zone and on larger routes that encompassed the work zone. One example in the westbound AM peak had tripled travel times due to an incident in the I-440W merge lane which caused lane closures. This factor also suggests that lane closures have a great effect on travel times. The example for March 25, 2014 is shown in Exhibit II - 11.

Exhibit II - 11 Route B EB (AM) Incident Comparison



3.1.2 NCDOT Routes

3.1.2.1 Work Zone Configuration 1

The travel time analysis was performed using field travel time data provided by NCDOT and filtering out the outlier days. The filtering was based on incident reports provided by NCDOT and weather events affecting the area. The time duration of analysis prior to work zone configuration change is from February 3, 2014 to July 18, 2014. The average travel time variations over time by day of week are shown in Exhibit II - 12 and

Exhibit II - **13** for Configuration 1.

Exhibit II - 12 Average Travel Time on Westbound I-40 from NC42 to I-40/I-440 split in AM peak period –WZ Configuration 1

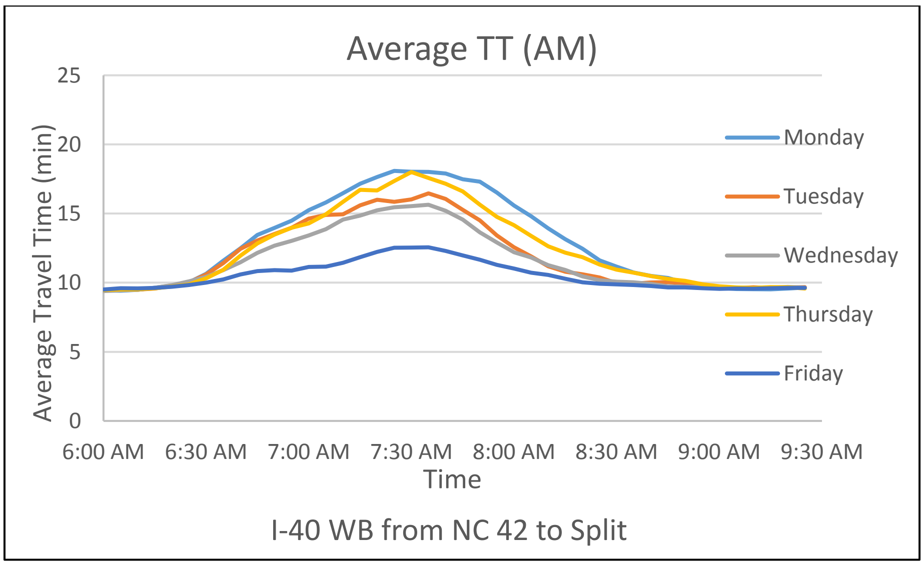
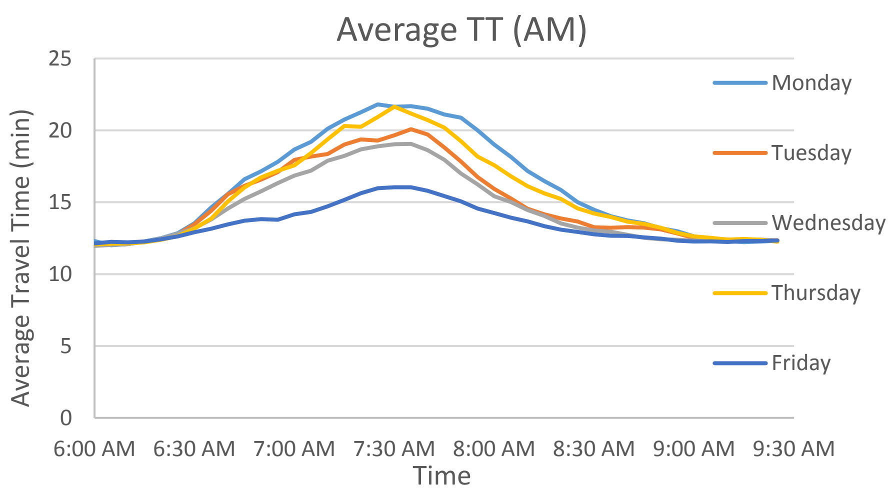


Exhibit II - 13 Average Travel Time on Westbound I-40 from NC42 to Poole Road Exit on I-440 in AM peak period –WZ Configuration 1



I-40 WB from NC 42 to I-440 WB Poole Rd Exit

The results in Exhibit II - 12 and Exhibit II -13 show an increasing trend in travel times from 6:30am to 7:30am as congestion builds upstream of the work zone, and a decreasing trend in travel times from 7:30am to 9:00am, which is quite consistent across different weekdays. Free flow travel times are achieved prior to 6:30am and after 9:00am. The peak travel time occurs between 7:30am to 7:40am, with travel times almost twice as high as the free flow travel time.

The average travel time on Monday is higher than the rest of weekdays. Tuesday, Wednesday and have similar travel time patterns while Thursday travel times are slightly lower than Mondays. Friday has the lowest average travel time on regular weekdays in the area of interest. The highest observed 5-minute average travel time on I-40 from NC 42 to the Poole Road Exit on I-440 prior to changed configuration was 23 minutes.

In addition to day-of-week analysis, the team compared the travel times across different months. The average travel time variations over time by different months are shown in Exhibit II - 14 and Exhibit II - 15.

Exhibit II - 14 Average Travel Time on Westbound I-40 from NC42 to I-40/I-440 split in AM peak period –Work Zone Configuration 1

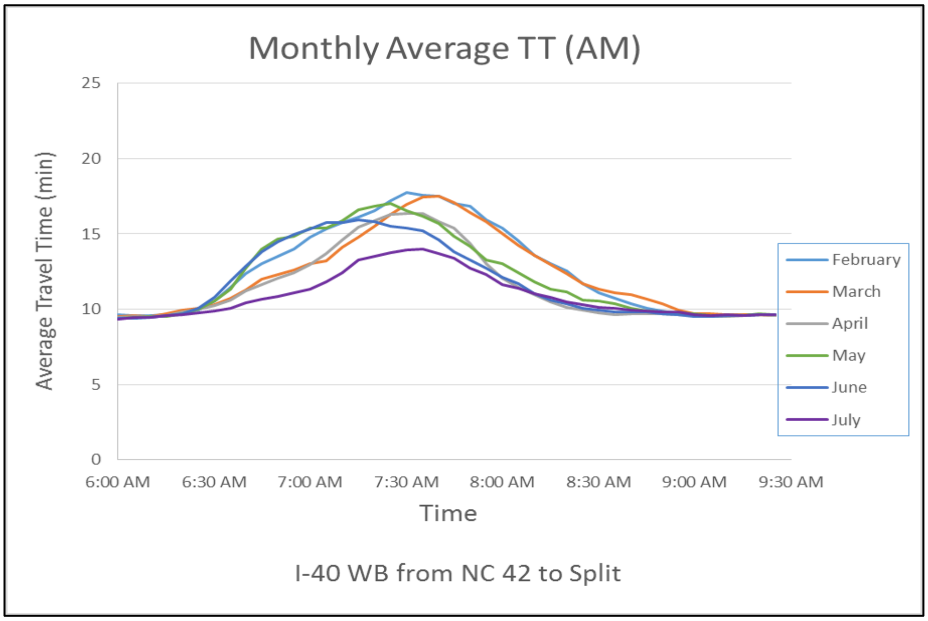
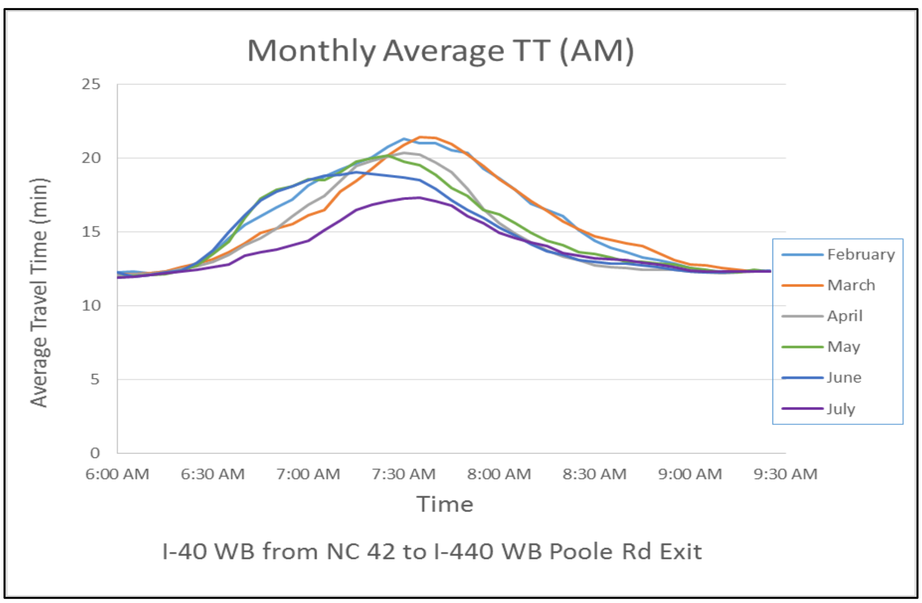


Exhibit II - 15 Average Travel Time on Westbound I-40 from NC42 to Poole Road Exit on I-440 in AM peak period –Work Zone Configuration 1

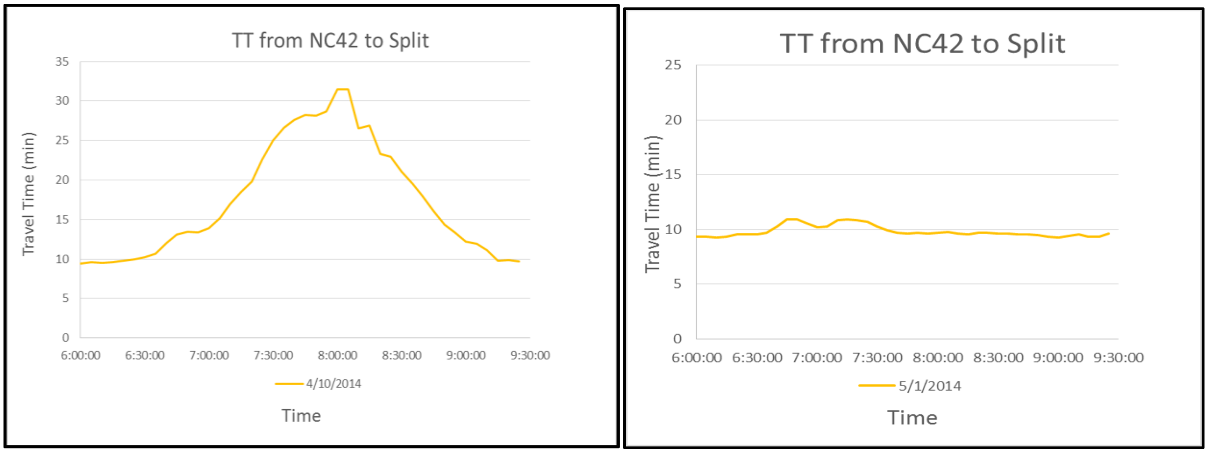


The results in Figure 11a and 11b show similar travel time patterns between February and March and among April, May, and June. Meanwhile, the travel time patterns in February and March are significantly different from the patterns on April, May, and June. During February and March, travel times are increasing from 6:30am to 7:40am and then are decreasing from 7:40am to 9:00am. During April, May, and June, travel times have an increasing trend from 6:30am to 7:15am and the peak time remain for 15 minutes. The decreasing trend is from 7:30am to 8:30am. The peak travel time on February and March is 2 minutes longer than that on April, May, and June. The graphs make apparent that the peak appears to have shifted earlier in April through June (with congestion starting around 6:40am) compared to February-March (with congestion starting around 7:10am).

Travel times for July appear to be lower than prior months, although a reduced sample size in this month for Configuration 1 could be influencing this result. Another possible explanation is summer break for university and public schools, which may reduce the AM peak travel demands for the summer months. Lower travel times over time may also be explained by a change in driver habits. This indicates that travelers may have adjusted their departure times along with the increasing demand reduction over time. Overall, the travel time curves for April through June have shifted to the left towards earlier departures, relative to February and March. One important consideration in this analysis is that daylight savings time started on March 9 in 2014, although the travel time shift isn't evident until April and May.

In the analysis, several days were identified as outlier days without significant incident or weather events. Exhibit II - 16 shows two of those outlier days of April 10th, and May 1st (right). April 10th represents a Thursday with unusually high travel times, but without any weather or incident events recorded. May 1 represents a Thursday with unusually low travel times, and in fact without any notable congestion or delays.

Exhibit II - 16 Travel Time on Westbound I-40 from NC42 to I-40/I-440 Split in AM peak period



3.1.2.2 Work Zone Configuration 2

The time duration of analysis after the work zone configuration change is from July 21, 2014 to December 31, 2014. Incident and weather events were filtered out of the analysis, as was done for Configuration 1. Exhibit II - 17 and Exhibit II - 18 shows the travel time trends for the two routes by day of week.

Exhibit II - 17 Average Travel Time on Westbound I-40 from NC42 to I-40/I-440 split in AM peak period – Work Zone Configuration 2

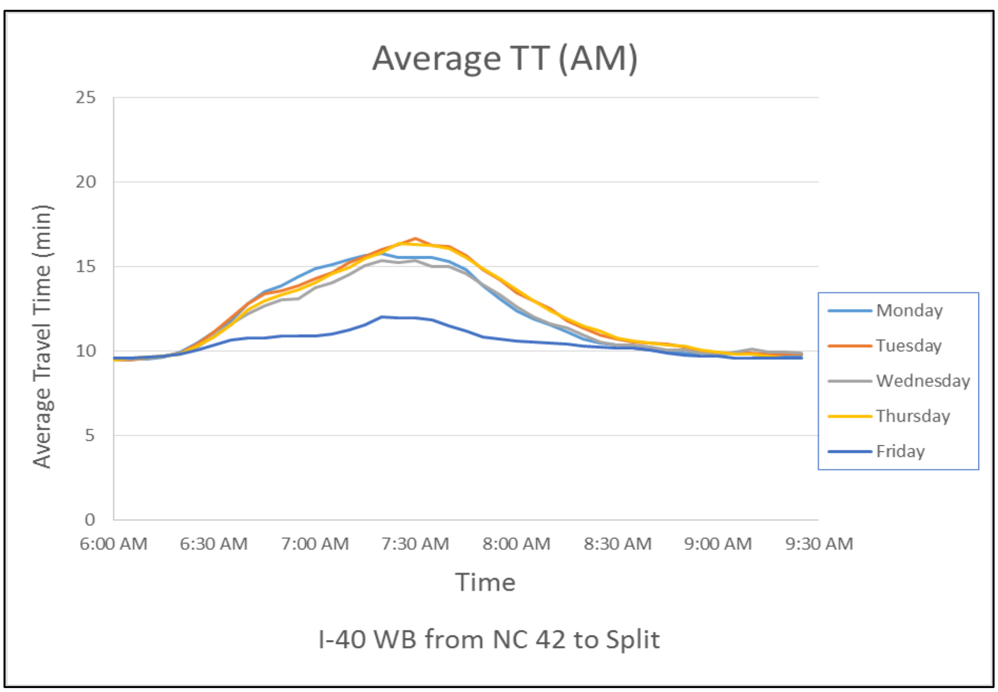
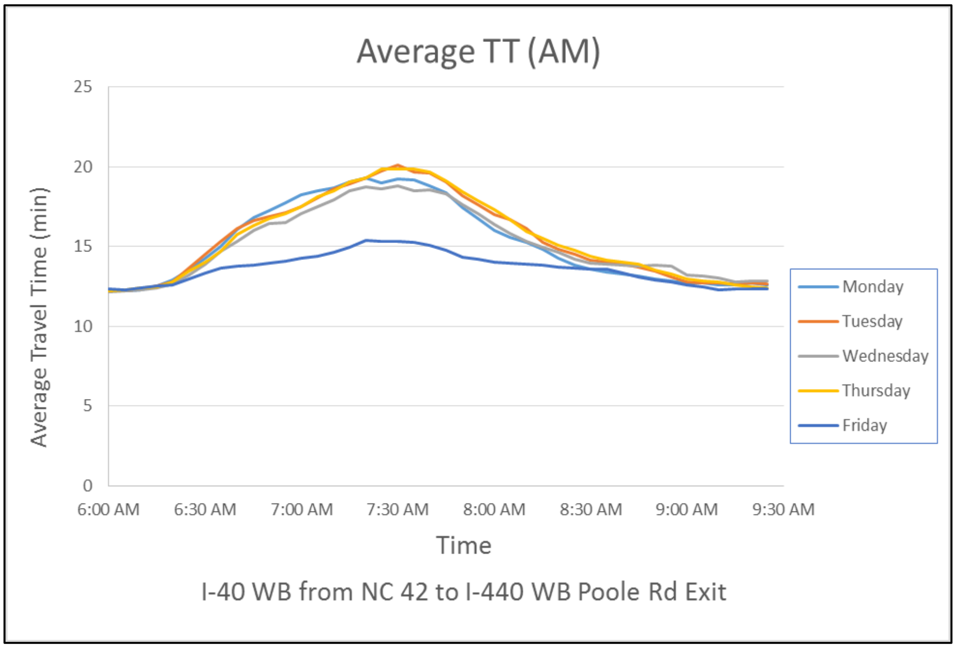


Exhibit II - 18 Average Travel Time on Westbound I-40 from NC42 to Poole Road Exit on I-440 in AM peak period – Work Zone Configuration 2



The results in Exhibit II - 17 and Exhibit II - 18 show similar trends in travel times for Monday through Thursday while Friday continues to have the lowest travel times. Compared to Configuration 1, it does appear that the travel time curves have shifted left toward earlier departure times and that overall travel times are lower.

The peak average travel time for the shorter route is approximately 16.2 minutes which is slightly lower than the peak average travel time observed for Configuration 1 Exhibit II - 12 of approximately 18.0 minutes. For the longer NCDOT route which encompasses the Area 3 work zone, travel times in Configuration 2 appear to be somewhat lower than what were shown in Figure 10b for Configuration 1. The prior peak average travel time of approximately 21.8 minutes (Monday and Thursday), is reduced to 15.7 minutes for a Monday and 16.3 minutes for a Thursday. This apparent reduction in traffic may be an indication for improved flow through the work zone due to the newly constructed pavement on the inside lanes of I-440. However, the results may also be biased as Configuration 2 data partially represent summer traffic with potential demand reductions during weekdays due to school closings.

Comparisons for the NCDOT routes by month for Configuration 2 follow. Exhibit II - 19 and Exhibit II - 20 show the travel times for the AM peak period.

Exhibit II - 19 Average Travel Time on Westbound I-40 from NC42 to I-40/I-440 split in AM peak period – Work Zone Configuration 2

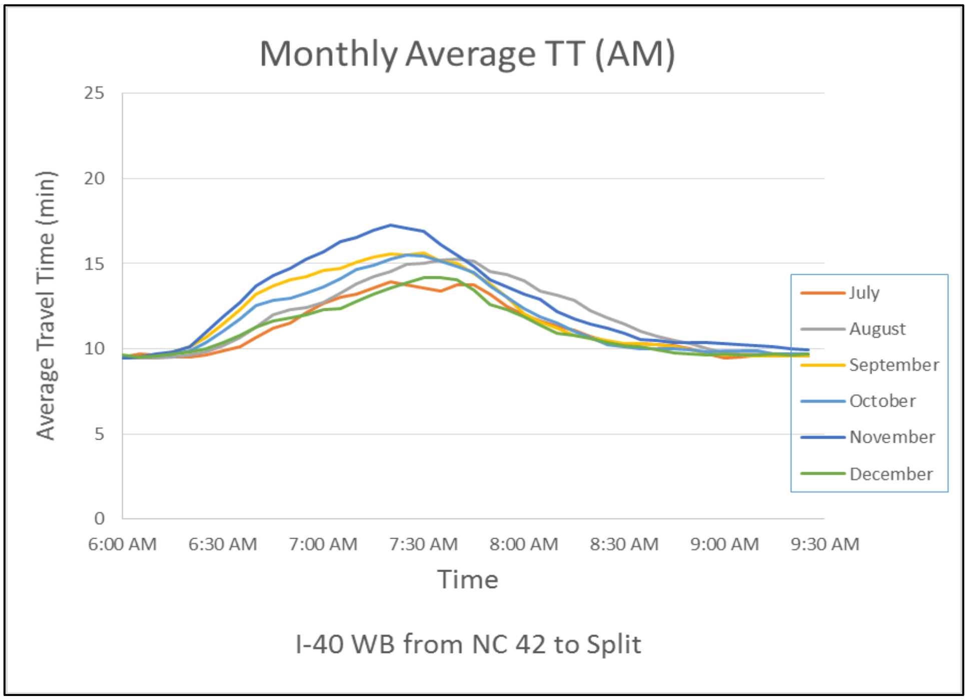
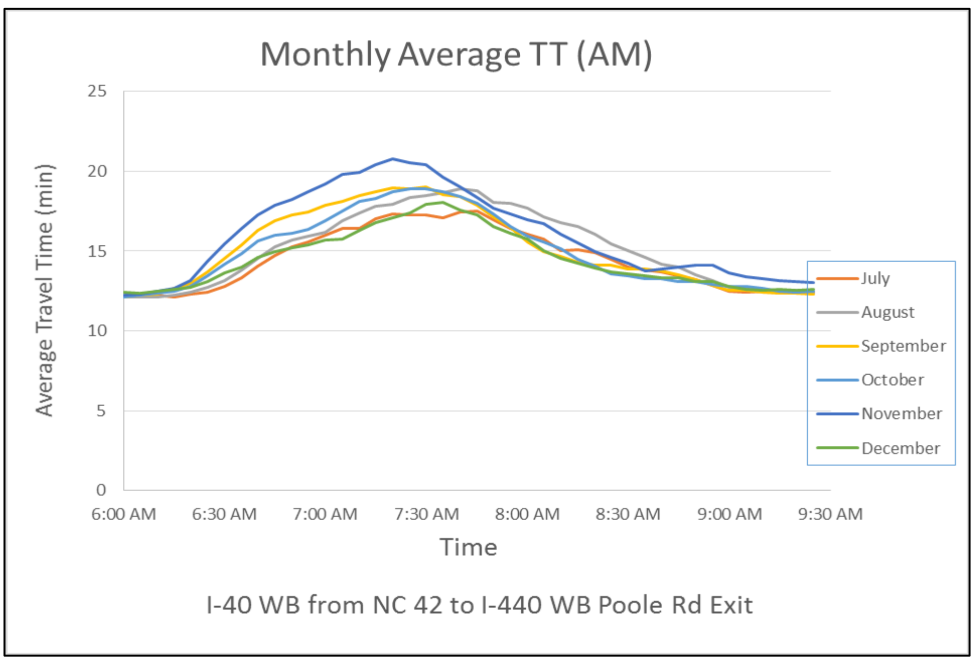


Exhibit II - 20 Average Travel Time on Westbound I-40 from NC42 to Poole Road Exit on I-440 in AM peak period – Current Work Zone Configuration

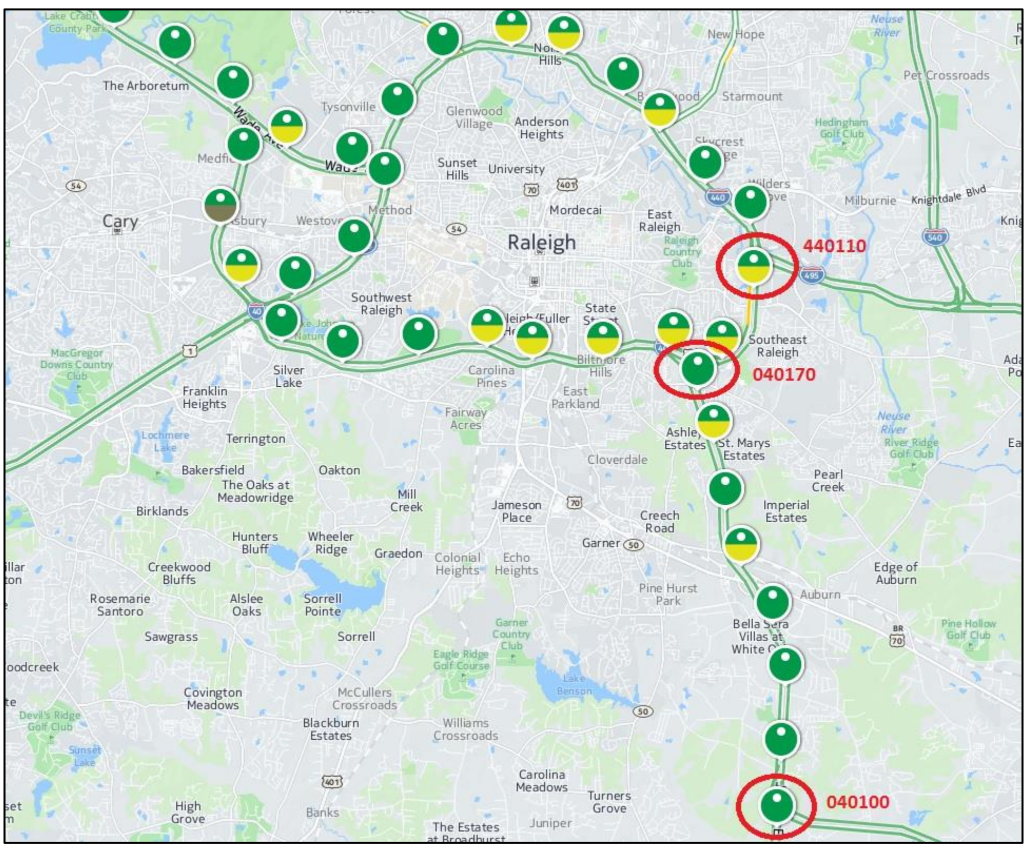


The monthly travel time graphs in Exhibit II - 20 show a fairly consistent trend of travel times across the months of July, August, September, October, and December, with November showing slightly higher peak travel times. The peak average travel times for July are lowest, which may be indicative of reduced demand over summer break for schools. August represents a mix of school and no-school traffic, with September representing the "regular" morning demand after universities and public schools are back in session. Overall, these travel times appear to be lower and have shifted toward earlier departure times compared to previous months. This reduction in travel time suggests that drivers were getting more familiar with the work zone, leaving earlier, or taking alternative routes.

3.2 Volume Data Collection and Analysis

The team used the HERE® website to collect and download traffic volume data. The database provides 5-min, 15-min, or 1-hour aggregated volume and speed data. The team collected volume data for each weekday from February to May 2014 for several sensors in and surrounding the work zone. However, for final analysis of Area 3, the team focused on three key sensors. Exhibit II - 21 shows a map of the sensors that were the primary focus for volume analysis. These sensors give a sense of the traffic volume in the area upstream of the work zone and in the work zone itself (Route B). Volume data was collected for similar time periods both prior to construction and during construction.

Exhibit II - 21 Key Sensors for Volume Analysis (HERE®)



Throughout the volume analysis section, all the volume values are from "average" days which exclude non-recurring sources of congestion (such as inclement weather or incidents). The outlier days for weather and incidents were filtered using collected weather data and using incident reports provided by NCDOT.

Exhibit II - 22 shows the volume level at different sensors along the route traveling westbound on I-40 from Exit 309 to Exit 301 during the AM peak hour (7:00 AM to 8:00 AM) before and during the Area 3 construction. The analysis was performed by averaging volumes for 12 normal weekdays in February 2014 and 20 normal weekdays in February 2013 to show the immediate impacts of the new work zone. In the volume vs. distance plots, the data points on the left hand side correspond to the sensors located inside the work zone. As the distance increases in Figure 3 (left to right), the sensors are located further from the work zone while traffic travels towards the work zone. The last sensor (040100) is located at Exit 309, approximately 10.5 miles from the first sensor in the work zone.

Exhibit II - 22 Comparison of Volume between WZ and NWZ at route 3

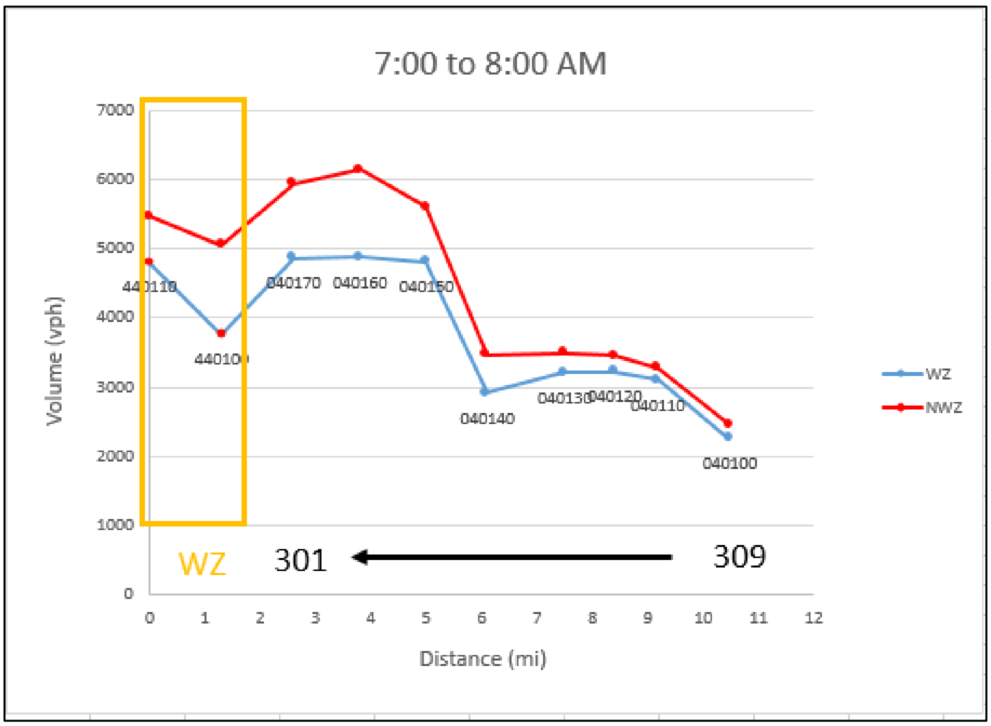


Exhibit II - 22 shows that the observed volume dropped with the start of construction activities. The closer to the work zone, the more significant is the volume decrease, which can be attributed to increased congestion. It is emphasized that the sensors measure "volume served" rather than the true demand, which may be metered by the congestion. However, for sensors further away from the work zone, the measured volumes are likely to be closer to the true demand. For sensor 040170 at Exit 301 (the upstream sensor closest to the work zone), the figure shows a volume reduction from 5936 vph to 4858 vph, which is an approximately 18% decrease during the 7:00 AM to 8:00 AM peak hour.

Exhibit II - 23 shows the average volume at each sensor traveling from Exit 4 on I-440 EB to Exit 293 on I-40 WB during the PM peak hour. The analysis was performed for the same days in February 2013 and 2014 as the previous route, both during construction and prior to construction. In the plots, the data points going from the left to the right represent the average volume of the sensors from the start point to end point of the route.

Exhibit II - 23 Comparison of Volume between WZ and NWZ at route 6

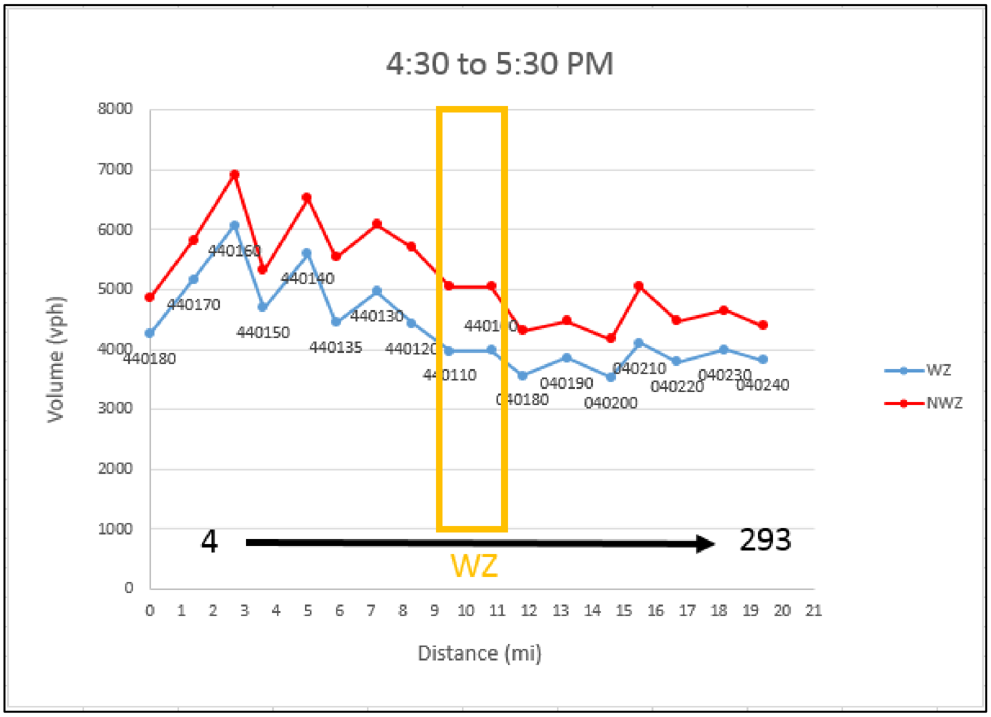
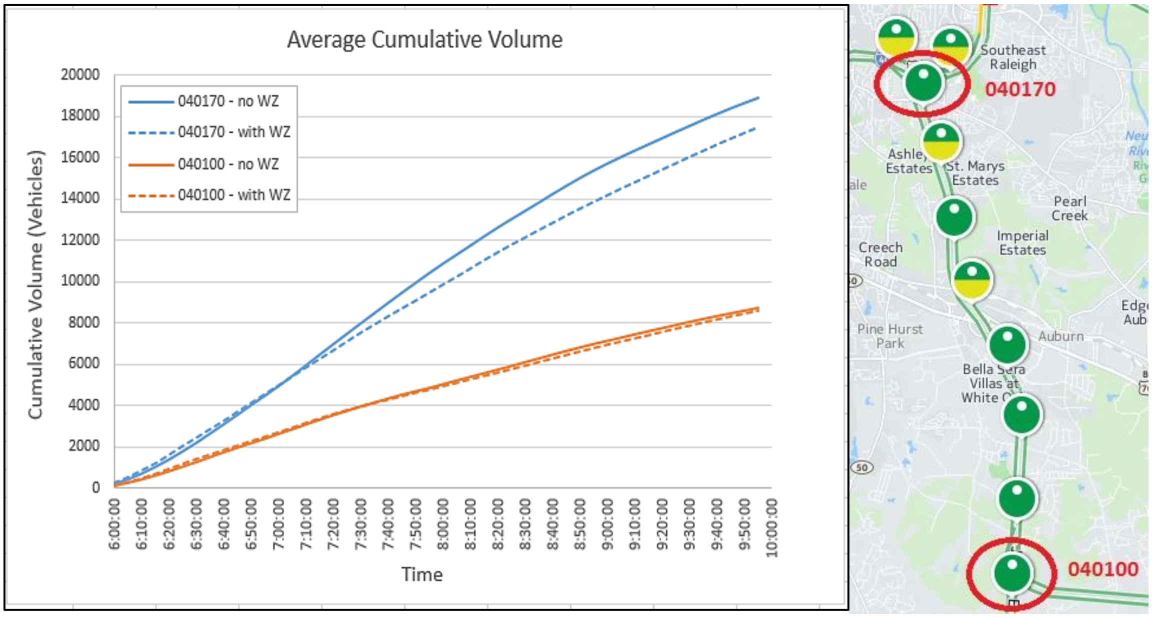


Exhibit II - 23 also shows significant volume reduction throughout the entire route. For sensors nearer to the work zone, the reduction in traffic volume is more significant. For sensor 440120 at Exit 14 on I-440, the graph shows a volume reduction from 5706 vph to 4427 vph, which is an approximately 22% decrease in the 4:30 PM to 5:30 PM peak hour. An interesting observation in Figure 4 is that the total traffic demand on I-440 dropped significantly even in segments upstream and downstream from the work zone. This includes segments upstream of the work zone when traveling the beltline in a clockwise direction, where traffic demands dropped by approximately 15%. A significant drop in traffic is also evident downstream of the work zone, where traffic volumes are down approximately 20% in the westbound direction of I-40 between Exits 301 and 293. These traffic reductions are at least partly related to a metering effect of the work zone, where throughput is reduced by the lane closures compared to similar days in 2013.

To further explore the volume reduction due to potential diversion effects, the team studied average cumulative traffic volume levels over time on the three key sensors to identify changes in traffic demand level. Exhibit II - 24 shows the results for sensors 040100 and 040170 during the AM peak period.

Exhibit II - 24 Average Cumulative Volume @sensor 040100 & 040170



As shown in Exhibit II - 24, for sensor 040170, which is just upstream of the work zone, the total number of vehicle counts during the AM peak period before construction (approximately 19200 vehicles) is significantly larger than that during the construction (approximately 17200 vehicles). The approximately 10% reduction may be due to drivers reacting to capacity loss in the construction zone and avoiding it by either selecting alternative routes or car-pooling, telecommuting, etc. It is emphasized here that the four-hour period starts and end in non-congested periods, to assure that the true demand is being measured. The estimated traffic reduction was approximately 13%. The difference between that earlier number and the new 10% estimate is that the former was an estimate for one typical day, while the new number represents an average over multiple days. Therefore, the team is more confident in this new estimate as an average reduction effect in the work zone, while recognizing that individual days may have a large effect (and some a smaller effect).

Exhibit II - 24 also shows the average cumulative volume over time for sensor 040100 (far upstream of work zone), which indicates no significant decrease in traffic volume due to the work zone.

Exhibit II - 24 Exhibit II - 27 present an analysis of average cumulative volume variation in different weeks from February to May to explore a traffic diversion effect over time. The figures are presented for sensor 040170 just upstream of the work zone, sensor 040100 far upstream of the work zone, and sensor 440100 within the work zone. The figures also show a comparison of before construction and during work zone patterns for the three sensors. Each column in each figure refers to the average of four-hour cumulative volumes during AM peak period (6:00am to 10:00am) of regular days in the corresponding week. The blue column refers to the average cumulative volume before work zone (data from 2013), while the orange color represents the volume in the work zone (data from 2014). The team filtered out outlier days with inclement weather conditions and incidents that significantly affected prevailing conditions. Week 1 represents the first week in February and week 15 represents the last week in May.

Exhibit II - 25 Average Cumulative Volume for different weeks @sensor 040170 in morning peak

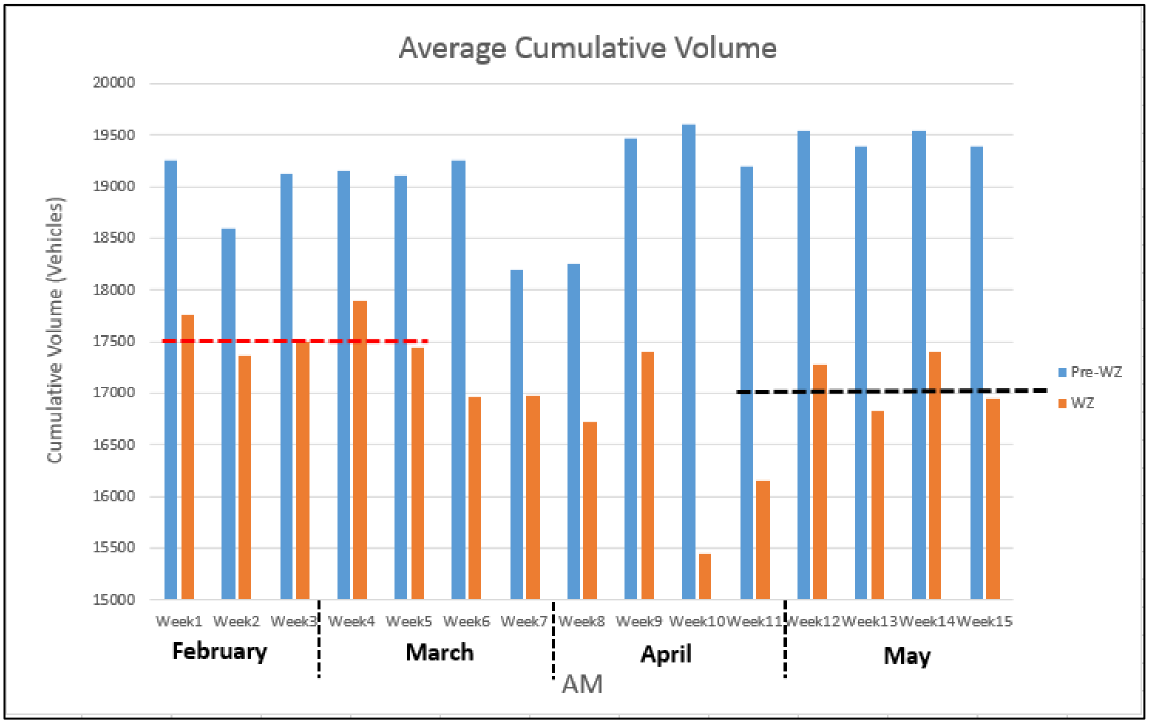
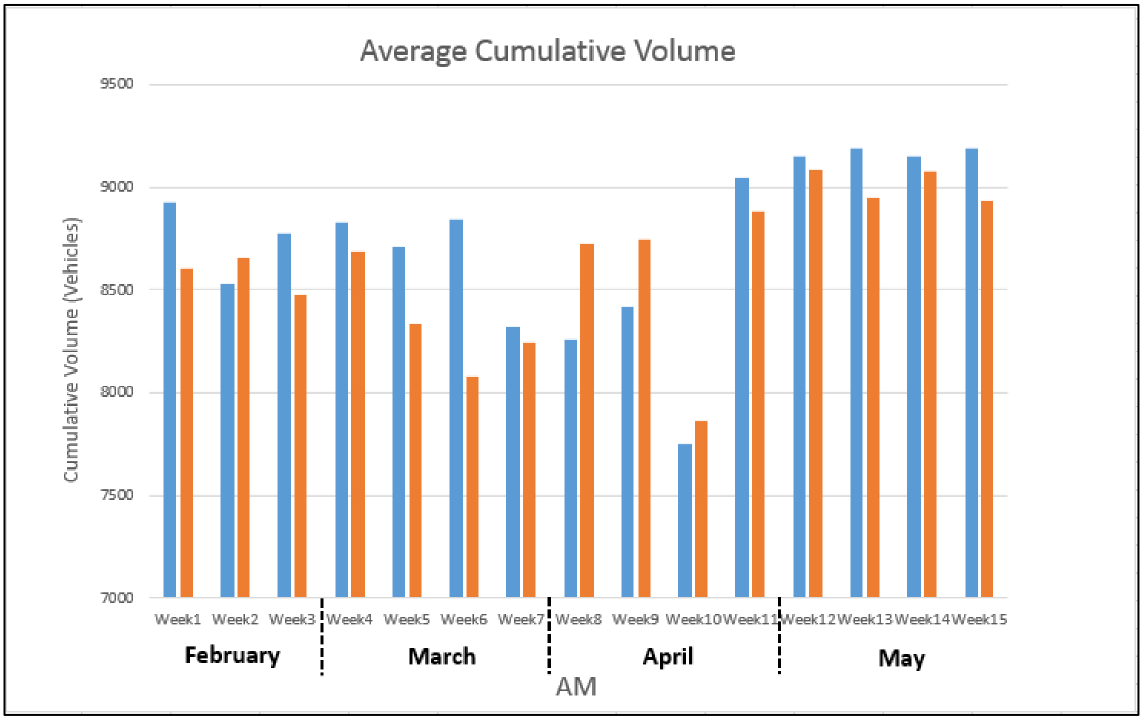


Exhibit II - 25 shows the average cumulative volume variation over days at sensor 040170 (just upstream of the work zone). As shown in the figure, the volume significantly decreased during work zone and the values before work zone were stable across different weeks. For the average cumulative volume during the work zone, the variation at the beginning of the construction period displayed fluctuation (from week 1 to week 5) and then remain stable along with the passage of time. The total number of vehicles at week 10 and Week 11 (duration from mid to the end of April) were abnormally lower than any other weeks, which may be attributable to lower traffic demand levels due to national and school holidays (spring holiday, spring break etc.).

Throughout the construction period from February to May, a reduction of volume of approximately 3% occurred on sensor 040170 when comparing the red dashed line (average of weeks 1 through 5) and the black dashed line (average of weeks 11 through 15). It reflected a reduction of approximately 3% in traffic demand level at this point after the travelers became familiar with the work zone. Further, the travel time variation in following section may explained by the above results. Demand levels in week 10 and 11 are excluded from this comparison due to unusually low volumes. These lower volumes can be seen on both sensors 040170 and 440100, suggesting a general trend across the region. The team attributes this drop to lower holiday traffic during spring break periods, but also suggests that this can be attributed to potential impacts from increased construction activity during these weeks.

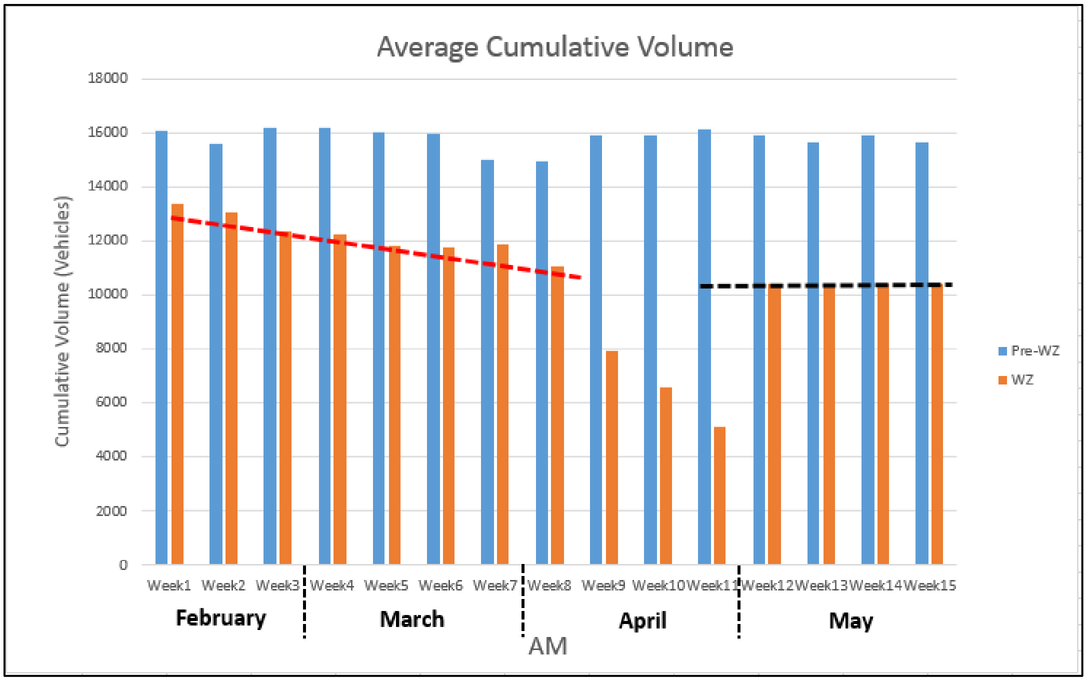
Exhibit II - 26 shows the average cumulative volume at sensor 040100 (far upstream of the work zone). No large demand reduction occurred during construction, which is consistent with the findings in Exhibit II - 22. The y-axis here is exaggerated to show a reduction of less than 200-300 vehicles at this upstream sensor, which is only about a 3% drop over the 4-hour period. So while some reduction in volume is evident, it is at a much lower magnitude than in the immediate viccinity of the work zone.

Exhibit II - 26 Average Cumulative Volume for different weeks @sensor 040100 in morning peak



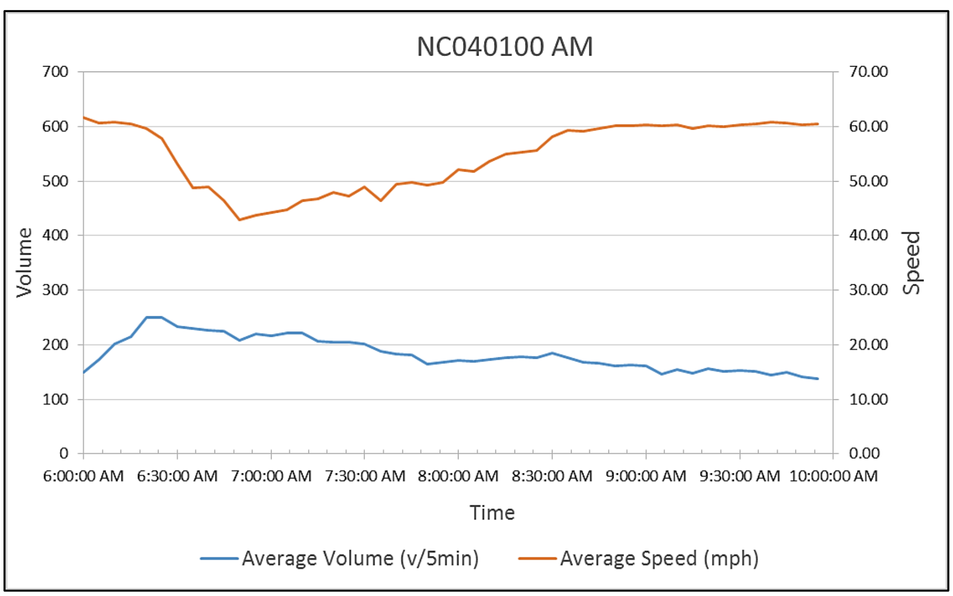
Finally, Exhibit II - 27 shows the variation of average cumulative volume at sensor 440100 (inside the work zone). The figure suggests a steady drop in traffic through the work zone from weeks 1 through 8 after construction, as indicated by the red dashed line. The lower values from week 9 to week 11 may refer to lower traffic demand at that time period. The demand level in weeks 12 through 15 appears stable at a level similar to week 8. Comparing the initial demand to this stable demand level, an approximate reduction of 26% in four-hour traffic demand is evident at sensor 440100 inside the work zone. It appeared to take approximately 8-10 weeks or 40-50 working days to reach this apparent equilibrium volume level. This equilibrium volume level of just over 10,000 vehicles over four hours represents an approximately 35% reduction over the four-hour pre-work zone throughout of that section.

Exhibit II - 27 Average Cumulative Volume for different weeks @ sensor 440100 in morning peak



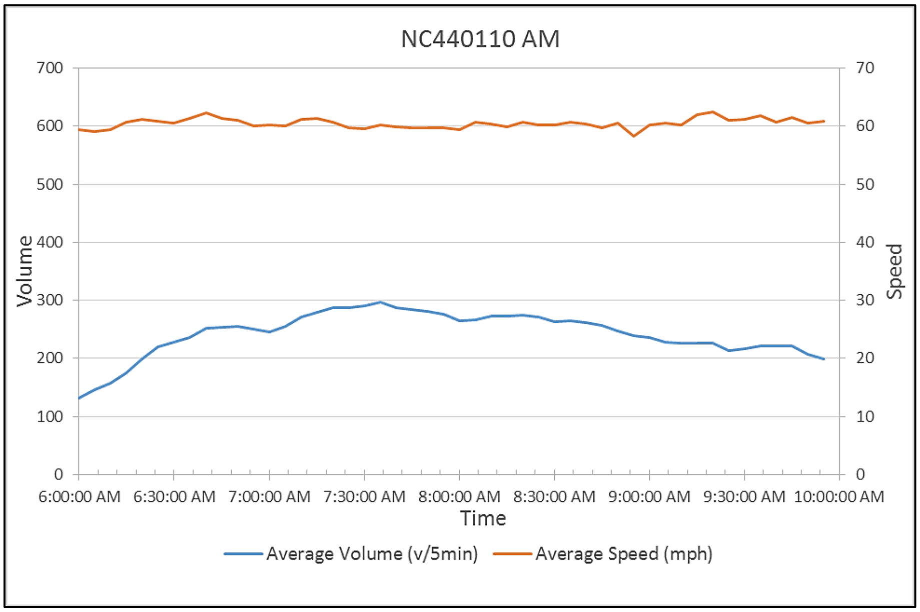
The team also examined volume versus speed effects over the three primary sensors for peak directions in peak periods. Exhibit II - 28 represents the trend over the AM peak for sensor 040100 heading in the westbound direction. While the volume peaks just before 6:30 AM and continues to decrease until 10:00 AM, speed sees a sharp decrease around 6:45 AM. After this initial steep decrease, speed rises steadily until the end of the peak period and never sees a drop below 40 mph on average. This analysis takes into account the average days over the study period.

Exhibit II - 28 Volume vs. speed in AM peak for Sensor 040100



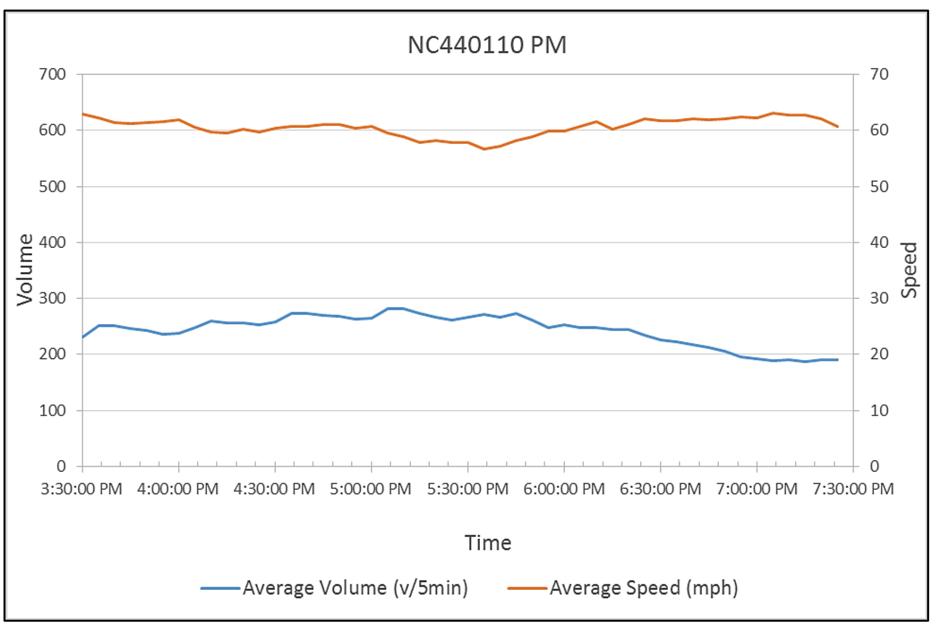
Sensor 440110 has a volume peak occuring at 7:35 AM, as vehicles travel along the route. This is shown in Exhibit II - 29 However, speeds remain fairly constant around 60 mph during the whole peak period. This seems slightly unusual, as this sensor is located within the work zone, but could suggest that more people head west on I-40, rather than taking I-440 at the split, in order to avoid the work zone.

Exhibit II - 29 Volume vs. speed in AM peak for Sensor 440110



In the PM peak direction for sensor 440110, both volume and speed remain stable, also suggesting that drivers are taking alternative routes to avoid the work zone. This is shown in Exhibit II - 30. The lowest average speed is 57 mph, occuring at 5:35 PM.

Exhibit II - 30 Volume vs. speed in PM peak for Sensor 440110



4.0 MACROSCOPIC MODELING RESULTS FOR AREA 3

4.1FREEVAL Overview

The FREEVAL (FREeway EVALuation) tool was first developed as a computational engine for the Highway Capacity Manual (HCM) freeway facilities methodology in 2000. It has since gone through several improvements and the latest FREEVAL 2010 is now executed in a Microsoft Excel – Visual Basic for Applications (VBA) platform. The tool provides an easy to use and reliable environment for freeway facilities analysis. The tool is also capable of modeling different work zone scenarios.

4.2FREEVAL Analysis

Corridor Analysis Results (FREEVAL)

In the first analysis, the FREEVAL tool was used to evaluate the impact of the work zone on a long commuter route from Exit 312 in Clayton, NC to Exit 284 in Cary, NC. The route selected for this analysis was “Route D”, which uses the I-440 northern loop to complete the roughly 30-mile trip. All traffic volumes and geometry inputs were adapted from prior work zone analysis for NCDOT performed as part of project 2012-36. The analysis included the AM peak period (6:00am to 10:00am) in the westbound direction and PM peak period (3:30pm to 7:30pm) in the eastbound direction.

Exhibit II - 31 shows the results of the AM Peak period analysis. The table highlights the maximum queue length, maximum travel time, free-flow travel time, and the maximum travel time index observed during that period. FREEVAL results are shown for the base case, the expected work zone scenario without diversion effect, and the work zone with a 20% traffic diversion onto other routes.

Exhibit II - 31 AM Peak Period FREEVAL Results

Performance Measure	AM Peak Westbound (6:00-10:00AM)		
	Base	WZ (No Diversion)	WZ (20% Div.)
Max Queue Length (mi)	0.2	8.0	5.4
Max Travel Time (min)	34.7	92.3	75.0
Free-Flow Travel Time (min)	27.3	27.3	27.3
Max Travel Time Index (TTI)	1.27	3.38	2.75

The table shows that minimal queuing is present on the selected route in the base case, which increases to an 8.0 mile queue with the work zone. The associated increase in travel time goes from 34.7 minutes to 92.3 minutes, in the peak fifteen-minute period – a travel time index of 3.38. Under consideration of 20% traffic diversion, the AM peak queue is estimated at 5.4 miles and a maximum travel time of 75.0 minutes and a TTI of 2.75.

Results for the PM peak period are shown in Exhibit II - 32. The results show a 1-mile queue in the base condition increase to 6.6 miles with the work zone. The travel time accordingly increases from a maximum of 35.0 minutes to a maximum of 74.4 minutes. With a 20% diversion, the queue is reduced to 2.8 miles and the travel time to 52.8 (a TTI of 1.93).

Exhibit II - 32 PM Peak Period FREEVAL Results

	PM Peak Eastbound (3:30-7:30pm)		
Performance Measure	Base	WZ (No Diversion)	WZ (20% Div.)
Max Queue Length (mi)	1.0	6.6	2.8
Max Travel Time (min)	35.0	74.4	52.8
Free-Flow Travel Time (min)	27.4	27.4	27.4
Max Travel Time Index (TTI)	1.28	2.72	1.93

In addition to these numbers, FREEVAL provides the ability to output color-coded travel time contour plots, which are shown in Exhibit II - 33 for the AM Peak and Exhibit II - 34 for the PM Peak. Exhibit II - 33 shows little congestion in the AM Peak period prior to the work zone. With the work zone, the queue extends across various segments upstream of the work zone, but it well contained within the time-space domain (no spillover effects). With the 20% diversion, the size of the low-speed region is reduced further.

In the PM peak period, some isolated queuing hotspots can be seen in the base file. With the work zone, more significant queuing is evident towards the end of the facility starting at the US264 interchange and the work zone. The PM Peak queue is contained within the analysis length, but is maintained past the four-hour analysis window. With 20% diversion or traffic reduction, the queue length is reduced significantly.

Exhibit II - 33 Speed Contour Plots - AM Peak

	Segment																															
Time	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
1	63	70	62	70	64	69	70	61	69	67	70	65	70	62	70	63	70	70	55	70	70	64	70	54	70	60	61	68	55	70	64	64
2	63	70	62	70	64	69	70	61	69	65	70	65	70	61	70	63	70	70	55	70	70	64	70	50	70	57	61	68	53	70	64	64
3	63	70	62	70	63	69	70	61	69	64	70	65	70	60	70	63	70	70	55	70	70	63	70	49	70	56	60	68	54	70	64	64
4	63	70	62	70	63	69	70	61	69	62	70	65	70	60	70	62	70	70	55	70	70	62	70	49	70	55	59	68	54	70	64	64
5	63	70	62	70	64	69	70	61	69	60	69	65	70	62	70	62	70	70	55	70	70	63	70	48	70	53	60	68	51	70	64	64
6	63	69	62	70	61	69	55	61	60	59	69	62	67	63	70	59	65	65	55	70	70	63	70	45	70	51	60	68	47	70	64	60
7	63	68	62	70	49	20	53	61	58	57	69	61	65	63	69	57	61	61	55	70	70	65	70	44	69	47	61	68	41	70	62	60
8	63	69	62	70	33	22	54	61	58	56	69	60	64	64	68	55	58	58	55	70	70	65	70	45	69	45	61	68	38	70	62	60
9	63	68	62	70	63	69	58	61	61	56	69	59	63	64	66	56	58	58	55	70	70	66	70	45	69	43	61	68	36	70	62	61
10	63	70	62	70	63	69	63	61	65	58	69	63	68	64	70	60	65	65	55	70	70	66	70	50	70	49	61	68	44	70	63	61
11	63	70	61	70	62	69	61	61	64	58	69	63	69	63	70	61	67	67	55	70	70	66	70	52	70	54	60	68	53	70	64	60
12	63	70	61	70	62	69	60	61	63	59	69	63	69	64	70	62	68	68	55	70	70	65	70	54	70	56	61	68	54	70	64	61
13	63	70	61	70	61	69	59	61	63	58	69	63	69	64	70	62	68	68	55	70	70	64	70	56	70	57	60	68	55	70	64	61
14	63	70	62	70	63	69	66	61	67	58	69	64	70	64	70	62	69	69	55	70	70	64	70	57	70	58	58	67	57	70	64	62
15	63	70	61	70	64	69	68	61	68	59	69	64	70	64	70	63	70	70	55	70	70	66	70	58	70	56	60	68	55	70	65	63
16	63	70	62	70	64	69	67	61	68	59	69	64	70	64	70	63	70	70	55	70	70	65	70	58	70	57	60	68	56	70	66	63

Time	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70
1	62	67	62	58	70	57	59	63	48	65	59	64	59	65	60	65	59	63	64	46	49	64	52	65	53	65	56	70	65	69	68	70	65	69	64	70	65	70
2	62	67	58	55	70	54	59	63	42	65	57	64	58	65	60	65	59	63	64	46	48	64	52	65	52	65	55	70	65	69	67	70	64	69	64	70	64	70
3	61	67	57	56	70	56	59	63	41	65	57	64	59	65	60	65	59	63	64	52	48	64	54	65	53	65	56	70	65	69	67	70	64	69	64	70	64	70
4	62	67	55	58	70	57	59	63	49	65	56	64	59	65	59	65	59	63	65	51	48	64	53	65	53	65	57	70	65	69	67	70	64	69	65	70	64	70
5	61	67	52	56	70	55	59	63	44	65	54	64	58	65	60	65	59	63	64	52	49	64	52	65	52	65	56	70	64	69	66	70	64	69	66	70	64	70
6	60	67	51	52	70	52	59	63	39	65	51	63	57	64	60	65	58	63	64	32	46	64	47	65	47	63	56	70	63	68	66	69	63	68	66	70	63	68
7	60	67	49	48	69	49	58	63	30	65	50	63	56	61	60	64	57	61	61	19	46	63	47	65	47	62	54	70	63	68	66	69	63	68	66	69	62	67
8	60	65	45	49	69	47	58	63	30	65	48	63	57	62	59	65	57	62	62	38	46	63	48	65	47	62	55	70	63	68	66	69	63	68	66	70	62	67
9	61	64	47	49	68	48	58	63	32	65	50	63	57	63	59	65	58	63	64	50	49	64	51	65	50	65	57	70	64	69	67	70	64	69	66	70	63	69
10	61	67	50	51	70	52	58	63	32	65	49	63	58	64	59	65	59	63	64	51	49	64	53	65	51	65	57	70	65	69	67	70	64	69	66	70	63	69
11	60	67	52	57	70	55	58	63	40	65	48	63	59	65	59	65	60	64	65	49	50	64	53	65	51	65	58	70	65	69	67	70	64	69	65	70	64	70
12	61	67	52	56	70	55	58	63	42	65	48	63	59	65	59	65	60	64	65	51	50	64	53	65	51	65	57	70	65	69	67	70	63	69	65	70	65	70
13	61	67	53	59	70	58	58	63	54	65	54	64	59	65	59	65	60	64	65	52	51	64	55	65	53	65	58	70	66	69	68	70	64	69	66	70	65	70
14	62	68	55	59	70	60	57	63	55	65	58	64	59	65	58	65	60	64	65	55	53	64	56	65	56	65	60	70	66	69	67	70	66	69	67	70	66	70
15	63	68	56	58	70	58	58	63	49	65	58	64	59	65	59	65	60	64	65	51	53	64	55	65	54	65	58	70	66	69	67	70	65	69	68	70	65	70
16	63	68	56	59	70	58	58	63	51	65	59	64	59	65	59	65	60	64	65	52	52	64	54	65	54	65	59	70	66	69	67	70	65	69	68	70	65	70

(a) Base Case AM

	Segment																															
Time	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
1	63	70	62	70	64	69	70	61	69	67	70	65	70	62	70	63	70	70	55	51	51	51	54	49	70	61	61	68	57	70	64	64
2	63	70	62	70	64	69	70	61	69	65	70	65	70	61	70	63	70	70	53	40	40	40	51	34	69	58	61	68	54	70	64	64
3	63	70	62	70	63	69	70	61	69	65	70	65	70	60	70	63	70	70	50	37	37	37	51	30	69	56	60	68	56	70	64	64
4	63	70	62	70	63	69	70	61	69	63	70	65	70	60	70	62	70	70	47	32	32	32	52	32	69	56	59	68	56	70	64	64
5	63	70	61	70	63	69	63	61	65	61	70	64	69	61	70	61	70	22	25	25	25	25	48	29	69	54	60	68	53	70	64	61
6	63	69	62	70	61	69	55	61	60	59	69	62	67	63	70	37	14	10	25	25	25	25	47	24	69	51	60	68	48	70	64	60
7	63	68	62	70	49	20	53	61	58	57	69	61	60	26	8	8	8	8	25	25	25	25	46	25	69	48	61	68	41	70	63	60
8	63	69	62	70	33	22	54	61	69	35	16	13	8	7	6	8	8	8	25	25	25	25	43	30	69	45	61	68	38	70	63	60
9	63	68	62	70	63	69	18	10	7	5	5	6	6	6	5	7	7	7	25	25	25	25	42	32	69	44	61	68	37	70	63	61
10	62	70	62	70	41	11	10	9	7	7	5	7	7	7	6	8	7	7	25	25	25	25	39	32	69	49	61	68	45	70	63	61
11	63	70	61	70	25	10	11	11	9	9	6	10	9	9	7	12	10	10	25	25	25	25	40	23	69	54	61	68	54	70	64	61
12	63	70	61	70	58	68	21	25	14	37	19	26	17	21	13	26	18	23	25	25	25	25	42	13	69	57	60	68	54	70	64	61
13	63	70	61	70	58	68	67	67	37	60	69	52	41	35	16	28	18	64	52	33	33	33	49	36	69	58	61	68	56	70	64	62
14	63	70	62	70	58	68	70	61	69	70	70	48	70	70	61	44	26	70	53	31	31	31	49	40	69	59	60	68	58	70	65	62
15	63	70	61	70	70	70	70	61	69	59	69	69	70	65	70	70	70	70	33	25	25	25	50	48	70	57	58	67	56	70	64	62
16	63	70	62	70	70	70	70	61	69	60	69	69	70	65	70	59	70	27	25	25	25	25	45	43	70	57	60	68	56	70	65	63

Time	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70
1	62	67	63	58	70	58	59	63	48	65	59	64	59	65	60	65	59	63	64	46	50	64	53	65	53	65	56	70	65	69	68	70	65	69	64	70	65	70
2	62	67	58	56	70	55	59	63	42	65	57	64	58	65	60	65	59	63	64	46	49	64	52	65	52	65	56	70	65	69	67	70	64	69	64	70	64	70
3	61	67	57	57	70	56	59	63	41	65	57	64	59	65	60	65	59	63	64	52	49	64	54	65	53	65	57	70	65	69	67	70	64	69	64	70	64	70
4	62	67	56	59	70	58	59	63	49	65	57	64	59	65	59	65	59	63	65	51	48	64	53	65	53	65	57	70	65	69	67	70	64	69	65	70	64	70
5	61	67	53	57	70	56	58	63	44	65	54	64	58	65	60	65	59	63	64	52	49	64	53	65	52	65	57	70	65	69	67	70	64	69	67	70	64	70
6	60	67	51	53	70	52	59	63	39	65	51	63	57	64	60	65	58	63	64	33	46	64	47	65	47	63	56	70	63	68	66	70	63	68	66	70	63	68
7	60	67	49	48	70	49	58	63	30	65	50	63	56	62	60	65	57	62	62	23	46	64	47	65	47	62	54	70	63	68	66	69	63	68	66	70	62	67
8	60	67	45	49	70	48	58	63	30	65	49	63	57	62	60	65	57	63	63	39	46	64	48	65	47	62	55	70	63	68	66	69	63	68	66	70	62	67
9	61	67	47	50	69	48	58	63	32	65	50	63	58	64	59	65	58	63	64	50	49	64	52	65	50	65	57	70	64	69	67	70	64	69	66	70	63	69
10	61	67	50	52	69	52	58	63	32	65	49	63	58	64	59	65	59	63	64	51	50	64	53	65	51	65	57	70	65	69	67	70	64	69	66	70	63	69
11	61	67	53	58	70	55	58	63	40	65	48	63	59	65	59	65	60	64	65	48	50	64	54	65	51	65	58	70	65	69	67	70	64	69	65	70	64	70
12	61	67	52	57	70	55	58	63	42	65	48	63	59	65	59	65	60	64	65	51	50	64	53	65	52	65	57	70	65	69	67	70	63	69	65	70	65	70
13	62	67	54	60	70	59	58	63	54	65	54	64	59	65	59	65	60	64	65	52	52	64	55	65	53	65	58	70	66	69	68	70	64	69	66	70	65	70
14	62	68	56	60	70	60	57	63	56	65	58	64	59	65	58	65	60	64	65	55	53	64	56	65	57	65	60	70	66	69	67	70	66	69	67	70	66	70
15	62	67	57	58	70	58	58	63	50	65	58	64	59	65	59	65	60	64	65	52	53	64	55	65	54	65	58	70	66	69	67	70	65	69	68	70	65	70
16	63	68	57	59	70	59	58	63	51	65	59	64	59	65	59	65	60	64	65	52	53	64	54	65	54	65	59	70	66	69	67	70	65	69	68	70	65	70

(b) AM Work Zone without Diversion Effect

	Segment																															
Time	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
1	63	70	62	70	64	69	70	61	69	68	70	65	70	62	70	63	70	70	55	53	53	53	54	51	70	61	61	68	57	70	65	65
2	63	70	62	70	64	69	70	61	69	66	70	65	70	61	70	63	70	70	53	47	47	47	52	44	70	59	61	68	55	70	65	65
3	63	70	62	70	64	69	70	61	69	66	70	65	70	60	70	63	70	70	52	46	46	46	53	43	70	58	60	68	56	70	65	65
4	63	70	62	70	64	69	70	61	69	64	70	65	70	61	70	63	70	70	50	43	43	43	53	43	70	57	59	68	56	70	64	64
5	63	70	62	70	64	69	70	61	69	62	70	65	70	62	70	63	70	70	41	30	30	30	49	37	69	56	60	68	54	70	64	64
6	63	70	62	70	63	69	65	61	67	61	70	64	70	63	70	62	70	20	25	25	25	25	47	32	69	54	60	68	51	70	64	61
7	63	70	62	70	62	69	61	61	64	60	69	63	68	64	70	41	12	8	25	25	25	25	44	29	69	52	61	68	47	70	64	61
8	63	70	62	70	62	69	60	61	62	59	69	62	70	32	8	8	8	8	25	25	25	25	43	35	69	50	61	68	45	70	64	61
9	63	70	62	70	62	69	58	61	60	69	26	17	8	6	5	7	7	7	25	25	25	25	42	36	69	49	61	68	44	70	64	61
10	62	70	62	70	63	69	70	32	19	7	5	7	7	7	5	7	7	7	25	25	25	25	39	35	69	53	61	68	49	70	64	62
11	63	70	61	70	64	69	66	23	13	10	7	10	9	9	7	11	10	10	25	25	25	25	40	28	69	56	61	68	55	70	65	62
12	63	70	62	70	64	69	70	61	69	30	19	27	20	21	13	25	18	28	33	26	26	26	42	19	69	58	60	68	55	70	64	62
13	63	70	61	70	64	69	70	61	69	60	69	70	70	69	28	36	22	70	53	30	30	30	48	38	69	59	61	68	57	70	65	62
14	63	70	62	70	64	69	70	61	69	60	69	69	70	64	70	70	70	69	54	36	36	36	50	44	70	59	59	68	58	70	65	63
15	63	70	61	70	64	69	70	61	69	61	70	67	70	65	70	64	70	70	43	28	28	28	47	46	70	58	59	68	57	70	65	63
16	63	70	62	70	64	69	70	61	69	61	70	69	70	65	70	64	70	70	43	45	45	45	51	50	70	59	60	68	58	70	65	63

Time	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70
1	62	68	64	59	70	59	59	63	51	65	60	64	60	65	60	65	60	63	65	50	51	64	54	65	55	65	58	70	66	69	68	70	65	69	65	70	66	70
2	62	68	60	57	70	57	59	63	47	65	58	64	59	65	60	65	59	63	65	50	50	64	54	65	54	65	57	70	66	69	68	70	65	69	64	70	65	70
3	62	67	59	58	70	58	59	63	47	65	59	64	59	65	60	65	60	63	65	53	50	64	55	65	55	65	58	70	65	69	67	70	65	69	65	70	65	70
4	62	68	58	59	70	59	58	63	52	65	58	64	59	65	59	65	60	63	65	53	50	64	54	65	55	65	58	70	65	69	67	70	64	69	65	70	65	70
5	62	67	55	58	70	58	58	63	48	65	56	64	59	65	60	65	59	63	65	53	51	64	54	65	54	65	58	70	65	69	67	70	64	69	67	70	65	70
6	61	67	54	55	70	55	58	63	45	65	53	64	59	65	60	65	59	63	64	44	49	64	50	65	51	65	58	70	65	69	67	70	64	69	67	70	64	70
7	61	67	52	52	70	53	58	63	39	65	53	63	58	65	60	65	59	63	64	39	49	64	50	65	50	65	57	70	65	69	67	70	64	69	67	70	64	69
8	61	67	49	53	70	52	58	63	39	65	51	63	58	65	60	65	59	63	64	46	49	64	51	65	50	65	57	70	64	69	67	70	64	69	66	70	64	69
9	61	67	51	53	70	52	58	63	40	65	53	63	59	65	60	65	59	63	65	52	51	64	53	65	53	65	58	70	65	69	67	70	64	69	67	70	64	70
10	62	67	53	55	70	55	58	63	40	65	52	63	59	65	60	65	60	63	65	52	51	64	55	65	53	65	58	70	66	69	67	70	64	69	66	70	64	70
11	62	67	55	59	70	57	58	63	46	65	51	63	60	65	59	65	60	64	65	51	52	64	55	65	53	65	59	70	66	69	68	70	64	69	66	70	65	70
12	62	67	55	58	70	57	58	63	47	65	51	63	60	65	59	65	61	64	65	52	52	64	55	65	54	65	58	70	66	69	68	70	64	69	65	70	65	70
13	62	67	56	60	70	60	58	63	55	65	56	64	59	65	59	65	61	64	65	53	53	64	57	65	55	65	59	70	66	69	68	70	65	69	66	70	66	70
14	63	68	58	60	70	61	57	63	56	65	59	64	59	65	59	65	61	64	65	55	54	64	57	65	57	65	61	70	66	69	67	70	66	69	67	70	66	70
15	63	68	59	59	70	60	58	63	52	65	60	64	60	65	59	65	60	64	65	53	55	64	57	65	56	65	59	70	66	69	67	70	66	69	68	70	66	70
16	63	68	59	60	70	60	58	63	53	65	60	64	59	65	59	65	61	64	65	53	54	64	55	65	56	65	60	70	66	69	68	70	65	69	68	70	65	70

(c) AM Work Zone with 20% Diversion Effect

ITRE Institute for Transportation Research and Education

Exhibit II - 34 Speed Contour Plots - PM Peak

	Segment																																			
Time	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
1	63	66	66	68	63	68	62	65	67	52	62	51	65	52	65	49	54	33	49	63	64	58	63	60	65	58	64	61	64	52	62	64	60	65	59	64
2	60	66	64	67	61	67	59	65	65	49	58	50	62	52	61	47	54	31	26	60	64	56	62	60	64	57	61	61	62	52	62	64	59	64	59	64
3	59	65	63	67	60	66	59	65	65	48	59	51	62	50	60	44	54	17	18	59	63	57	62	60	64	56	59	61	60	51	61	63	59	62	59	64
4	61	65	65	68	63	68	62	64	68	51	65	53	65	50	65	46	54	31	45	62	64	58	63	60	64	58	63	61	64	50	61	64	60	64	58	64
5	61	65	65	68	63	68	62	64	67	51	63	50	65	50	64	46	54	34	30	61	64	56	62	60	64	57	61	61	62	49	61	64	59	63	58	64
6	59	65	63	68	61	67	60	65	65	45	53	46	60	48	58	39	40	14	18	59	63	53	56	59	60	54	53	60	55	47	58	61	57	57	57	64
7	60	65	64	68	62	67	60	65	66	47	56	47	63	48	60	24	27	22	26	60	64	54	58	59	62	55	56	60	57	50	59	62	57	58	57	64
8	64	65	67	69	65	69	64	64	69	52	65	50	65	50	65	36	36	33	51	63	65	57	63	60	64	57	63	61	63	48	61	64	59	63	57	64
9	68	66	70	70	69	70	68	64	70	58	65	52	65	53	65	49	54	34	55	64	65	59	63	58	64	59	65	61	64	51	62	64	60	65	58	64
10	68	65	70	70	69	70	68	65	70	54	65	52	65	51	65	46	54	34	54	64	65	59	63	60	64	58	65	61	64	49	61	64	60	65	60	64
11	62	65	67	69	64	68	63	63	69	52	65	49	65	49	65	45	54	34	40	62	64	56	62	60	64	57	61	61	61	47	61	64	59	63	58	64
12	57	65	63	67	60	67	59	64	66	46	57	48	62	46	56	32	34	12	18	59	63	54	58	60	61	54	55	60	56	45	60	64	58	60	58	64
13	57	65	63	67	60	66	58	63	66	52	62	47	64	49	63	41	48	17	27	60	64	55	59	60	62	55	57	61	58	45	60	64	59	63	58	64
14	59	65	63	67	60	66	59	64	66	49	59	48	64	50	62	46	54	33	32	61	64	57	62	60	64	56	60	61	60	47	61	64	59	64	58	64
15	59	65	64	67	60	66	58	64	65	48	59	49	62	49	61	48	54	34	23	60	64	56	62	60	64	57	61	61	61	48	61	64	60	64	58	64
16	59	65	64	67	61	66	58	65	64	43	52	49	57	48	59	45	50	14	18	59	63	56	62	60	63	57	62	61	62	49	61	64	60	64	59	64

Time	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70
1	65	65	65	65	64	46	65	65	54	65	60	64	62	65	65	46	65	45	64	61	65	65	65	70	70	63	70	63	70	70	70	63	67	75
2	64	64	64	64	57	44	65	65	53	65	60	64	62	65	65	42	65	44	64	60	65	65	65	65	65	64	68	61	65	65	67	60	63	68
3	62	62	42	26	52	42	63	65	52	65	59	64	61	65	64	40	65	41	64	60	65	65	63	64	64	64	67	61	64	64	66	59	62	66
4	65	52	58	39	57	41	65	65	53	65	60	64	61	65	65	45	65	46	64	61	65	65	65	70	70	64	70	63	69	69	70	62	65	73
5	63	52	63	61	52	41	64	65	50	65	59	64	61	65	64	37	65	40	64	60	65	65	65	66	66	64	68	61	65	65	67	60	62	67
6	53	31	26	22	52	37	63	64	50	64	59	64	61	64	63	34	65	37	64	60	65	65	63	64	64	64	67	61	64	64	65	59	59	62
7	41	21	21	21	52	38	63	64	51	64	58	63	61	64	63	33	65	37	64	60	65	65	64	65	65	64	68	61	65	65	66	59	59	62
8	40	24	21	21	52	41	64	65	50	65	59	64	61	65	65	41	65	41	64	60	65	65	65	69	69	65	70	62	68	68	69	61	63	68
9	65	39	29	26	56	45	65	65	52	65	60	64	61	65	65	50	65	46	64	61	65	65	65	70	70	65	70	64	70	70	70	63	67	75
10	65	50	60	60	59	40	65	65	52	65	60	64	61	65	65	50	65	45	64	61	65	65	65	70	70	64	70	64	70	70	70	63	67	75
11	64	50	63	58	52	41	65	65	53	65	59	64	61	65	65	43	65	36	64	60	65	65	65	70	70	64	70	64	70	70	70	62	66	75
12	62	43	33	24	52	41	63	64	49	65	59	64	61	65	65	37	65	34	64	60	65	65	65	68	68	64	70	63	69	69	70	62	65	72
13	65	46	35	25	53	46	63	64	51	65	59	64	61	65	65	44	65	43	64	61	65	65	65	68	68	64	70	62	68	68	68	60	63	68
14	65	54	64	65	61	47	65	65	53	65	60	64	61	65	65	45	65	45	64	61	65	65	65	70	70	64	70	64	70	70	70	63	67	75
15	65	54	64	65	62	48	65	65	54	65	60	64	62	65	65	47	65	45	64	61	65	65	65	70	70	64	70	64	70	70	70	63	67	75
16	65	55	64	65	62	47	65	65	53	65	60	64	62	65	65	46	65	45	64	60	65	65	65	68	68	64	69	62	68	68	69	61	64	71

(a) Base Case PM

	Segment																																			
Time	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
1	63	66	66	68	63	68	62	65	67	52	62	51	65	53	65	49	54	33	49	63	64	58	63	60	65	58	64	61	64	52	62	64	60	65	59	64
2	60	66	64	67	61	67	59	65	65	49	58	51	62	53	61	48	54	31	26	60	64	56	62	60	64	57	61	61	62	52	62	64	59	64	59	64
3	59	65	63	67	60	66	59	65	65	48	59	51	62	50	60	44	54	17	18	59	63	57	62	60	64	56	59	61	60	51	61	63	59	62	59	64
4	61	65	65	68	63	68	62	64	68	51	65	53	65	50	65	46	54	31	45	62	64	58	63	60	64	58	63	61	64	50	61	64	60	64	58	64
5	61	65	65	68	63	68	62	64	67	51	63	50	65	50	64	46	54	34	30	61	64	56	62	60	64	57	61	61	62	49	61	64	59	63	58	64
6	59	65	63	68	61	67	60	65	65	45	53	47	60	49	58	39	40	14	18	59	63	53	56	59	60	54	53	60	55	47	58	61	57	57	57	64
7	60	65	64	68	62	67	60	65	66	46	56	47	63	48	60	24	27	22	26	60	64	54	58	59	62	55	56	60	57	50	59	62	57	53	37	23
8	64	65	67	69	65	69	64	64	69	52	65	50	65	50	65	36	36	33	51	63	65	57	63	60	64	57	63	61	63	48	61	64	59	28	17	10
9	68	66	70	70	69	70	68	64	70	58	65	52	65	54	65	49	54	34	55	64	65	59	63	58	64	59	65	61	64	51	62	64	60	45	38	26
10	68	65	70	70	69	70	68	65	70	53	65	52	65	51	65	46	54	34	54	64	65	59	63	60	64	58	65	61	64	49	61	64	60	59	60	64
11	62	65	67	69	64	68	63	63	69	52	65	50	65	50	65	45	54	34	40	62	64	56	62	60	64	57	61	61	61	47	61	64	59	63	58	64
12	57	65	63	67	60	67	59	64	66	46	57	48	62	46	56	32	34	12	18	59	63	54	58	60	61	54	55	60	56	45	60	64	58	60	58	60
13	57	65	63	67	60	66	58	63	66	52	62	47	64	49	55	49	53	18	27	60	64	55	59	60	62	55	57	61	58	45	60	64	59	63	58	64
14	59	65	63	67	60	66	59	64	66	49	59	48	64	50	62	46	54	33	32	61	64	57	62	60	64	56	60	61	60	47	61	64	59	64	58	64
15	59	65	64	67	60	66	58	64	65	48	59	49	62	49	61	48	54	34	23	60	64	56	62	60	64	57	61	61	61	48	61	64	60	64	58	64
16	59	65	64	67	61	66	58	65	64	43	52	49	57	49	59	45	50	14	18	59	63	56	62	60	63	57	62	61	62	49	61	64	60	64	59	64

Time	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70
1	65	65	65	65	64	47	65	65	55	65	60	64	62	65	65	12	58	10	56	39	39	39	52	70	70	63	70	64	70	70	70	63	67	75
2	64	64	64	64	57	44	65	65	53	65	60	64	62	47	15	15	42	14	33	26	22	20	32	70	70	64	70	64	70	70	70	62	66	74
3	62	62	42	26	52	42	63	65	52	65	45	29	19	11	12	16	65	10	7	15	15	15	25	70	70	65	70	64	70	70	70	62	66	74
4	65	52	58	39	57	41	65	65	53	25	10	10	10	9	9	11	51	7	7	16	14	13	25	70	70	65	70	63	70	70	70	62	65	73
5	63	52	63	61	52	41	64	65	15	10	10	10	10	9	10	14	65	14	10	15	15	15	25	70	70	65	70	63	70	70	70	62	66	74
6	53	31	26	22	52	18	13	9	7	9	10	11	10	9	11	15	65	19	11	12	11	11	25	70	70	65	70	63	70	70	70	62	65	72
7	20	13	12	11	12	10	9	8	7	8	10	10	9	8	10	14	64	8	7	13	12	12	25	70	70	65	70	63	70	70	70	62	65	72
8	12	10	9	8	10	9	9	7	6	8	9	9	9	8	9	11	57	6	7	15	13	14	25	70	70	65	70	63	70	70	70	62	64	71
9	19	11	10	9	11	11	9	8	7	8	10	10	10	8	8	9	65	11	13	21	17	18	25	70	70	65	70	64	70	70	70	62	66	75
10	32	18	11	10	12	21	13	15	11	12	15	18	15	12	8	8	5	35	59	36	17	15	65	70	70	64	70	65	70	70	70	63	67	75
11	37	24	11	10	13	41	35	17	10	12	16	18	14	12	10	15	62	11	53	39	17	26	53	70	70	64	70	64	70	70	70	63	67	75
12	41	22	11	10	13	41	64	38	8	10	13	14	12	11	10	15	46	13	43	31	15	25	37	70	70	64	70	64	70	70	70	62	66	75
13	41	24	12	10	13	21	12	8	7	8	10	10	10	8	8	11	50	11	21	24	15	21	25	70	70	65	70	64	70	70	70	62	65	72
14	31	13	9	8	11	11	12	9	8	9	12	12	11	10	9	13	59	21	10	21	16	41	38	70	70	64	70	64	70	70	70	63	67	75
15	35	11	10	9	12	17	14	13	10	11	14	15	13	11	10	16	53	15	10	18	13	25	52	70	70	64	70	64	70	70	70	63	67	75
16	38	19	11	10	13	18	13	11	9	10	13	12	11	10	10	16	29	8	9	18	13	20	25	70	70	65	70	64	70	70	70	62	66	74

(b) PM Work Zone without Diversion Effect

	Segment																																			
Time	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
1	68	67	69	70	68	70	68	66	70	55	65	53	65	55	65	52	55	36	51	63	65	59	64	61	65	59	65	61	64	55	62	64	61	65	60	64
2	67	66	69	70	67	69	67	66	69	53	64	53	65	55	65	51	55	34	41	62	64	58	63	60	65	59	65	61	64	54	62	64	60	65	60	64
3	67	66	68	70	67	69	66	66	69	52	64	53	65	53	65	48	54	35	34	61	64	58	63	61	65	58	64	61	64	53	62	64	60	65	59	64
4	67	66	69	70	68	70	68	65	70	55	65	55	65	53	65	50	54	37	50	63	64	59	64	60	65	59	65	61	64	53	62	64	61	65	59	64
5	67	66	69	70	68	70	68	65	70	54	65	53	65	53	65	49	54	37	43	62	64	58	63	60	64	58	65	61	64	52	62	64	60	65	59	64
6	67	66	68	70	68	69	67	66	69	51	61	50	64	52	64	47	54	34	30	61	64	57	62	60	64	57	61	61	62	50	61	64	59	63	58	64
7	67	66	69	70	68	69	67	66	69	51	63	50	65	51	65	49	54	33	43	62	64	58	63	60	64	58	63	61	64	53	62	64	59	64	58	64
8	69	66	70	70	69	70	69	65	70	55	65	52	65	53	65	50	54	36	53	63	65	59	64	60	64	59	65	61	64	51	62	64	60	65	58	64
9	70	66	70	70	70	70	70	65	70	59	65	54	65	55	65	51	55	36	55	64	65	59	64	59	64	60	65	61	64	54	62	64	61	65	58	64
10	70	66	70	70	70	70	70	66	70	56	65	55	65	53	65	49	54	37	54	64	65	59	64	60	65	59	65	61	64	52	62	64	61	65	61	64
11	68	66	70	70	69	70	68	64	70	55	65	52	65	52	65	48	54	37	47	63	64	58	63	60	64	58	65	61	64	50	61	64	60	65	59	64
12	66	66	68	70	67	69	67	65	69	51	64	51	65	49	63	46	54	35	27	60	64	57	63	60	64	57	62	61	62	49	61	64	59	64	59	64
13	66	66	68	70	67	69	66	64	69	55	65	50	65	52	65	49	54	38	47	63	64	58	63	60	65	58	64	61	64	48	61	64	60	65	59	64
14	66	66	68	70	67	69	66	65	69	53	64	51	65	53	65	49	54	36	43	62	64	58	63	60	65	58	64	61	64	50	61	64	60	65	59	64
15	67	66	69	70	67	69	66	65	69	52	64	52	65	52	65	51	54	37	39	62	64	58	63	60	64	58	65	61	64	51	62	64	61	65	59	64
16	67	66	69	70	67	69	66	66	69	50	61	52	63	52	64	50	54	38	30	61	64	58	63	60	65	58	65	61	64	52	62	64	61	65	60	64

Time	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70
1	65	65	65	65	65	50	65	65	57	65	61	64	62	65	65	39	60	10	56	44	44	44	54	70	70	63	70	64	70	70	70	63	67	75
2	65	65	65	65	64	48	65	65	56	65	61	64	62	65	65	30	47	23	18	22	20	18	28	70	70	65	70	64	70	70	70	62	66	74
3	65	65	65	65	60	46	65	65	54	65	60	64	62	61	17	16	41	8	7	15	14	14	25	70	70	65	70	64	70	70	70	62	66	74
4	65	65	65	65	64	46	65	65	55	65	61	64	62	65	34	11	50	6	7	14	13	12	25	70	70	65	70	64	70	70	70	62	66	74
5	65	65	65	65	62	46	65	65	54	65	60	64	62	47	14	14	50	16	8	15	14	14	25	70	70	65	70	64	70	70	70	62	66	74
6	64	64	64	64	56	43	64	65	53	65	59	47	24	11	11	15	46	11	7	12	11	11	25	70	70	65	70	64	70	70	70	62	65	73
7	65	65	65	65	58	43	64	65	53	22	13	11	11	10	11	14	27	6	7	13	12	12	25	70	70	65	70	64	70	70	70	62	65	73
8	65	65	65	65	63	46	65	65	53	10	11	11	11	9	9	11	17	6	7	15	13	13	25	70	70	65	70	64	70	70	70	62	65	72
9	65	65	65	65	65	49	65	65	55	42	24	21	15	12	8	9	46	13	11	21	18	18	25	70	70	65	70	64	70	70	70	63	66	75
10	65	65	65	65	64	46	65	65	55	65	61	64	62	65	54	8	5	35	47	22	17	15	65	70	70	64	70	65	70	70	70	63	67	75
11	65	65	65	65	62	46	65	65	55	65	60	64	62	65	65	15	60	11	63	44	20	26	53	70	70	64	70	64	70	70	70	63	67	75
12	65	65	65	65	58	46	64	65	53	65	59	64	61	63	17	15	45	13	38	25	21	25	37	70	70	64	70	64	70	70	70	62	66	75
13	65	65	65	65	64	50	65	65	54	65	60	64	62	65	22	11	50	11	23	28	20	21	25	70	70	65	70	64	70	70	70	62	65	73
14	65	65	65	65	65	51	65	65	56	65	61	64	62	65	65	13	59	22	11	21	20	39	39	70	70	64	70	64	70	70	70	63	67	75
15	65	65	65	65	65	52	65	65	57	65	61	64	63	65	65	16	52	17	11	18	17	25	52	70	70	64	70	64	70	70	70	63	67	75
16	65	65	65	65	65	50	65	65	55	65	61	64	62	65	65	16	40	8	9	18	16	19	25	70	70	65	70	64	70	70	70	62	66	74

(c) PM Work Zone with 20% Diversion Effect

5.0 MESOSCOPIC MODELING RESULTS FOR AREA 3: DTALITE

5.1 Recalibration of the Baseline Model

The calibration procedure ensures that the baseline model represents the pre-work zone conditions as closely as possible. Traffic counts before start of the work zone at important freeway and arterial sections for the network were used to adjust the model parameters in such a way that it simulates the measured conditions. The method used to calibrate DTALite is a single-level nonlinear optimization model. The model has the following key features:

The model is a path flow-based optimization model, which incorporates heterogeneous sources of traffic measurements and does not require explicit dynamic link-path incidences.

The objective is to minimize (i) the deviation between observed and estimated traffic states and (ii) the deviation between aggregated path flows and target OD flows, subject to the dynamic user equilibrium (DUE) constraint represented by a gap-function-based reformulation. A Lagrangian relaxation-based algorithm which dualizes the difficult DUE constraint to the objective function is used to solve the model. This algorithm integrates a gradient-projection-based path flow adjustment method within a column generation-based framework.

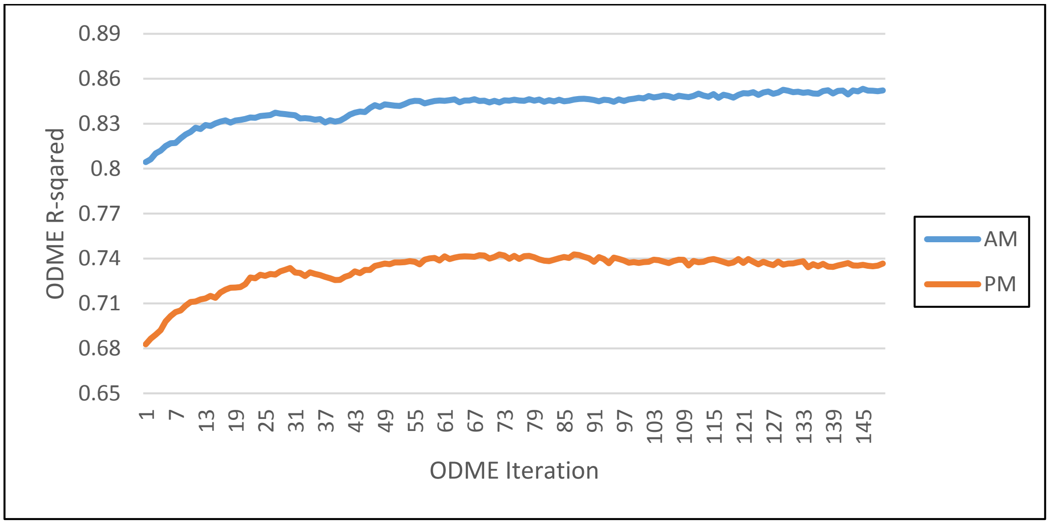
DTALite, a dynamic network loading (DNL) model which is based on Newell's simplified kinematic wave theory, is employed in the DUE assignment process to realistically capture congestion phenomena and shock wave propagation. This optimization also derives analytical gradient formulas for the changes in link flow and density due to the unit change of time-dependent path inflow in a general network under congestion conditions.

Reference: Lu C-C, Zhou*, X. Zhang, K. (2013) Dynamic Origin-Destination Demand Flow Estimation under Congested Traffic Conditions. Transportation Research Part C. 34, 16-37.

The calibration procedure is a four step process:

1. **Preparation of the input parameters:** In DTALite, there are several parameters that are needed to be prepared as input parameters for calibration or OD matrix estimation. The most important input file is the sensor count file. The current version of DTALite can deal with two different kinds of sensor information: 1) sensor volume count 2) link density count. For the I-40 Fortify project the sensor count mainly consisted of volume counts at 60 locations of freeway and arterials near the work zone. The sensor information is availed from Traffic.com. The sensors are then mapped against the nodes of corresponding links.
2. **Deciding on calibration settings:** The accuracy of the estimation process is dependent on the settings and the extent and reliability of the sensor information. There need to be some iterations of the traffic assignment model at the usual user equilibrium (UE) mode to stabilize the network flows and start ODME. For the recalibrated baseline model in both AM and PM peak period we have used 40 UE iterations to start the ODME up to a total iteration of 190. Exhibit II - 35 shows ODME performance as a function of an increasing number of iterations for the AM and PM peak periods. The graph shows that he measure stabilizes after approximately 50-75 iterations, but 150 iterations were used to be sure the results are valid and stable. The traffic flow model used for ODME is point-queue model, maximum percentage of deviation from historic demand information was set to 30% and ODME step size was set at 0.05. For each of the AM and PM peak period three hour sensor information was used.

Exhibit II - 35 Improvement of calibrated network performance by iteration



3. **Checking deviations between starting and final OD matrix:** The resulting OD matrix should provide different trip distribution across the network and it should be used as the matrix for future assignment process. Therefore, the redistribution of the trips across the network with respect to the default historic demand was checked.
4. **Preparation of calibrated network for further analysis:** The checked and adjusted network file was saved as the baseline model network. The recalibration process generated two network files: one for AM and another for PM peak period. It should be noted that the calibrated network will generate an agent file that stores the agent generated using the calibrated matrices and preferred departure time pattern. For further analysis on the network the user should use the agent.bin file as the demand information.

5.2 Simulation Process

The evaluation of construction effects on network performance relies on adding changes in the number of lanes and the per-lane capacity to the network within the construction area. The simulation results distinguish two different sets of results, the capture the two extreme conditions of travel behavior: (1) best-case scenario with all travelers making perfect re-routing decisions in the user-equilibrium (UE) solution, and (2) a worst-case scenario with no travelers diverting their paths due to the work zone, referred to as a no-diversion (ND) scenario.

UE- represents user equilibrium meaning that the drivers are allowed to change their routes to reduce their travel time. The calibrated baseline model demand can be assigned to the network with reduced capacity at work zone condition. This simulation process simulated the long term stabilization of the traffic. Typically, UE is achieved after 20-30 iterations of the model, although longer UE runs with more iterations can be performed as needed.

ND- represents no diversion. The calibrated O-D demand was assigned to the network for a one-shot assignment. This simulation process does not take into account any previous knowledge about the reduced capacity at the work zone. Therefore, it might be considered as the worst case scenario with all base network traffic attempting to go through the work zone without any diversions.

A modified speed limit of 55 mph was used for the work zone links. The work zone is modeled as three lane in each direction with a lane capacity of 1440 vph.

5.3Network Wide Simulation Results

The network wide results from the latest run of analysis are shown in Exhibit II - 36. The No-Diversion scenario is the result of ND and with-diversion is labeled UE. The with-diversion scenario produced higher travel time than the baseline scenario. However, network average travel time for no-diversion is much higher. The AM baseline model surprisingly shows higher travel times than the PM baseline model. This result is counter to the general expectation because PM demand (1,748,169) is much higher than AM demand (1,185,385).

Exhibit II - 36 Network Wide Simulation Result

Network Wide Results							
Scenario		Average TT (minutes)		Average Travel Distance (mile)		# of Unserved Vehicles	
		Min.	% Diff	Mile	% Diff	Vehicles	% Diff
AM Area 1&2	Baseline	19.6		13.2		63977	
	No-Diversion	54.3	+177.7%	12.7	-3.4%	233196	+264.5%
	With-Diversion	28.6	+46.3%	13.0	-1.3%	119689	+87.1%
PM Area 1&2	Baseline	16.9		10.3		94734	
	No-Diversion	98.0	+481.1%	9.1	-11.1%	660507	+597.2%
	With-Diversion	34.8	+106.2%	10.3	+0.3%	283095	+198.8%
AM Area 3	Baseline	19.6		13.2		63977	
	No-Diversion	22.5	+15.0%	13.1	-0.3%	81270	+27.0%
	With-Diversion	14.1	-27.8%	12.0	-8.7%	41696	-34.8%
PM Area 3	Baseline	16.9		9.4		52012	
	No-Diversion	34.8	+105.9%	9.4	+0.0%	247609	+376.1%
	With-Diversion	14.9	-11.8%	9.9	+5.4%	69846	+34.3%

In terms of the work zone effects, the newest model runs suggest that in the AM peak period, the Area 3 activity results in a 15% increase in network travel time for the no diversion case, but a 27.8% reduction in travel time in the UE results as drivers find alternate routes. For the PM peak, Area 3 estimates a 105.9% increase in travel time in the ND scenario, but a reduction of 11.8% in the UE scenario. The reduction in the UE case is attributed to drivers avoiding the overall work zone and finding quicker alternate routes. Also, the metering effect of the work zone can result in improved travel conditions downstream of construction.

For the Area 1 and 2 analysis, the AM peak analysis shows an increase of 177.7% in the ND scenario, which is mitigated to a 46.3% increase in the UE scenario. It is emphasized that local increases in travel time are expected to be much higher, but that these increases are offset when calculating an average of the entire model. In the PM peak, the ND scenario shows a very drastic increase in travel time of about 481% from 16.9 to 98 minute average travel time. But with the UE diversion, the increase drops to 106% and an average travel time in the network of 34.8 minutes.

The updated modeling results for the PM peak clearly confirm the earlier findings that work zone impacts are expected to be worse in the PM than AM peak periods. However, with the new contractor staging in Areas 1 and 2 that propose to close lanes in both directions, the new numbers appear to show a more significant delay effect than in the earlier model runs, in which the work zone affected only one direction at a time. It is noted that these results assume no modifications to the traffic demand inputs in terms of overall demand level (no car-pooling, transit use, or telecommuting) and in terms of departure times (no peak spreading).

The results also show a large number of vehicles being unserved by the network in the no-diversion scenarios for both AM and PM peak periods. The number of unserved vehicles show a 265% increase in AM and 597% increase in PM period compared to their corresponding baseline models. The implication of these numbers from a modeling point of view is that the trip makers are expected to change their trip making behavior (e.g. change in departure time preference, mode choice preference, and even decision to make the trip) with the disturbed conditions of the network. Overall, the numbers for travel time and travel distance for the network should be interpreted with caution as they represent only the vehicles that have completed their trips. The team plans to explore the spatial pattern of the vehicles that have not completed their trips. As the network covers a larger geographic extent than the construction area, the network wide numbers may not properly represent the overall zonal pair distribution that make trips over the impacted region.

The issue of travel time and travel distance distribution as mentioned in the earlier QPR over the AM and PM peak periods is still under scrutiny by the study team.

5.3.1 Route Based Volume Analysis

The AM peak period results for the selected major routes are shown in Exhibit II - 37. For construction in Area 1 & 2, there is a large diversion of volume from both directions in Route A. This route follows the links covering the work zone. At user equilibrium consideration, route A volume is reduced by 77.5% in Eastbound direction and 76% in westbound direction compared to the baseline model. For route C that follows a longer extent both upstream and downstream of the work zone, the reduction is 43.7% in the Eastbound and 36.2% in the West bound direction. This phenomenon suggests that there is a large amount of traffic that takes diversion at alternative routes in the vicinity of the work zone.

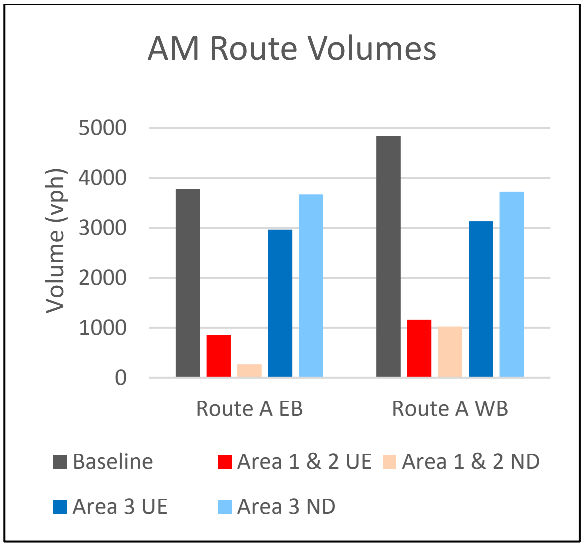
The longer length and importance of the links in Areas 1 & 2 makes it different from Area 3. For route B, which follows the same links as Area 3, there is an estimated 52.4% diversion in Westbound and 25.5% diversion in the eastbound direction. This numbers are quite low compared to the Area 1 & 2 numbers.

For both AM and PM peak periods, route D is the least impacted route from a volume diversion perspective. The volume level for route D in the no-diversion scenario is less than the user-equilibrium scenario. The possible explanation is that route D follows links that are not part of the construction links, but these links are major alternative to the work zone. Since no-diversion does not allow the traveler to divert at the alternative routes, it is expected that there would be reduced traffic flow at those routes, with some of the demand being metered by upstream queuing at the work zone.

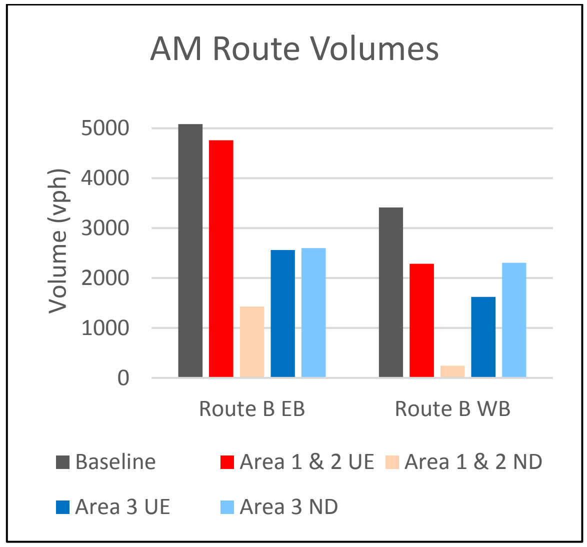
For the AM period no-diversion scenario, a noteworthy reduction occurred in route A Eastbound (92.9%) and route B Westbound (92.8%). The reduction is mainly due to the demand starvation at upstream locations for no-diversion scenario, and should not be interpreted as an overall demand reduction.

In both AM and peak period, route B volume has reduced by similar percentage for ND and UE in corresponding work zone configurations, except in AM for construction of *Areas 1& 2.* The reason is that a reduction in capacity upstream of the route can cause demand starvation at locations downstream of the congestion.

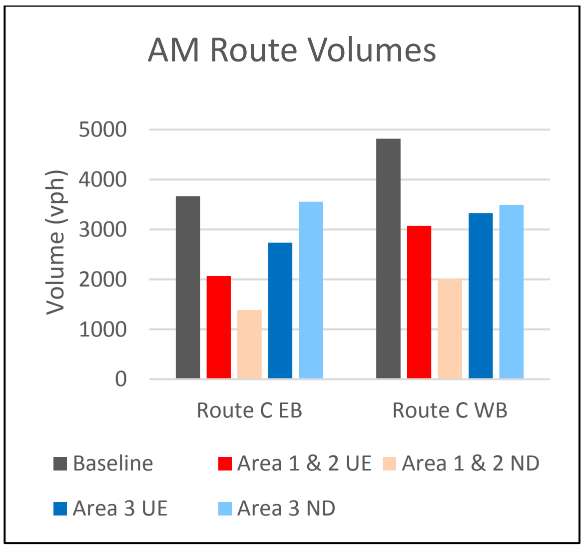
Exhibit II - 37 Volume for different routes for different scenarios in AM



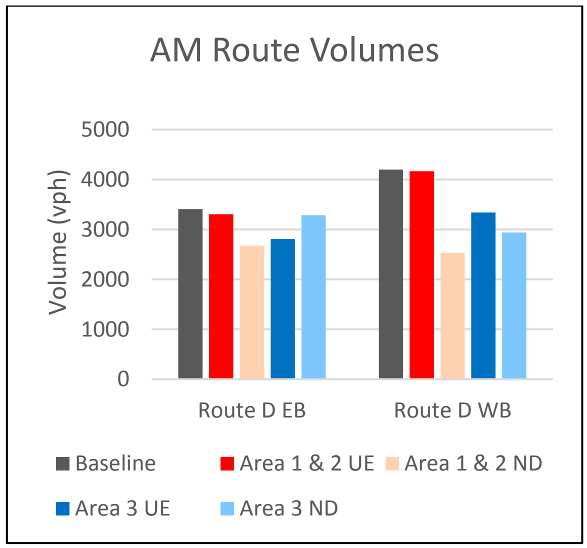
(a)



(b)



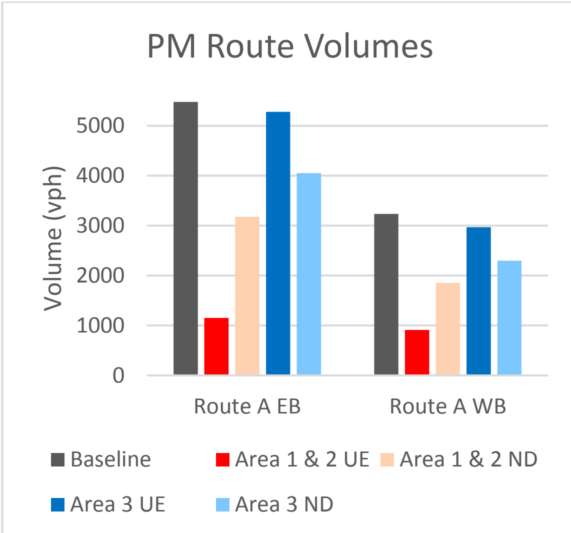
(c)



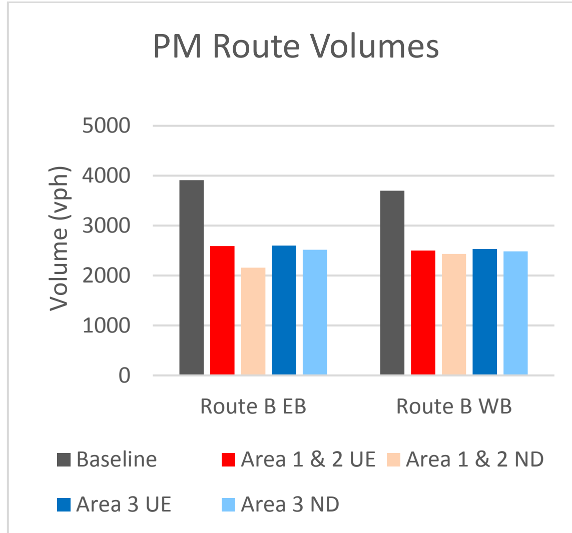
(d)

The model results for volumes at different routes for the PM peak period are summarized in Exhibit II - 38. There is 79% and 72% diversion in volume respectively for route A in the Eastbound and Westbound directions. But the reduction in volume is 42% at the no-diversion condition. This finding is in contradiction to the AM peak period, where no diversion diversions were greater. The reason is evident when the travel time for PM Area 1&2 No-Diversion condition is checked. The congestion at the network level even far upstream of the construction area is much more severe in PM than in AM. Therefore, route C (the longer route covering Areas 1 & 2) volume was found smaller for UE than for ND in the PM peak period.

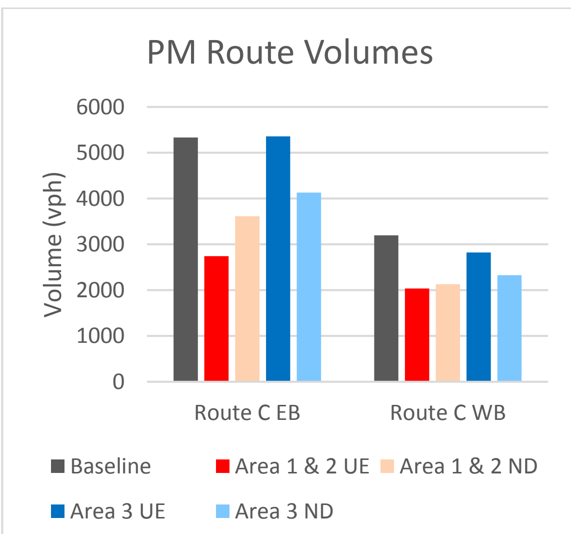
Exhibit II - 38 Volume for different routes for different scenarios in PM



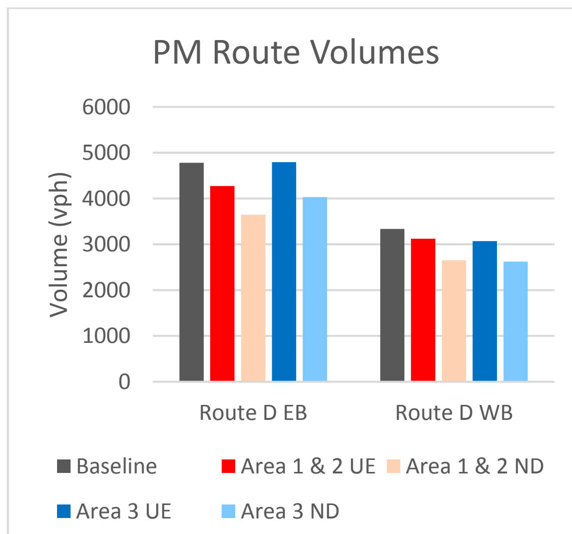
(a)



(b)



(c)



(d)

The route based volume analysis provides a basic idea about the expected conditions with the work zone. The volume results derived in the previous step ae done by averaging the link flows along a path or route. The averaging process however ignores major bottlenecks and diversion points that fall within the path. The study team is working on the process of figuring out how the link volume can be summarized properly.

5.3.2 Route Based Travel Time Analysis

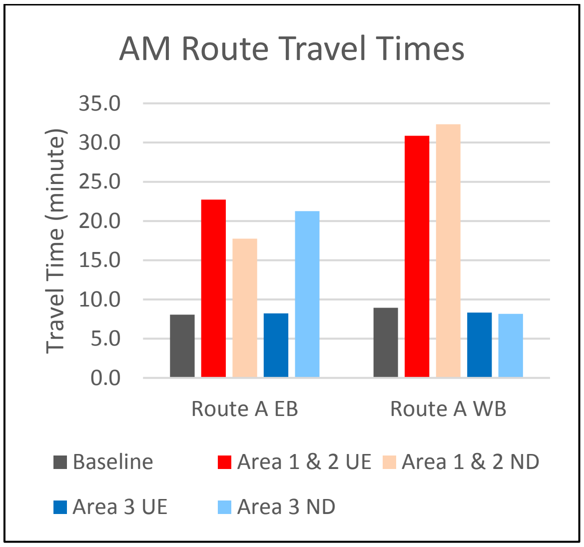
An alternative of looking at the route performance is looking at the average travel time of the network. Even though the average travel time reported here is the average of travel time at a fixed interval of time (hence lacks temporal resolution), the spatial resolution is maintained through these numbers. If an assumption of constant demand patterns along the temporal scope of the analysis period can be made (which is quite fair as the demand distribution inputs are the same in each of AM and PM peak periods, with and without the work zone), the route based travel time reported in this study stands as more reliable representation than the volume.

Exhibit II - 39 and Exhibit II - 40 summarize the travel time analysis for the AM peak period. For Area 1 & 2 construction there is a 182% increase for UE and 120% increase for ND in route A Eastbound; a 246% increase for UE and 262% increase for ND in route A Westbound. However, the increase is 52% in route C Eastbound, 49% in route C Westbound for UE; 108% in route C Eastbound, 364% for route C Westbound for ND. This suggests that for UE, even though vehicles have diverted, the reduced speed limit at the work zone and the congestions occurring upstream of the bottleneck cause higher travel time for both longer and shorter routes. For ND, longer route (route C) travel time is higher than UE (despite less volume than UE), due to the similar reason. It confirms that less volume served does not always guarantee a lower travel time, but that the previous results were impacted by metered demand due to congestion.

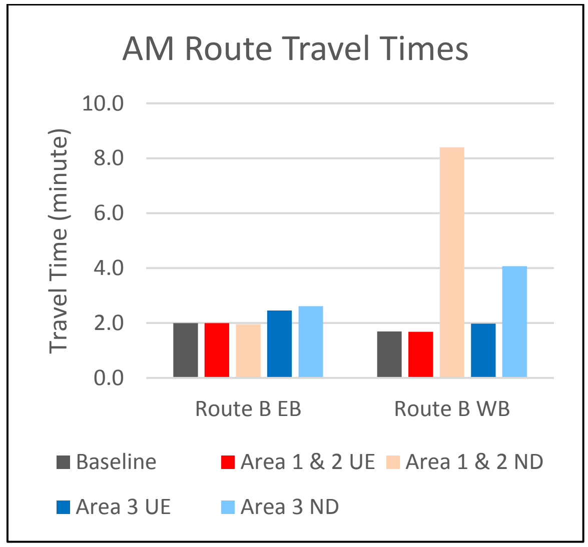
Exhibit II - 39 Travel Time Statistics for Major Routes- AM Period

	Travel Time AM (minutes)				
Route	**Base**	**Area 12 UE**	**Area 12 ND**	**Area 3 UE**	**Area 3 ND**
Route A EB	8.1	22.7	17.8	8.2	21.3
Route A WB	8.9	30.9	32.3	8.3	8.2
Route B EB	2.0	2.0	2.0	2.5	2.6
Route B WB	1.7	1.7	8.4	2.0	4.1
Route C EB	26.5	40.3	55.0	26.0	44.7
Route C WB	32.8	48.7	152.1	29.1	257.1
Route D EB	30.0	31.4	85.3	30.5	33.2
Route D WB	37.8	37.2	152.6	33.5	260.6
Toll Road NB	14.4	20.9	14.4	14.6	14.4
Toll Road SB	15.4	26.8	15.4	14.4	15.5

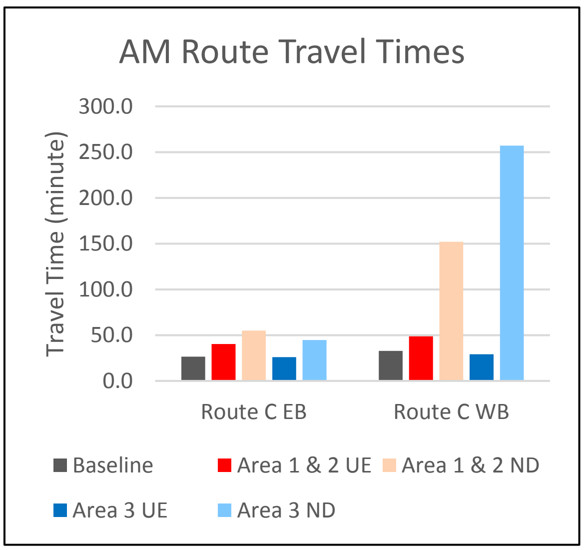
Exhibit II - 40 Travel Times for different routes for different scenarios in AM



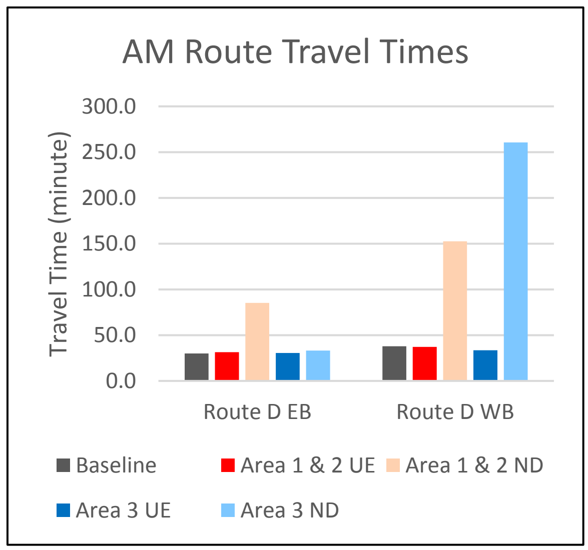
(a)



(b)



(c)



(d)

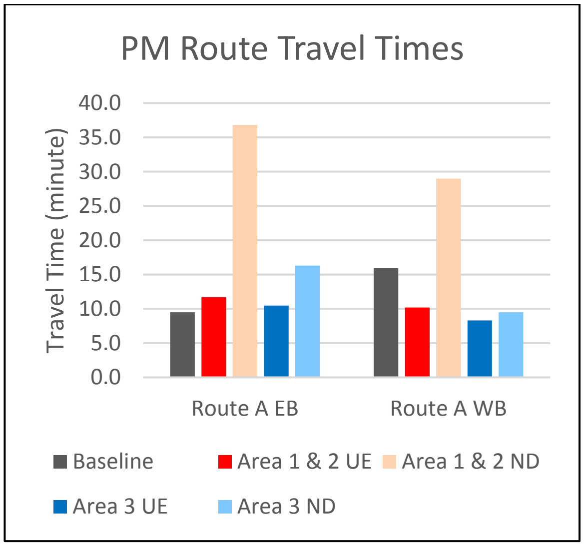
The travel time analysis for PM period is summarized in Exhibit II - 41 and Exhibit II - 42. For construction of work zone in Area 1 & 2 and no-diversion simulation results, the travel time is increased by 288% in route A Eastbound direction and 70% in route C Eastbound direction. This increase is much greater than user-equilibrium simulation (23% in route A Eastbound and 36% in route C Eastbound). The reason for the user equilibrium simulation producing a smaller difference with respect to baseline is that there is a great diversion effect of traffic from the areas affected by work zone construction and the baseline PM peak condition on the freeway was congested. Therefore, network assignment procedure has the scope of reducing the travel time by diverting the traffic to alternative routes.

Route D travel times are the least impacted by the construction process. For route B Westbound direction in UE simulation, there is a 338% increase in travel time for work zone construction in Areas 1 & 2. This high increase is attributed to the acute bottleneck created downstream of the route.

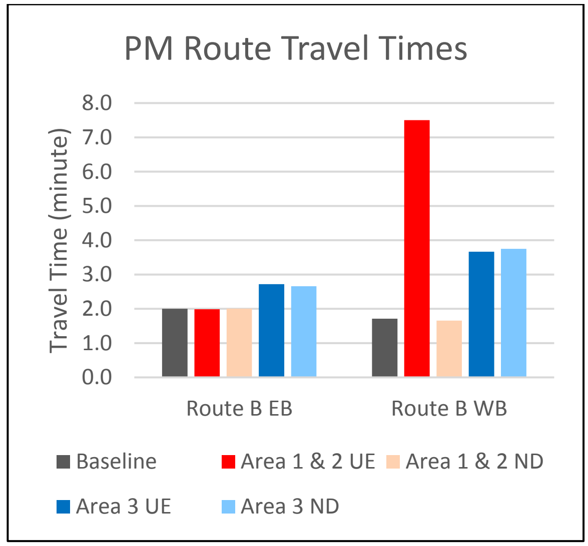
Exhibit II - 41 Travel Time Statistics for Major Routes- PM Period

	Travel Time PM (minutes)				
Route	**Base**	**Area 12 UE**	**Area 12 ND**	**Area 3 UE**	**Area 3 ND**
Route A EB	9.5	11.7	36.8	10.5	16.3
Route A WB	15.9	10.2	29.0	8.3	9.5
Route B EB	2.0	2.0	2.0	2.7	2.7
Route B WB	1.7	7.5	1.7	3.7	3.7
Route C EB	30.9	42.0	52.5	31.9	48.8
Route C WB	33.4	41.4	57.1	27.7	33.5
Route D EB	46.9	53.8	36.4	38.9	61.4
Route D WB	30.8	29.5	30.8	32.6	38.1
Toll Road NB	14.4	14.4	14.4	15.0	14.6
Toll Road SB	14.5	102.3	80.4	15.3	14.8

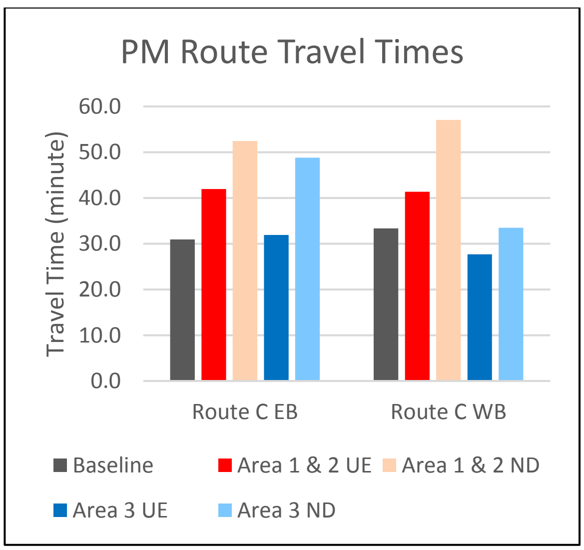
Exhibit II - 42 Travel Times for different routes for different scenarios in PM



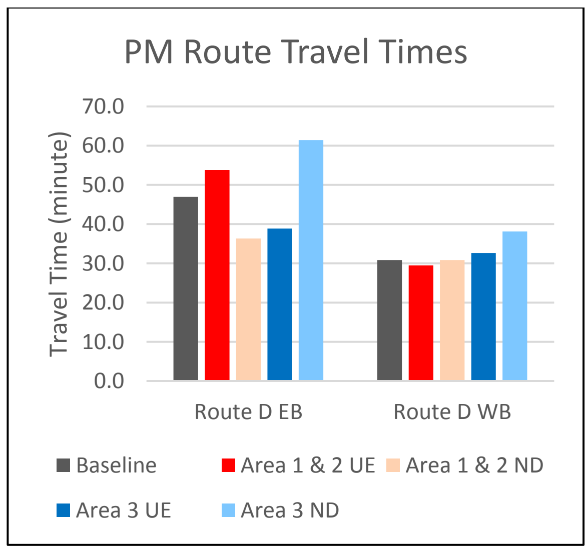
(a)



(b)



(c)



(d)

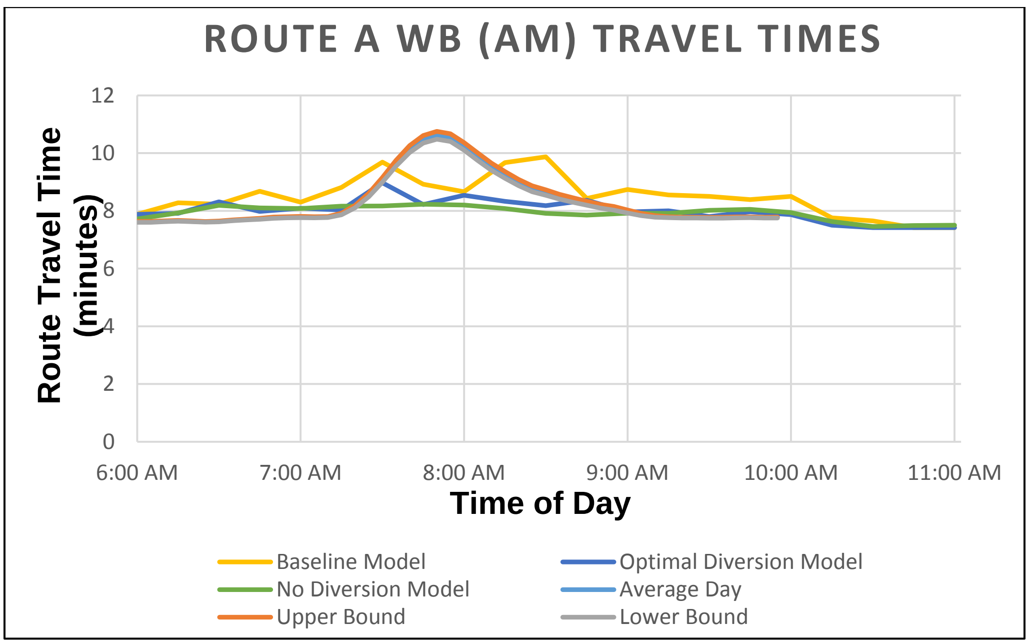
6.0 VALIDATION OF AREA 3

6.1 Travel Time within Work Zone (AM/PM)

The following figures show the estimated travel times for each of the four routes described in the table in section 5.3 against the time of day. The graphs show a comparison between the travel times with different simulation configurations and field data gathered on an average day during the morning and evening hours. In all cases, it is observed that the travel times for the No-Diversion Model are very high, since it assumes that none of the vehicles divert their routes and represemts the worst case scenario. This leads to traffic congestion and hence very large travel times. The travel times in Optimal Diversion model are significantly lower than the No-Diversion model, since the model looks for the best possible alternative routes that the vehicles can take and reduces congestion near the work zone. The Baseline model simulates travel times for the case when there is no work zone.

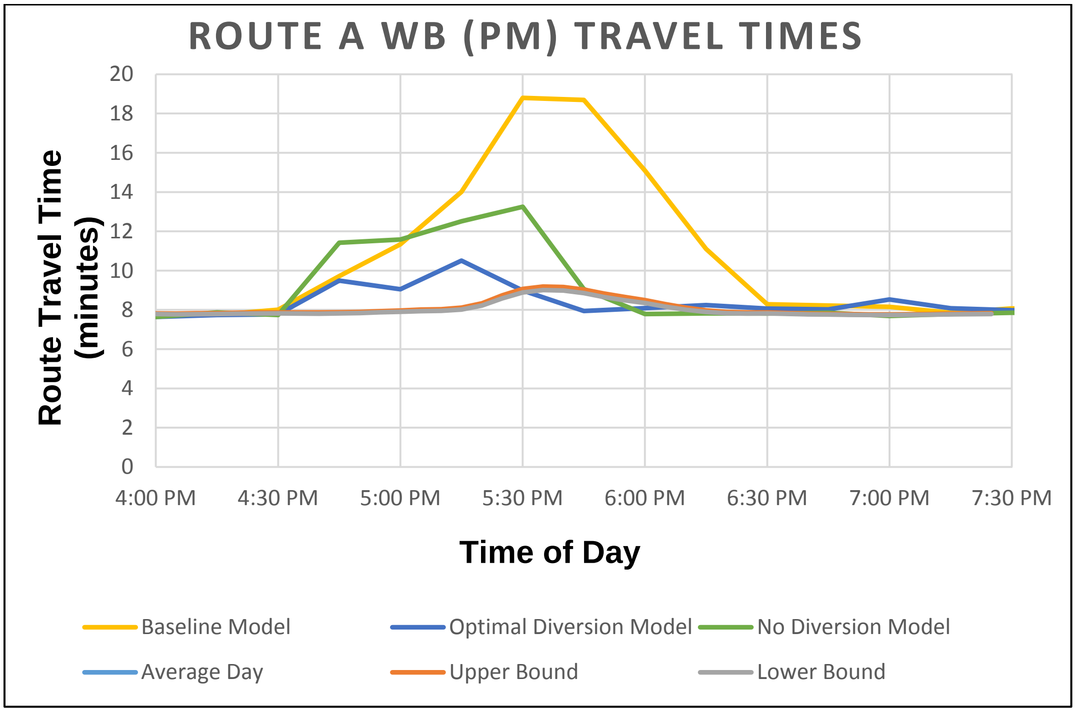
The simulation for Route A West Bound (Exhibit II - 43 andExhibit II - 44) shows that the travel time in the Baseline model has a higher peak than the No-Diversion Model. This indicates that Rouate A (WB) is more congested even when there are no work-zones and is also validated by the travel times observed on that route during a normal day.

Exhibit II - 43 Estimated Travel Times for Route A (West-Bound) in the evening.



The yellow line shows the travel time in the baseline model, dark blue line shows travel times in the Optimal Diversion Model and the green line shows travel times in the No Diversion Model. The light blue line shows the observed travel times during the morning hours.

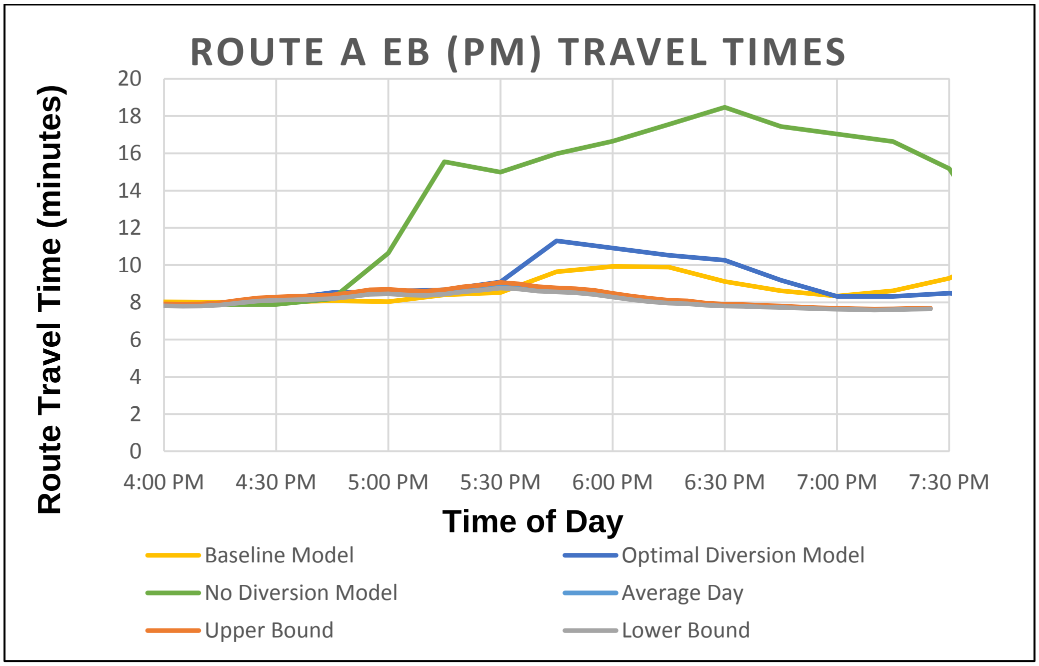
Exhibit II - 44 Estimated Travel Times for Route A (West-Bound) in the evening.



The yellow line shows the travel time in the baseline model, dark blue line shows travel times in the Optimal Diversion Model and the green line shows travel times in the No Diversion Model. The light blue line shows the observed travel times during the evening hours.

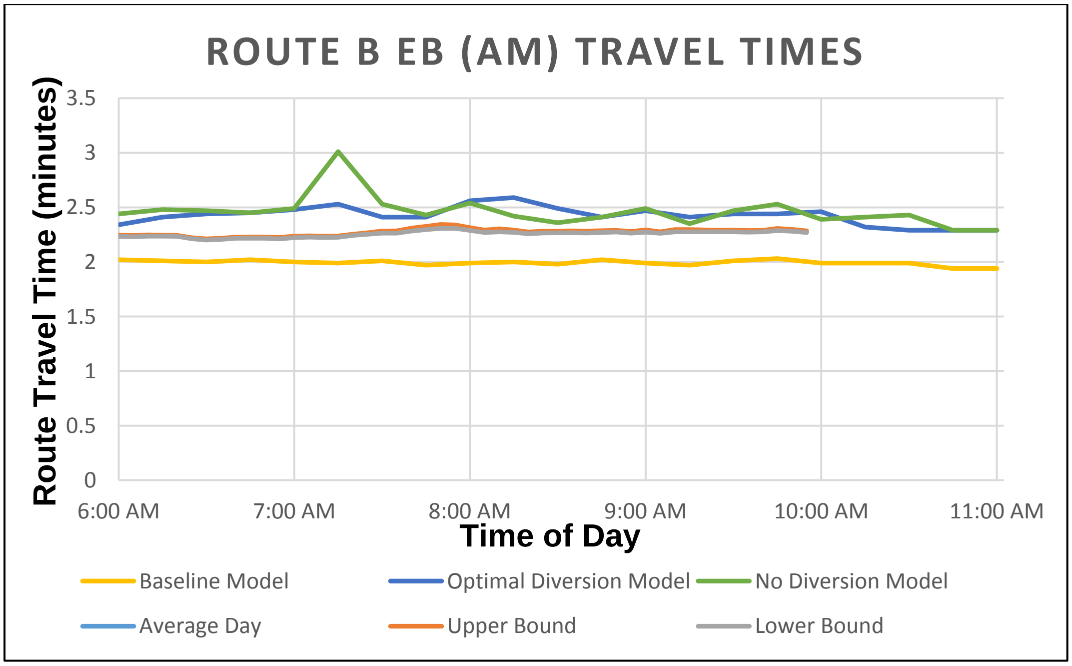
In the following routes, the baseline travel time is less than that in the No-Diversion model as expected and can be compared to the observed travel times on an average day. The Optimal Diversion model brings down the travel time considerably, but it still remains higher than the baseline model. The Optimal Diversion Model shows travel times higher than the observed travel times on an average day.

Exhibit II - 45: Estimated Travel Times for Route A (East-Bound) in the evening.



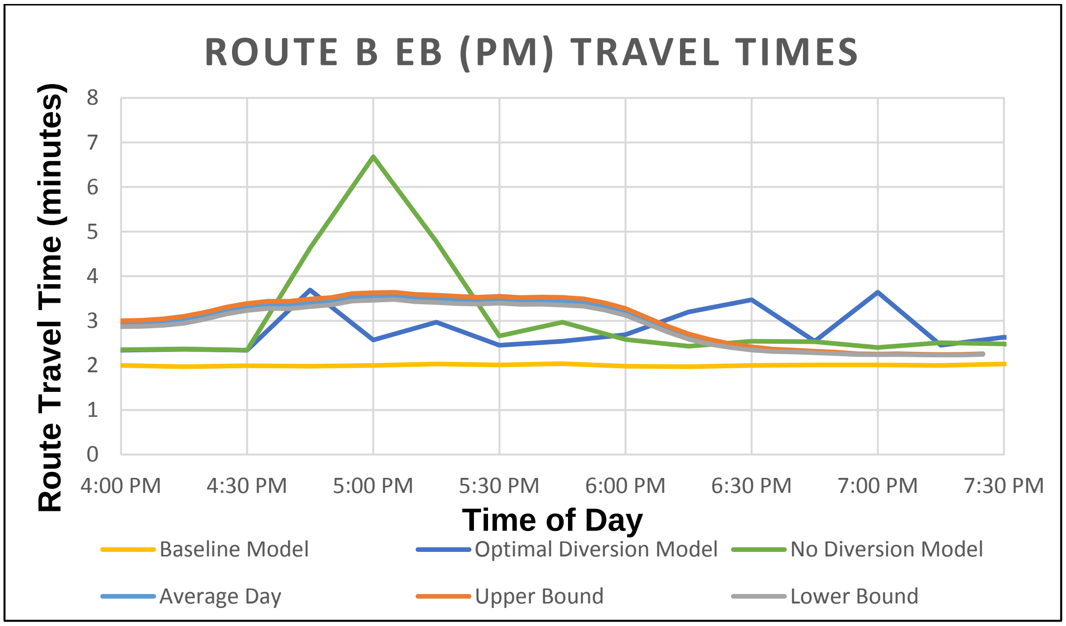
The yellow line shows the simulated travel time in the baseline model, dark blue line shows travel times in the Optimal Diversion Model and the green line shows simulated travel times in the No Diversion Model. The light blue line shows the observed travel times during the evening hours.

Exhibit II - 46 Estimated Travel Times for Route B (East-Bound) in the morning.



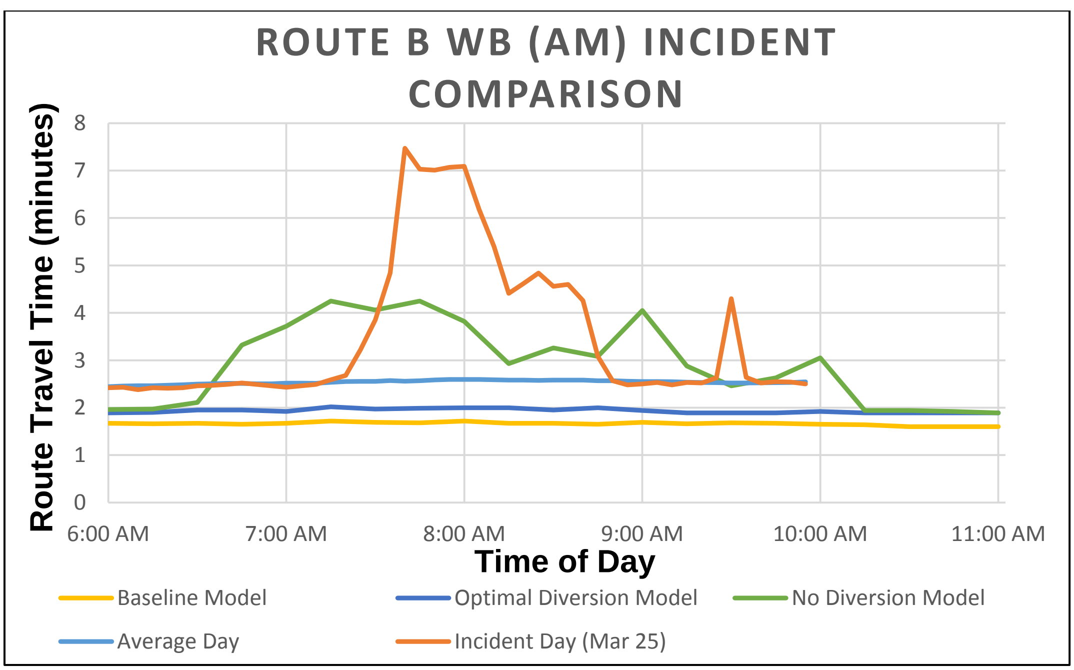
The yellow line shows the travel time in the baseline model, dark blue line shows travel times in the Optimal Diversion Model and the green line shows travel times in the No Diversion Model. The light blue line shows the observed travel times during the morning hours.

Exhibit II - 47 Estimated Travel Times for Route B (East-Bound) in the evening.



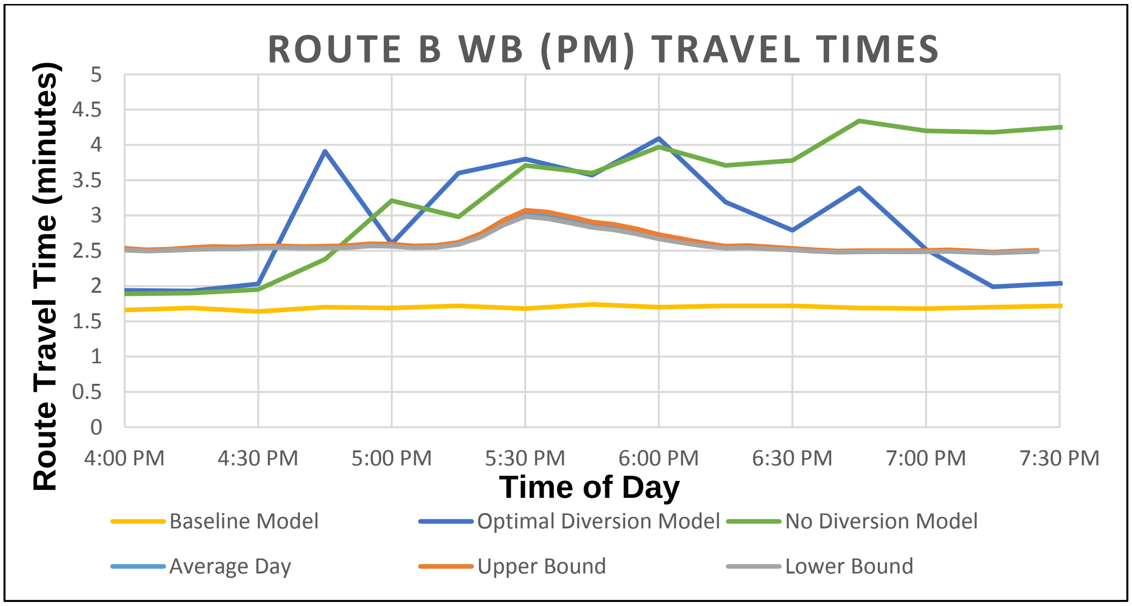
The yellow line shows the travel time in the baseline model, dark blue line shows travel times in the Optimal Diversion Model and the green line shows travel times in the No Diversion Model. The light blue line shows the observed travel times during the evening hours.

Exhibit II - 48 Estimated Travel Times for Route B (West-Bound) in the morning.



The yellow line shows the travel time in the baseline model, dark blue line shows travel times in the Optimal Diversion Model and the green line shows travel times in the No Diversion Model. The light blue line shows the observed travel times during the morning hours. The orange line shows increased travel time due to an incident on March 25 between 7:00 am and 9:00 am.

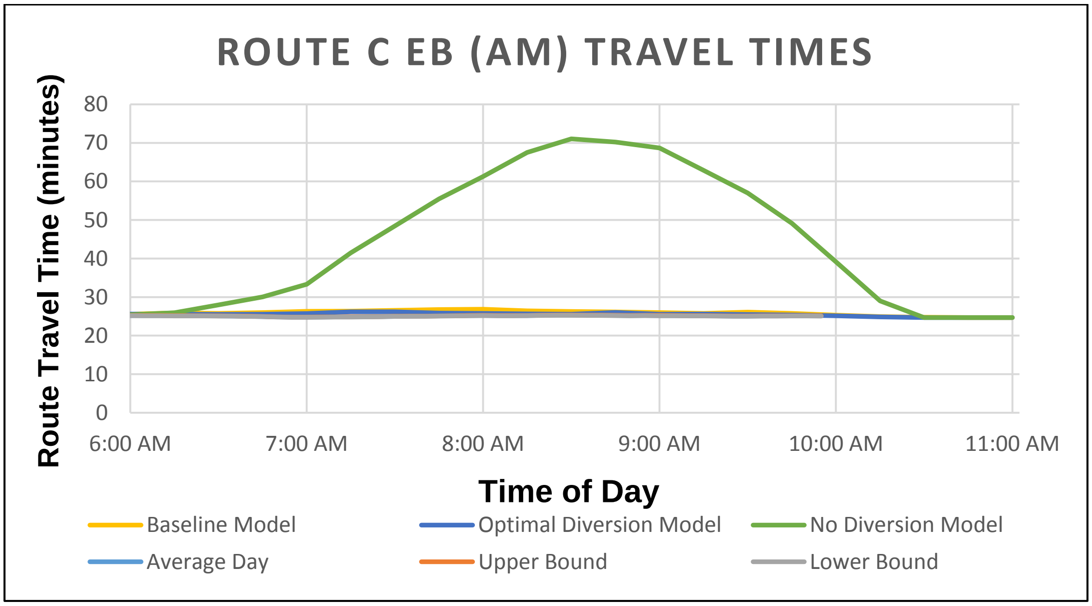
Exhibit II - 49 Estimated Travel Times for Route B (West-Bound) in the evening



The yellow line shows the travel time in the baseline model, dark blue line shows travel times in the Optimal Diversion Model and the green line shows travel times in the No Diversion Model. The light blue line shows the observed travel times during the evening hours.

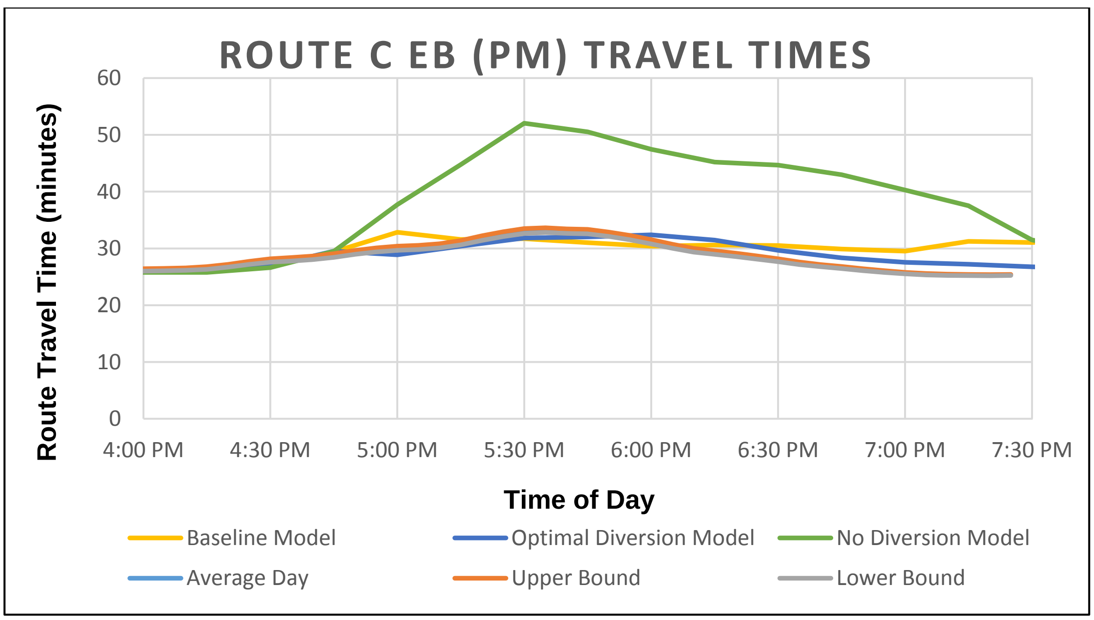
In the following graphs for Route C and D, the simulated travel times in the optimal diversion model shows much larger reduction from the No-Diversion models. In most cases, the Optimal Diversion model shows travel times lower than the baseline model and is comparable to the observed travel times. This shows that the Optimal Diversion model works very well for Route C and D. In case of Route D, we note that the Optimal Diversion Model gives us travel times lesser than the observed travel times.

Exhibit II - 50 Estimated Travel Times for Route C (East-Bound) in the morning.



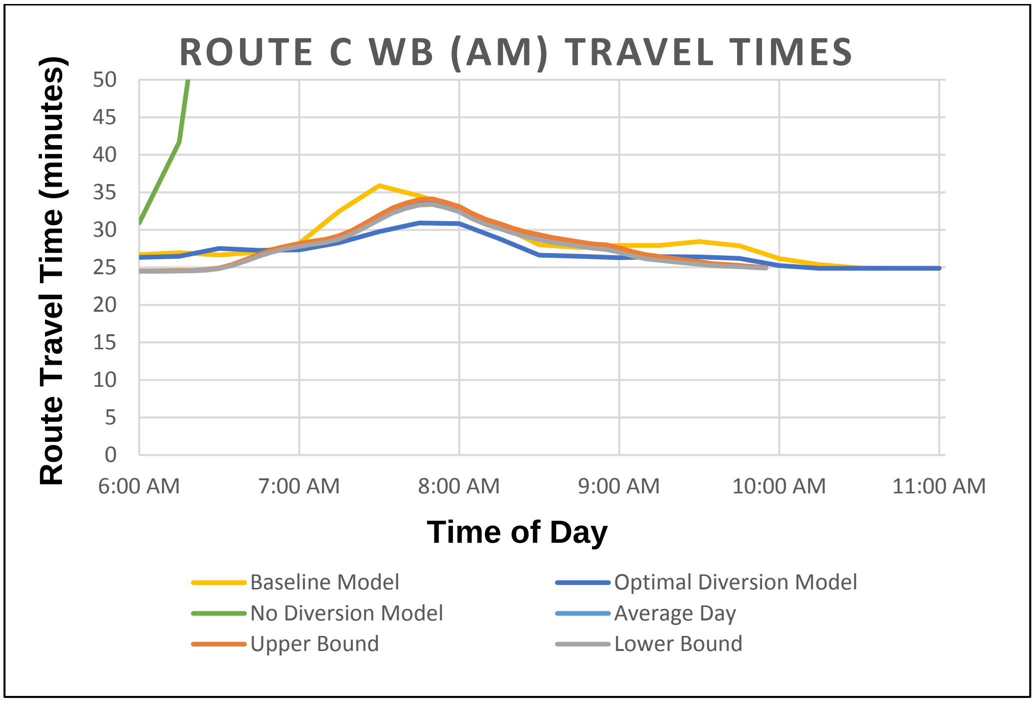
The yellow line shows the travel time in the baseline model, dark blue line shows travel times in the Optimal Diversion Model and the green line shows travel times in the No Diversion Model. The light blue line shows the observed travel times during the morning hours.

Exhibit II - 51 Estimated Travel Times for Route C (East-Bound) in the evening.



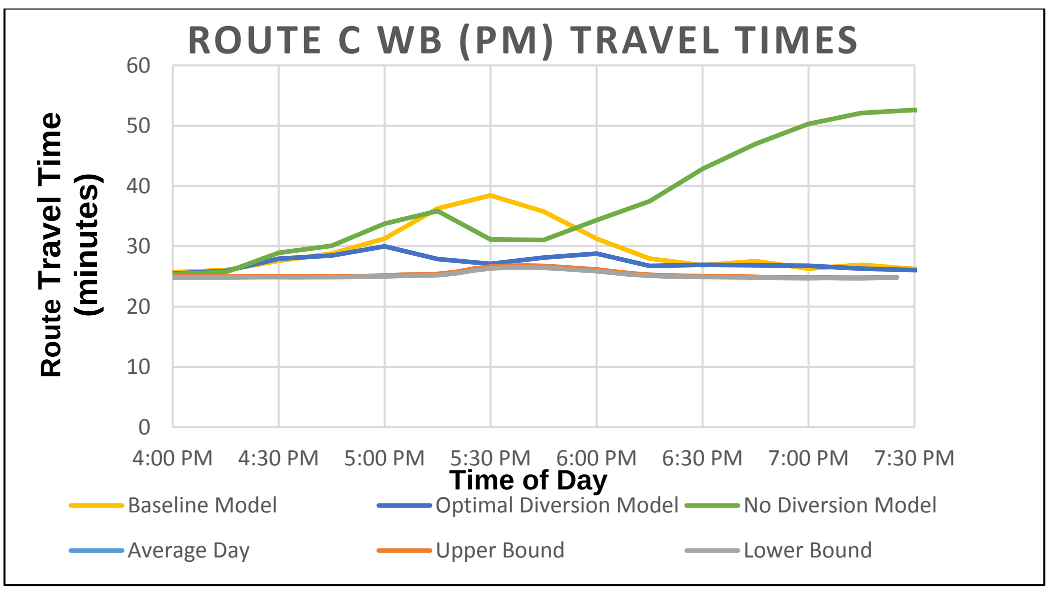
The yellow line shows the travel time in the baseline model, dark blue line shows travel times in the Optimal Diversion Model and the green line shows travel times in the No Diversion Model. The light blue line shows the observed travel times during the evening hours.

Exhibit II - 52 Estimated Travel Times for Route C (West-Bound) in the evening



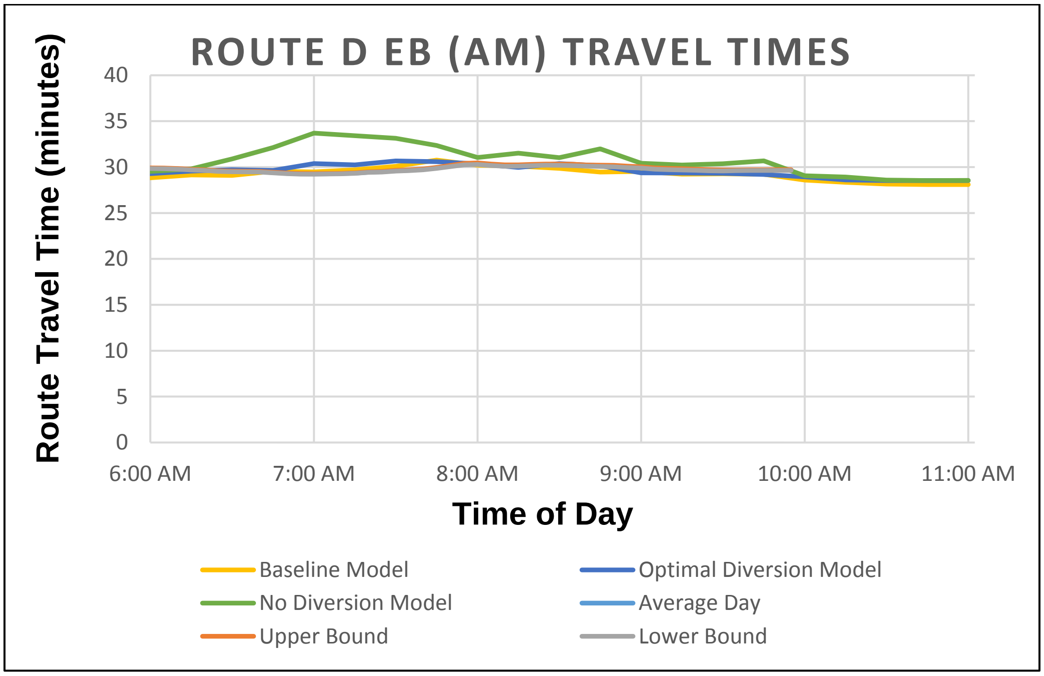
The yellow line shows the travel time in the baseline model, dark blue line shows travel times in the Optimal Diversion Model and the green line shows travel times in the No Diversion Model. The light blue line shows the observed travel times during the evening hours.

Exhibit II - 53: Estimated Travel Times for Route C (West-Bound) in the evening



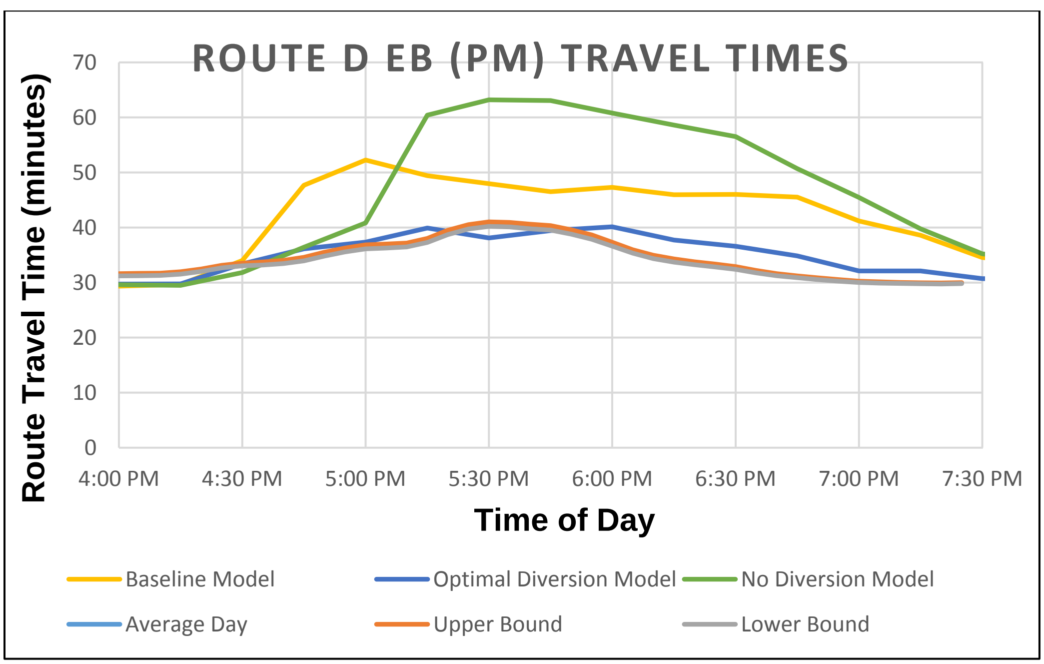
The yellow line shows the travel time in the baseline model, dark blue line shows travel times in the Optimal Diversion Model and the green line shows travel times in the No Diversion Model. The light blue line shows the observed travel times during the evening hours.

Exhibit II - 54 Estimated Travel Times for Route D (East-Bound) in the evening.



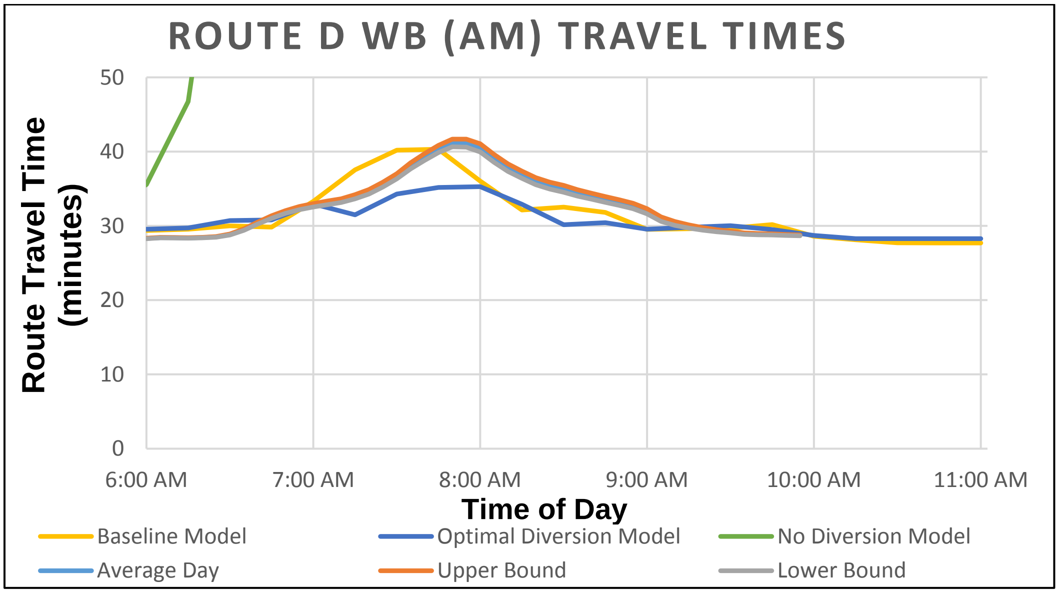
The yellow line shows the travel time in the baseline model, dark blue line shows travel times in the Optimal Diversion Model and the green line shows travel times in the No Diversion Model. The light blue line shows the observed travel times during the evening hours.

Exhibit II - 55 Estimated Travel Times for Route D (East-Bound) in the evening.



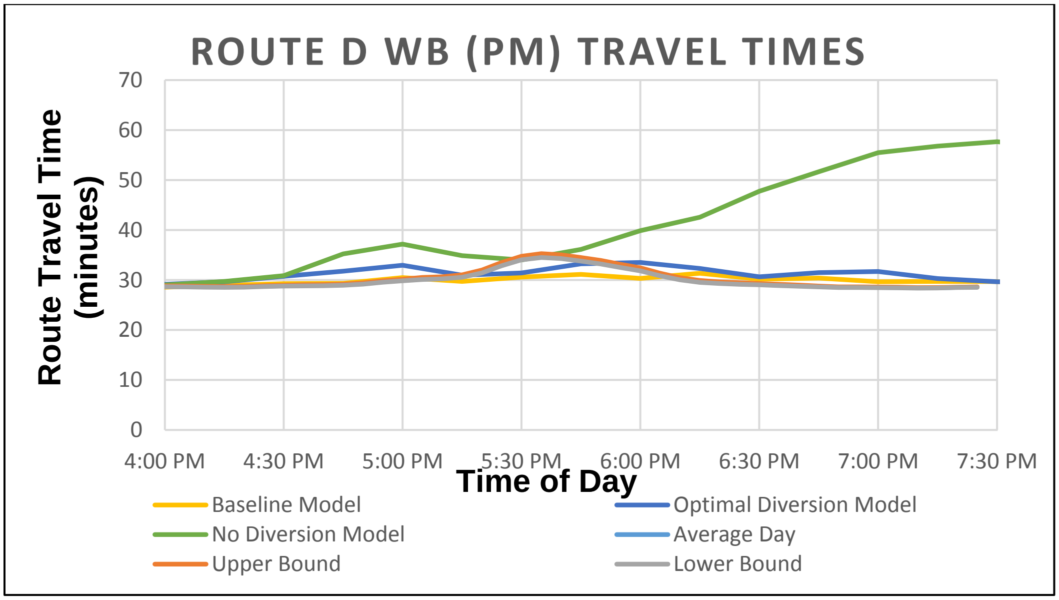
The yellow line shows the travel time in the baseline model, dark blue line shows travel times in the Optimal Diversion Model and the green line shows travel times in the No Diversion Model. The light blue line shows the observed travel times during the evening hours.

Exhibit II - 56 Estimated Travel Times for Route D (West-Bound) in the evening.



The yellow line shows the travel time in the baseline model, dark blue line shows travel times in the Optimal Diversion Model and the green line shows travel times in the No Diversion Model. The light blue line shows the observed travel times during the evening hours.

Exhibit II - 57 Estimated Travel Times for Route D (West-Bound) in the evening



The yellow line shows the travel time in the baseline model, dark blue line shows travel times in the Optimal Diversion Model and the green line shows travel times in the No Diversion Model. The light blue line shows the observed travel times during the evening hours.

6.2 Sensor Volume and Speed Comparison

This section shows comparison between field measured volume and speed data and that obtained from the User Equilibrium and No Diversion simulation models using DTAlite, for AM and PM periods. Exhibit II - 58shows a Google Earth image of the Work Zone and the area just upstream and far upstream from it. The graphs that follow give a comparison of how the time of day and location relative to the Work Zone.

Exhibit II - 58 Google Earth Image of Area 3

Exhibit II - 59 and Exhibit II - 60 show that in the No Diversion model, there is a lot of congestion caused just upstream of the work zone and this causes the average speed of the vehicles to go down below 10 mph. This causes a queueing effect far upstream of the work zone and the average speed of the vehicles reduces gradually over time to about 15 mph. This will lead to grossly overestimated travel times upstream of the work zone.

Exhibit II - 59 Comparison between the speed data collected from traffic sensors and that obtained from the No Diversion simulation model in the morning

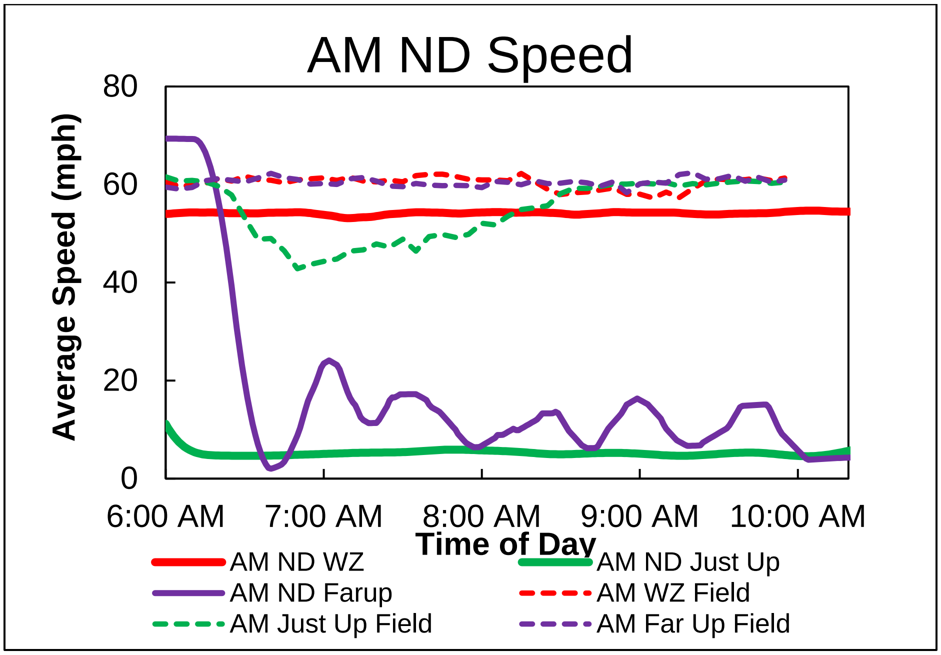


Exhibit II - 59 shows the comparison between the speed data collected from traffic sensors and that obtained from the No Diversion simulation model in the morning. The average speed in the Work Zone Area, far upstream and just upstream of the Work Zone Area from the UE simulation model are shown by blue, red and green solid lines. The field speed observations at the work-zone, far upstream and just upstream are plotted by blue, red and green dotted lines.

Exhibit II - 60 Comparison between the speed data collected from the sensors and that obtained from the No Diversion simulation model in the evening

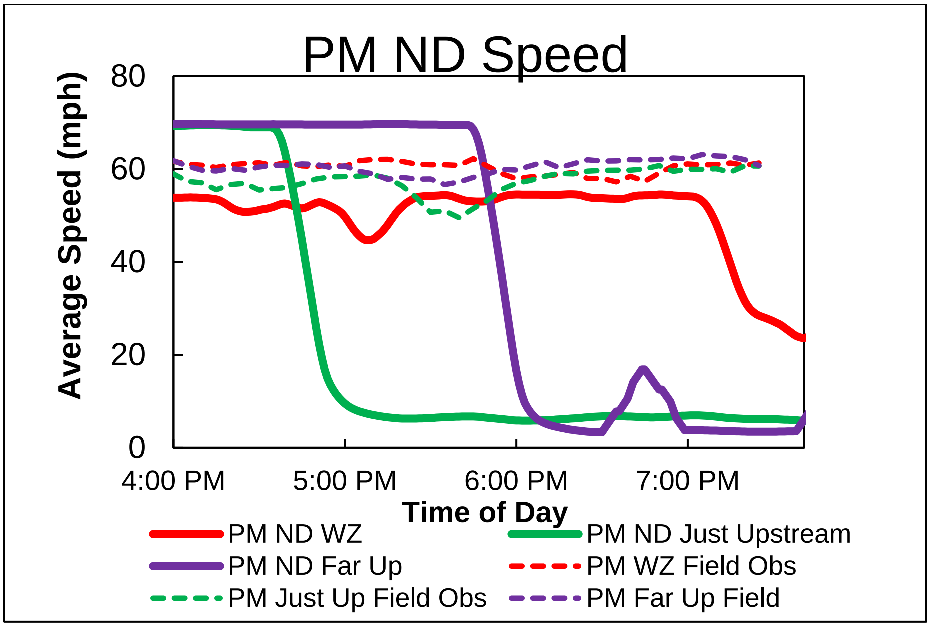


Exhibit II - 60 shows the comparison between the speed data collected from the sensors and that obtained from the No Diversion simulation model in the evening. The average speed in the work-zone, far upstream and just upstream from the UE simulation model are shown by red and green solid lines. The field speed observations at the work-zone, far upstream and just upstream are plotted by red, purple and green dotted lines.

In Exhibit II - 61Exhibit II - 62, it is seen that the hourly volume in the No Diversion model is lower than the observed field data just upstream of the work zone. But the congestion just upstream of the work zone causes the hourly volume to decrease considerably gradually. The ND model overestimates the hourly volume, since it assumes that none of the drivers opt to take alternative routes.

Exhibit II - 61 Comparison between the hourly volume data collected from traffic sensors and that obtained from the No Diversion simulation model in the morning

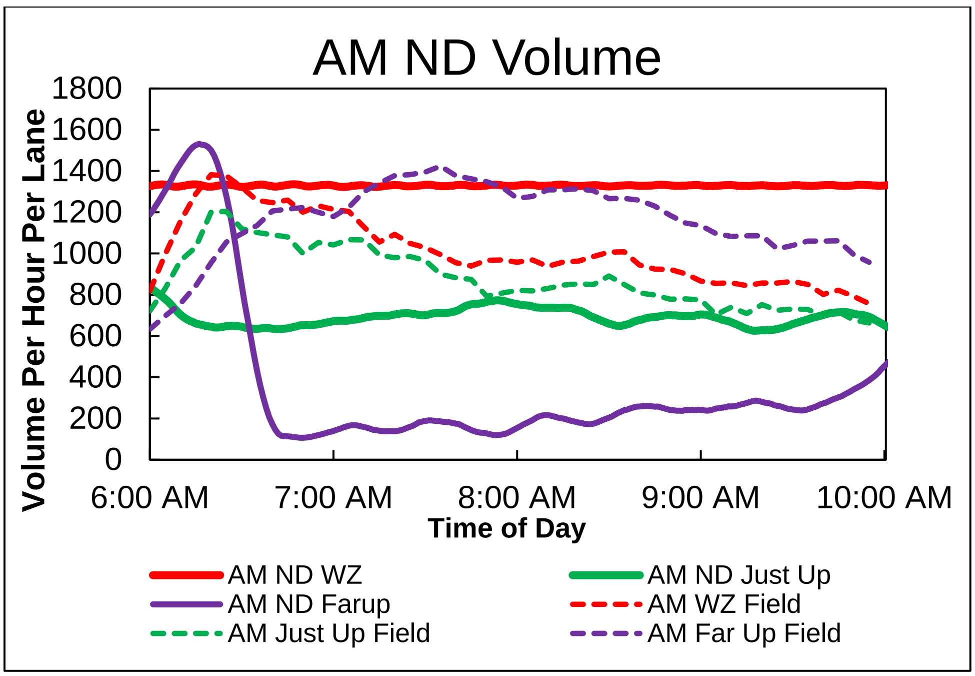


Exhibit II - 61 shows the comparison between the hourly volume data collected from traffic sensors and that obtained from the No Diversion simulation model in the morning. The hourly volume per lane in the Work Zone Area, far upstream and just upstream of the Work Zone Area from the UE simulation model are shown by blue, red and green solid lines. The field speed observations at the work-zone, far upstream and just upstream are plotted by blue, red and green dotted lines.

Exhibit II - 62 Comparison between the hourly volume data collected from traffic sensors and that obtained from the No Diversion simulation model in the evening

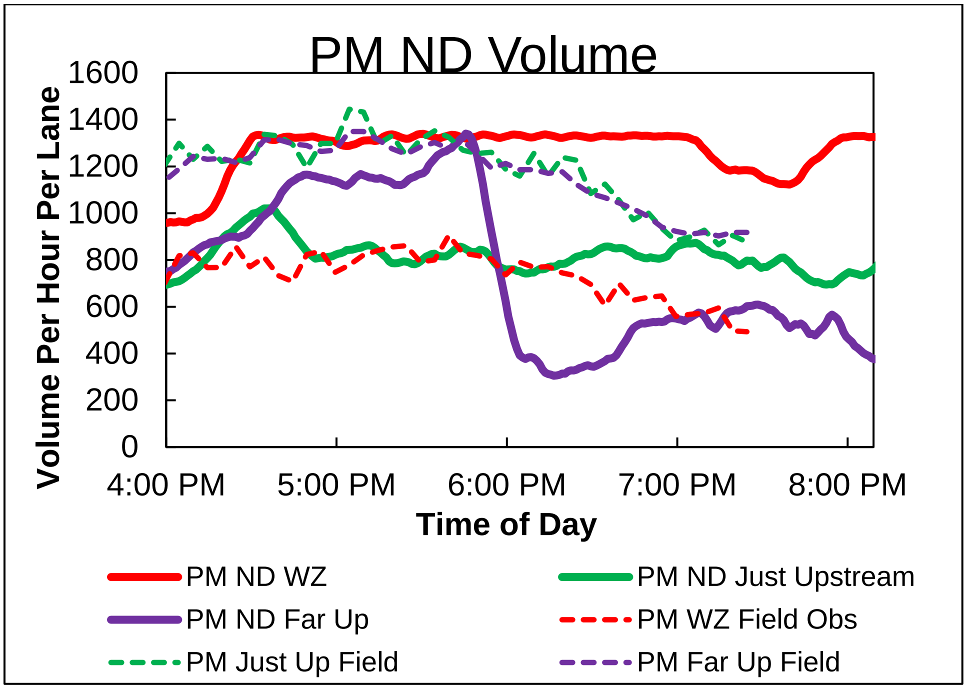


Exhibit II - 62 shows the comparison between the hourly volume data collected from traffic sensors and that obtained from the No Diversion simulation model in the evening. The hourly volume per lane in the Work Zone Area, far upstream and just upstream of the Work Zone Area from the UE simulation model are shown by blue, red and green solid lines. The field speed observations at the work-zone, far upstream and just upstream are plotted by blue, red and green dotted lines.

Exhibit II - 63 and Exhibit II - 64 show that vehicles move at a relatively constant speed far upstream and inside the work zone. But just upstream of the Work Zone, the average speed decreases drastically, due to bottleneck traffic. The User Equilibrium model shows higher average speed just upstream of the work zone than what is observed, which suggests that the User Equilibrium is a better model.

Exhibit II - 63 Comparison between the speed data collected from traffic sensors and that obtained from the UE simulation model in the morning

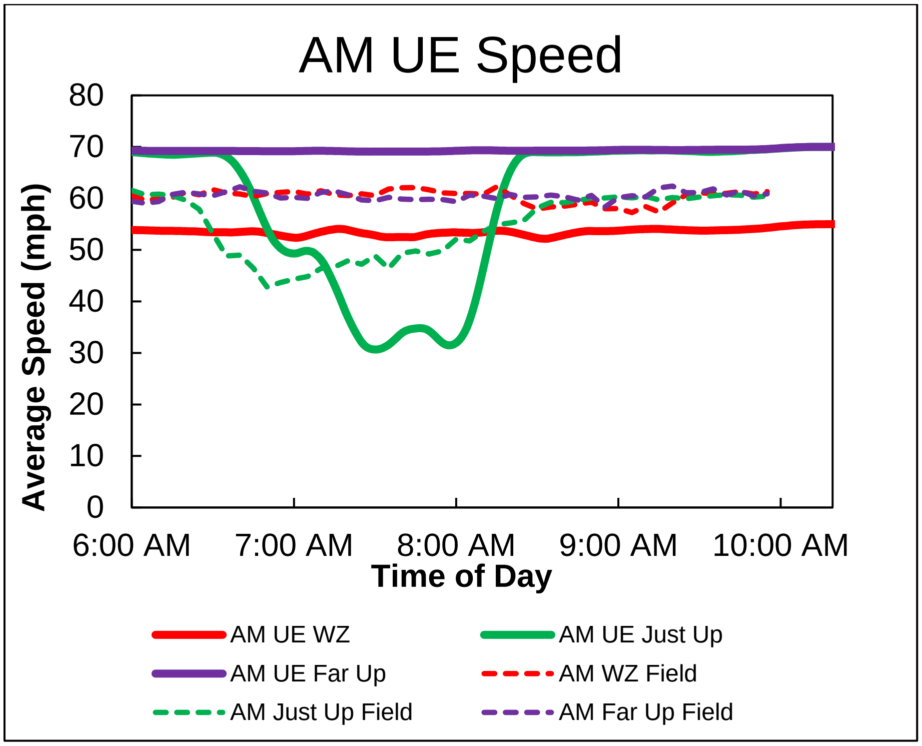


Exhibit II - 63 shows the comparison between the speed data collected from traffic sensors and that obtained from the UE simulation model in the morning. The average speed in the Work Zone Area, far upstream and just upstream of the Work Zone Area from the UE simulation model are shown by blue, red and green solid lines. The field speed observations at the work-zone, far upstream and just upstream are plotted by blue, red and green dotted lines.

Exhibit II - 64 Comparison between the speed data collected from the sensors and that obtained from the UE simulation model in the evening

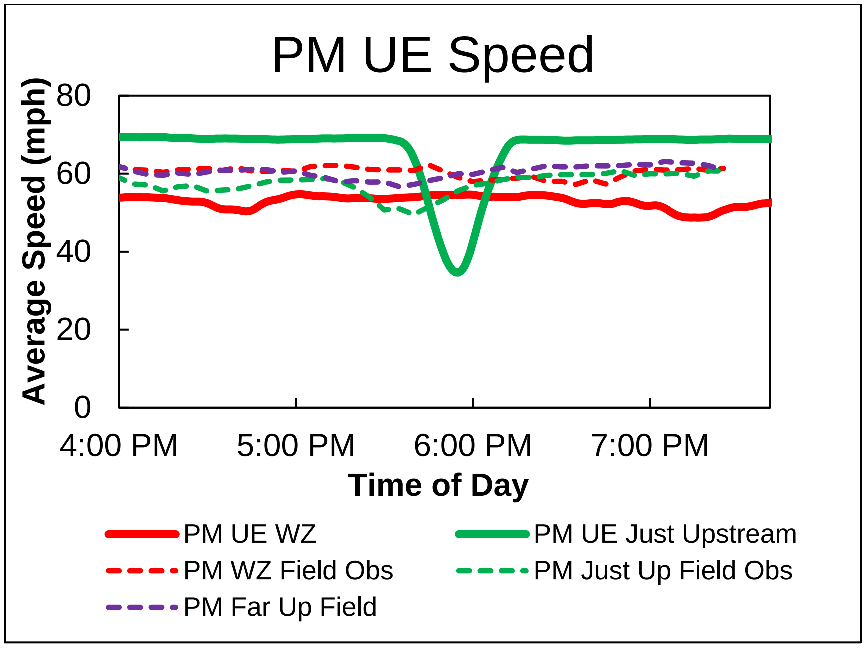


Exhibit II - 64 shows the comparison between the speed data collected from the sensors and that obtained from the UE simulation model in the evening. The average speed in the work-zone, far upstream and just upstream from the UE simulation model are shown by red and green solid lines. The field speed observations at the work-zone, far upstream and just upstream are plotted by red, purple and green dotted lines.

Exhibit II - 65 and Exhibit II - 66show that the hourly traffic volume per lane is much lower just upstream of the work zone. This is a consequence of the significant decrease in speed of the vehicles and the bottleneck that is created just as the vehicles enter the work zone. The hourly traffic volume far upstream is much higher than in the work zone because of the unimpeded average speed of vehicles. The UE model shows a much higher volume of traffic far upstream and through the work zone than the field observed data.

Exhibit II - 65 Comparison between the hourly volume per lane collected from the sensors and that obtained from the UE simulation model in the morning

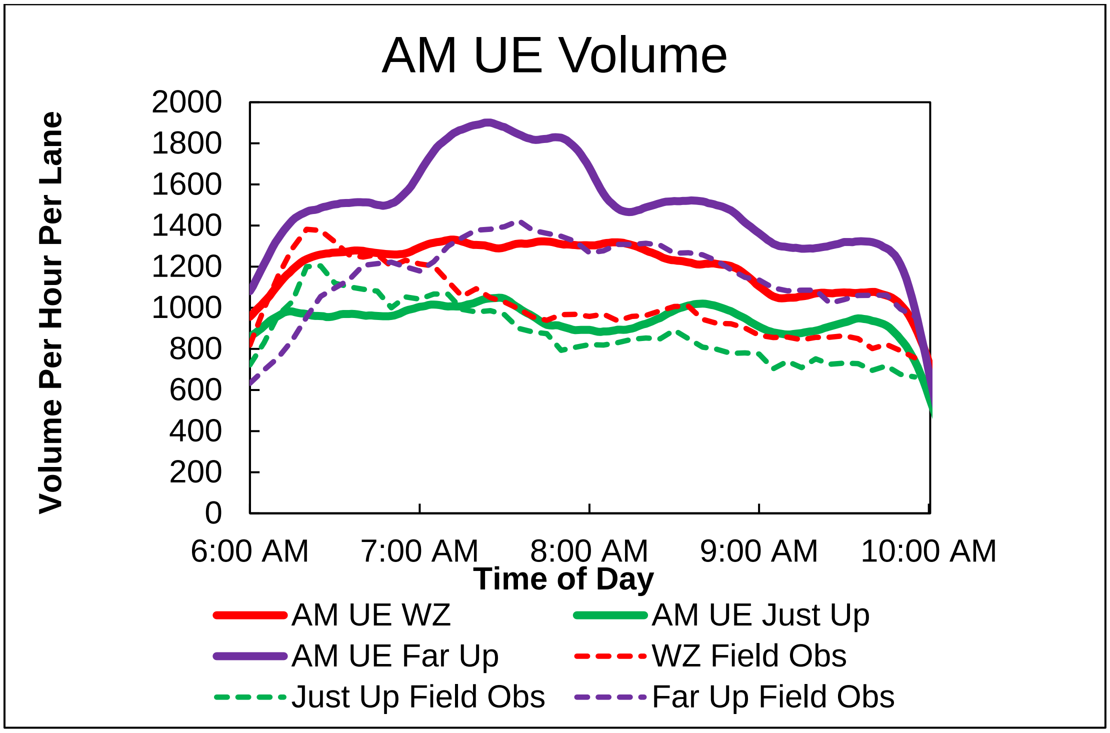


Exhibit II - 65 shows the comparison between the hourly volume per lane collected from the sensors and that obtained from the UE simulation model in the morning. The hourly volume per lane in the work-zone, far upstream and just upstream from the UE simulation model are shown by red and green solid lines. The field volume observations at the work-zone, far upstream and just upstream are plotted by red, purple and green dotted lines.

Exhibit II - 66 Comparison between the hourly volume per lane collected from the sensors and that obtained from the UE simulation model in the evening.

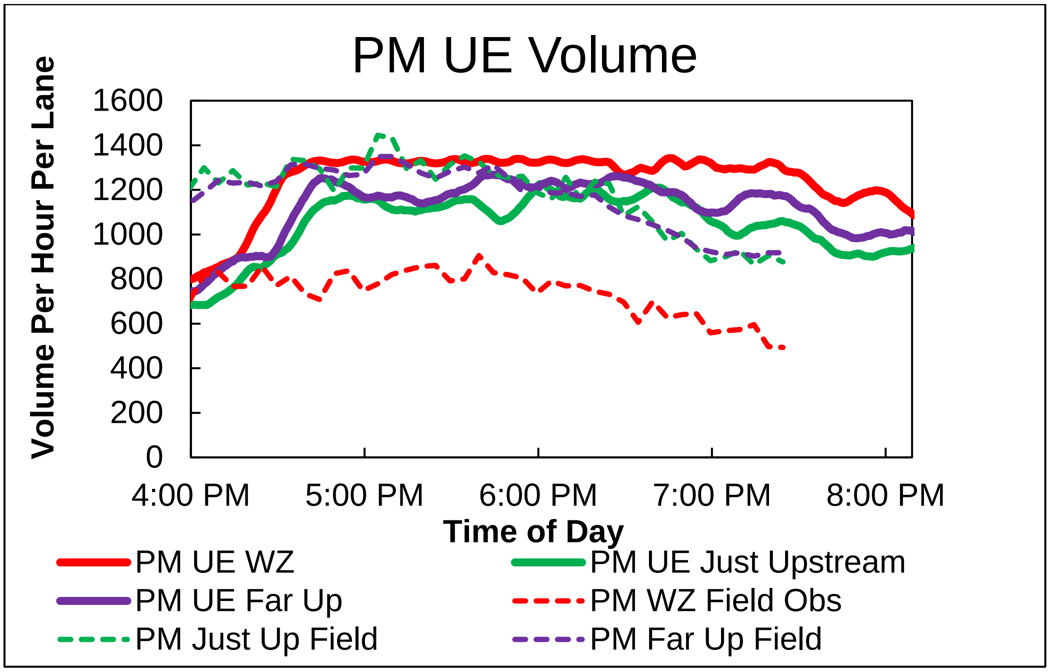


Exhibit II - 66 shows the comparison between the hourly volume per lane collected from the sensors and that obtained from the UE simulation model in the evening. The hourly volume per lane in the work-zone, far upstream and just upstream from the UE simulation model are shown by red and green solid lines. The field volume observations at the work-zone, far upstream and just upstream are plotted by red, purple and green dotted lines.

APPENDIX II - A: DETAILED FREEVAL RESULTS

Exhibit II - A 1 Sensitivity Analysis to Diversion Rates on Work Zone Traffic Impact (Route C WB/AM)

Scenario	DAF	Travel Time (Minutes)	Max DEQL (Miles)	Max Queue Length (Miles)	Max d/c Ratio
Base	1.0	27	0.0	0.0	1.2
WZ1	0.50	50	0.0	4.9	1.9
	0.60	75	0.0	7.8	2.3
	0.70	90	0.0	11.0	2.7
	0.80	98	0.0	11.3	3.1
	0.90	111	1.3	13.3	3.4
	0.95	114	0.0	13.5	3.6
	1.00	116	1.4	13.5	3.8
WZ1b	0.50	30	0.0	0.0	1.3
	0.60	34	0.0	1.3	1.5
	0.70	39	0.0	3.3	1.8
	0.80	47	0.0	5.9	2.1
	0.90	53	0.0	8.8	2.3
	0.95	56	0.0	8.8	2.4
	1.00	59	0.0	8.8	2.6
WZ3	0.50	29	0.0	0.0	1.3
	0.60	31	0.0	1.3	1.5
	0.70	36	0.0	2.3	1.8
	0.80	38	0.0	4.5	2.0
	0.90	43	0.0	7.6	2.3
	0.95	46	0.0	8.8	2.4
	1.00	47	0.0	10.9	2.5
WZ5	0.50	30	0.0	0.0	1.3
	0.60	32	0.0	1.3	1.5
	0.70	36	0.0	2.3	1.8
	0.80	38	0.0	4.5	2.0
	0.90	43	0.0	7.6	2.3
	0.95	46	0.0	8.8	2.4
	1.00	47	0.0	10.9	2.5
WZ7	0.50	26	0.0	0.0	0.8
	0.60	26	0.0	0.0	1.0
	0.70	28	0.0	0.6	1.1
	0.80	30	0.0	1.1	1.3
	0.90	33	0.0	1.3	1.5
	0.95	35	0.0	2.2	1.6
	1.00	36	0.0	2.1	1.6

Exhibit II - A 2 Sensitivity Analysis to Diversion Rates on Work Zone Traffic Impact (Route D WB/AM)

Scenario	DAF	Travel Time (Minutes)	Max DEQL (Miles)	Max Queue Length (Miles)	Max d/c Ratio
Base	1.0	47.4	0.0	7.2	1.7
WZ2	0.50	36.5	0.0	2.5	1.5
	0.60	44.8	0.0	4.9	1.8
	0.70	56.4	0.0	7.3	2.1
	0.80	70.5	0.0	11.8	2.4
	0.90	82.3	0.0	14.5	2.7
	0.95	87.2	0.0	15.8	2.8
	1.00	92.9	0.0	16.8	3.0
WZ2b	0.50	31.2	0.0	0.0	1.3
	0.60	34.0	0.0	2.0	1.5
	0.70	39.7	0.0	3.4	1.8
	0.80	48.2	0.0	8.6	2.1
	0.90	58.6	0.0	13.2	2.3
	0.95	63.0	0.0	13.2	2.4
	1.00	67.9	0.0	14.5	2.6
WZ4	0.50	30.5	0.0	0.0	1.0
	0.60	32.5	0.0	1.9	1.2
	0.70	34.4	0.0	2.4	1.4
	0.80	39.9	0.0	5.9	1.6
	0.90	47.8	0.0	9.9	1.8
	0.95	52.3	0.0	14.2	1.9
	1.00	55.6	0.0	14.0	2.0

Exhibit II - A 3 Sensitivity Analysis to Diversion Rates on Work Zone Traffic Impact (Route D EB/PM)

Scenario	DAF	Travel Time (Minutes)	Max DEQL (Miles)	Max Queue Length (Miles)	Max d/c Ratio
Base	1.0	31.7	0.0	1.0	1.2
WZ1	0.50	33.1	0.0	0.2	1.9
	0.60	42.1	0.0	0.9	2.2
	0.70	47.2	0.0	2.0	2.6
	0.80	51.9	0.0	3.5	3.0
	0.90	59.4	0.0	6.1	3.4
	0.95	63.2	0.0	7.6	3.5
	1.00	68.0	0.0	8.9	3.7
WZ1b	0.50	30.7	0.0	0.2	1.2
	0.60	31.7	0.0	0.4	1.5
	0.70	32.3	0.0	0.4	1.7
	0.80	34.2	0.0	1.1	2.0
	0.90	37.1	0.0	1.4	2.2
	0.95	38.9	0.0	2.0	2.4
	1.00	40.3	0.0	3.0	2.5
WZ3	0.50	30.1	0.0	0.2	1.2
	0.60	30.8	0.0	0.2	1.5
	0.70	31.4	0.0	0.2	1.7
	0.80	33.2	0.0	0.7	2.0
	0.90	36.1	0.0	1.0	2.2
	0.95	38.0	0.0	1.7	2.4
	1.00	39.5	0.0	2.6	2.5

Exhibit II - A 4 Route C EB/PM: WZ-2 (Maintain Two Lanes Open) and WZ-6 (Maintain Three Lanes Open) Average Travel Time Comparison by % Traffic Remaining on the Freeway

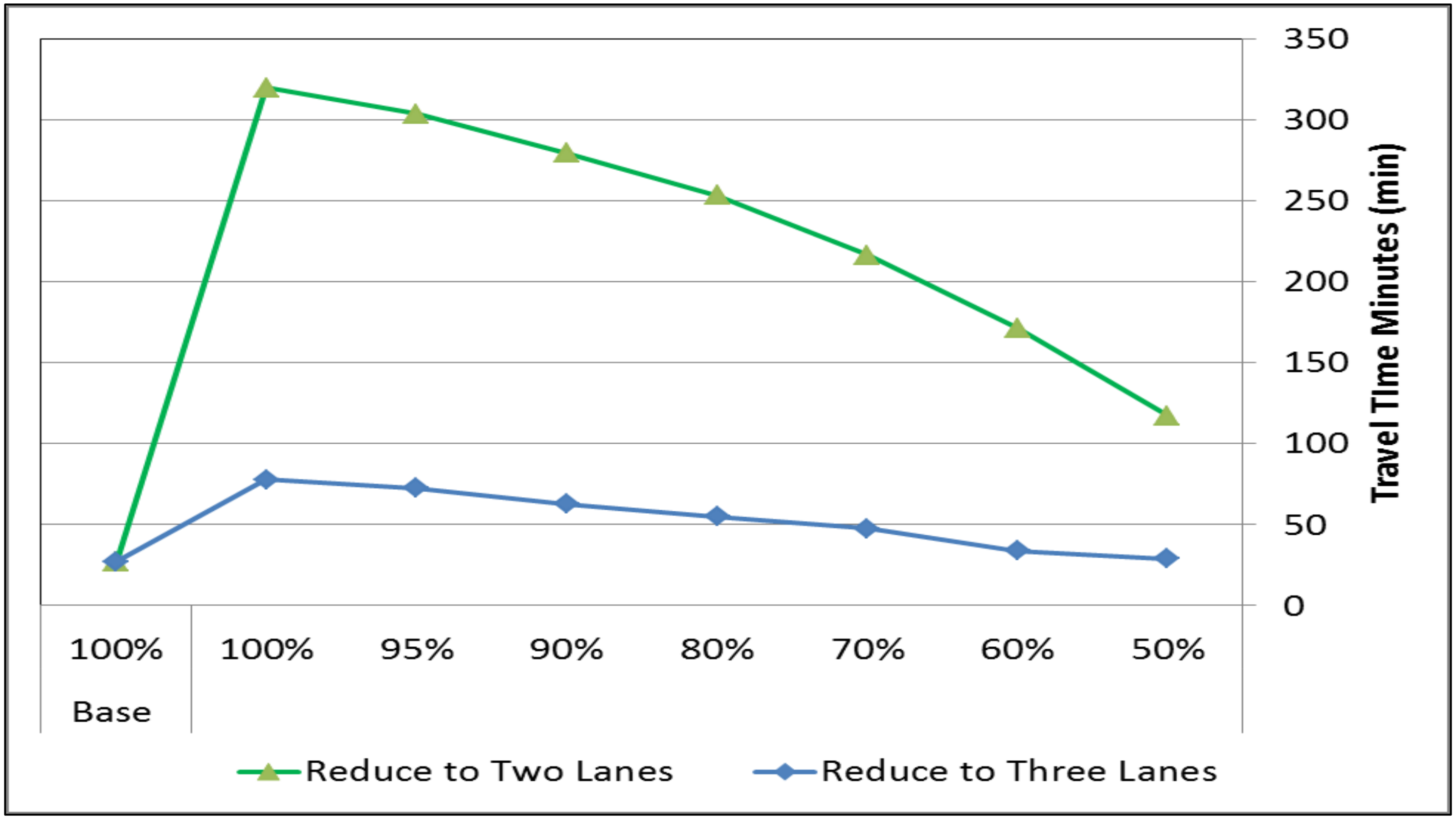


Exhibit II - A 5 Route C WB/AM: WZ-1 (Maintain Two Lanes Open) Average and Maximum Travel Time by % Traffic Remaining on the Freeway

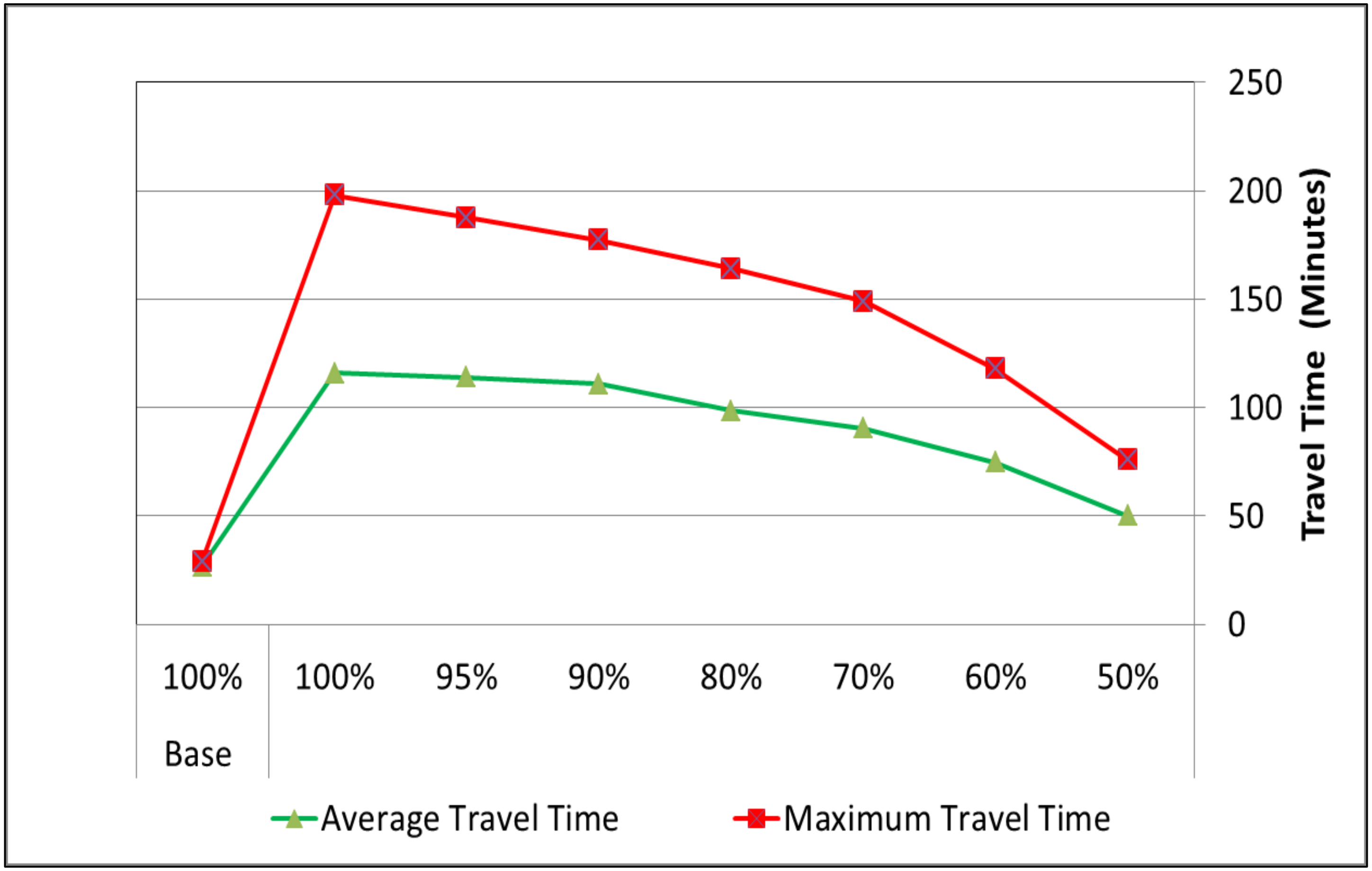


Exhibit II - A 6 Route C WB/AM: WZ-5 (Maintain Three Lanes Open) Average and Maximum Travel Time by % Traffic Remaining on the Freeway

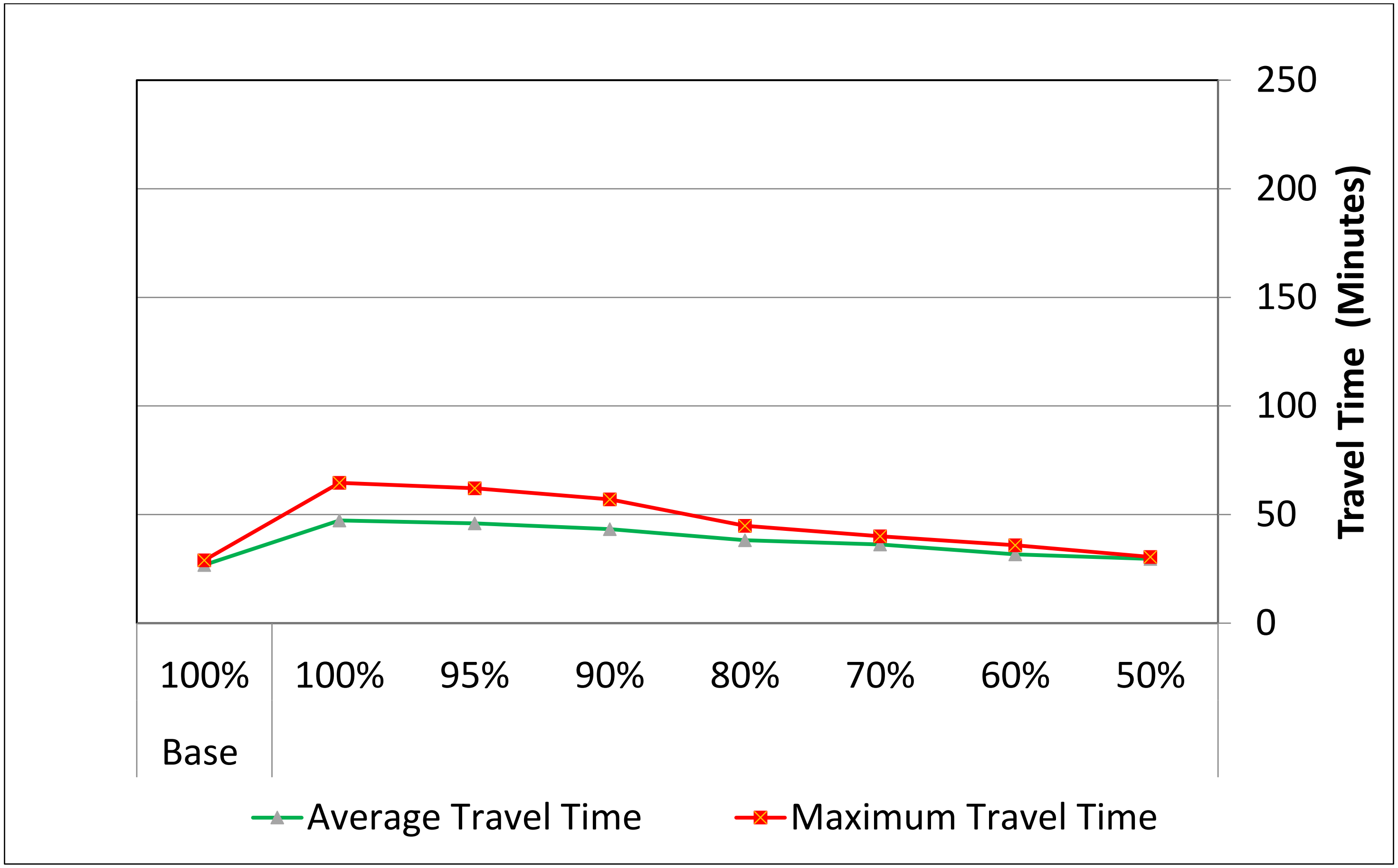


Exhibit II - A 7 Route C WB/AM: WZ-1b (Maintain Two Lanes Open) Denied Entry Queue Length (DEQL) and Mainline Queue Length

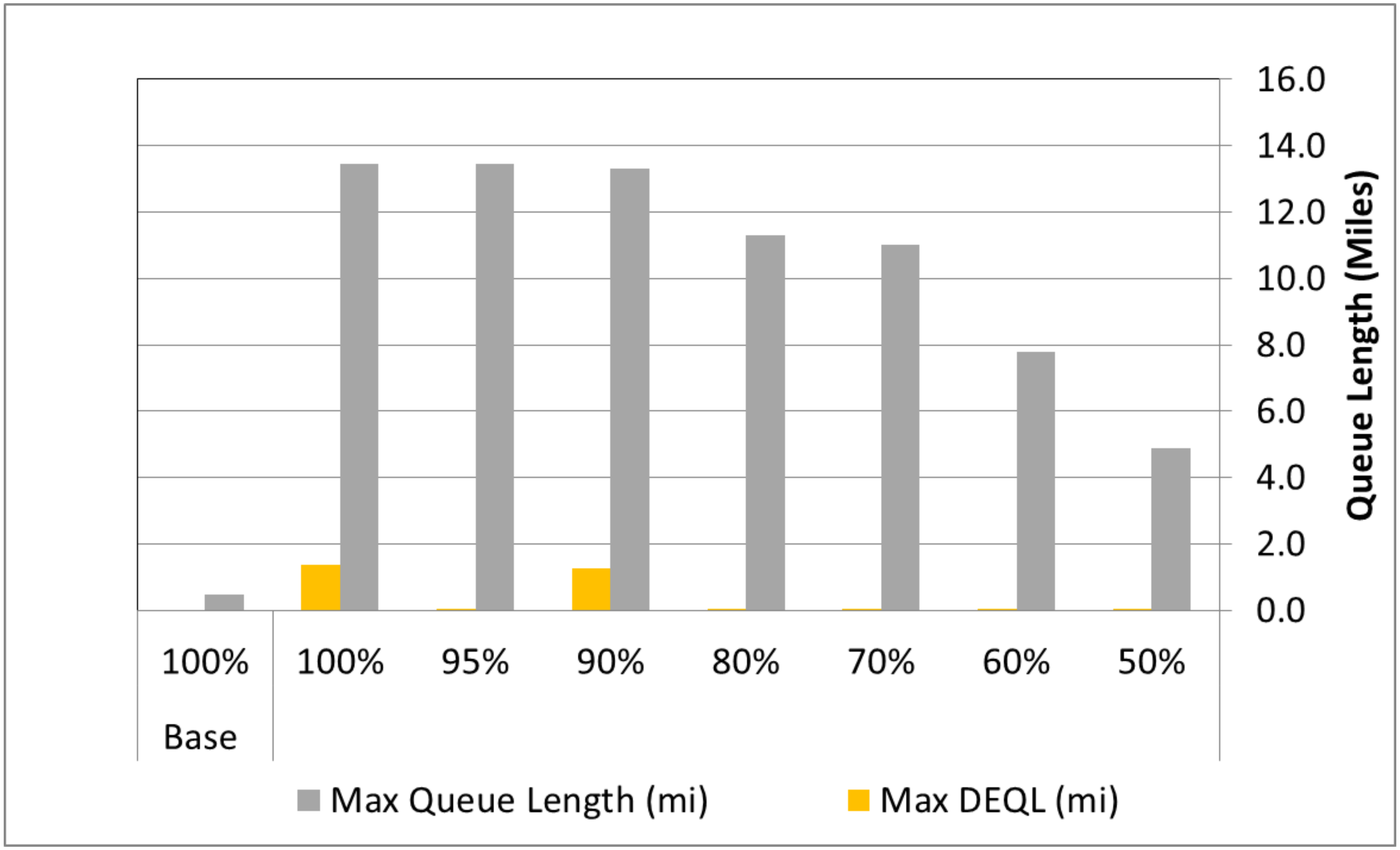


Exhibit II - A 8 Route C WB/AM: WZ-5 (Maintain Three Lanes Open) Denied Entry Queue Length (DEQL) and Mainline Queue Length

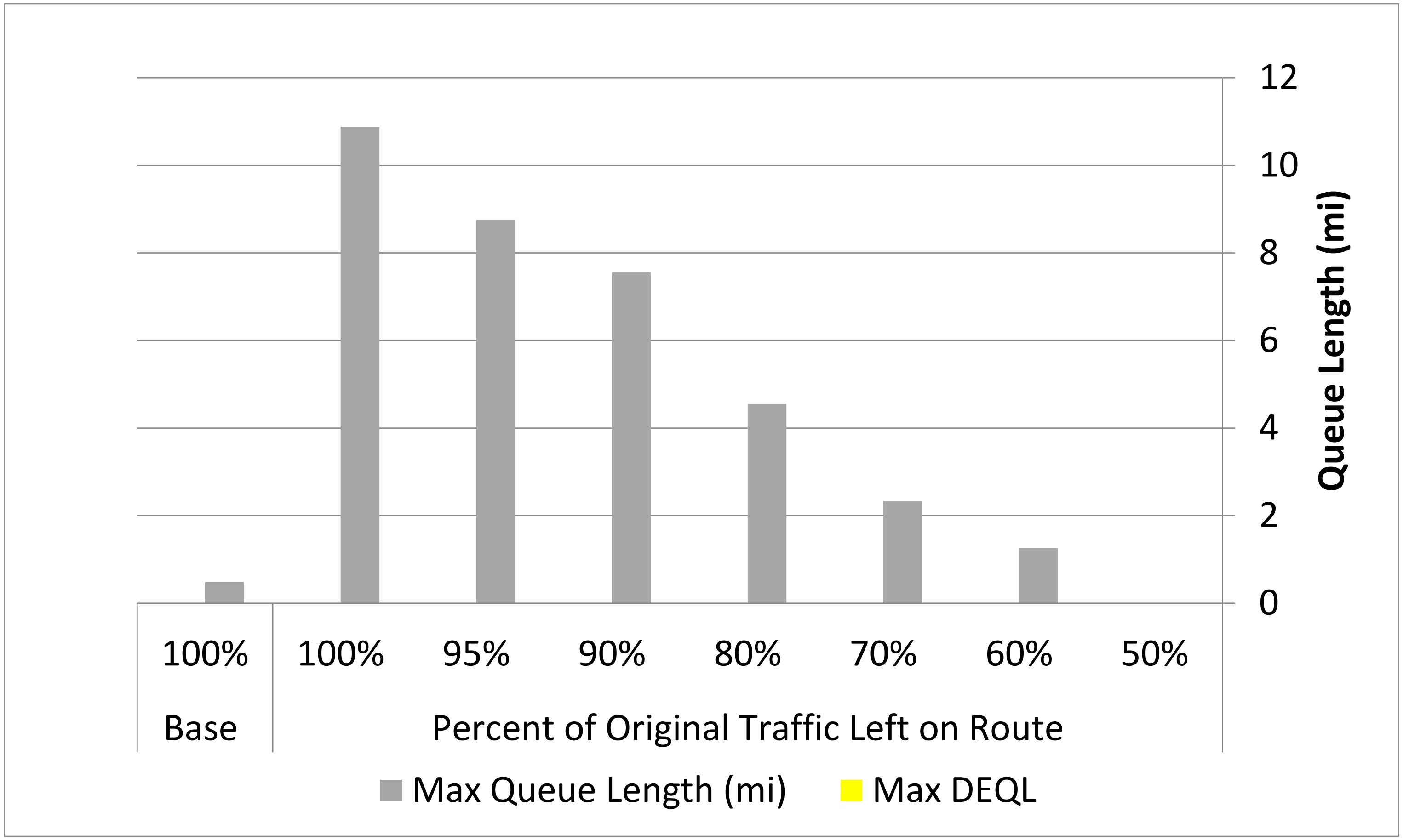
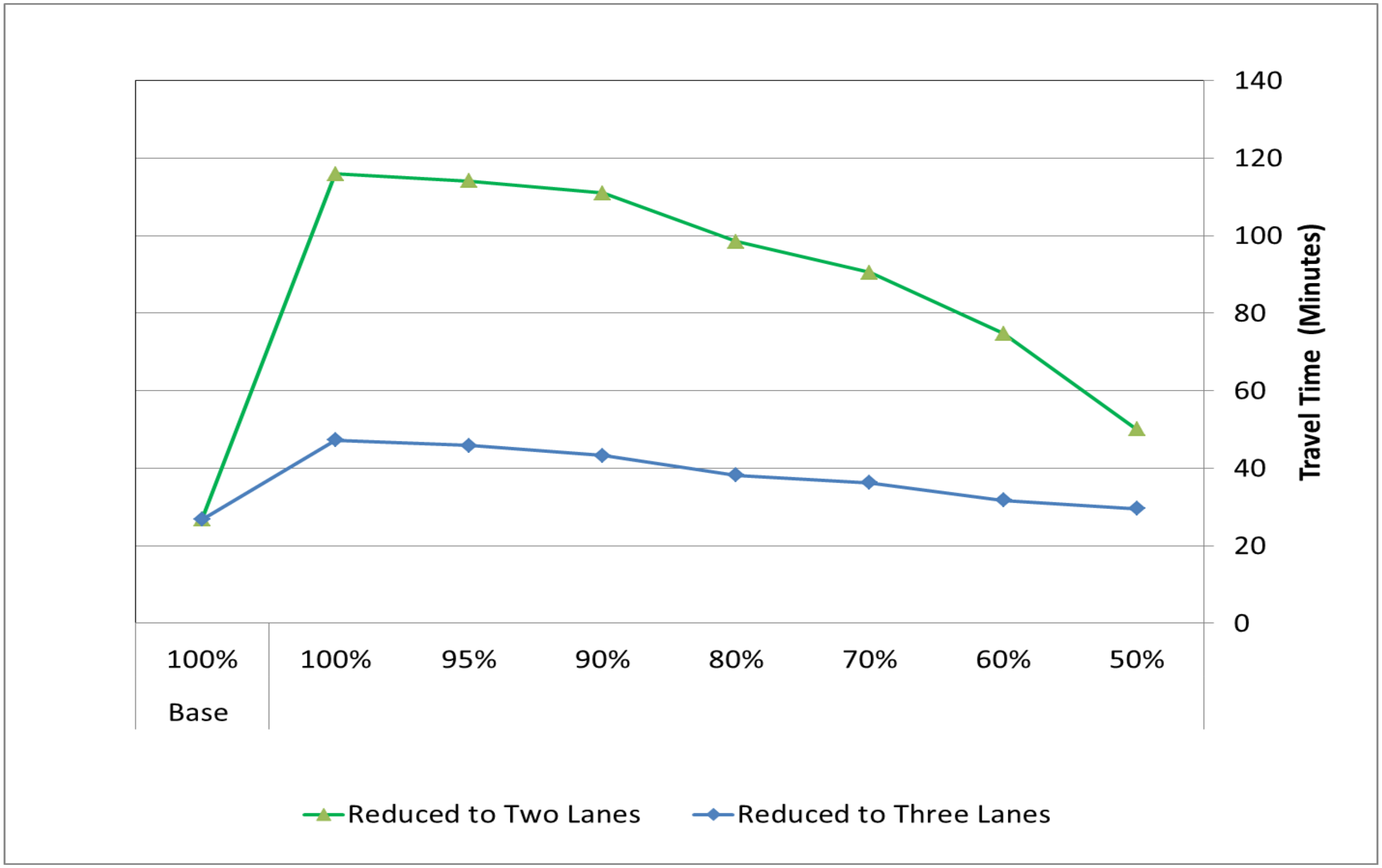


Exhibit II - A 9 Route C WB/AM: WZ-1 (Maintain Two Lanes Open) and WZ-5 (Maintain Three Lanes Open) Average Travel Times Comparison by % Traffic Remaining on the Freeway



FREEVAL Contour Maps

Exhibit II - A 10 - Speed Contours for the Base and Work Zone Scenarios for Route C in (WB/AM)

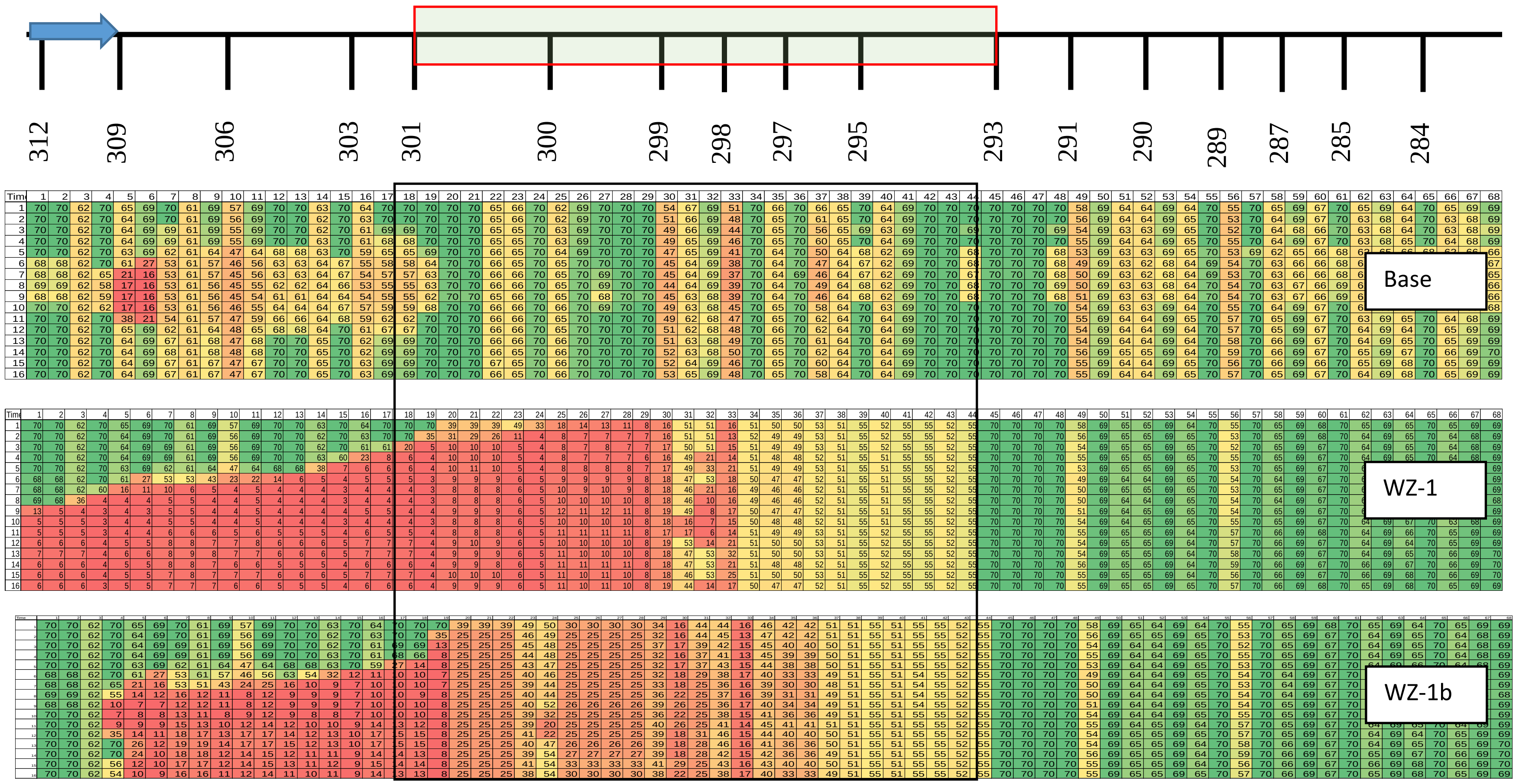


Exhibit II - A 110 (continued)

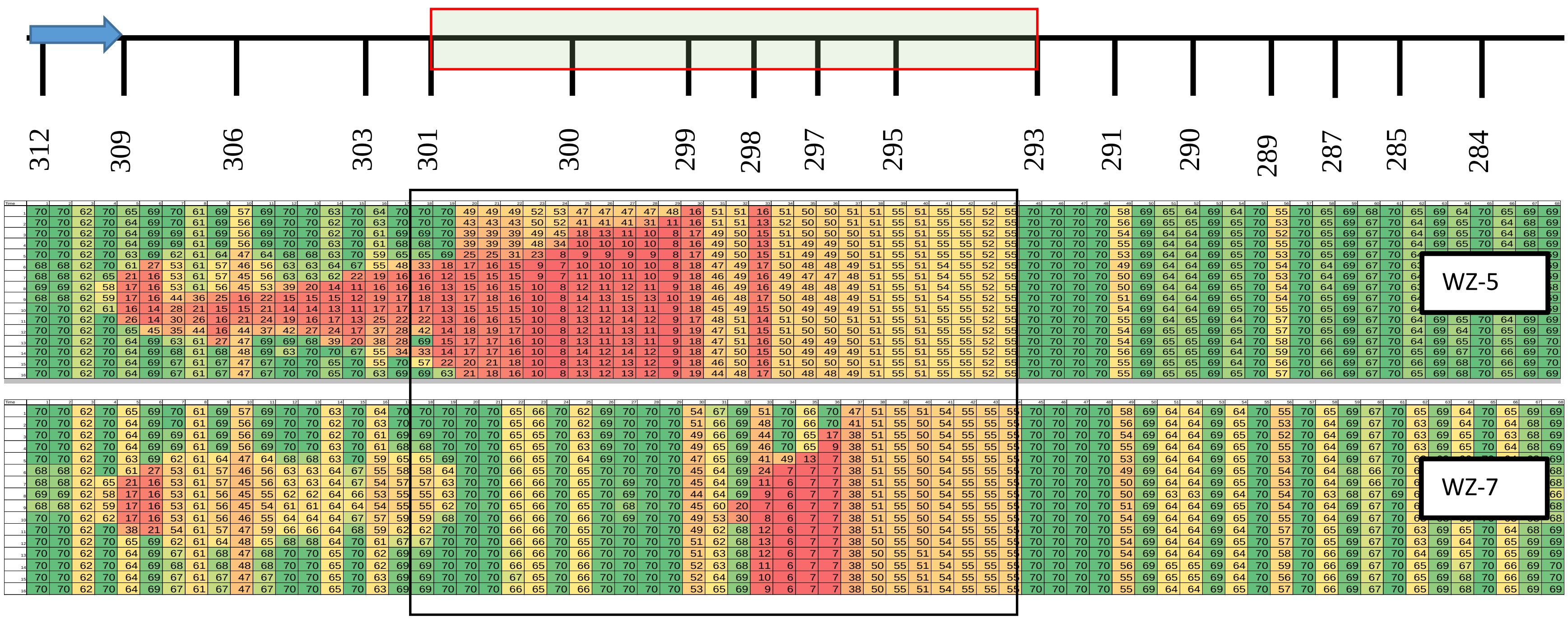


Exhibit II - A 12 - Speed Contours for the Base and Work Zone Scenarios for Route D in (WB/AM)

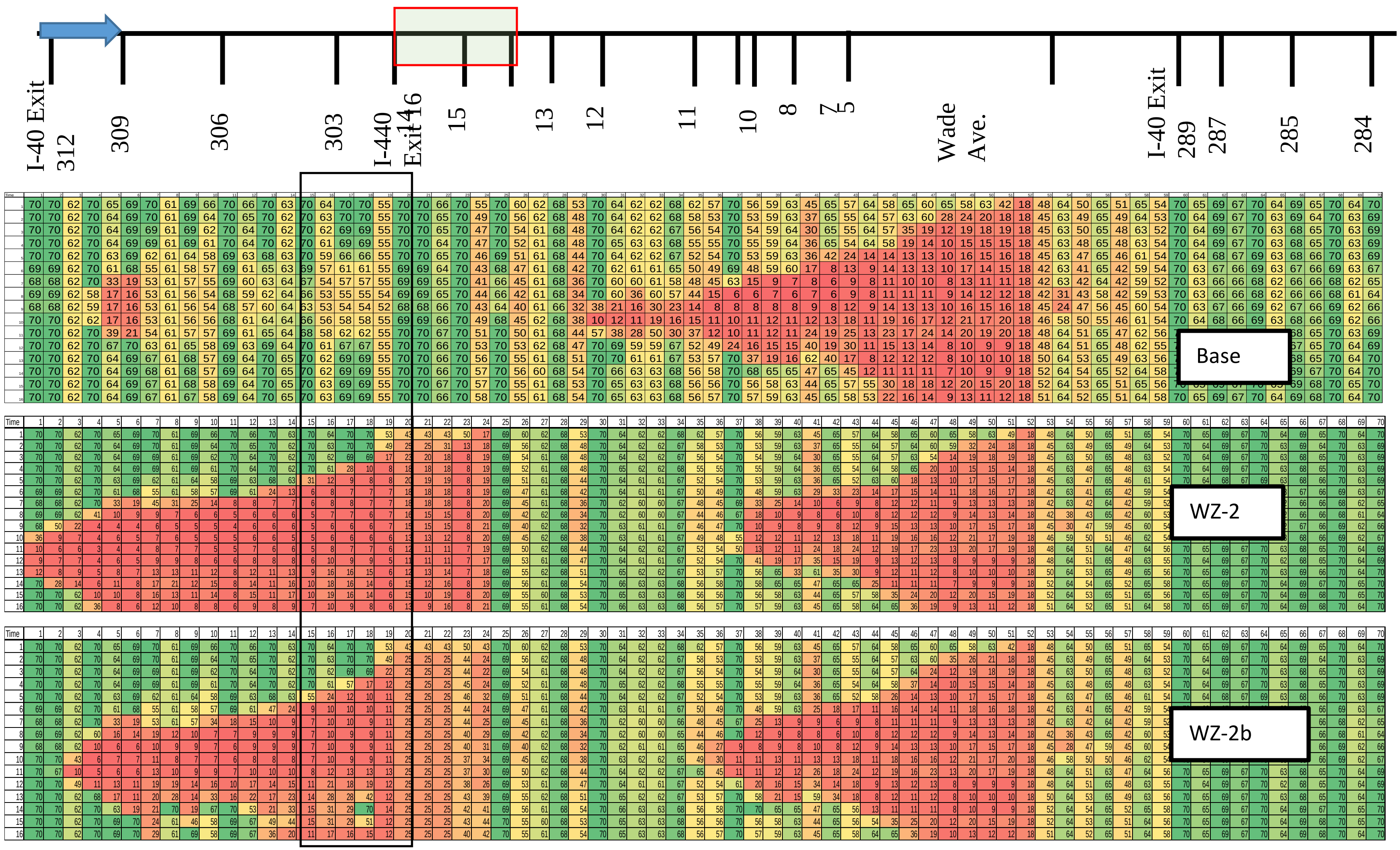
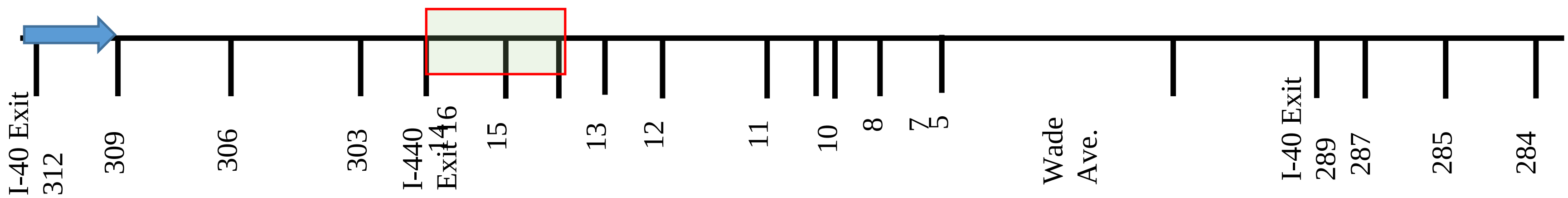


Exhibit II - A 12 (continued)



Time	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	70	70	62	70	65	69	70	61	69	66	70	66	70	63	70	64	70	70
2	70	70	62	70	64	69	70	61	69	64	70	65	70	62	70	63	70	70
3	70	70	62	70	64	69	69	61	69	62	70	64	70	62	70	62	69	69
4	70	70	62	70	64	69	69	61	69	61	70	64	70	62	70	61	69	69
5	70	70	62	70	63	69	62	61	64	58	69	63	68	63	70	59	62	25
6	69	69	62	70	61	68	55	61	58	57	69	61	65	63	58	33	22	17
7	68	68	62	70	33	19	53	61	57	55	69	60	60	37	15	18	18	16
8	69	69	62	58	17	16	53	61	56	54	41	27	17	14	11	17	17	15
9	68	68	62	59	17	16	37	27	22	13	9	14	14	14	11	17	16	15
10	70	70	62	57	13	12	20	17	11	12	9	14	13	13	11	16	16	15
11	70	70	60	55	10	9	24	19	13	13	10	17	15	15	12	20	22	24
12	70	70	62	70	28	16	31	41	18	43	24	33	22	24	17	35	31	49
13	70	70	62	70	69	68	35	61	44	68	70	67	41	36	18	36	31	70
14	70	70	62	70	64	69	65	61	69	57	69	65	70	70	34	39	32	53
15	70	70	62	70	64	69	67	61	68	58	69	64	70	65	70	64	64	55
16	70	70	62	70	64	69	67	61	67	58	69	64	70	65	70	59	70	50

Time	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
1	53	50	50	50	53	43	70	60	62	68	53	70	64	62	62	68	62	57
2	49	41	41	41	49	18	69	56	62	68	48	70	64	62	62	67	58	53
3	39	30	30	30	48	19	69	54	61	68	48	70	64	62	62	67	56	54
4	32	25	25	25	50	19	69	52	61	68	48	70	65	62	62	68	55	55
5	25	25	25	25	31	19	69	51	61	68	44	70	64	62	62	67	52	54
6	25	25	25	25	18	19	69	47	61	68	42	70	63	61	61	67	50	49
7	25	25	31	28	12	20	69	45	61	68	36	70	62	60	60	66	48	45
8	30	26	22	20	11	20	69	42	62	68	34	70	62	60	60	64	44	36
9	29	39	39	26	13	21	69	40	62	68	32	70	62	61	61	64	46	18
10	29	39	39	39	15	20	69	45	62	68	38	70	62	62	62	64	47	17
11	54	39	39	39	12	19	69	50	62	68	44	70	64	62	62	67	67	23
12	55	40	40	43	10	17	69	53	61	68	47	70	64	61	61	67	52	58
13	55	45	51	53	17	20	69	55	62	68	51	70	65	62	62	67	53	57
14	55	46	46	46	55	29	69	56	61	68	54	70	66	63	63	68	56	58
15	54	27	27	54	39	20	69	55	60	68	53	70	65	63	63	68	56	56
16	38	25	25	51	16	21	69	55	61	68	54	70	65	63	63	68	56	57

Time	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54
1	70	56	59	63	45	65	57	64	58	65	60	65	58	63	42	18	48	64
2	70	53	59	63	37	65	55	64	57	63	60	31	25	21	18	18	45	63
3	70	54	59	64	30	65	55	64	57	52	22	12	19	18	19	18	45	63
4	70	55	59	64	36	65	54	64	58	28	14	10	15	15	14	18	45	63
5	70	53	59	63	36	65	52	38	20	13	13	10	17	15	17	18	45	63
6	70	48	59	63	24	15	16	11	14	14	14	11	18	16	17	18	42	63
7	67	22	12	8	9	6	9	8	12	11	11	9	13	13	13	18	42	63
8	33	9	8	7	8	6	10	8	12	12	12	9	14	13	14	18	42	34
9	9	8	9	8	10	8	12	9	15	13	13	10	17	15	17	18	45	28
10	11	12	13	12	13	12	18	11	19	16	16	12	21	17	19	18	46	58
11	11	11	14	12	24	17	24	12	19	17	23	13	20	17	19	18	48	64
12	33	17	18	16	35	15	20	9	13	12	13	8	9	9	9	18	48	64
13	70	47	20	15	60	34	19	8	12	12	12	8	10	10	10	18	50	64
14	69	70	65	65	47	65	55	14	11	11	11	8	10	9	9	18	52	64
15	70	56	58	54	44	65	61	44	32	24	19	12	20	15	20	18	52	56
16	70	57	59	63	45	65	58	64	56	27	17	9	13	11	12	18	51	64

Time	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70
1	50	65	51	65	54	70	65	69	67	70	64	69	65	70	64	70
2	49	65	49	64	53	70	64	69	67	70	63	69	64	70	63	69
3	50	65	48	63	52	70	64	69	67	70	63	68	65	70	63	69
4	48	65	48	63	54	70	64	69	67	70	63	68	65	70	63	69
5	47	65	46	61	54	70	64	68	67	69	63	68	66	70	63	69
6	41	65	42	59	54	70	63	67	66	69	63	67	66	69	63	67
7	42	64	42	59	52							66	66	68	62	65
8	43	60	42	60	53							66	66	68	61	64
9	47	59	45	60	54							67	66	69	62	66
10	50	50	46	62	54							68	66	69	62	67
11	51	64	47	64	56	70	65	69	67	70	63	68	65	70	64	69
12	51	65	48	63	55	70	64	69	67	70	62	68	65	70	64	69
13	53	65	49	63	56	70	65	69	67	70	63	68	65	70	64	70
14	54	65	52	65	58	70	65	69	67	70	64	69	67	70	65	70
15	53	56	51	64	56	70	65	69	67	70	64	69	68	70	64	70
16	52	65	51	61	58	70	65	69	67	70	64	69	68	70	64	69

WZ-4

Exhibit II - A 13 - Speed Contours for the Base and Work Zone Scenarios for Route D (EB/PM)

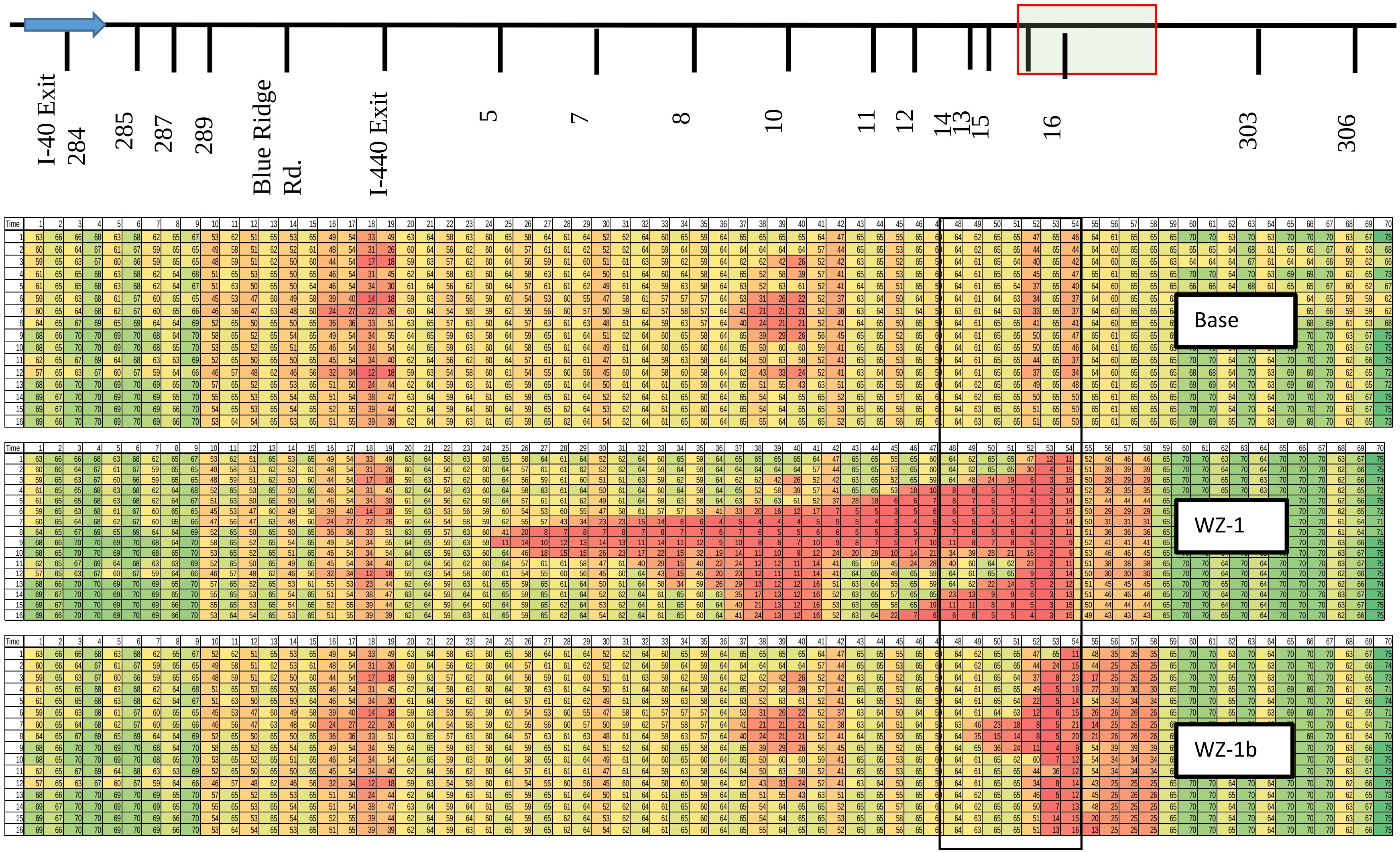
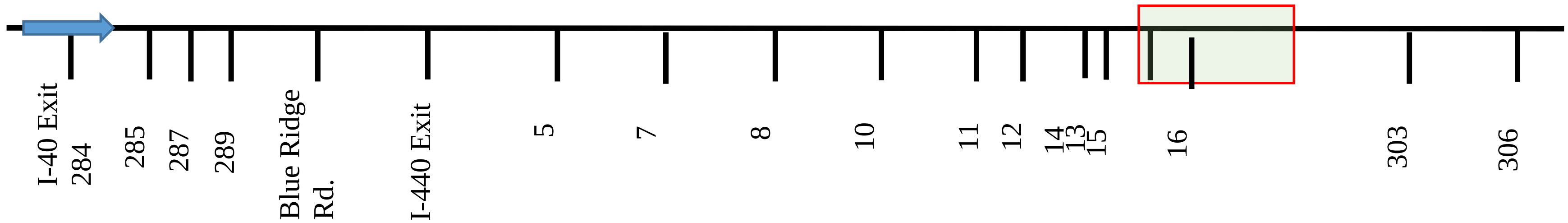


Exhibit II - A 13 (continued)



Time	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
1	63	66	66	68	63	68	62	65	67	52	62	51	65	53	65	49	54	33
2	60	66	64	67	61	67	59	65	65	49	58	51	62	53	61	48	54	31
3	59	65	63	67	60	66	59	65	65	48	59	51	62	50	60	44	54	17
4	61	65	65	68	63	68	62	64	68	51	65	53	65	50	65	46	54	31
5	61	65	65	68	63	68	62	64	67	51	63	50	65	50	64	46	54	34
6	59	65	63	68	61	67	60	65	65	45	53	47	60	49	58	39	40	14
7	60	65	64	68	62	67	60	65	66	46	56	47	63	48	60	24	27	22
8	64	65	67	69	65	69	64	64	69	52	65	50	65	50	65	36	36	33
9	68	66	70	70	69	70	68	64	70	58	65	52	65	54	65	49	54	34
10	68	65	70	70	69	70	68	65	70	53	65	52	65	51	65	46	54	34
11	62	65	67	69	64	68	63	63	69	52	65	50	65	50	65	45	54	34
12	57	65	63	67	60	67	59	64	66	46	57	48	62	46	56	32	34	12
13	68	66	70	70	69	70	69	65	70	57	65	52	65	53	65	51	50	24
14	69	67	70	70	69	70	69	65	70	55	65	53	65	54	65	51	54	38
15	69	67	70	70	69	70	69	66	70	54	65	53	65	54	65	52	55	39
16	69	66	70	70	69	70	69	66	70	53	64	54	65	53	65	51	55	39

Time	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36
1	49	63	64	58	63	60	65	58	64	61	64	52	62	64	60	65	59	64
2	26	60	64	56	62	60	64	57	61	61	62	52	62	64	59	64	59	64
3	18	59	63	57	62	60	64	56	59	61	60	51	61	63	59	62	59	64
4	45	62	64	58	63	60	64	58	63	61	64	50	61	64	60	64	58	64
5	30	61	64	56	62	60	64	57	61	61	62	49	61	64	59	63	58	64
6	18	59	63	53	56	59	60	54	53	60	55	47	58	61	57	57	57	64
7	26	60	64	54	58	59	62	55	56	60	57	50	59	62	57	58	57	64
8	51	63	65	57	63	60	64	57	63	61	63	48	61	64	59	63	57	64
9	55	64	65	59	63	58	64	59	65	61	64	51	62	64	60	65	58	64
10	54	64	65	59	63	60	64	58	65	61	64	49	61	64	60	65	60	64
11	40	62	64	56	62	60	64	57	61	61	61	47	61	64	59	63	58	64
12	18	59	63	54	58	60	61	54	55	60	56	45	60	64	58	60	58	64
13	44	62	64	59	63	61	65	59	65	61	64	50	61	64	61	65	59	64
14	47	63	64	59	64	61	65	59	65	61	64	52	62	64	61	65	60	64
15	44	62	64	59	64	60	64	59	65	62	64	53	62	64	61	65	60	64
16	39	62	64	59	63	61	65	59	65	62	64	54	62	64	61	65	60	64

Time	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54
1	65	65	65	65	64	47	65	65	55	65	60	64	62	65	65	47	65	11
2	64	64	64	64	57	44	65	65	53	65	60	64	62	65	65	44	24	15
3	62	62	42	26	52	42	63	65	52	65	59	64	61	65	64	37	8	15
4	65	52	58	39	57	41	65	65	53	65	60	64	61	65	65	49	4	10
5	63	52	63	61	52	41	64	65	51	65	59	64	61	65	64	22	5	14
6	53	31	26	22	52	37	63	64	50	64	59	64	61	64	63	12	6	15
7	41	21	21	21	52	38	63	64	51	64	58	63	47	24	19	8	5	14
8	40	24	21	21	52	41	64	65	50	65	59	64	33	14	13	8	5	11
9	65	39	29	26	56	45	65	65	52	65	60	64	61	33	24	11	4	9
10	65	50	60	60	59	41	65	65	53	65	60	64	61	65	62	60	7	12
11	64	50	63	58	52	41	65	65	53	65	59	64	61	65	65	44	36	12
12	62	43	33	24	52	41	63	64	50	65	59	64	61	65	65	34	8	14
13	65	51	55	43	63	51	65	65	55	65	60	64	62	65	65	46	5	12
14	65	54	64	65	65	52	65	65	57	65	61	64	62	65	65	50	7	13
15	65	54	64	65	65	53	65	65	58	65	61	64	63	65	65	51	14	15
16	65	55	64	65	65	52	65	65	56	65	61	64	63	65	65	51	12	15

Time	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70
1	52	48	48	48	65	70	70	63	70	64	70	70	70	63	67	75
2	50	43	43	43	65	70	70	64	70	63	70	70	70	62	66	74
3	50	39	39	39	65	69	69	64	70	63	69	69	70	61	65	72
4	52	44	44	44	65	69	69	64	70	63	69	69	70	61	64	71
5	52	48	48	48	65	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	70	70	62	66	74
6	50	39	39	39	65	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	69	69	61	64	70
7	50	40	40	40	65	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	69	69	61	63	69
8	51	44	44	44	65	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	69	69	61	63	69
9	52	47	47	47	65	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	70	70	63	66	75
10	53	50	50	49	65	70	70	64	70	65	70	70	70	63	67	75
11	51	44	44	45	65	70	70	64	70	64	70	70	70	63	67	75
12	50	40	40	40	65	70	70	64	70	64	70	70	70	62	66	74
13	51	47	47	47	65	70	70	65	70	64	70	70	70	62	65	73
14	51	48	48	48	65	70	70	64	70	64	70	70	70	63	67	75
15	50	46	46	46	65	70	70	64	70	64	70	70	70	63	67	75
16	49	45	45	45	65	70	70	65	70	64	70	70	70	62	66	74

WZ-3

CHAPTER III -

PERFORMANCE REPORT FOR WORK ZONE STAGE 2 (CONSTRUCTION IN AREAS 1&2)

TABLE OF CONTENTS

1.0 INTRODUCTION

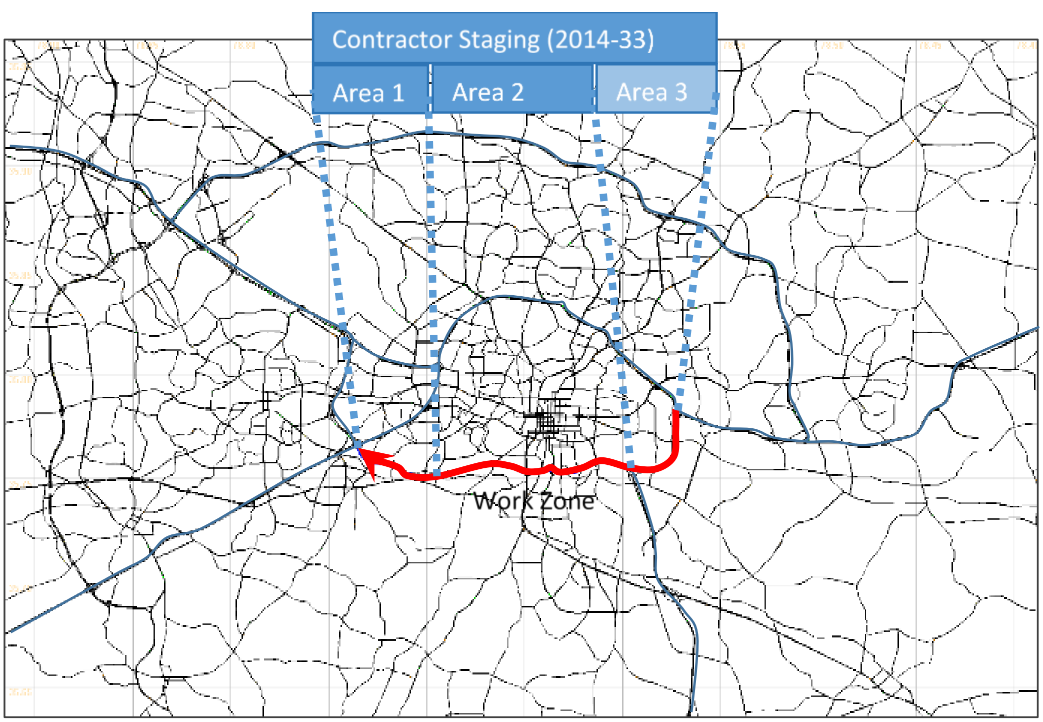
This report presents the final results and findings for an NCDOT research project focused on continued monitoring and assessment of a large work zone project in North Carolina. The work zone project covers work to be completed under TIP numbers I-5311/I-5338: I-40 and I-440 Re-Construction Work from Exit 293 to I-40 Exit 301 and I-440 Exit 14. In a previous project to the team was focused on predicting operational impacts of this work zone using network-wide and corridor-level evaluations tool to estimate the congestion and traffic diversion impacts of the eleven-mile work zone. With this project, ITRE and the NCDOT have a unique opportunity to conduct a real-time evaluation of the eleven-mile work zone under construction and network impacts, to develop public outreach material, and to develop future analysis and calibration guidance for similar projects in North Carolina.

The work zone project, also referred to as the *Fortify* project, is constructed in two primary operational stages. This report focuses on the evaluation of what has been labeled *Area 1 & 2*, which is the section of the work zone on I-40 from the I-40/440 split at exit 301 to the US1/64 interchange at Exit-293 on I-40. This report presents corridor and network-level analyses of this phase in FREEVAL, VISUM and DTALite.

1.1 Project Overview

The results presented in this report represent the second construction stage as part of the "Fortify" work zone project under TIP I-5338 and I-5311. The work area in this stage, referred to as "Area 1 & 2", is constrained to a roughly eight-mile stretch of freeway on I-40, extending from I-40/440 split (Exit-301) to Exit- 293 on both direction of the freeway I-40. Capacity of the freeway has also been reduced in both directions to three lanes in the work zone area. The contractor has also specified closing three ramps: Exit 298A on I-40 East, Exit 298 B on I-40 West and on ramp from Hammond Road on I-40 East. These ramps have alternatives in the close vicinity. A map of the study area is shown in Exhibit III - 1.

Exhibit III - 1: Map of Study Area



The ITRE team monitored the work zone using three different types of sensors and technology:

1. HERE.Com (previously Traffic.com) side-fire radar sensors deployed throughout the triangle, which provide traffic volume and (spot) speed estimates on the freeway network.
2. INRIX probe-based data that is available for all freeways and major arterials in North Carolina, and provides travel time and (segment) speed estimates. By looking at speed estimates over multiple segments, it is further possible to estimate queue lengths. It is noted that INRIX data can be unreliable for arterial performance, especially over short segments.
3. Video observations from overhead-mounted NCDOT traffic cameras. These video stream are used to provide a visual of work zone performance, as well as confirm traffic volumes and queue lengths if needed.
4. The team also deployed Bluetooth sensors across the network to test actual route diversion patterns as a result of the work zone. Even though Bluetooth sensors can capture a fraction of the overall traffic volume, the station counts can serve as a surrogate for volume.

The lessons learned from this activity will be available for this and future research, to offer more North Carolina-specific modeling and calibration guidance for freeway work zones. This project is a long-term monitoring and assessment effort conducted in parallel to the construction activities. The project builds on an available calibrated mesoscopic network simulation model in DTALite, corridor-level macroscopic models in the FREEVAL tool and also a network-level macroscopic model in VISUM. Both the mesoscopic and macroscopic tools have been continuously refined in this project.

This report is focused on performance assessment of the work zone in the initial phase of construction, which is estimated to occur in “Area 1&2” as defined by the contractor. The task will allow the team to collect detailed data on opening day, week, and month traffic characteristics, and develop an estimate of traffic congestion and diversion impacts over time. This performance assessment stage will also serve as feedback to NCDOT in the early construction stages, and provide recommendations for potential improvements to the network-wide traffic management plan and the network model calibration. This stage also provides invaluable information on the traffic patterns that are expected at the onset of other phases of the construction.

1.2 Description of Analysis Routes

The results presented in this report focused on the analysis of four key routes in the triangle area:

Route A: An 8 mile section of I-40 between the I-40 and US1 interchange (Exit 293) and the I-40/440 split (Exit 301). This route combines areas 1 and 2 of the Fortify project, which is a key diversion route to the construction in Area 3.

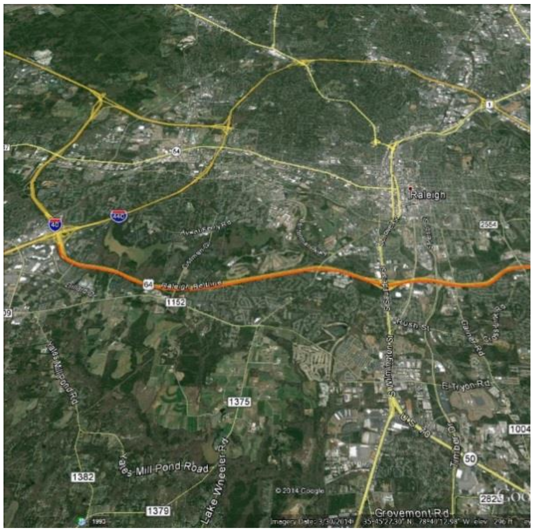
Route B: A 3-mile section of I-440 between the I-40/440 split (Exit 301) and the I-440 and US264 interchange (Exit 16 on I-440). This route represents area 3 of the Fortify project, which contains the construction activity focused on in this analysis.

Route C: An approximately 28-mile section from Exit 312 on I-40 and Exit 284 on I-40, with a path along I-40 (southern loop). This route includes areas 1 and 2 of the Fortify project, and represents a primary diversion route to the construction activity in Area 3, but may also be impacted by queue spillback resulting from the construction.

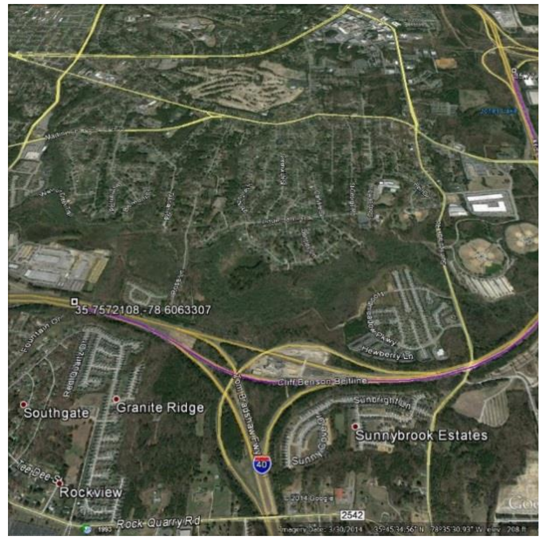
Route D: An approximately 28-mile section from Exit 312 on I-40 and Exit 284 on I-40, with a path along I-440 (northern loop). This route includes the construction activity in area 3, as well as upstream and downstream sections that are likely impacted by queue spillback from the construction.

The routes are shown in Exhibit III - 2.

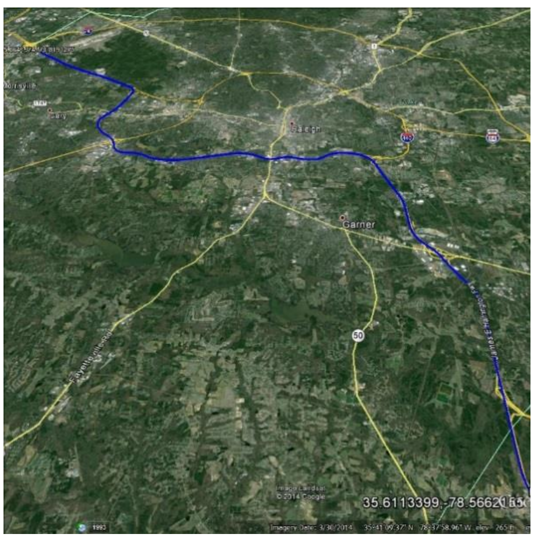
Exhibit III - 2 Major routes for work zone analysis: (a) Route A (b) Route B (c) Route C (d) Route D



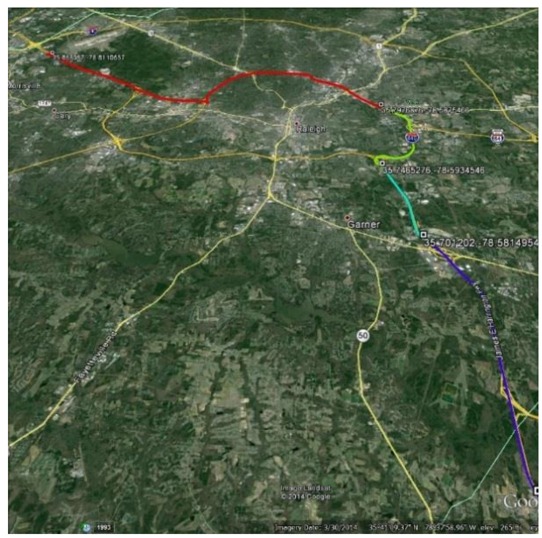
(a)



(b)



(c)



(d)

2.0 METHODS OF ANALYSIS

The team employed three primary methods of analysis: (1) Field data obtained during construction, (2) macroscopic modeling data from the FREEVAL tool, (3) macroscopic modeling and network reduction using VISUM, and (4) mesoscopic modeling data from the DTALite tool. The following sections summarize the analysis and data collection methodologies for these three study approaches.

2.1 Field Data

The ITRE team monitored the Area 3 work zone using three different types of sensors and technology:

1. HERE® (previously known as Traffic.com) side-fire radar sensors deployed throughout the Triangle region, which provide traffic volume and (spot) speed estimates on the freeway network.
2. INRIX probe-based data that is available for all freeways and major arterials in North Carolina, and provides travel time and (segment) speed estimates. By looking at speed estimates over multiple segments, it is further possible to estimate queue lengths. It is noted that INRIX data can be unreliable for arterial performance, especially over short segments.

For travel time analysis, INRIX probe technology was the primary source for data collection. The Vehicle Probe Project Suite through the Regional Integrated Transportation Information System (RITIS) was used to download travel time data that was collected through the INRIX probe technology. Peak period data was gathered for each weekday between January 2015 and December 2015, where the peaks are between 6:00 AM and 10:00 AM and between 3:30 PM and 7:30 PM. The team focused on Routes A through D both eastbound and westbound as previously defined, covering the extent of the Area 1&2 work zone and much of I-40/440 in the Triangle Region. Data from NCDOT was also obtained for the westbound AM peak between I-40 at NC 42 and the I-440 Split (Exit 301) extending until I-440 at Poole Road (Exit 15).

All these data allowed the team to determine the extent of the effects of the work zone on various traffic patterns and routes. Once these data were collected, they were organized into Excel spreadsheets for analysis. By statistical analysis, days with unusual travel times were removed from the data set and an "average" day was generated. Outliers were considered to be days that had a travel time outside of plus or minus two standard deviations of average travel time for the entire data set. After the outlier days were removed, these were then classified as days with incidents, holidays, inclement weather, or another cause for unusual travel times. Incident data provided by NCDOT was utilized in this step, along with archival weather data to help explain outlier events. The effects of various lane configurations, seasons, and the day of week were also determined. The findings were then summarized and compared to modeling data.

Speed data was also collected from RITIS for Routes A through D during the specified peak periods in a similar manner to travel time data, with outliers filtered out of the analysis. Speed analysis was generally not as in depth as travel time analysis, as travel time does help to give an estimate of how fast vehicles in the Area 1&2 work zone were traveling. In this analysis, speed data were more useful in comparison against traffic volume for the various routes. Factors considered in analyzing speed were capacity of the lanes and the speed limit or free flow speed in the segment of travel.

Volume analysis utilized HERE® sensors deployed throughout the specified routes. Data was collected for a number of sensors along the work zone and upstream and downstream of the work zone to assess its impacts, with a focus on three key sensors. Data was also collected for similar time periods one year prior to construction to assess the impacts of the work zone in specific areas. Similar to travel time data analysis, data was collected for each weekday throughout the study period during the peak periods between 6:00 AM and 10:00 AM and between 3:30 PM and 7:30 PM. The data was filtered for outliers due to inclement weather, incidents, or other valid reasons to develop average volumes.

2.2 Bluetooth Data Collection

The team deployed Bluetooth sensors across the network to test actual route diversion patterns as a result of the work zone. Bluetooth sensors are capable of capturing signals from any active Bluetooth devices roaming within the sensing range of deployed sensors. The signals include unique MAC IDs of those devices and timestamps of when these devices were sighted. Bluetooth devices can include cellphones, headphones, in-vehicle communication devices, computing devices.

ITRE used 9 Bluetooth sensors to cover several major routes of interest in the mesoscopic model analysis. The sensors are called ‘BluFAX Standard Portable’. Details of the sensors can be found at www.traffaxinc.com. The devices have a built-in GPS system that can be used for geolocation in post processing. It also comes with a MATLAB based post processing software, called ‘BluSTATS’.

The Bluetooth sensors were deployed to serve the following purposes:

1) To find the actual level and pattern of diversion from the affected work zone route to the alternative freeway and arterial routes.
2) To complement and validate travel time information gathered from INRIX web portal.
3) To verify travel time changes at different stages of construction e.g. before construction, during construction, after construction on the work zone and alternative routes.
4) Even though Bluetooth sensors can capture a fraction of the overall traffic volume, the station counts can serve as a surrogate for volume. This is specifically important for the alternative arterial routes where HERE.com sensors are not present.

The team was able to carry out two separate deployments of the devices to cover two major phases of the project e.g. before lane shift, after lane shift (before lane closure), after lane closure, and after construction. Lane shift means that the total number of lanes before and after construction are the same, just the lane positioning is shifted through construction of additional lanes. Lane closure refers to reduction in number of available lanes from before construction condition.

The analysis of collected data involved two major parts: station processing and route processing. Station processing involves a single sensor station at a time with relevant quality assurances for device sightings. Route processing is the estimation of number of trips made through a pair of Bluetooth sensors and their corresponding travel times. Longer Origin Destination pairs (for example: Johnston County to Research Triangle Park) are decomposed into several routes. One of the routes pass through work zone and others are important alternative freeway and arterial routes found from model analysis.

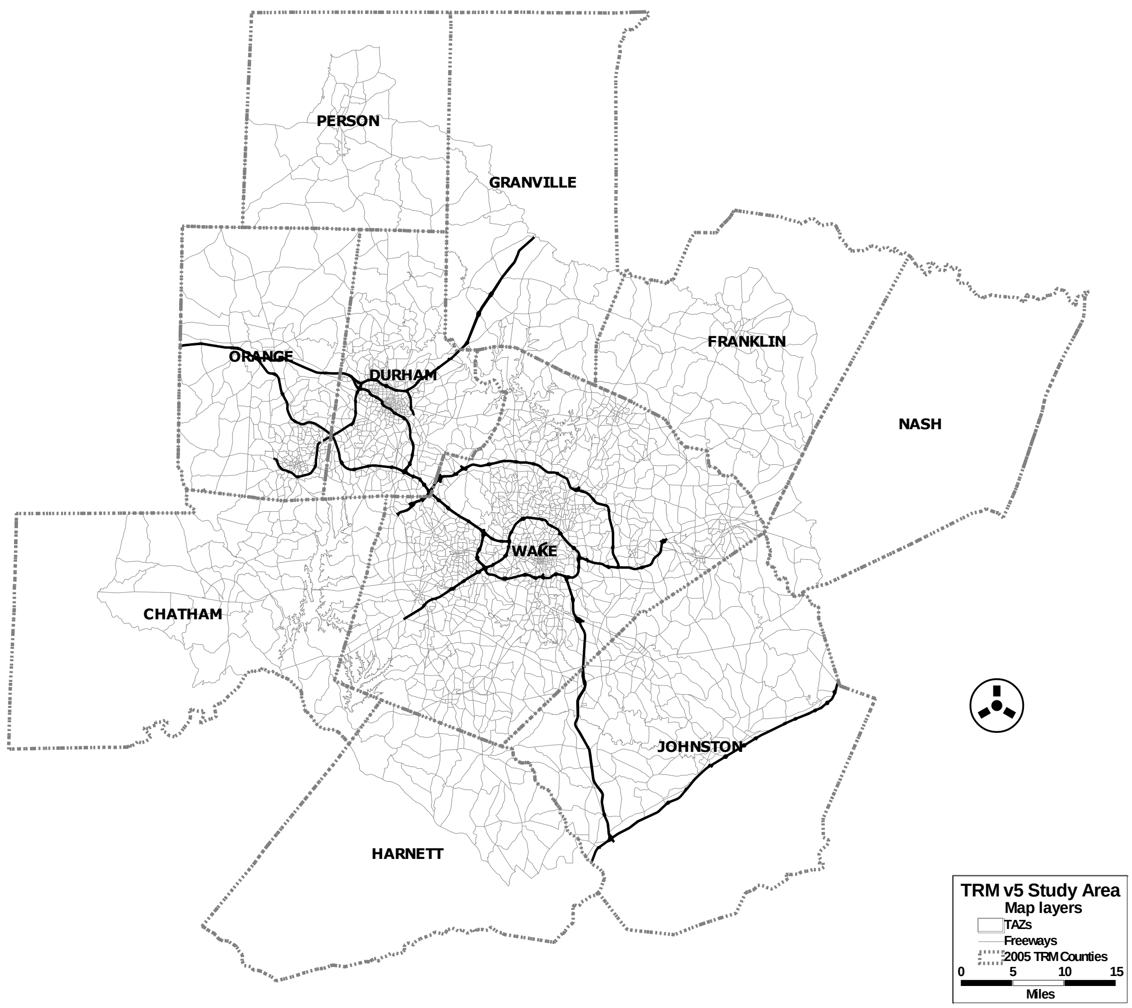
2.3 Macroscopic Network Level Simulation Analysis: VISUM

2.3.1 Model Overview

The TRM is a joint project of the Durham Chapel Hill Carrboro Metropolitan Planning Organization, the Capital Area Metropolitan Planning Organization, North Carolina Department of Transportation, and Triangle Transit. A macroscopic analysis of the work zone was done to get a quick overview of the volume shift that is brought about by the work zone and help reduce the network complexity and extent of the model to avoid unrealistic diversions.

The TRM is the travel demand forecasting tool for the Triangle region of North Carolina. The study area region is composed of all of Orange, Wake and Durham counties, and parts of Chatham, Person, Granville, Franklin, Nash, Johnston, and Harnett counties. The model region covers 3,380 square miles. The model was developed using population and employment data for 2005. The region had a population of 1,388,231 and 716,417 employees in 2005. The model region is divided into 2,678 Traffic Analysis Zones (TAZs) and there are ninety nine external stations. The model region is shown in the map below in Exhibit III - 3.

Exhibit III - 3 Map of TRM v5 Region Showing Traffic Analysis Zones



2.3.2 Simulation Process

The traffic demand is assigned to the network in following order:

- Step 1: Incremental assignment of demand segment TRUCK
- Step 2: Multiclass incremental assignment of demand segments SOV, HOV
- Step 3: Equilibrium assignment of demand segments SOV, HOV

Despite the high sensitivity of trucks to the travel time based on their high Value of Time, the truck demand is assigned incrementally in Step 1. Because there is no penalty function to the truck segment for taking local roads (e.g. through residential areas etc.), this prevents the trucks from finding alternative routes on local roads and assigns the demand to the main traffic corridors. Next, the car demand segments are assigned incrementally to find an initial feasible solution to preload the network and reduce the computation time of the user equilibrium assignment that is computed in Step 3.

2.3.3 Network Complexity Reduction

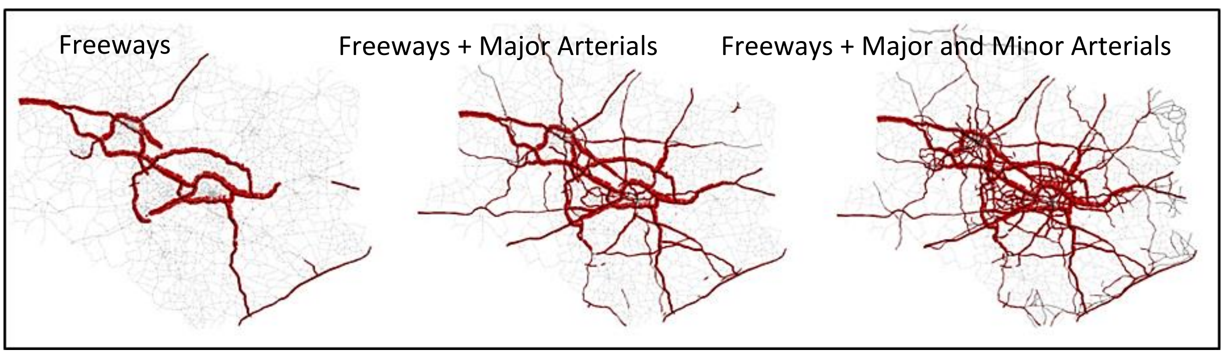
One of the tasks of traffic engineering is to identify an appropriate type of traffic model and its level of detail for the intended traffic analysis. The TRM represents a large regional model intended for traffic demand forecasting and can model effects of measures such as road tolling, socio economic changes in the demography, renewal of the infrastructure and so on. However, the rather large extent of the model and its complexity put a burden on the traffic assignment process often leading to unrealistic behavior of the model. Thus it has drawn the focus of researches to reduce the complexity of the model by scaling the model down in a finite number of steps to achieve more realistic results.

The framework is fitted to the task of replicating the diversion estimates of drivers traveling before and after work zone at interstate I-40 in Raleigh, NC, but can be generally applied to any kind of traffic impact analysis.

The process of reducing the complexity and areal extent of the network has been described in the following steps:

1. **Reducing Link Choice Set**: First, the set of links in the model is reduced and the local roads are omitted to reduce the complexity of the network. This reduces the driver's link choice set and helps the model from making unrealistic diversions. Exhibit III - 4 shows the results of filtering the three link classes in TRM.

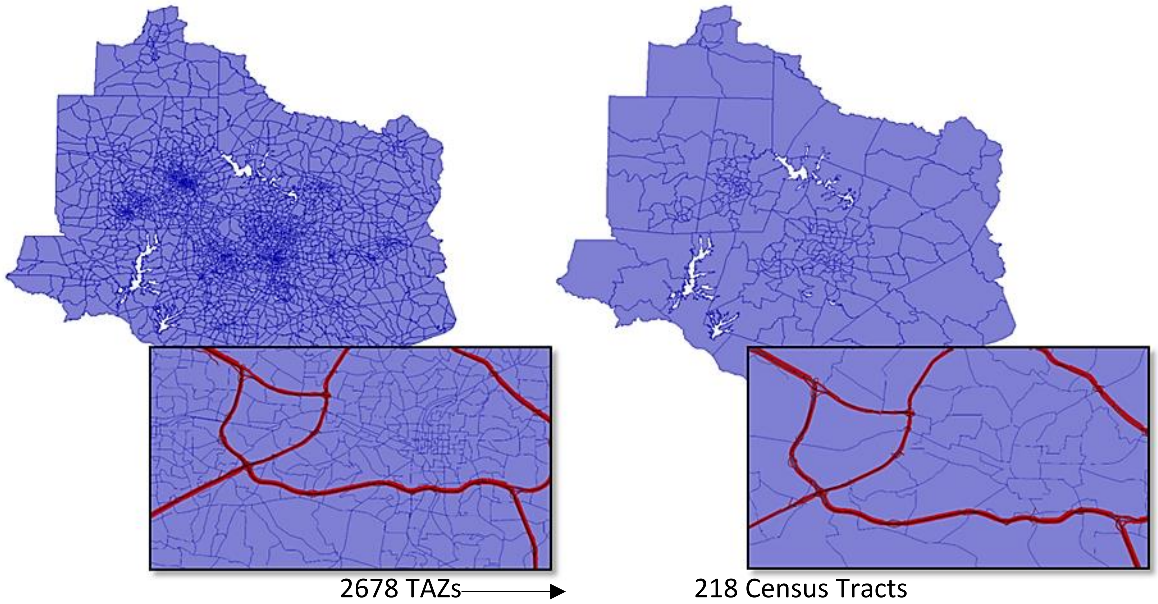
Exhibit III - 4: Filtered TRM link sets



2. **Zone aggregation:** To keep the model resolution consistent with the reduced link set, it is necessary to reduce the resolution of the zones within the model. The zones represent origins

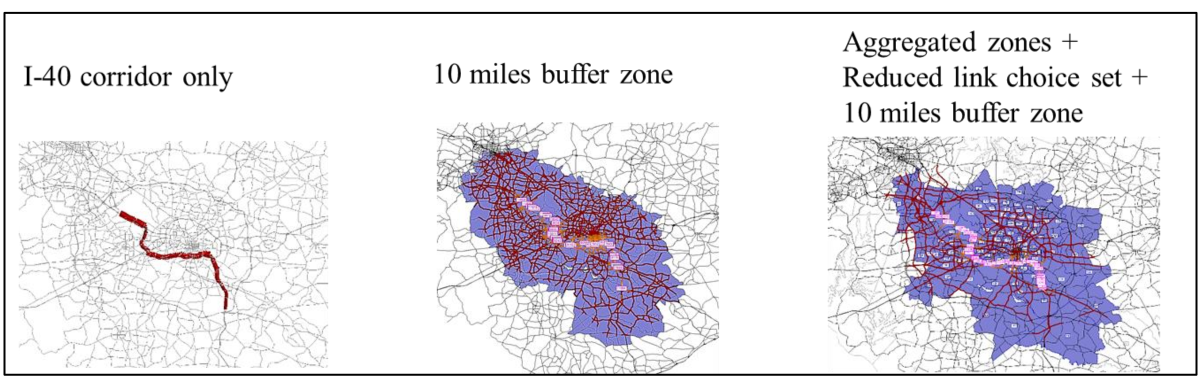
and destinations of the traffic stream and are usually aggregated to mirror demographic structure in the zone homogenously. Common aggregation levels in regional models are represented by traffic analysis zones (TAZ), census tracts and counties. The 2678 TAZs in the TRM were aggregated to the 218 census tract zone, as shown in Exhibit III - 5.

Exhibit III - 5: Zone aggregation in TRM



3. **Creating a Sub-network:** Mesoscopic analysis of the larger network can be used to assess a buffer zone radius, beyond which the effects of the work zone, in terms of volume change resulting from traffic diversions, can be found to be almost negligible. Therefore, to further reduce the complexity of the model, it is beneficial to reduce the network extent to a subnetwork within this buffer zone. As a result, the complexity of the network loading is reduced by avoiding simulating unnecessary effects beyond the work zone impact area. The traffic demand beyond the sub-network is collapsed and assigned as an external traffic demand. The sub-network for the Area 1&2 analysis was created using a 10 mile buffer radius around the work zone and is illustrated in Exhibit III - 6.

Exhibit III - 6: Creating a Sub-network around the work zone



3.0 WORK ZONE MONITORING: FIELD DATA ANALYSIS

3.1 Travel time Data Analysis – INRIX

For travel time analysis, INRIX probe technology was the primary source for data collection. The Vehicle Probe Project Suite through the Regional Integrated Transportation Information System (RITIS) was used to download travel time data that was communicated through the INRIX probe technology. The team focused on Routes A through D both eastbound and westbound as previously defined, covering the extent of the Area 3 work zone and much of I-40/440 in the Triangle Region. By looking at speed estimates over multiple segments, it is further possible to estimate queue lengths. It is noted that INRIX data can be unreliable for arterial performance, especially over short segments.

The travel time analysis in the following sections is focused on routes A, B, C and D in the AM and PM peak periods. Peak period data was gathered for each weekday between January 1, 2015 and December 21 2015, where the peaks are between 6:00 AM and 10:00 AM and between 3:30 PM and 7:30 PM. The team conducted its own analysis using INRIX travel time data for travel time analysis of the four routes at AM and PM peak periods. The four routes are described in the previous section. The aggregation level for travel time data is 5 minutes. The analysis first presents results by day of week, followed by an analysis by month of year between January and December. A short commentary of observed trends is included in the monthly analysis. Major work in Areas 1 and 2 is currently underway, with major effects due to lane closures in this area of the work zone starting to appear in August 2015.

3.1.1 Travel Time Analysis over Days of Week

The following sections include results of daily travel time analysis for each day of the week for routes A, B, C and D for both Eastbound and Westbound direction of the paths during AM and PM peak periods. The tables provided in each section show the total number of observed weekdays, the number of outlier days and the sample size classified by different days of week for the four routes. Outliers were removed if the outlier travel time was significantly different from the average travel time (outside of two standard deviations). Therefore, these graphs show what travel times can generally be expected during “average” days in the work zone. However, outlier days can range from 9% to 43% of all weekdays, as shown in the tables. In future analysis, the team will endeavor to explain these outlier days which may be due to weather or incidents. The most notable observation is that Friday travel times are worse traveling eastbound in the afternoon through the current work zone in Areas 1 and 2 (Routes A and C). Monthly trends presented after daily travel time analysis will provide a bigger picture of travel time trends as work zones areas have shifted.

Route A Travel Time Analysis

Exhibit III - 7 Sample Size for Route A weekday analysis in East Bound direction for AM peak period

	Monday	Tuesday	Wednesday	Thursday	Friday	Total
Total No of weekdays	51	50	50	51	51	253
No of Outlier days	7	6	4	1	4	22 (9%)
Sample Size	45	44	46	50	47	231

Exhibit III - 8 Average Travel Times for different days of the week for Route A in East Bound direction for AM peak period

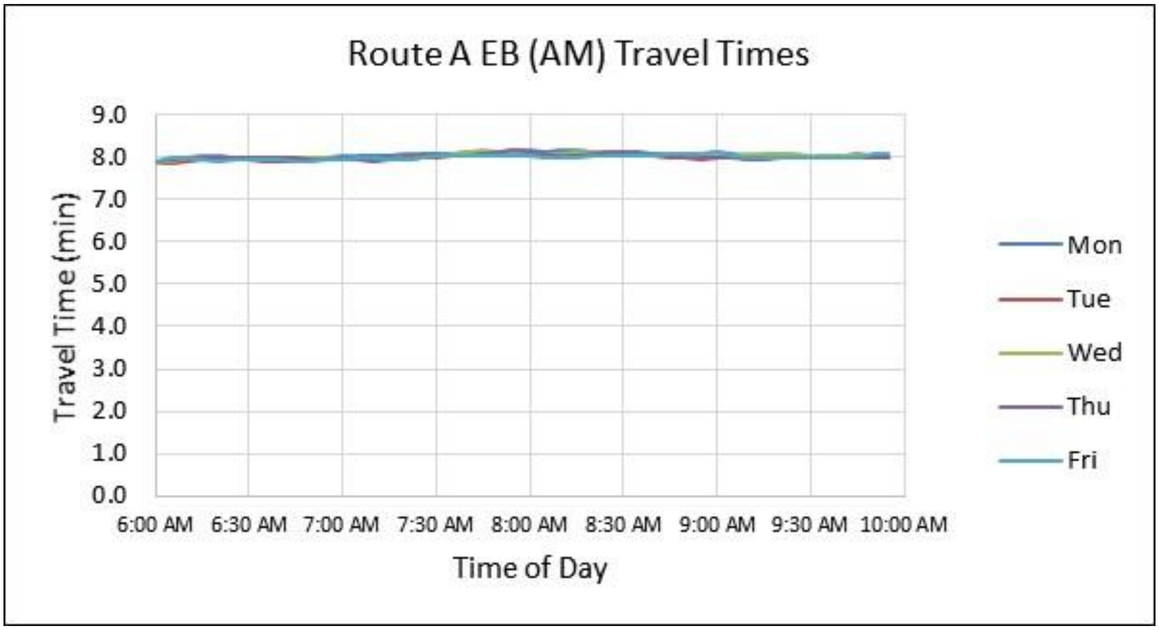


Exhibit III - 9 Sample Size for Route A weekday analysis in East Bound direction for PM peak period

	Monday	Tuesday	Wednesday	Thursday	Friday	Total
Total No of weekdays	51	50	50	51	51	253
No of Outlier days	8	8	6	14	14	50 (20%)
Sample Size	43	42	44	37	37	203

Exhibit III - 10 Average Travel Times for different days of the week for Route A in East Bound direction for PM peak period.

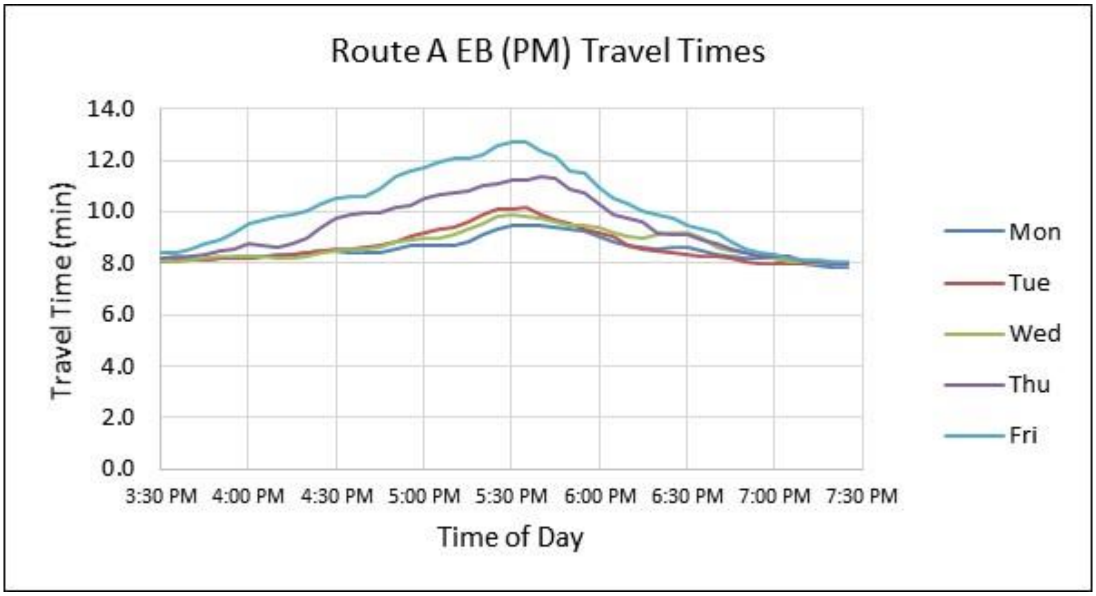


Exhibit III - 11 Sample Size for Route A weekday analysis in West Bound direction for AM peak period

	Monday	Tuesday	Wednesday	Thursday	Friday	Total
Total No of weekdays	51	50	50	51	51	253
No of Outlier days	10	8	13	6	7	44 (17%)
Sample Size	41	42	37	45	44	209

Exhibit III - 12 Average Travel Times for different days of the week for Route A in West Bound direction for AM peak period

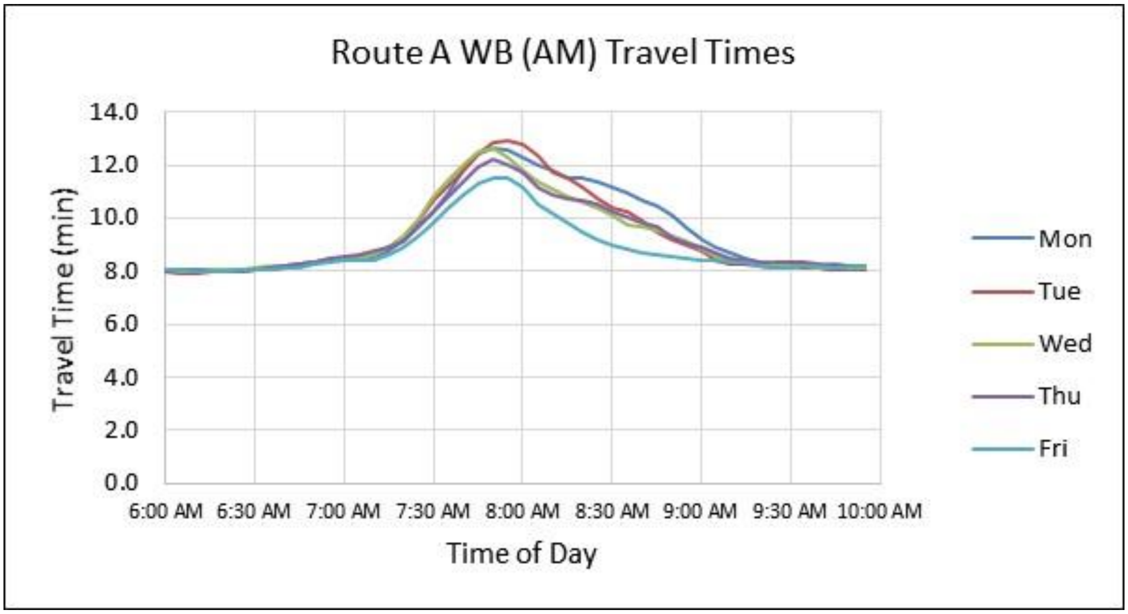
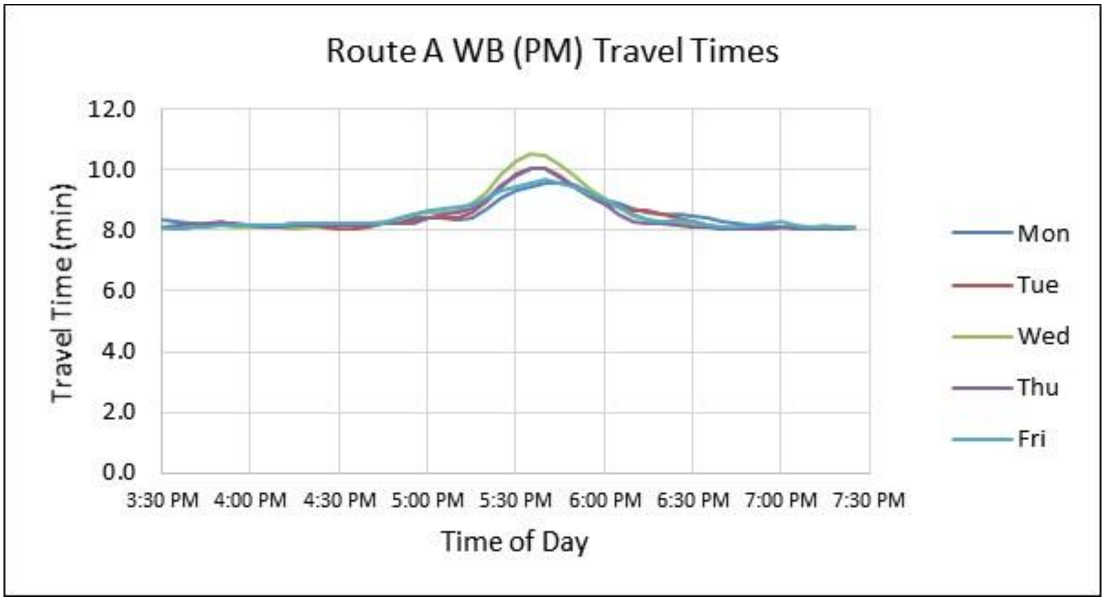


Exhibit III - 13 Sample Size for Route A weekday analysis in West Bound direction for PM peak period

	Monday	Tuesday	Wednesday	Thursday	Friday	Total
Total No of weekdays	51	50	50	51	51	253
No of Outlier days	5	6	12	13	11	47 (19%)
Sample Size	46	44	38	38	40	206

Exhibit III - 14 Average Travel Times for different days of the week for Route A in West Bound direction for PM peak period



Route B Travel Time Analysis

Exhibit III - 15 Sample Size for Route B weekday analysis in East Bound direction for AM peak period

	Monday	Tuesday	Wednesday	Thursday	Friday	Total
Total No of weekdays	51	50	50	51	51	253
No of Outlier days	17	21	18	6	15	77 (30%)
Sample Size	34	29	32	45	36	176

Exhibit III - 16 Average Travel Times for different days of the week for Route B in East Bound direction for AM peak period

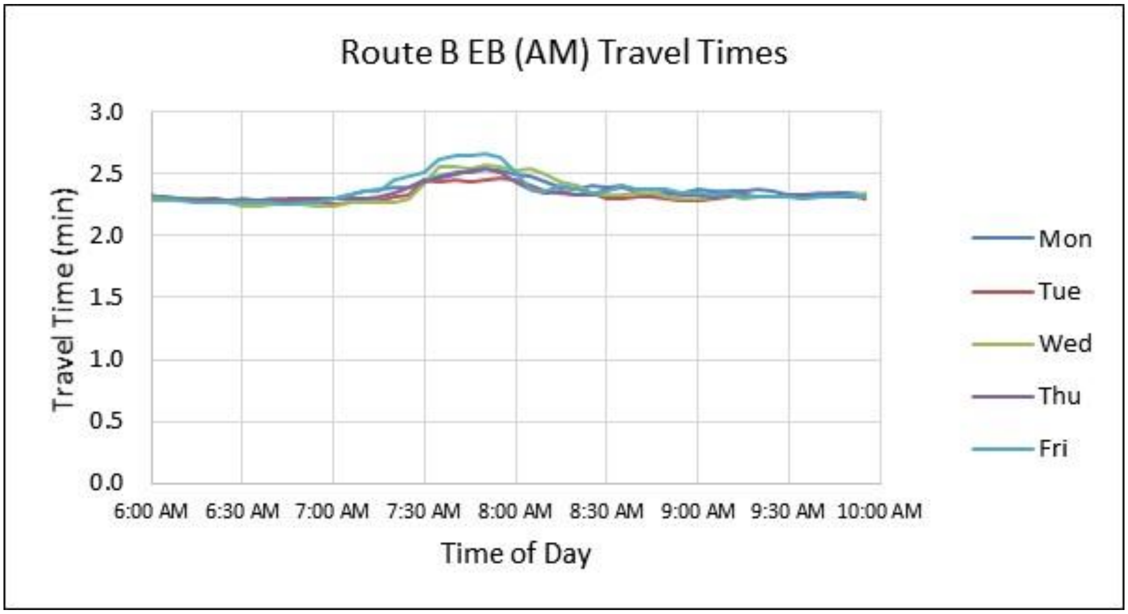


Exhibit III - 17 Sample Size for Route B weekday analysis in East Bound direction for PM peak period

	Monday	Tuesday	Wednesday	Thursday	Friday	Total
Total No of weekdays	51	50	50	51	51	253
No of Outlier days	11	14	14	17	19	75 (28%)
Sample Size	40	36	36	34	32	186

Exhibit III - 18 Average Travel Times for different days of the week for Route B in East Bound direction for PM peak period

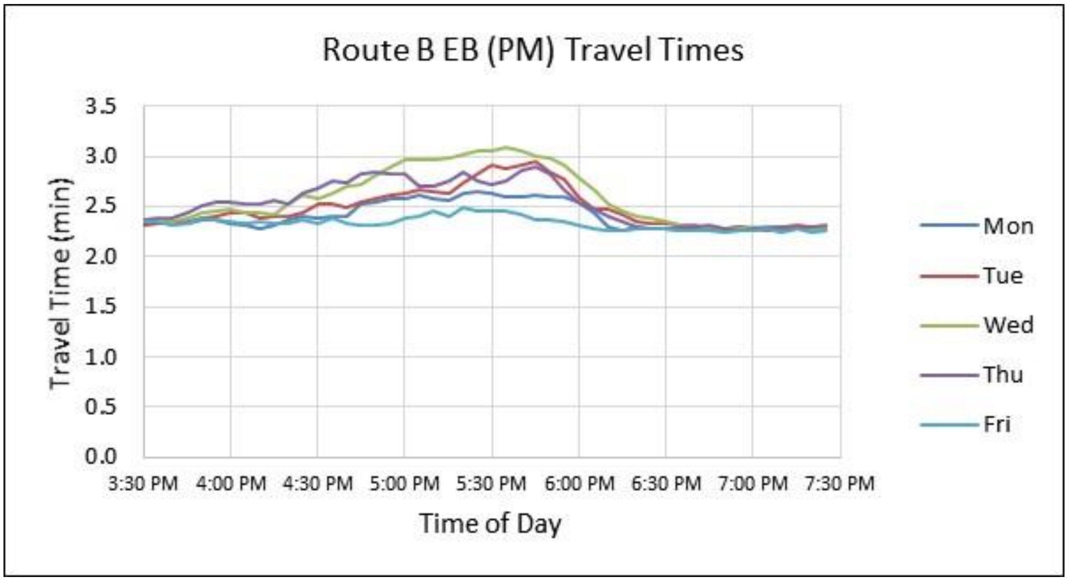


Exhibit III - 19 Sample Size for Route B weekday analysis in West Bound direction for AM peak period

	Monday	Tuesday	Wednesday	Thursday	Friday	Total
Total No of weekdays	51	50	50	51	51	253
No of Outlier days	10	12	14	13	6	55 (22%)
Sample Size	41	38	36	38	45	198

Exhibit III - 20 Average Travel Times for different days of the week for Route B in West Bound direction for AM peak period.

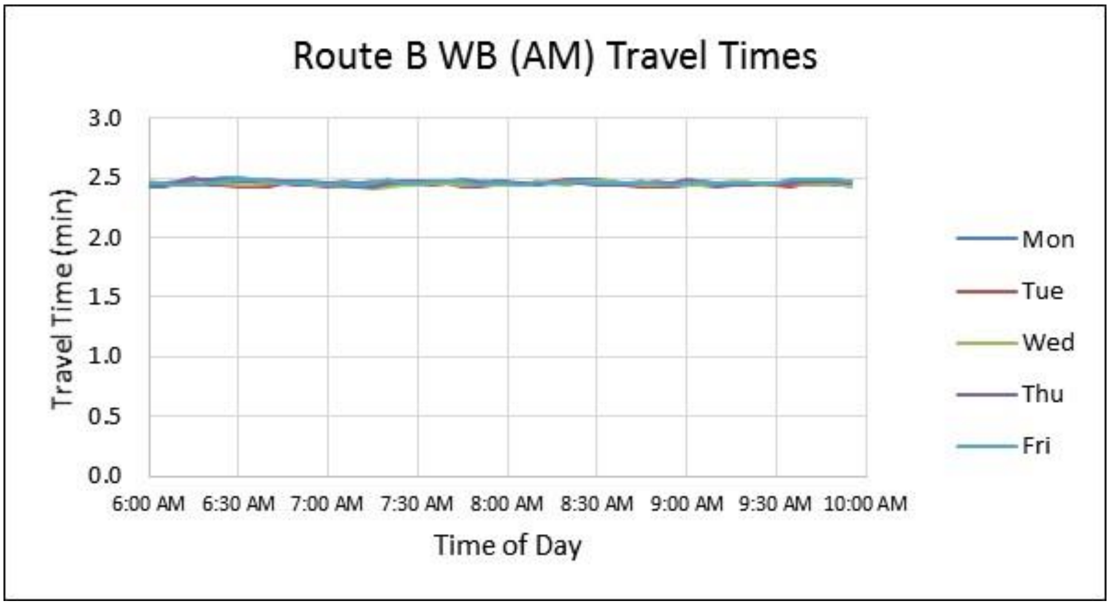
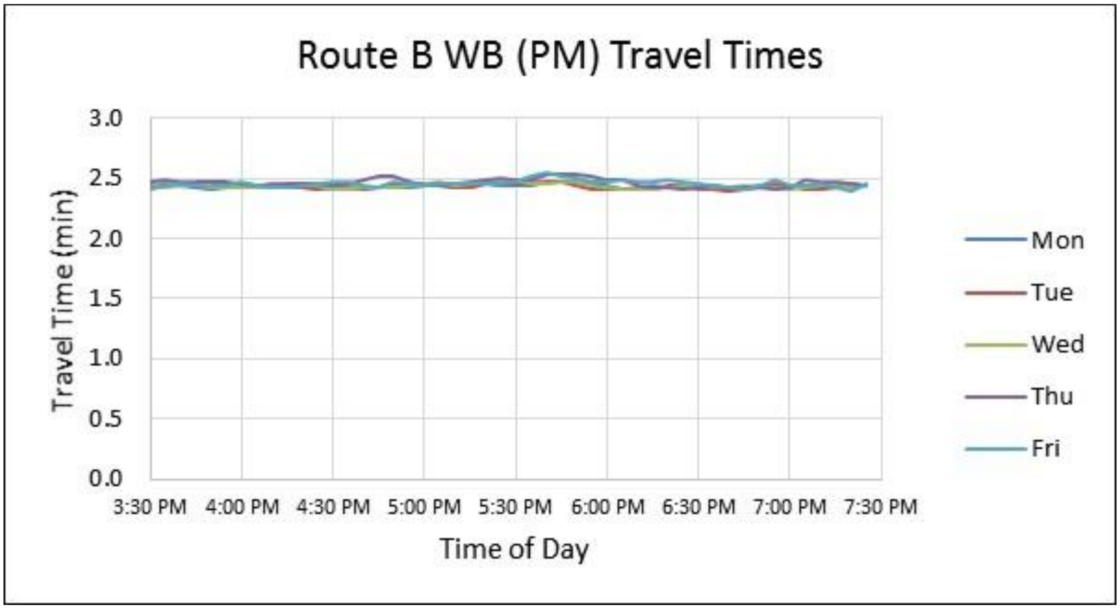


Exhibit III - 21 Sample Size for Route B weekday analysis in West Bound direction for PM peak period

	Monday	Tuesday	Wednesday	Thursday	Friday	Total
Total No of weekdays	51	50	50	51	51	253
No of Outlier days	12	20	20	24	33	109 (43%)
Sample Size	39	30	30	27	18	144

Exhibit III - 22 Average Travel Times for different days of the week for Route B in West Bound direction for PM peak period



Route C Travel Time Analysis

Exhibit III - 23 Sample Size for Route C weekday analysis in East Bound direction for AM peak period

	Monday	Tuesday	Wednesday	Thursday	Friday	Total
Total No of weekdays	51	50	50	51	51	253
No of Outlier days	10	6	7	4	3	30 (12%)
Sample Size	41	44	43	47	48	223

Exhibit III - 24 Average Travel Times for different days of the week for Route C in East Bound direction for AM peak period

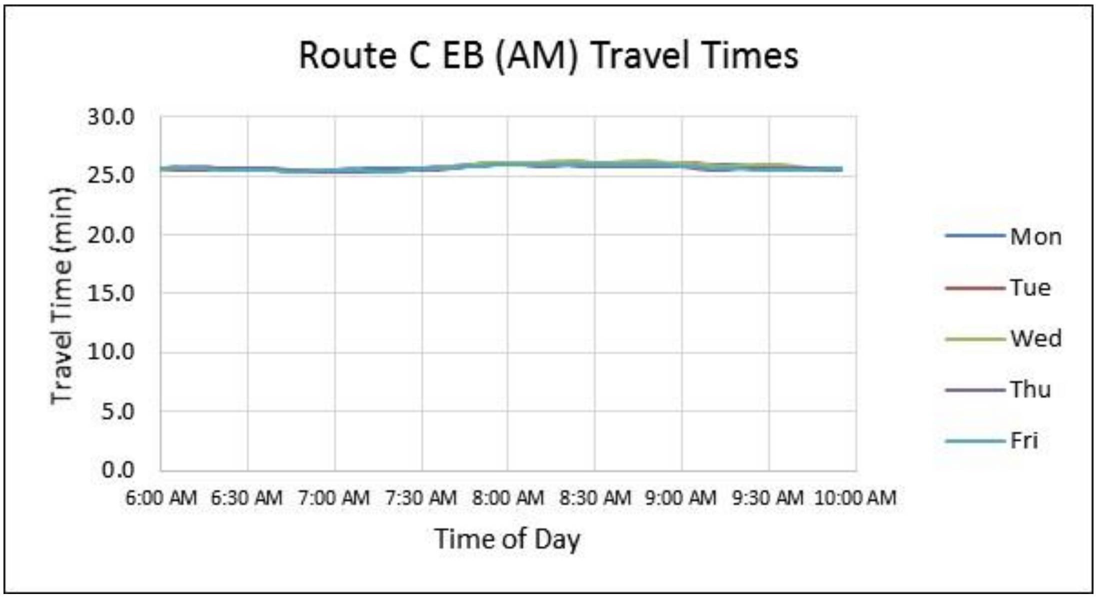


Exhibit III - 25 Sample Size for Route C weekday analysis in East Bound direction for PM peak period

	Monday	Tuesday	Wednesday	Thursday	Friday	Total
Total No of weekdays	51	50	50	51	51	253
No of Outlier days	8	7	8	14	15	52 (21%)
Sample Size	43	43	42	37	36	201

Exhibit III - 26 Average Travel Times for different days of the week for Route C in East Bound direction for PM peak period

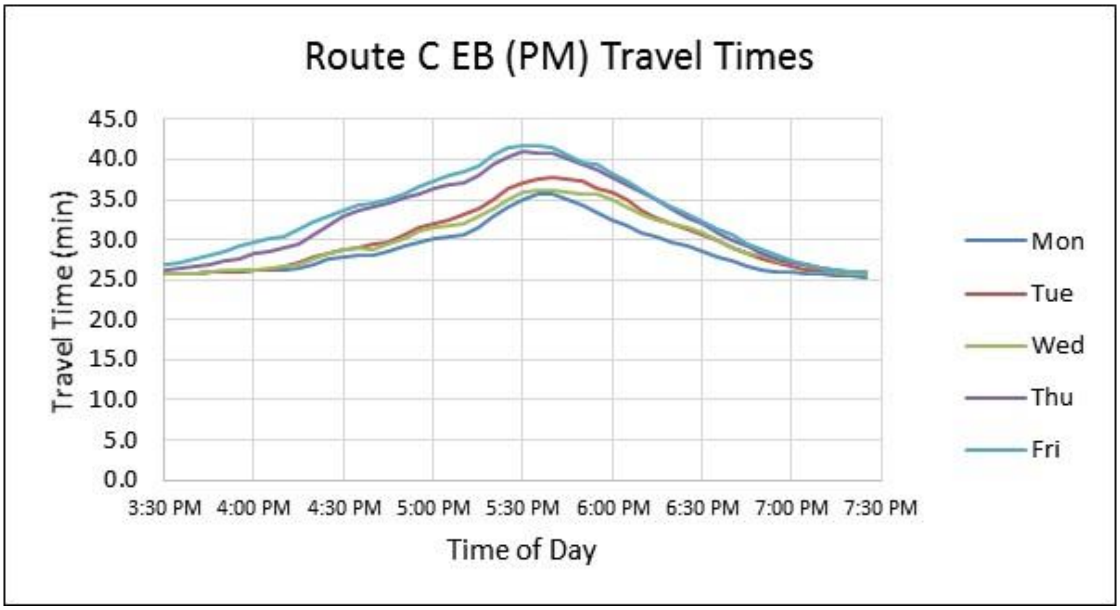


Exhibit III - 27 Sample Size for Route C weekday analysis in West Bound direction for AM peak period

	Monday	Tuesday	Wednesday	Thursday	Friday	Total
Total No of weekdays	51	50	50	51	51	253
No of Outlier days	9	7	13	6	9	44 (17%)
Sample Size	42	43	37	45	42	209

Exhibit III - 28 Average Travel Times for different days of the week for Route C in West Bound direction for AM peak period.

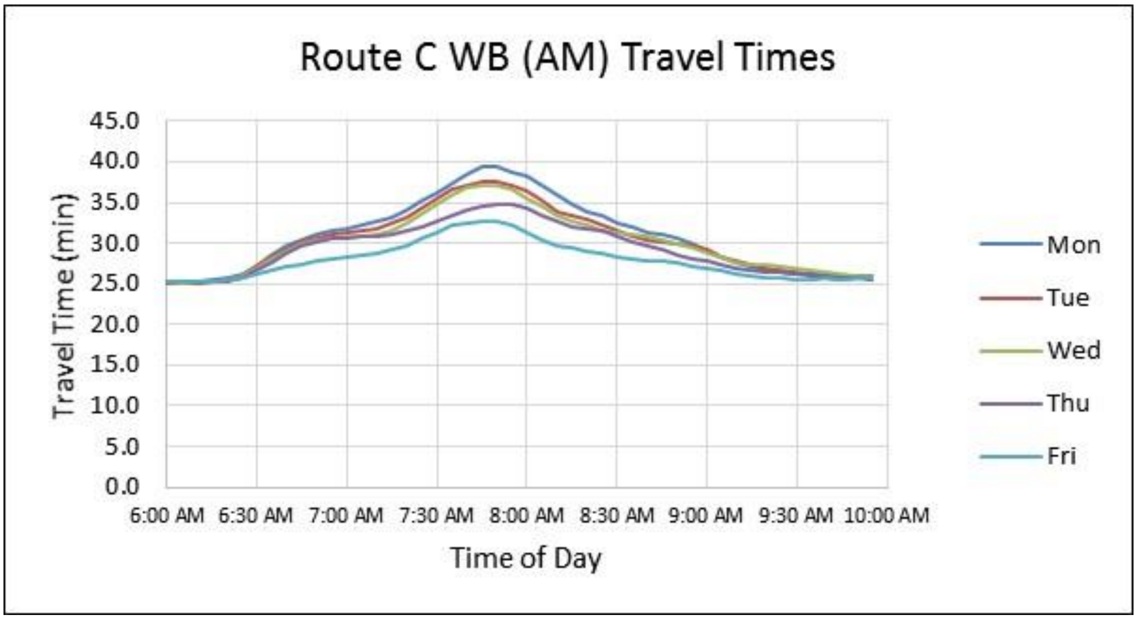
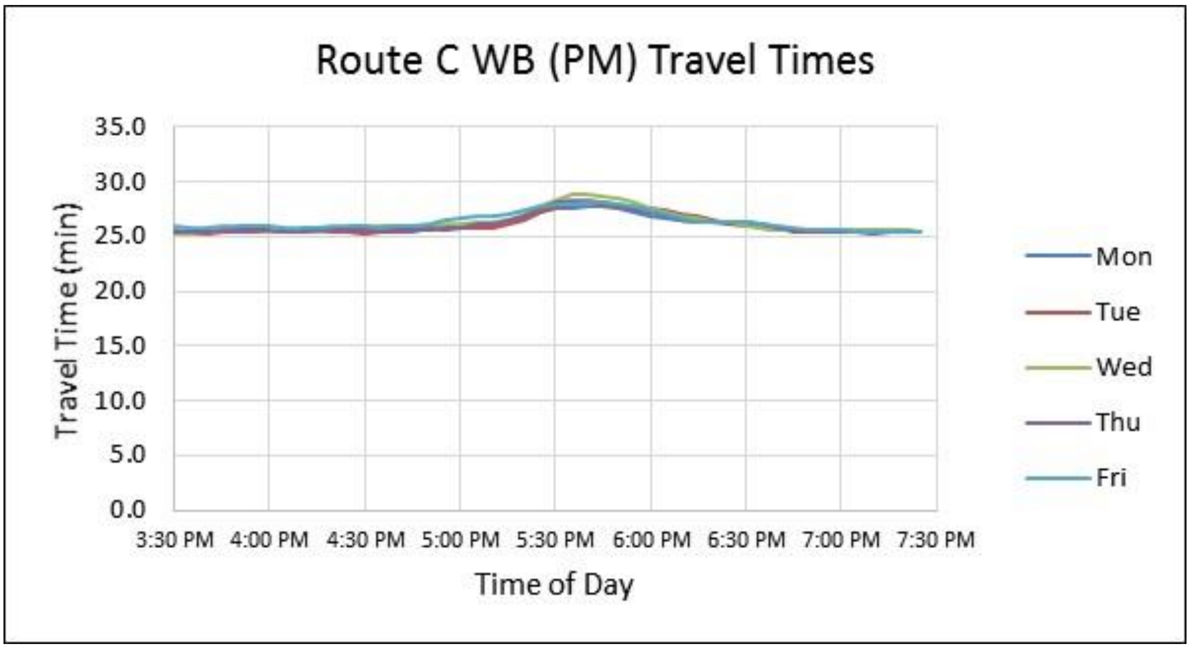


Exhibit III - 29 Sample Size for Route C weekday analysis in West Bound direction for PM peak period

	Monday	Tuesday	Wednesday	Thursday	Friday	Total
Total No of weekdays	51	50	50	51	51	253
No of Outlier days	8	8	10	14	7	47 19%)
Sample Size	43	42	40	37	44	206

Exhibit III - 30 Average Travel Times for different days of the week for Route C in West Bound direction for PM peak period



Route D Travel Time Analysis

Exhibit III - 31 Sample Size for Route D weekday analysis in East Bound direction for AM peak period

	Monday	Tuesday	Wednesday	Thursday	Friday	Total
Total No of weekdays	51	50	50	51	51	253
No of Outlier days	16	11	10	11	6	54 (21%)
Sample Size	35	39	40	40	45	199

Exhibit III - 32 Average Travel Times for different days of the week for Route D in East Bound direction for AM peak period

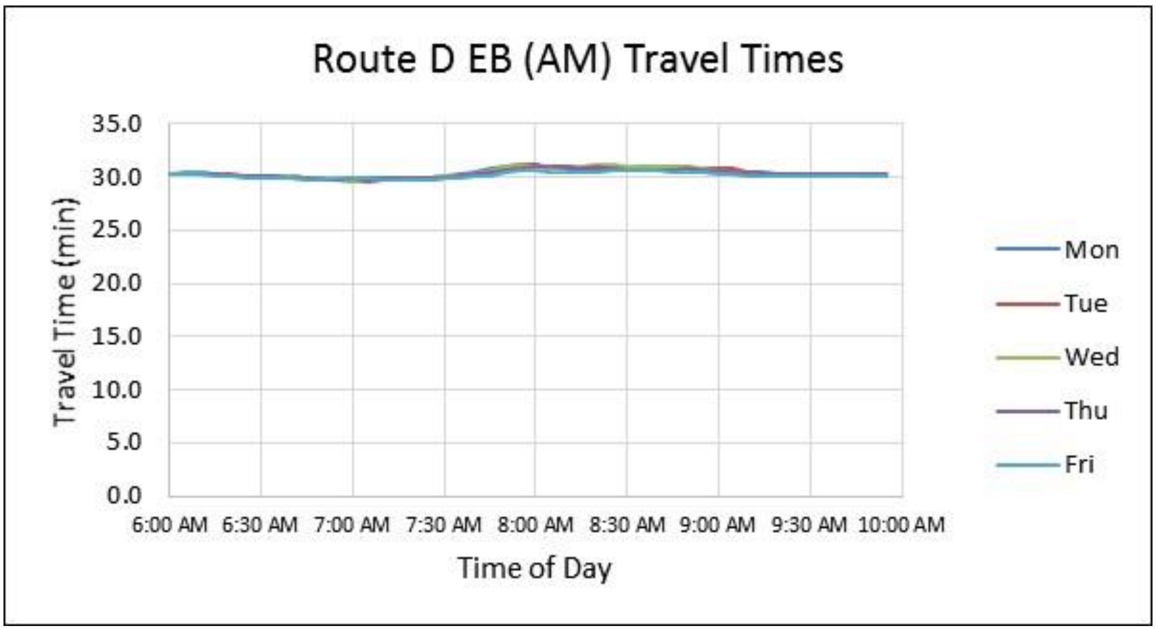


Exhibit III - 33 Sample Size for Route D weekday analysis in East Bound direction for PM peak period

	Monday	Tuesday	Wednesday	Thursday	Friday	Total
Total No of weekdays	51	50	50	51	51	253
No of Outlier days	8	11	11	18	17	65 (26%)
Sample Size	43	39	39	33	34	188

Exhibit III - 34 Average Travel Times for different days of the week for Route D in East Bound direction for PM peak period

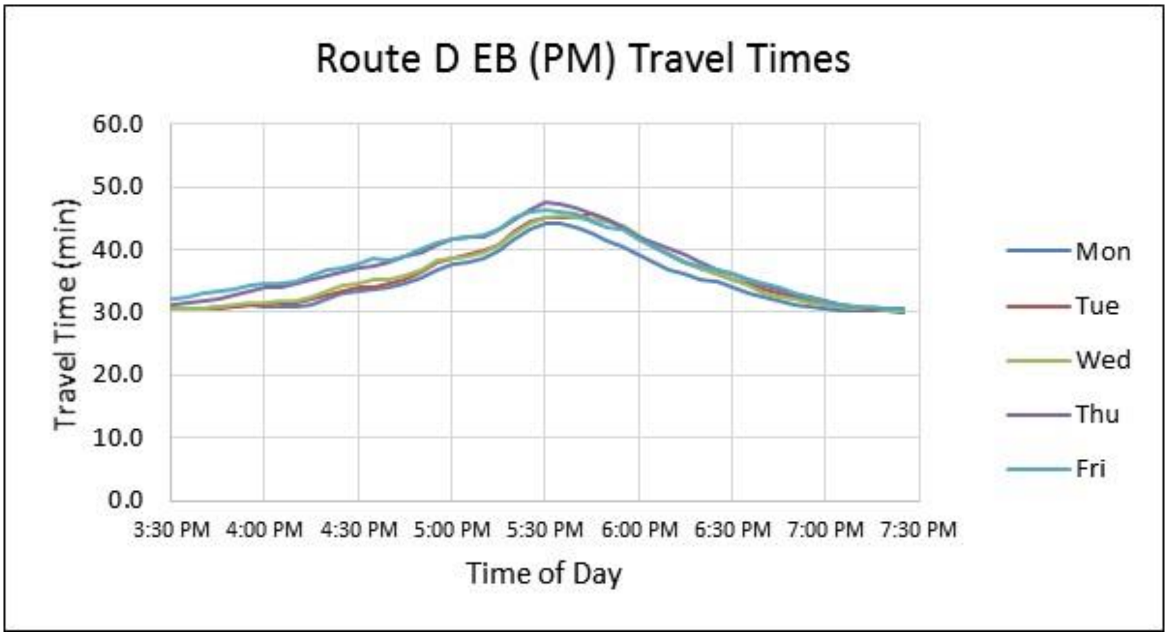


Exhibit III - 35 Sample Size for Route D weekday analysis in West Bound direction for AM peak period

	Monday	Tuesday	Wednesday	Thursday	Friday	Total
Total No of weekdays	51	50	50	51	51	253
No of Outlier days	14	7	11	7	10	49 (19%)
Sample Size	37	43	39	44	41	204

Exhibit III - 36 Average Travel Times for different days of the week for Route D in West Bound direction for AM peak period

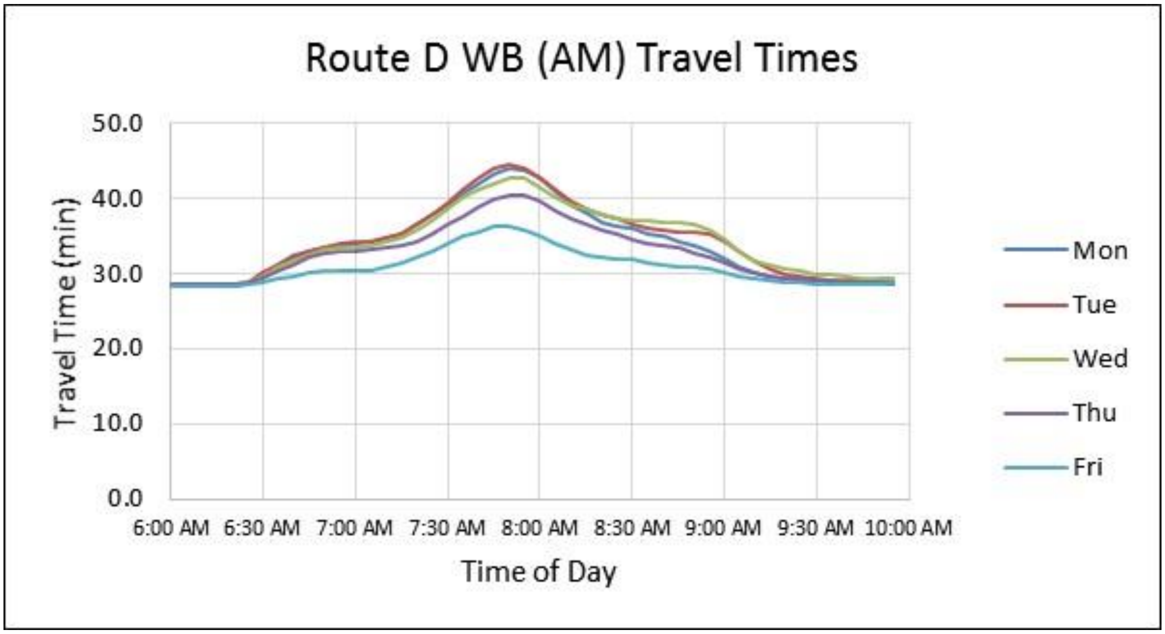
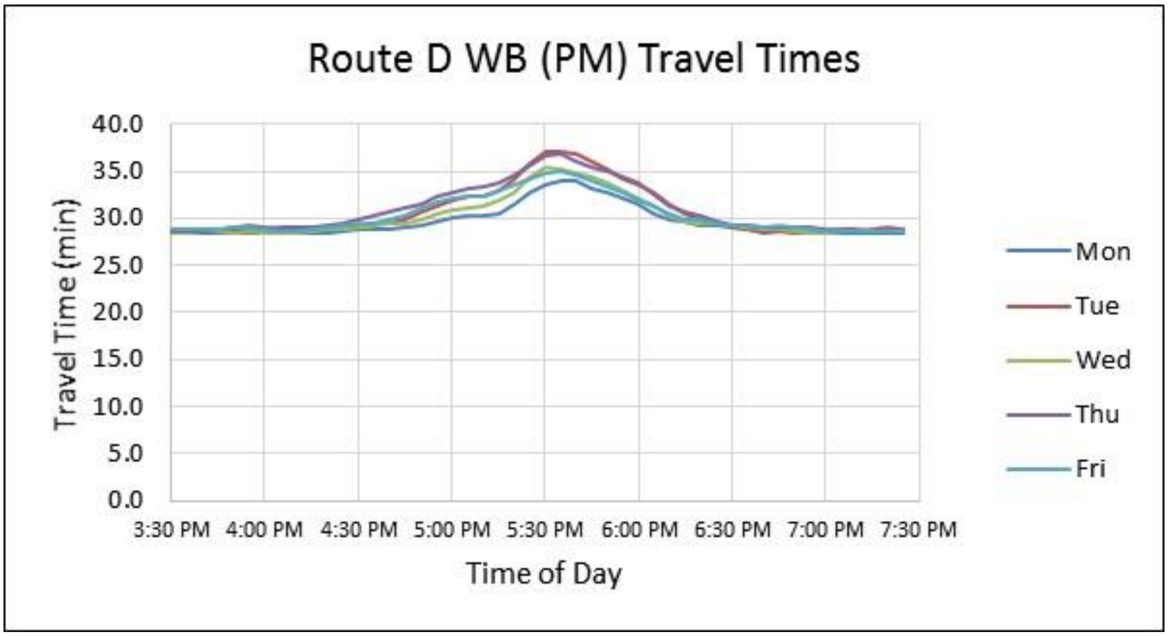


Exhibit III - 37 Sample Size for Route D weekday analysis in West Bound direction for PM peak period

	Monday	Tuesday	Wednesday	Thursday	Friday	Total
Total No of weekdays	51	50	50	51	51	253
No of Outlier days	14	8	10	12	7	51 (20%)
Sample Size	37	42	40	39	44	202

Exhibit III - 38 Average Travel Times for different days of the week for Route D in West Bound direction for PM peak period



3.1.2 Monthly Average Travel Time Analysis

This section presents comparisons by month for the four routes under consideration. The figures following the tables show the travel times for the four routes in eastbound and westbound directions during both AM and PM peak periods, averaged by month. They are presented as contour graphs to better display the changes in travel time over each month.

Route A Travel Time Analysis

Travel times for Route A remain consistent for the morning non-peak direction. Higher travel times are observed starting in the month of September as new construction occurred through Areas 1 and 2. There is also a shift to earlier departure times for Route A WB in the morning as drivers begin to understand the current work zone pattern. Higher travel times in Route A EB in the PM peak are especially noticeable in later months.

Exhibit III - 39 Average Travel Times for different months for Route A in East Bound direction for AM peak period

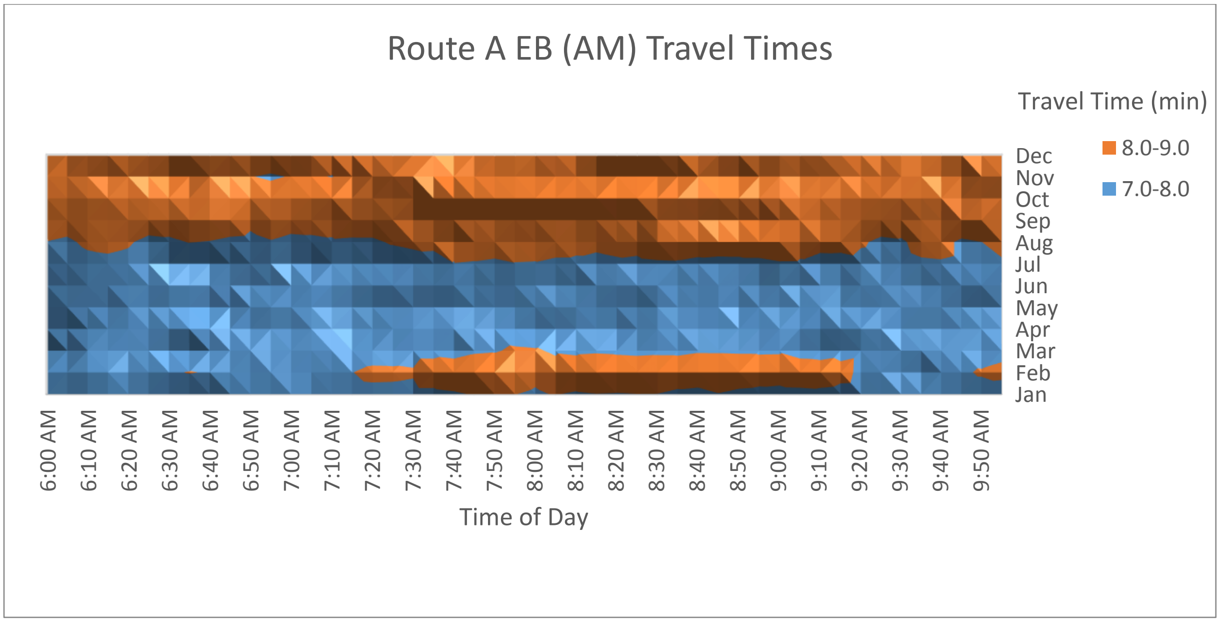


Exhibit III - 40 Average Travel Times for different months for Route A in East Bound direction for PM peak period

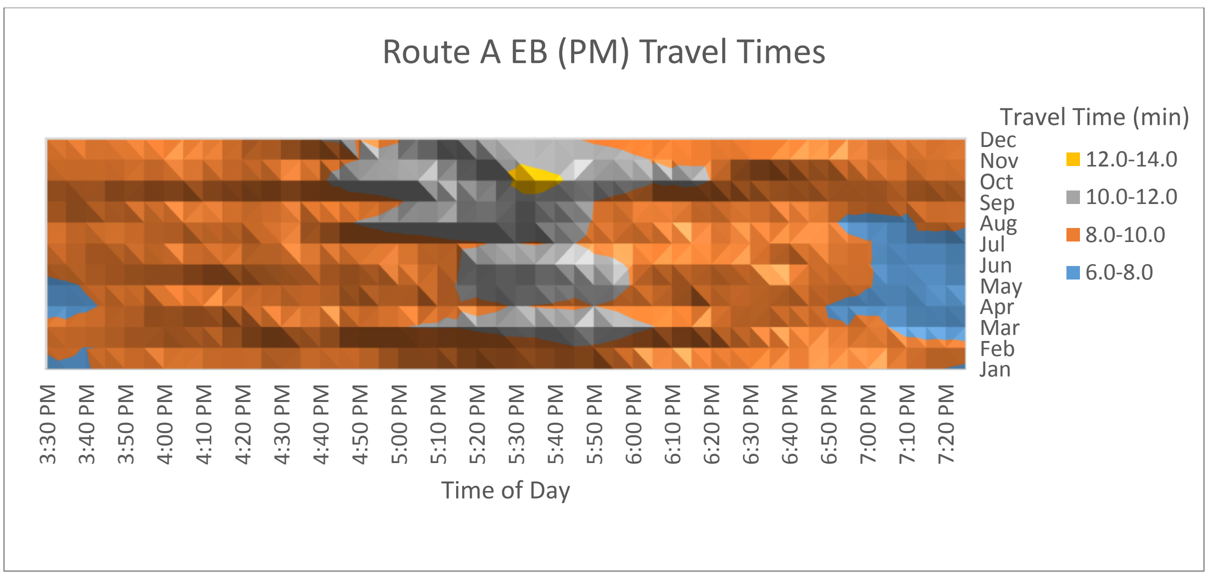


Exhibit III - 41 Average Travel Times for different months for Route A in West Bound direction for AM peak period

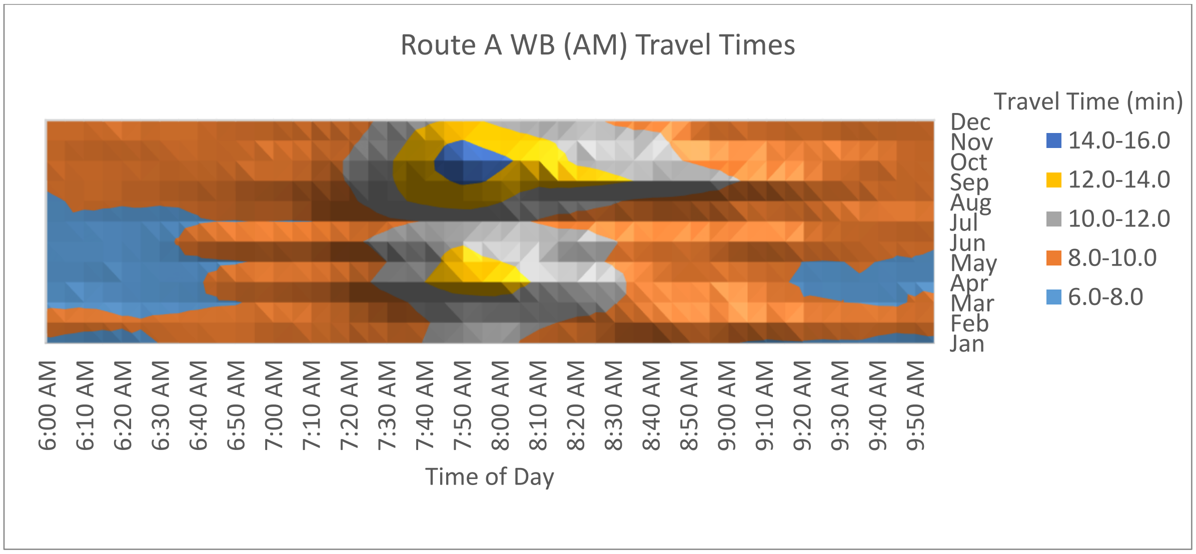
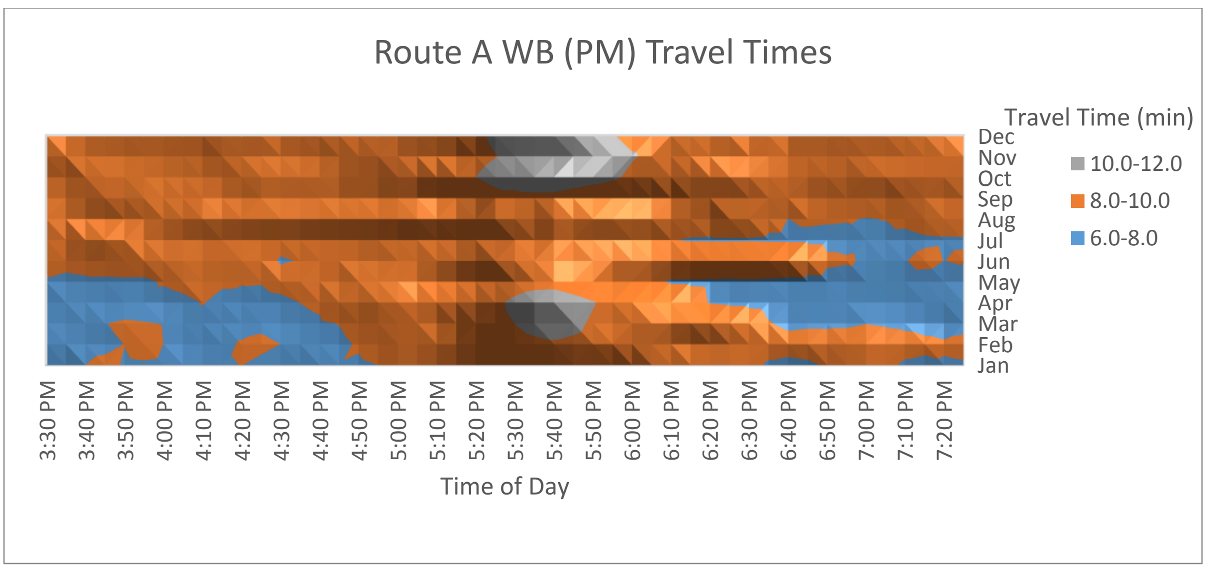


Exhibit III - 42 Average Travel Times for different months for Route A in West Bound direction for PM peak period



Route B Travel Time Analysis

Although travel times in Route B EB improved after work in Area 3 was completed, travel times have become slightly higher in later months as construction occurs in Areas 1 and 2. Bottlenecks from the Area 1 and 2 work zone have likely cause increased travel time on I-440 East. Travel times on Route B WB have been consistent throughout the year.

Exhibit III - 43 Average Travel Times for different months for Route B in East Bound direction for AM peak period

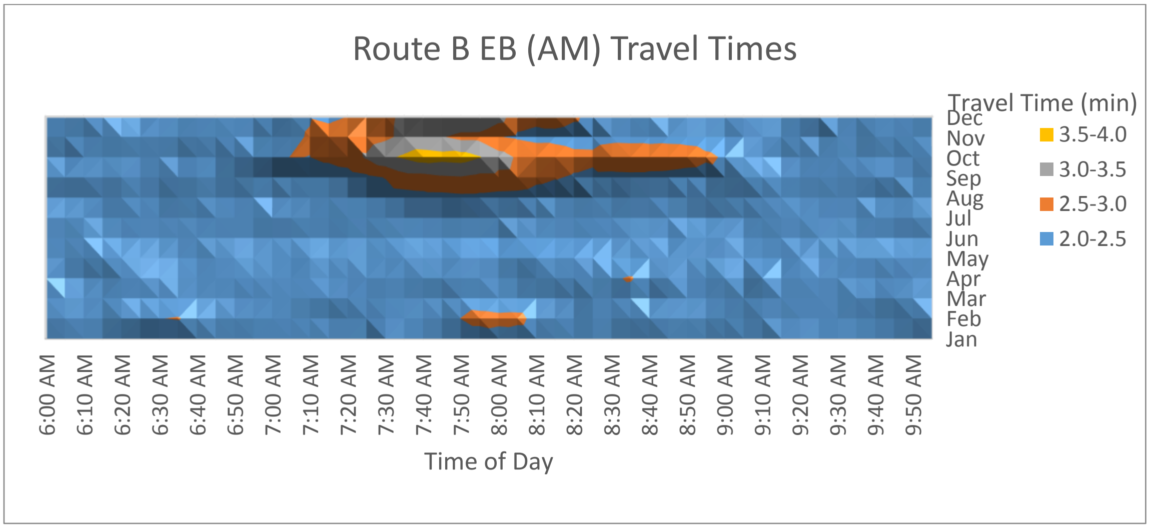


Exhibit III - 44 Average Travel Times for different months for Route B in East Bound direction for PM peak period

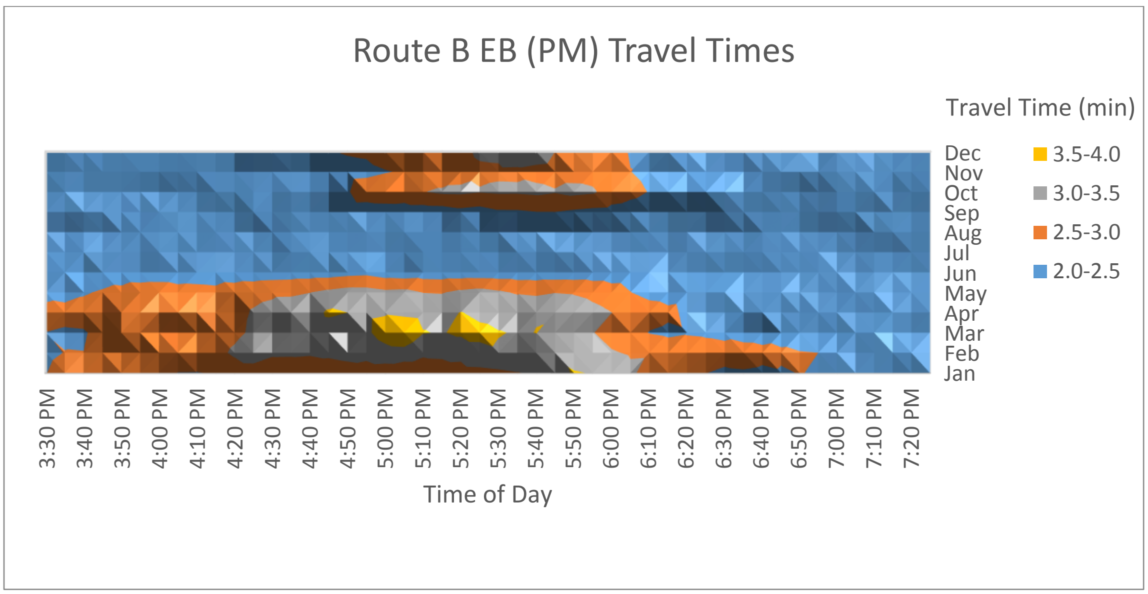


Exhibit III - 45 Average Travel Times for different months for Route B in West Bound direction for AM peak period

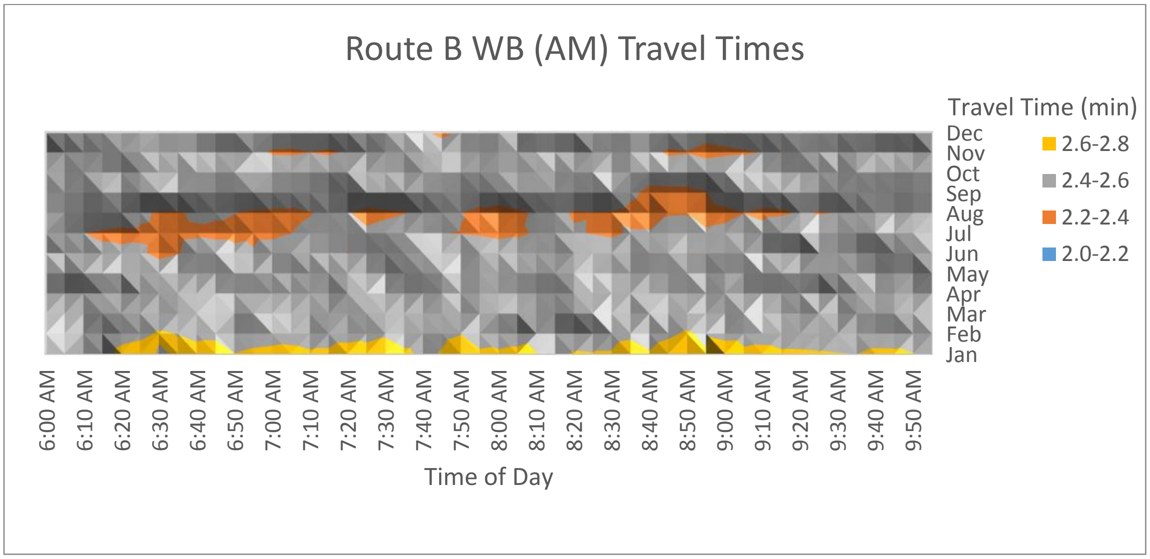
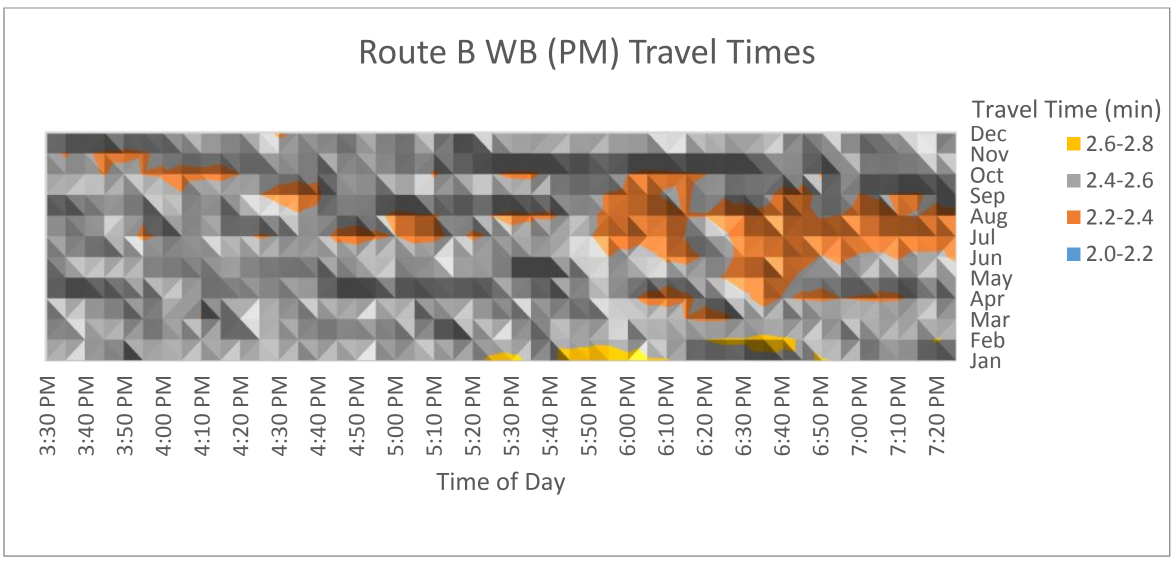


Exhibit III - 46 Average Travel Times for different months for Route B in West Bound direction for PM peak period



Route C Travel Time Analysis

Route C travel times have similar trends to Route A, with shifts to earlier departure times occurring in the eastbound direction in the afternoon and westbound direction in the morning. Travel times improved in the middle of the year and have increased in later months.

Exhibit III - 47 Average Travel Times for different months for Route C in East Bound direction for AM peak period

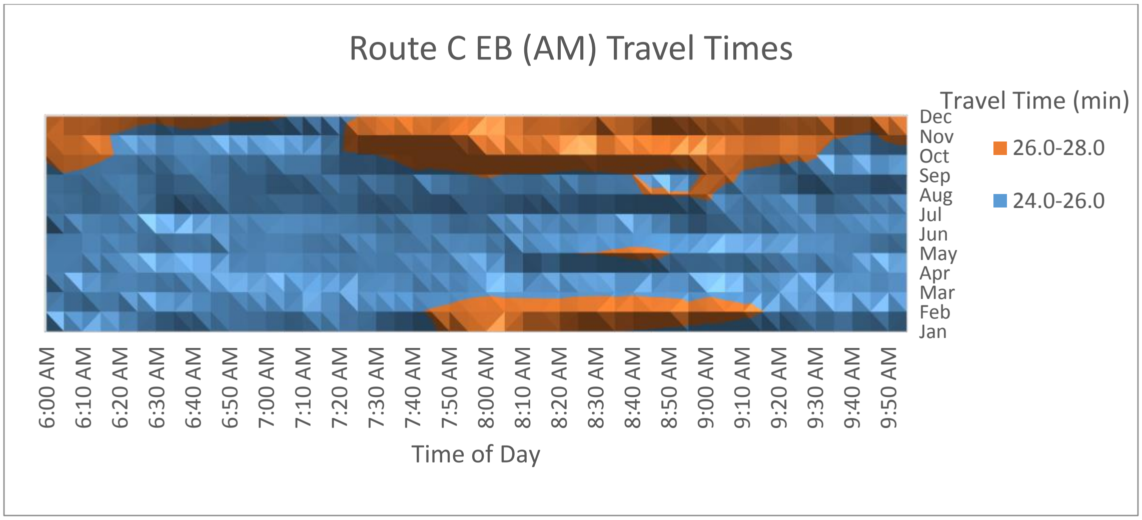


Exhibit III - 48 Average Travel Times for different months for Route C in East Bound direction for PM peak period

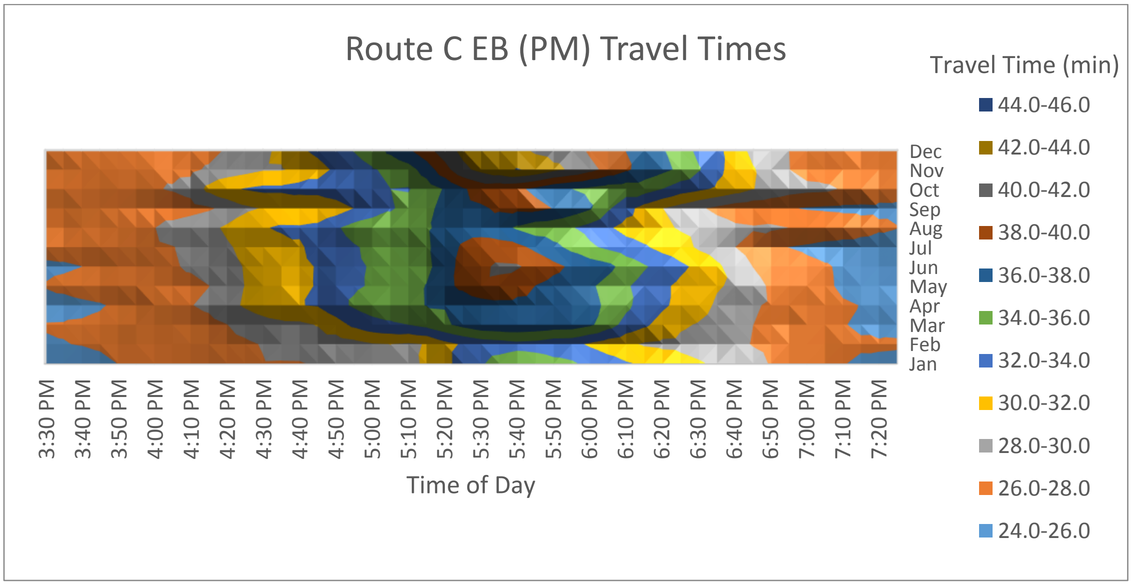


Exhibit III - 49 Average Travel Times for different months for Route C in West Bound direction for AM peak period

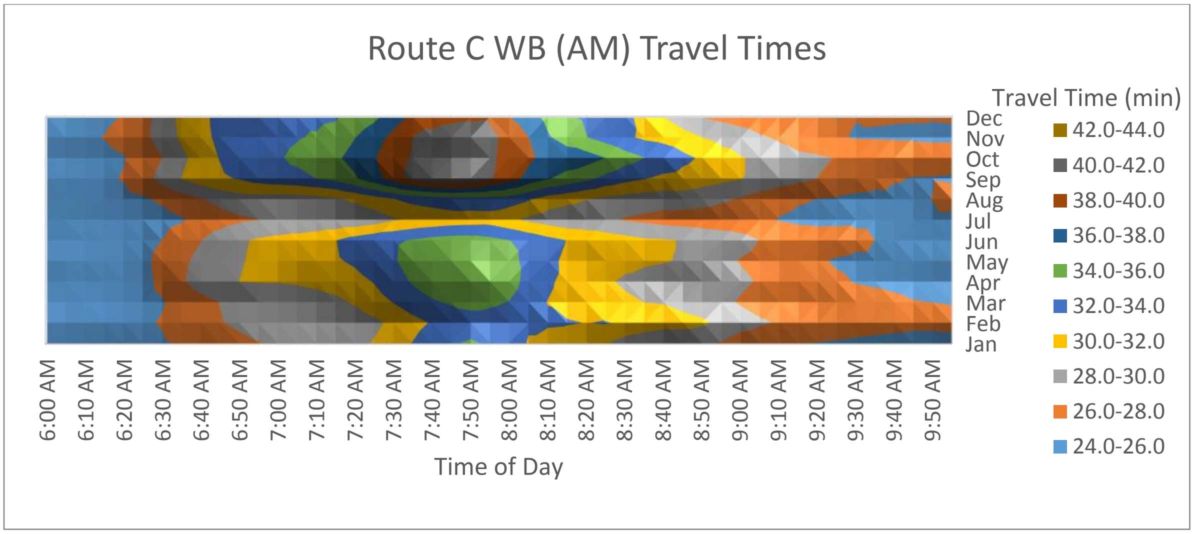
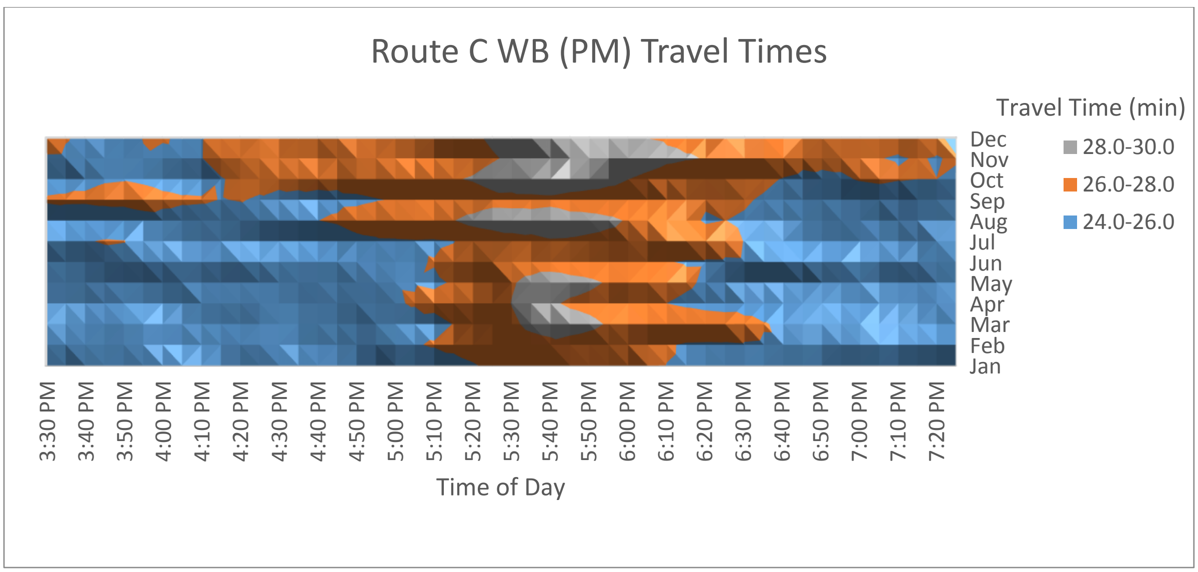


Exhibit III - 50 Average Travel Times for different months for Route C in West Bound direction for PM peak period



Route D Travel Time Analysis

Route D may be experiencing higher travel times for later months due to drivers trying to avoid the current work zone in Areas 1 and 2. Overall, these travel times are consistent in their peaks over each month. Higher travel times are seen in later months after improvements in the middle of the year.

Exhibit III - 51 Average Travel Times for different months for Route C in East Bound direction for AM peak period

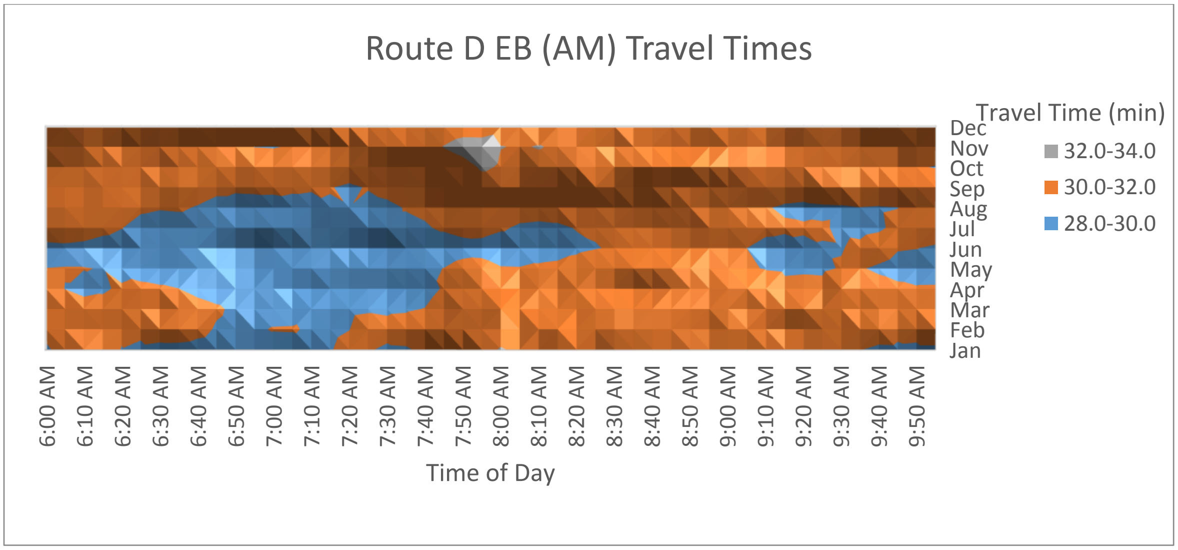


Exhibit III - 52 Average Travel Times for different months for Route C in East Bound direction for PM peak period

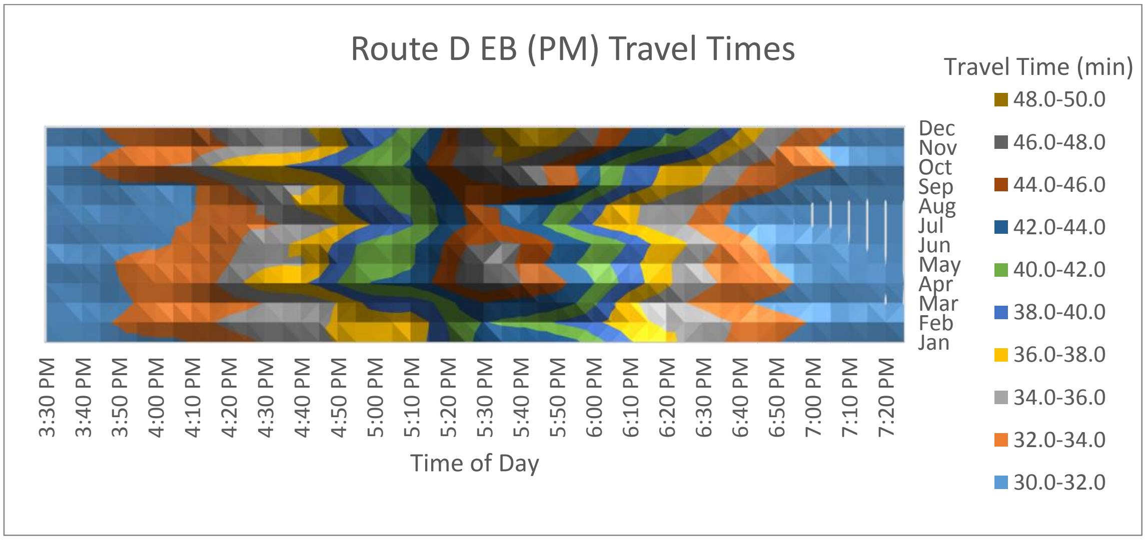


Exhibit III - 53 Average Travel Times for different months for Route C in West Bound direction for AM peak period

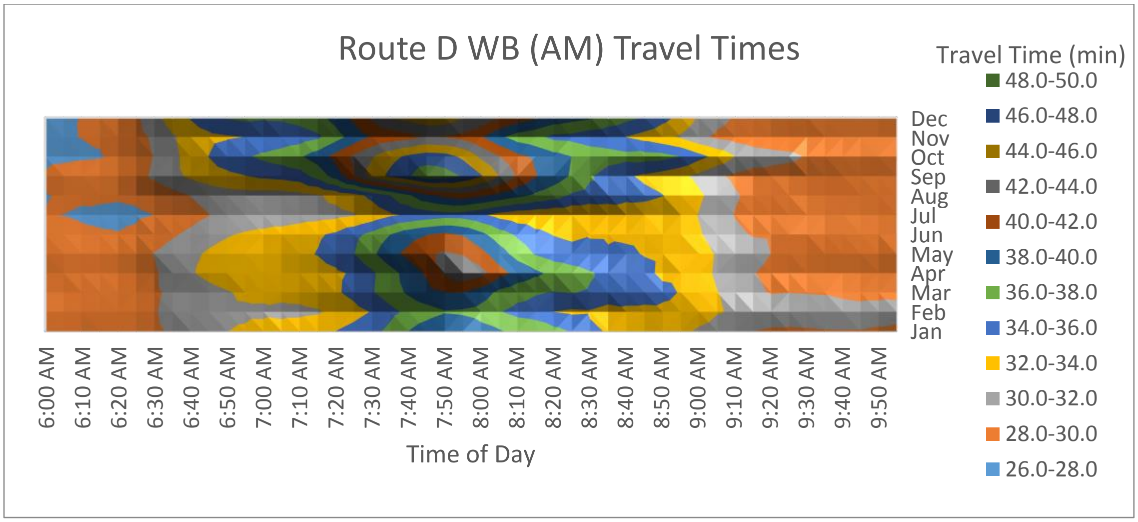
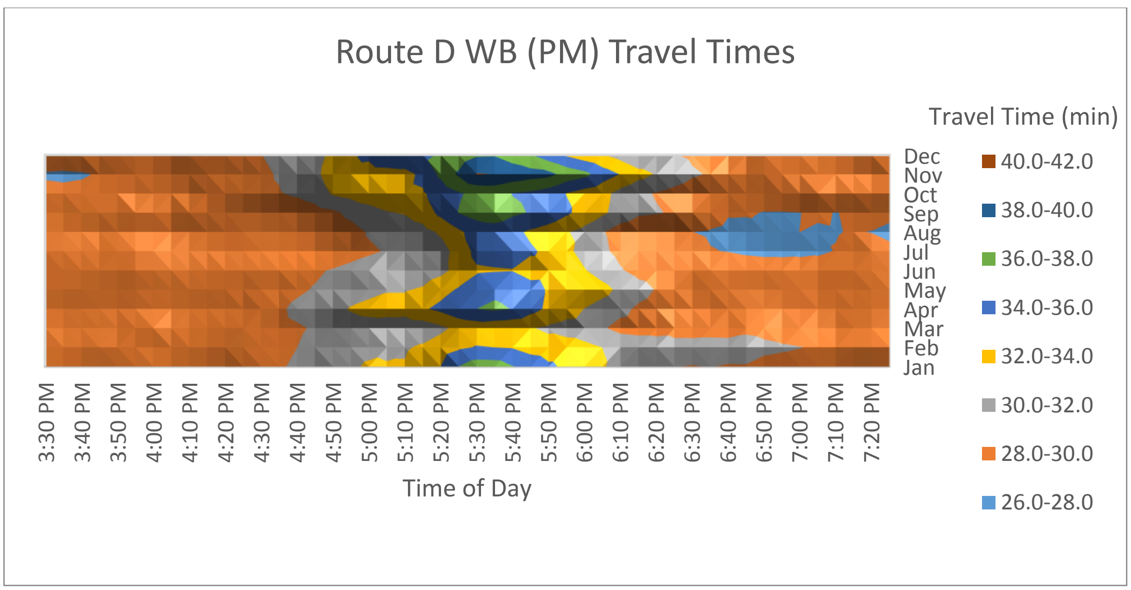


Exhibit III - 54 Average Travel Times for different months for Route C in West Bound direction for PM peak period



3.2 Volume Data Collection and Analysis

This section presents an updated analysis of traffic diversion resulting from the Fortify work zone on I-40 and I-440. This analysis includes observations during the work in *Area 3* as well as *Area 1 & 2* performed to the present date. The diversion analysis is performed on point sensor data collected on sections of I-40 and I-440 approaching active work zones.

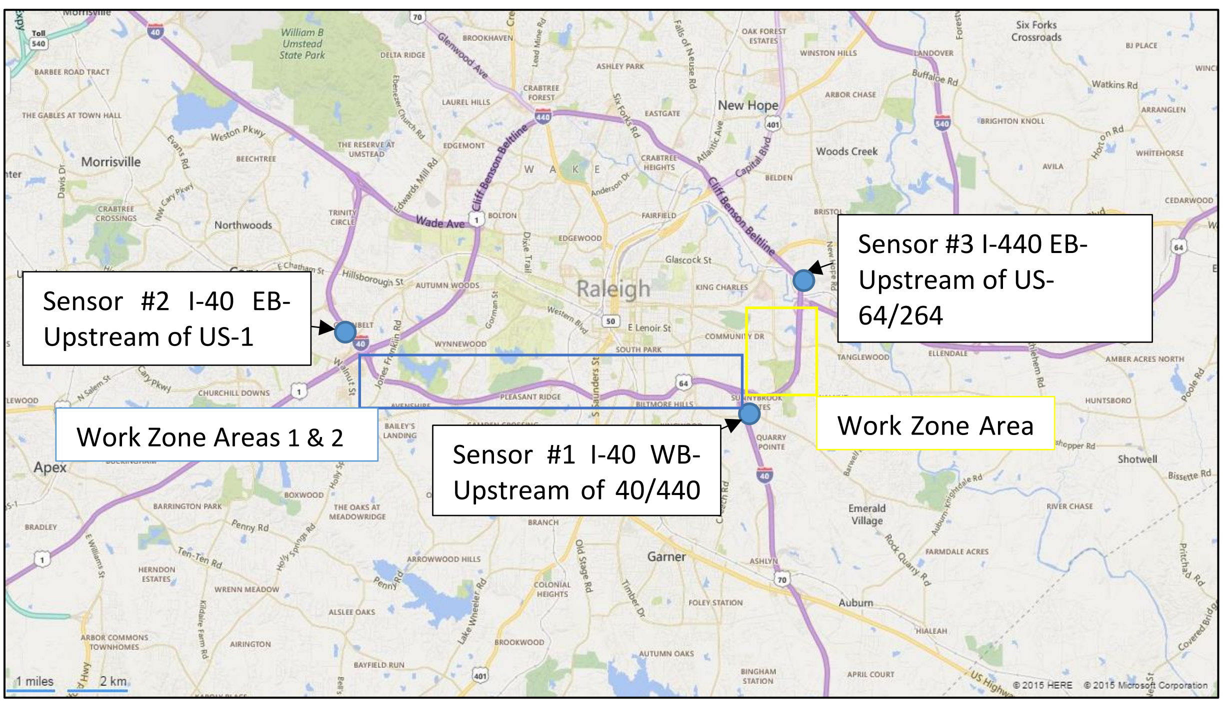
First, the team looked at *four-hour peak period volumes* at the three primary entry-points to the construction area. These volumes were collected for the months of February, August, and September for the years of 2009 through 2015. Second, the team looked at *peak-hour volumes* for different sequences of sensors leading up to and into the work zone for the years 2013, 2014, and 2015 using the same three primary approaches into the work zone for both AM and PM peak periods.

3.2.1 Four Hour Peak Period Volume Data Collection and Analysis

Volume data were collected for three sensors directly upstream of work zone areas for the months of February, August and September in each of the years of 2009 to 2015 in order to observe long term trends as well as estimate diversion during work in each work zone area. Exhibit III - 55 shows the two work zone regions and the three sensors used in this analysis, with details on each listed below:

1. I-40 WB Upstream of 40/440 Split: HERE Sensor ID NC040170, 3 lanes
2. I-40 EB Upstream of US-1: HERE Sensor ID NC040250, 4 lanes
3. I-440 EB Upstream of US-64: HERE Sensor ID NC440120, 4 lanes

Exhibit III - 55 Sensors used in Peak Period Diversion Estimate



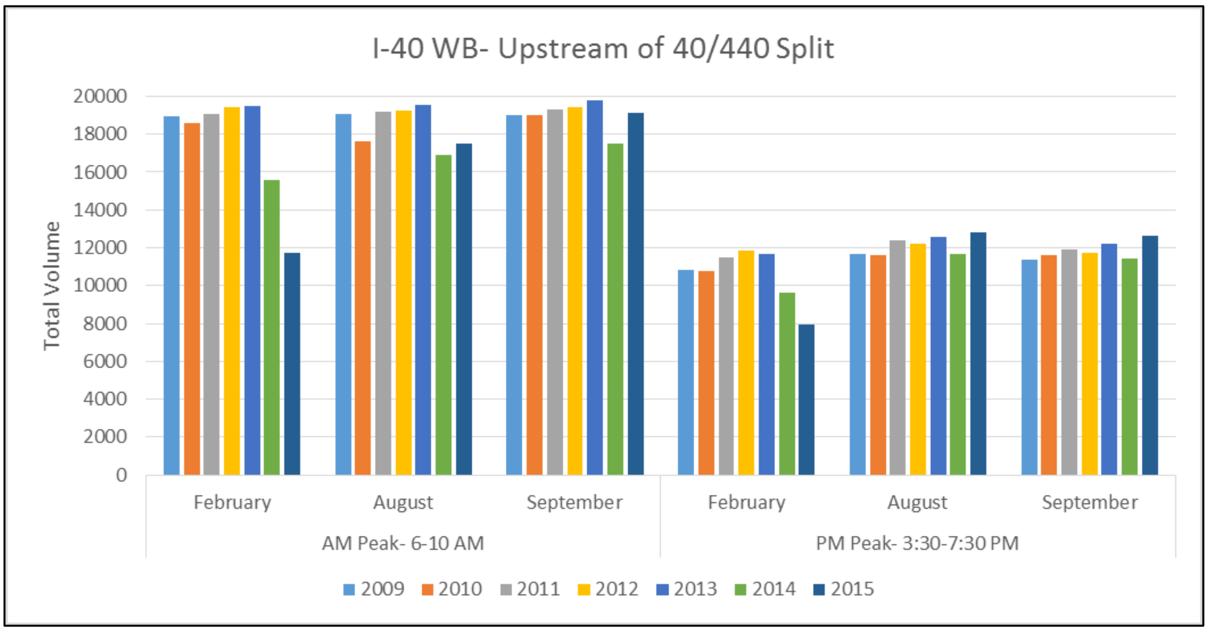
Volume data were collected at each of the three sensors for Tuesdays, Wednesdays, and Thursdays in the months of February, August, and September, and for each year between 2009 and 2015. Volumes are compared at these points to identify diversion during work in Area 3 (includes all of 2014 and February 2015) and in Areas 1 & 2 (August and September 2015).

Exhibit III - 56 shows the trends for the AM and PM peak period total volume at Sensor #1, which is focused on the NB/WB traffic on I-40 approaching the work zone. The analysis shows that there are clear decreases in traffic volume for 2014 relative to prior year. Compared to the average volume of roughly 19,500 vehicles in the 4-hour AM peak, the sensor showed a reduction of 20% in February 2014, and of 40% in February 2015 due to the work zone.

For the months of August and September, 2014 traffic showed similar reductions of approximately 12.5% compared to the prior years. These traffic reductions are partially or totally recovered in 2015 for the months of August and September, with the 2015 volumes showing reductions of only 10.6% and 3.4%, respectively, over 2013.

For the PM peak period, February 2014 and 2015 similarly show decreases in volumes of 17.4% and 32.2% relative to 2013, indicating that diversion has increased during the duration of the construction activity in Area 3. For the construction in areas 1 and 2 starting in August 2015, the traffic volumes appear to have recovered to 2013 levels without any diversion of traffic.

Exhibit III - 56 Sensor #1 AM/PM Peak Period Trends



Sensor #2 is located on I-40 eastbound upstream of US-1 (west of the work zone), and shows similar trends as shown in Exhibit III - 57. The AM peak in February moving towards the work zone shows a decrease of 7.4% and 36.5% in 2014 and 2015 relative to 2013, respectively. For August and September, those traffic reductions are no longer visible, and volumes in 2014 and 2015 are actually higher than 2013.

The PM peak had a large decrease in total volume prior to the construction work covered in this project, and February volumes in 2014 and 2015 dropped further relatively to 2013 (13.5% and 30.9%, respectively). For August and September, no volume differences are observed.

Exhibit III - 57 Sensor #2 AM/PM Peak Period Trends

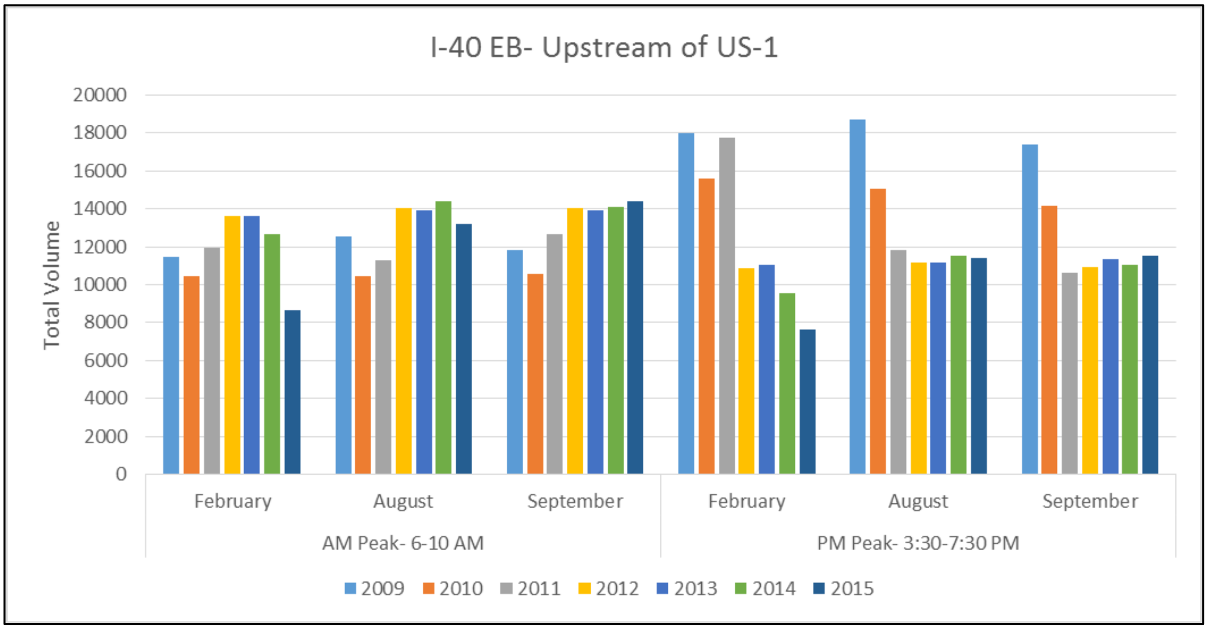


Exhibit III - 58 shows two different trends for the AM and PM peaks at sensor #3, which is on I-440 north of the work zone. In the AM peak, volume has continued to decrease during the activity in Area 3. February volumes in 2015 are down 39% relative to 2013 pre work zone conditions. For August and September, volumes are down 11% and 11.6%, respectively.

In the PM peak, February volumes were down significantly in 2014 (14.5%) and 2015 (39.2%) relative to 2013 pre work zone conditions. However, the total volume in August has returned to a similar level as 2013, and September volumes have even exceed the levels before any construction activity.

Exhibit III - 58 Sensor #3 AM/PM Peak Period Trends

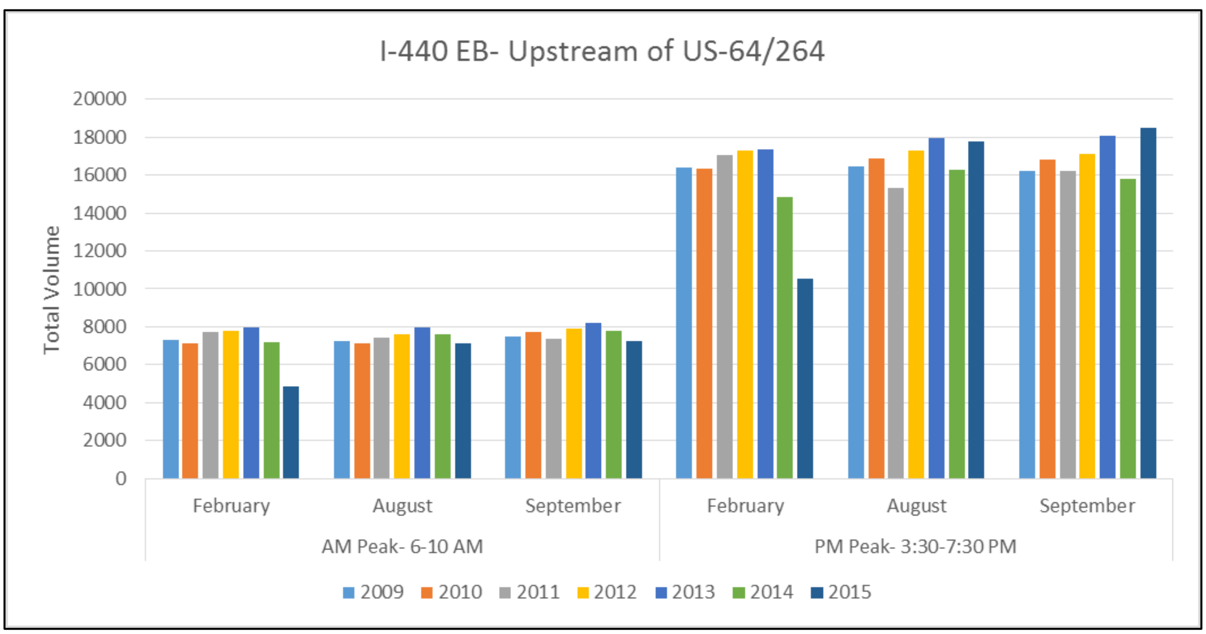


Exhibit III - 59 shows the summary change in total peak period volume at the three locations for each of the months studied for the years 2014 and 2015 in comparison to 2013. The percent changes in italics indicate time periods with work in Area 3 and bold indicate time periods with construction activity in Areas 1 & 2. Overall, the average change for all periods during Area 3 work is -15.2%, while it is -2.3% for periods during Areas 1 & 2 work. This is in comparison to estimated diversion of 13% from the March 2013 quarterly report and 10% from the June 2014 report.

Exhibit III - 59 Change in Peak Period Total Volume during Work Zone

		AM Peak- 6-10 AM			PM Peak- 3:30-7:30 PM		
Location	**Comparison Years**	**February**	**August**	**September**	**February**	**August**	**September**
1) I-40 WB- Upstream of 40/440 Split	2013-2014	-20.0%	-13.6%	-11.7%	-17.4%	-7.0%	-6.0%
	2013-2015	-39.9%	-10.6%	-3.4%	-32.2%	1.9%	3.5%
2) I-40 EB- Upstream of US-1	2013-2014	-7.4%	3.2%	1.3%	-13.5%	3.2%	-2.5%
	2013-2015	-36.5%	-5.4%	3.5%	-30.9%	2.2%	1.4%
3) I-440 EB- Upstream of US-64/264	2013-2014	-9.7%	-4.3%	-4.8%	-14.5%	-9.3%	-12.4%
	2013-2015	-38.9%	-10.9%	-11.6%	-39.2%	-1.1%	2.5%

In summary, it was observed that diversion has increased to an average of 18.5% at sensor #1, 10.4% at sensor #2 and 16.6% at sensor #3 during the duration of the construction activity in Area 3, but overall diversion (in comparison to the 2013 before period) is only about 2.1% at sensor #1, no diversion at sensor #2 and 5.3% at sensor #3 for the first two months of activity in Areas 1 & 2. This limited diversion in the current work zone pattern may be due to drivers testing their pre-construction routes to see how much the construction will affect their commutes during this new area of work, and finding that the travel time impacts are acceptable to them.

3.2.2 Peak Hour Volume Data Collection and Analysis

In addition to the four-hour peak period volume data collection, peak hour volume data were collected for various routes going through each of the Area 3 and Area 1 & 2 work zones. These routes include several sensors spanning portions of I-40 and I-440 in eastbound and westbound directions. Average volumes were collected for each sensor for the peak hour (7:00 AM to 8:00 AM and 4:30 PM to 5:30 PM) in the peak direction for the route. Similar to the peak period, volume data was collected for Tuesdays, Wednesdays, and Thursdays in the months of February, August, and September, and for each year between 2009 and 2015.

Exhibit III - 60 shows the route and sensors studied from Exit 306 on I-40 to Exit 15 on I-440. For this route, trends for the AM peak hour in February were studied for the years 2013, 2014, and 2015, as shown in Exhibit III - 61. The impacts of work zone Area 3 are most significant for this route. The trends show a consistent decrease in volume for all sensors over the years (except for 040120 which may have missing data in 2013) and larger decreases approaching the work zone. From 2013 to 2015, a 54% decrease in volume was observed at sensor 440100 and a 49% decrease at sensor 440110, both in work zone Area 3.

Exhibit III - 60 Sensors for route from Exit 306 to Exit 15 (WB)

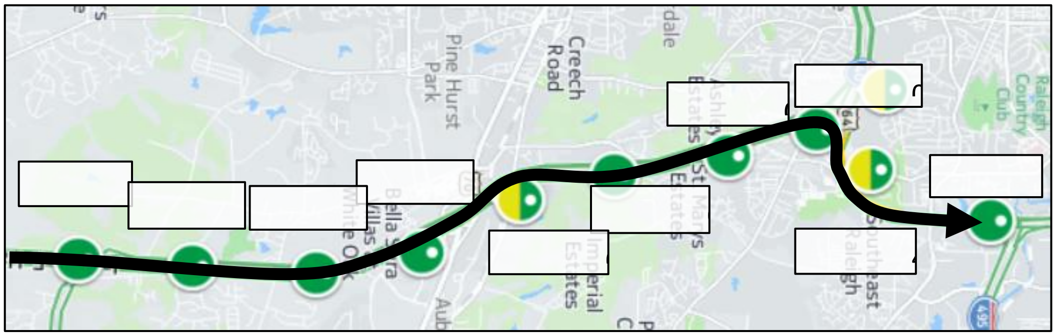


Exhibit III - 61 Trends for WB I-40 Exit 306 to WB I-440 Exit 15 in the AM peak hour during February

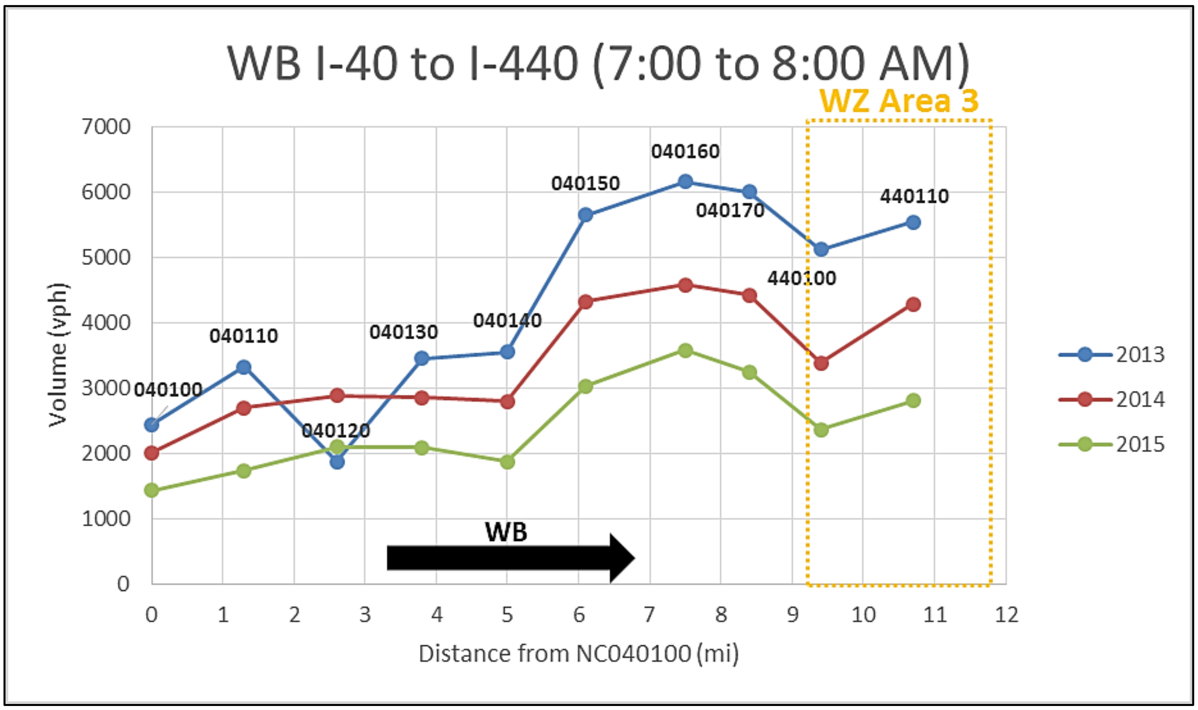


Exhibit III - 62 shows the route and sensors studied from Exit 4 on I-440 to Exit 293 on I-40. For this route, trends for the PM peak hour in February were studied for the years 2013, 2014, and 2015, as shown in Exhibit III - 63. The impacts of all areas of the Fortify work zone may be seen in the data trends for this route. The graph shows a very consistent decrease in volume over the years studied. An 89% decrease in volume can be seen from 2013 to 2015 at sensor 440110 in the Area 3 work zone during the PM peak hour, which may be related to a sensor malfunction given the drastic drop not reflected elsewhere on the route. But still, for most of the route, 2015 volumes in the peak hour are 40-50% lower than 2014.

Areas 1 & 2 may be having some effects on volume, however, work was being completed mainly in Area 3 during the time period studied for this route. These volume decreases observed during the peak hour may not be entirely indicative of the diversion taking place throughout the day. These decreases in volume during the peak hour may be due to diverting to another route, but may also indicate drivers leaving earlier or later than the typical peak hour to avoid congestion in the work zone (also referred to as peak spreading).

Exhibit III - 62 Sensors for route from EB I-440 Exit 4 to WB I-40 Exit 293

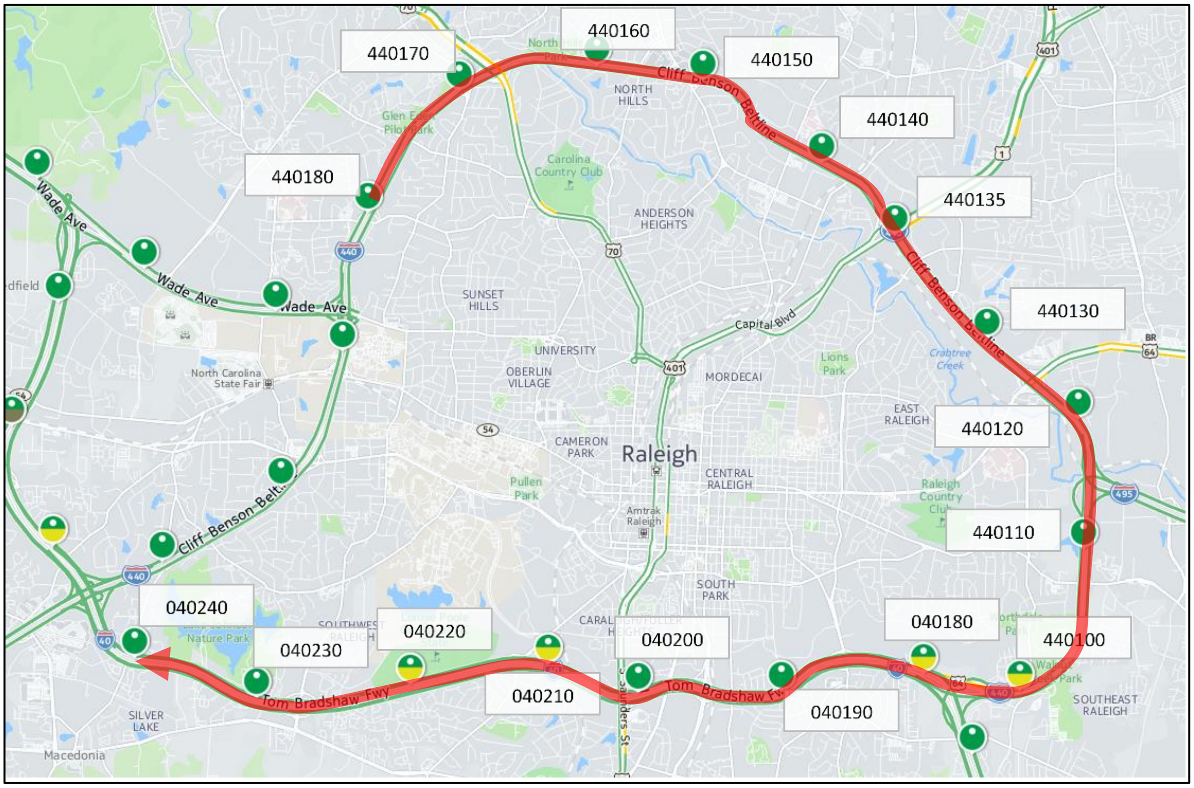
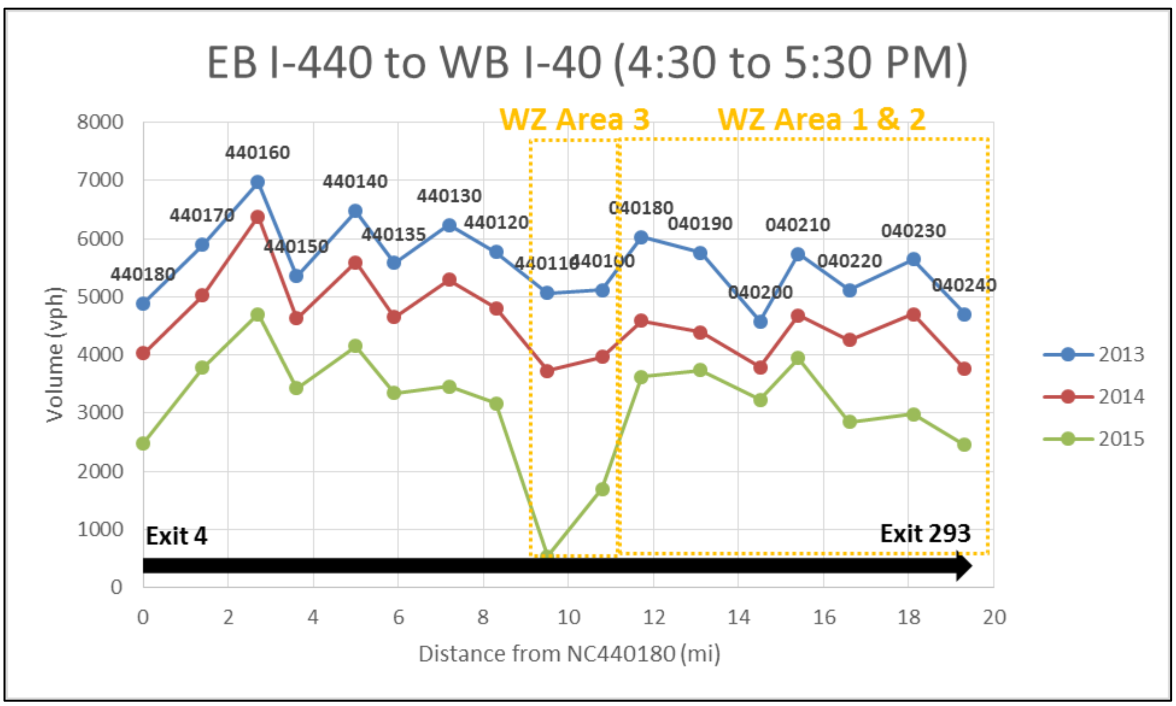


Exhibit III - 63 Trends for EB I-440 Exit 4 to WB I-40 Exit 293 in the PM peak hour during February



With work in Areas 1 & 2 gaining the most traction in August and September of 2015, volume data was studied for these months for routes along I-40 westbound and eastbound. Data was collected for the AM and PM peak hours for typical Tuesdays, Wednesdays, and Thursdays for the years 2013, 2014, and 2015. Exhibit III - 64 shows the sensors along the route which stretches from Exit 281 to Exit 306 in the eastbound direction and from Exit 306 to Exit 281 in the westbound direction. The AM peak was studied for the westbound direction in August and September and the PM peak was studied for the eastbound direction in August and September.

Exhibit III - 64 Sensors along I-40 from Exit 281 to Exit 306

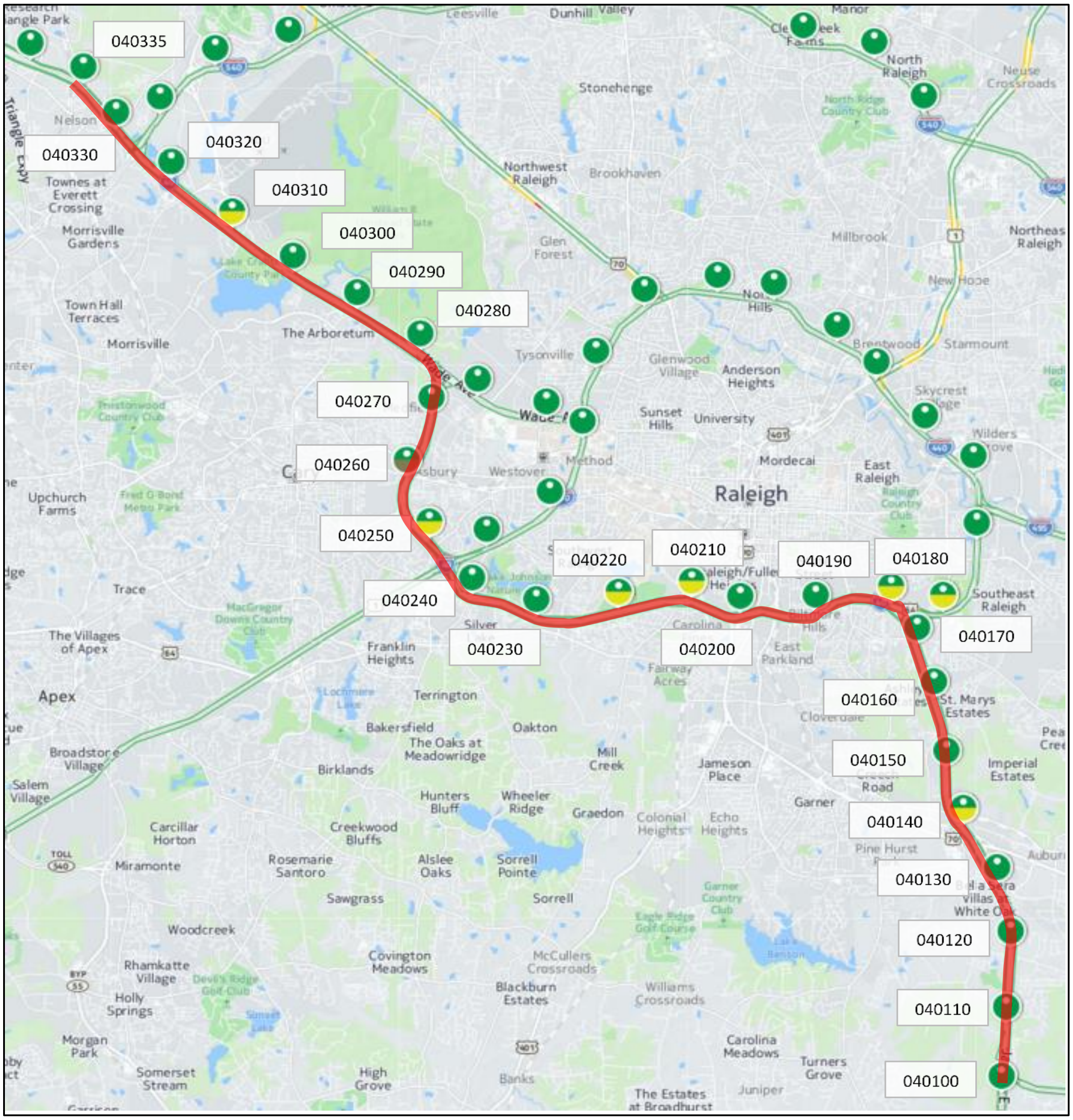


Exhibit III - 65 and Exhibit III - 66 show trends along I-40 westbound in the AM peak hour. Here, effects of the work zone in Areas 1 & 2 can be seen. The months of August and September 2015 are quite similar in volume data. Volumes maintain a consistent trend along other portions of I-40, suggesting that the work zone does play a role in decreasing volumes. In August, a 46% decrease in volume was observed at sensor 040240 from 2013 to 2015 and a 45% decrease was observed at sensor 040240 in September. Both of these differences are likely to be a combination of diversion, peak spreading, as well as natural capacity constrained metering of traffic flowing into the work zone.

Exhibit III - 65 Trends in volume for the AM peak hour along I-40 WB from Exit 306 to Exit 281 in August

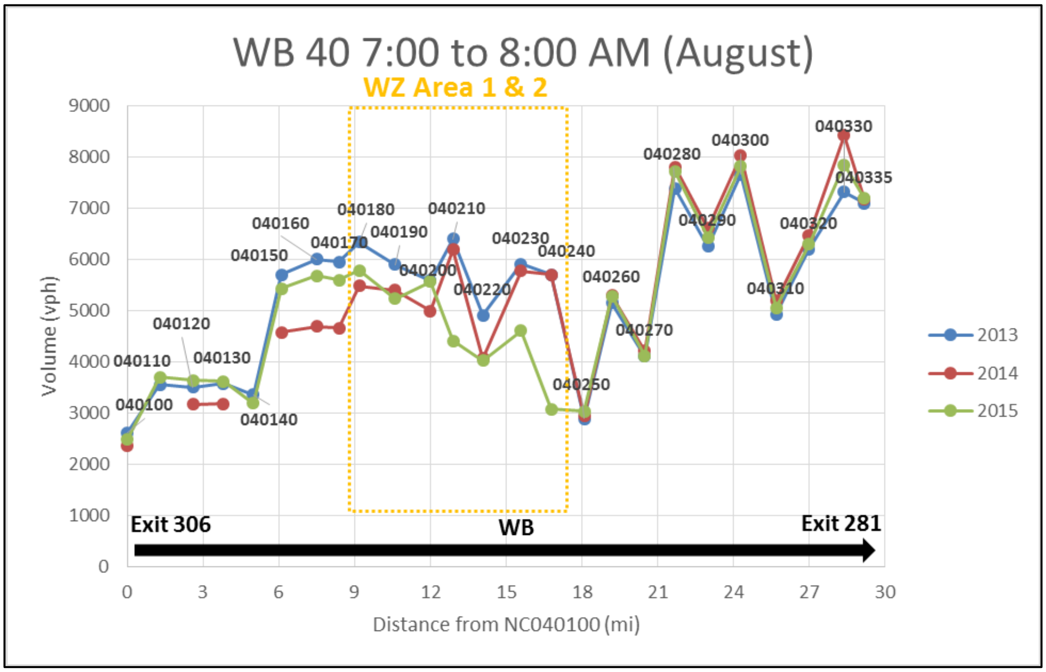


Exhibit III - 66 Trends in volume for the AM peak hour along I-40 WB from Exit 306 to Exit 281 in September

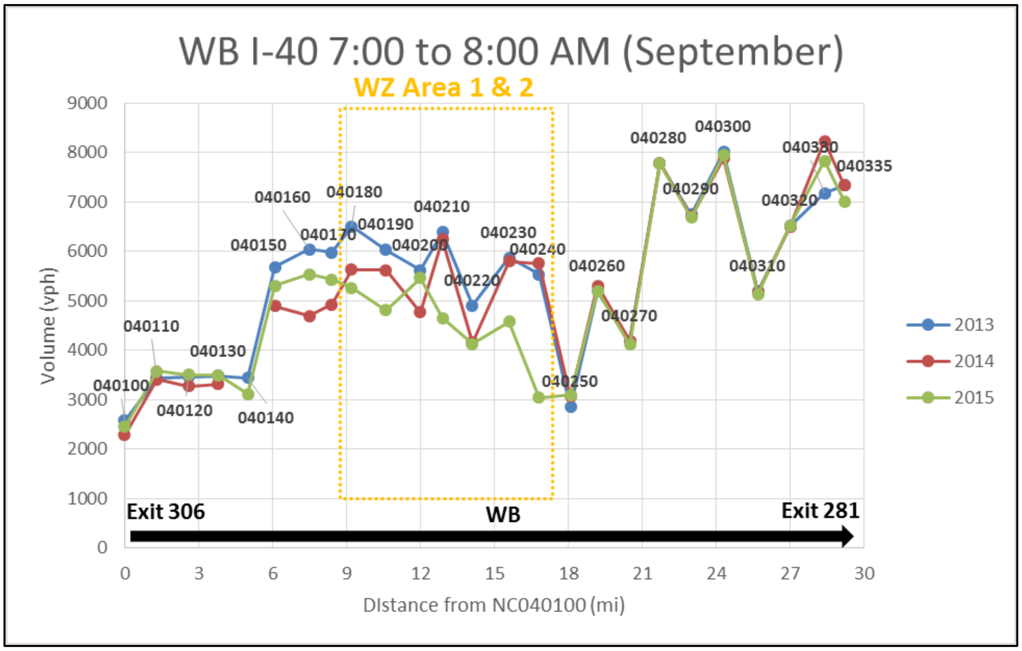


Exhibit III - 67 and Exhibit III - 68 show trends along I-40 eastbound in the PM peak hour, where the major work zone effects are the result of Areas 1 & 2. The months of August and September 2015 are somewhat similar in volume data, with September showing slightly larger diversion rates in the work zone. Volumes maintain a consistent trend along other portions of I-40, suggesting again that the work zone does play a role in decreasing volumes. Sensor 040220 (between Lake Wheeler Rd. and Gorman St.) showed the highest volume diversion, with 89% in August and 86% in September, which may be related to an equipment malfunction. For other sensors, peak hour traffic volumes are down approximately 17%, which is likely due to a combination of route diversion, peak spreading, and capacity-induced metering of traffic flow through the work zone. At an approximate work zone capacity of 1,600-1,800 vehicles per hour per lane, the three-lane cross-section is expected to be able to carry up to 4,800 to 5,400 vehicles per hour, which is about where the measured volumes max out.

Exhibit III - 67 Trends in volume for the PM peak hour along I-40 EB from Exit 281 to Exit 306 in August.

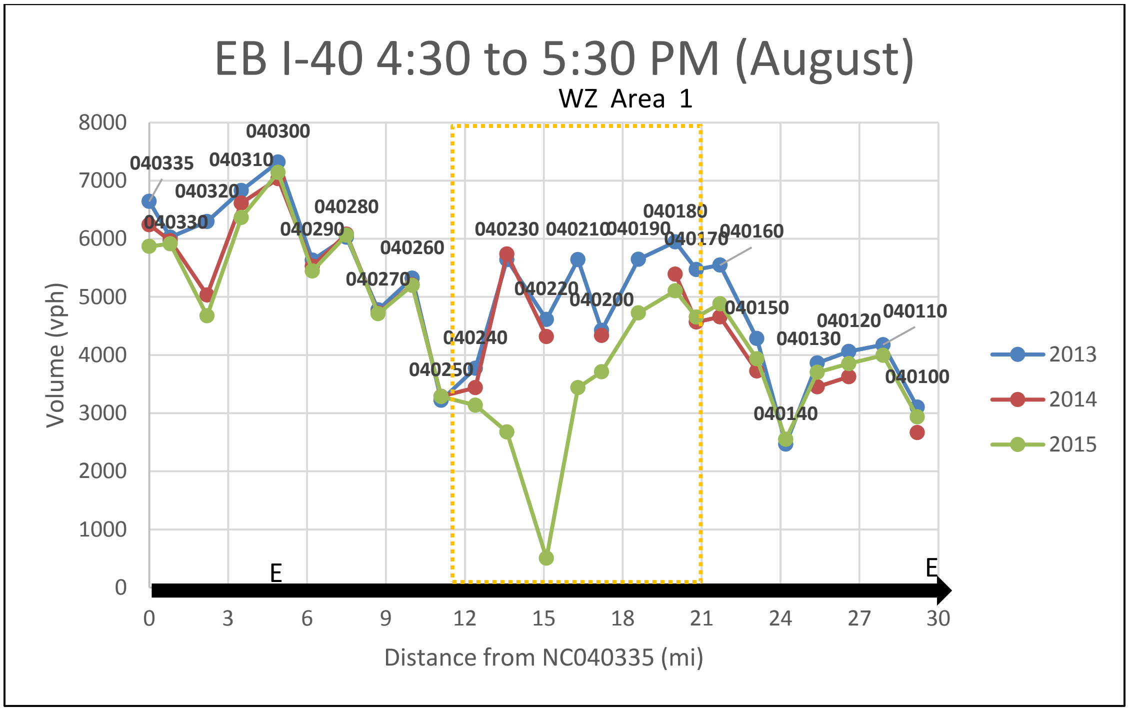
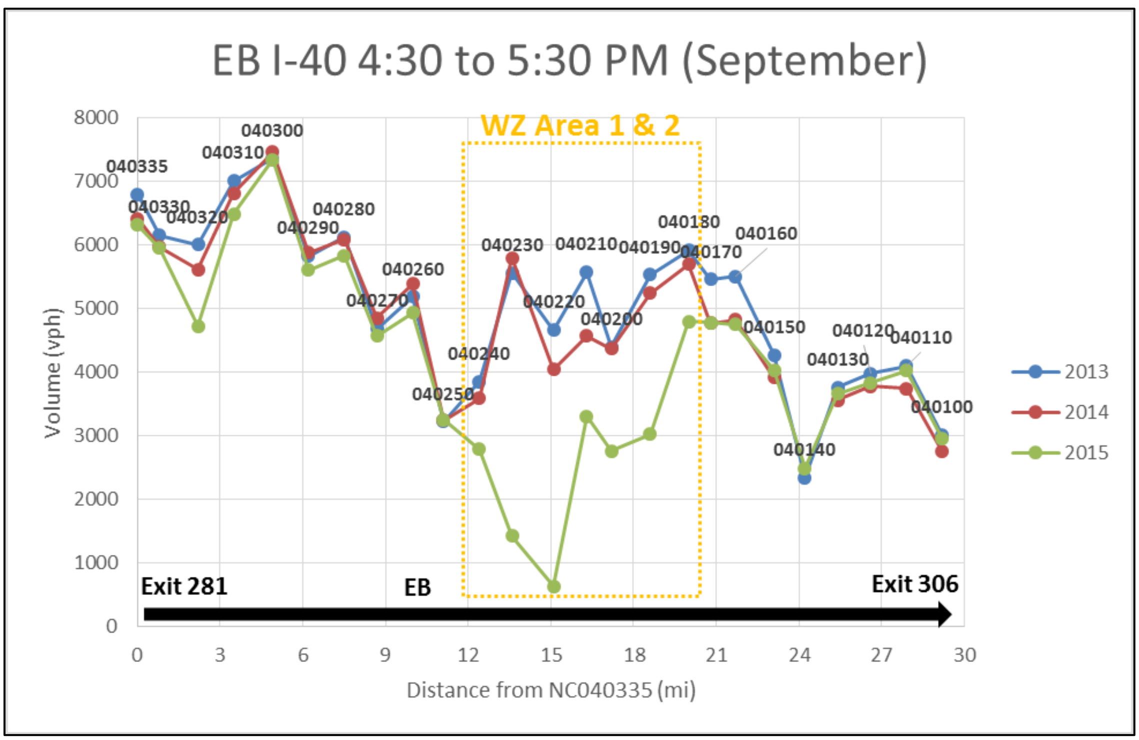


Exhibit III - 68 Trends in volume for the PM peak hour along I-40 EB from Exit 281 to Exit 306 in September



For the analysis of the one-hour peak, the study showed more drastic reductions in peak traffic. For the one-hour traffic through the work zone, 2014 data (area 3 work) suggests a 20-25% reduction in volume observe, while the 2015 data (area 1 and 2 work) shows a 45-50% reduction in volumes. This diversion in the peak hour seems more drastic, and likely due to a combination of route diversion, peak spreading, and capacity-induced metering of traffic flow through the work zone. At an approximate work zone capacity of 1,600-1,800 vehicles per hour per lane, it is expected that the possible throughput is less than the actual demand (resulting in queuing upstream).

Combining the two analysis, a few interesting conclusions can be drawn. First, the initial work in Area 3 resulted in a 10-19% net reduction in trips over the four-hour peak period, depending on the direction of interest. During that time, the one-hour peak volume was reduced by approximately 20%, suggesting that in addition to a net-reduction of trips, some peak spreading may have occurred (as also confirmed by earlier ITRE analysis).

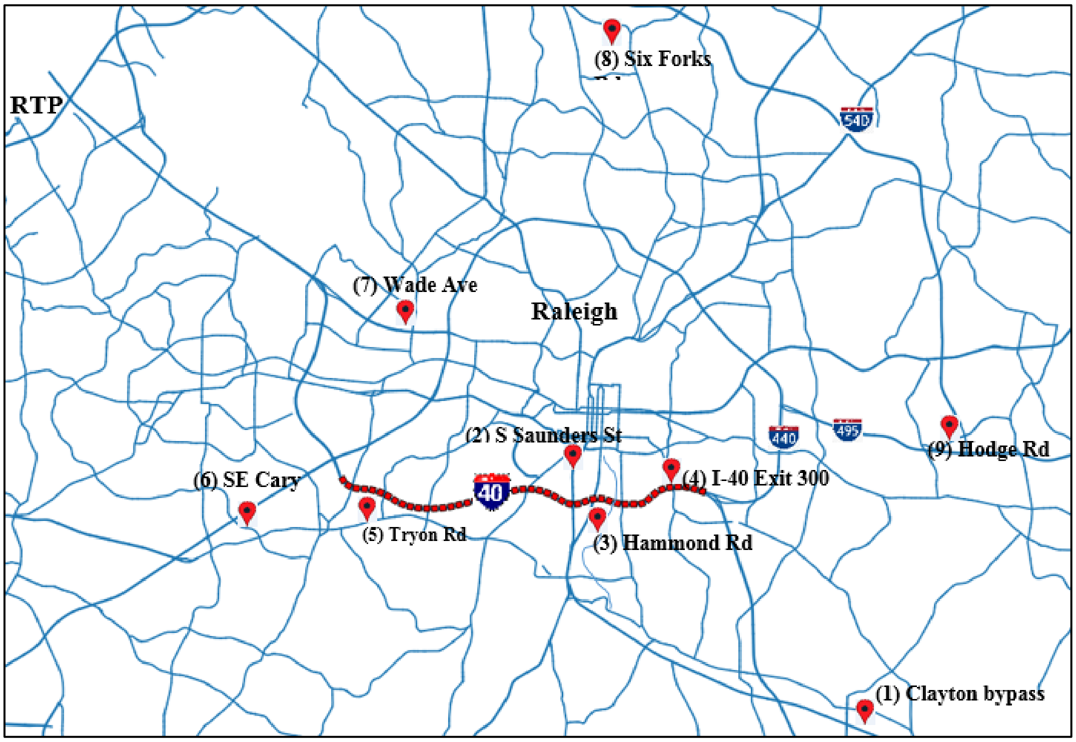
However, when looking at the 2015 data for areas 1 and 2, it is evident that much of the initial four-hour diversion has been reduced or even fully eliminated, while the one-hour peak diversion has grown to 45-50%. This gives a strong indication that drivers have adapted their travel habits and shifted to departure times outside of the historic one-hour peak. It is expected that capacity constraints (and resulting congestion) are the reason for at least some of that reduction, but overall it appears that a significant amount of peak-spreading has occurred. The team hypothesizes that most of that spreading went to the “outside” of the peak hour, with the AM peak starting earlier in the day, and the PM peak shifting later in the day.

4.0 BLUETOOTH DATA COLLECTION AND ANALYSIS

4.1 Sensor Deployment

All the Bluetooth sensors were simultaneously deployed at locations shown in Exhibit III - 69. The batteries of the devices last for about two weeks. To be conservative, the team decided to deploy them for an effective period of 10 days. All the sensors have contact information on them and are secured with locks and chains. The research team collects all the devices back on a single day to make sure all resources are simultaneously utilized for a maximum time.

Exhibit III - 69 Locations of Deployed Bluetooth Sensors



The timeframe for the sensor deployment is illustrated in Exhibit III - 70.

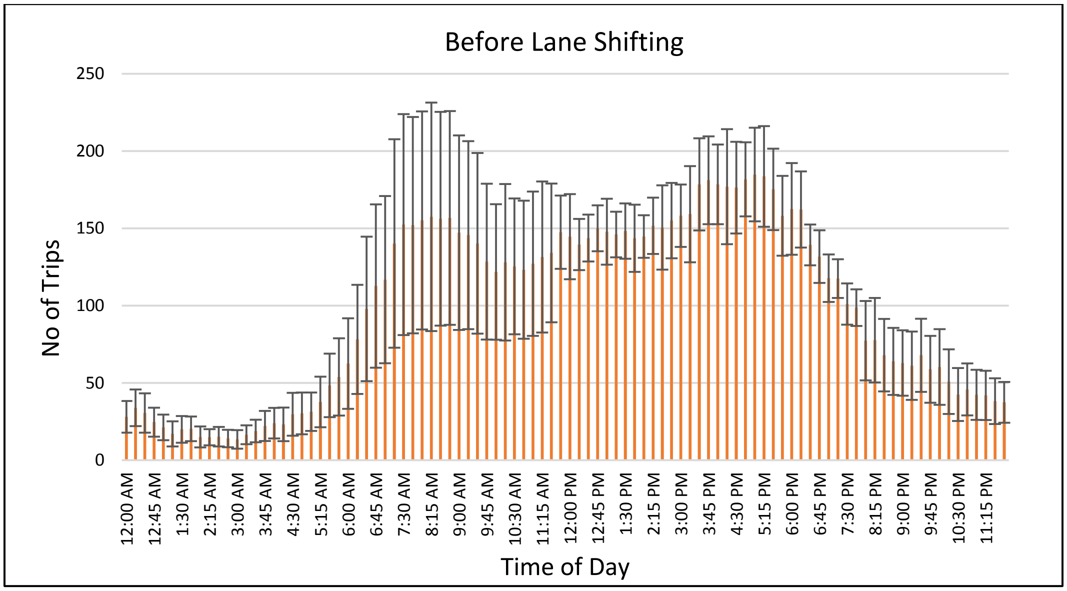
Exhibit III - 70 Schedule for Bluetooth Deployment

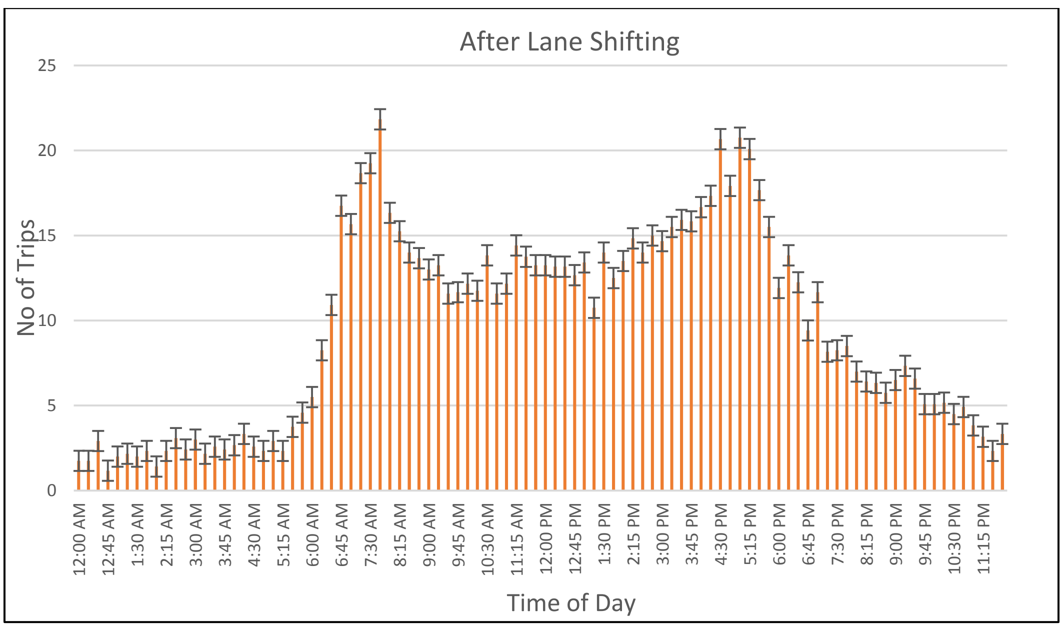
Phase	Analysis Period
Before Lane Shifting	March 16, 2015 – March 26, 2015
After Lane Shifting	July 6, 2015 – July 16, 2015

4.2 Station Processing

Each Bluetooth sensor station collects time stamped device sighting records and stores them inside the device storage memory. However, due to the technological issues, multiple sightings of the same device can occur. Moreover, there could be devices not related to moving vehicles and a single vehicle can have multiple active devices. The station processing eliminates such distortions in the collected data. As an example, station processing for a single sensor placed at Hammond Rd is shown in Exhibit III - 71. It is to be noticed that the sensed sample follows the diurnal pattern of the overall traffic volume. However, the second round of data collection resulted in much lower sample size as compared to the first round.

Exhibit III - 71 Temporal profile for number of cars sensed at Hammond Rd. (Device 3) before and after Lane shifting





Bars are average numbers across days and error bars represent inter-day standard deviation.

4.3 Segment Processing

Segment processing is the estimation of number of trips made through a pair of Bluetooth sensors and their corresponding travel times. It matches the MAC IDs recorded in a pair of devices and reports the travel times for those corresponding trips. Longer OD pairs can be decomposed into several segments and analyzed using a set of segments processed data.

To capture the effects of lane shifting on driver route choice and the change in travel time from the Bluetooth sensor data, the team primarily focused on route analysis of two major origin destination pairs.

Route 1 – 7: from Johnston County to Research Triangle Park – West Bound (WB)

Subroute 1-2-7: trips that pass through S Saunders St

Subroute 1 -4 -7: trips that pass through work zone

Subroute 1 -8-7: trips that pass through northern side of I-440

Route 7 – 1: from Research Triangle Park to Johnston County – East Bound (EB)

Subroute 7-2-1: trips that pass through S Saunders St

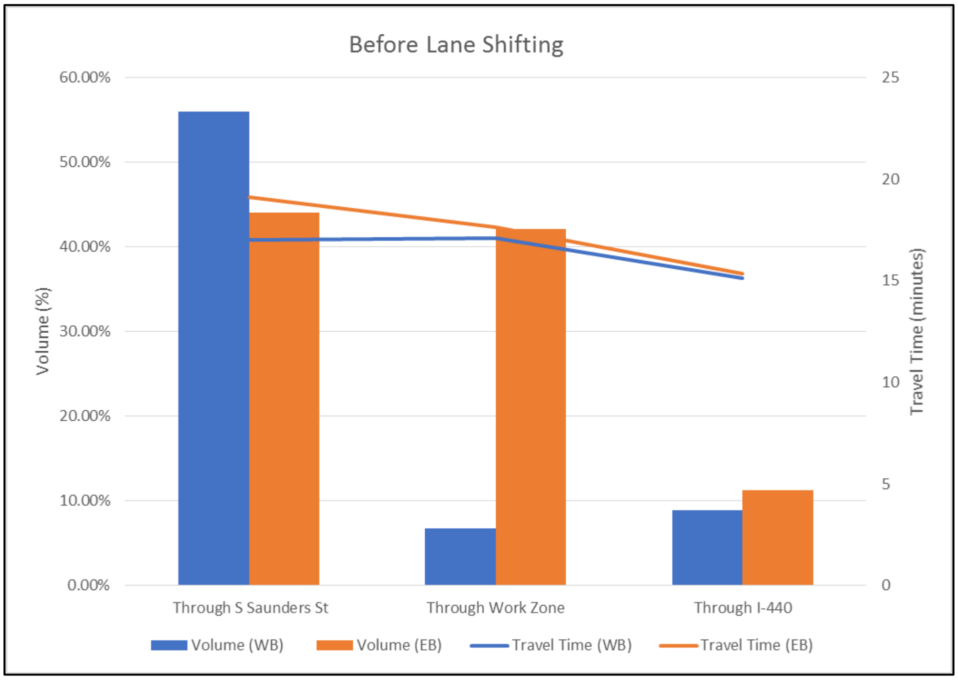
Subroute 7-4-1: trips that pass through work zone

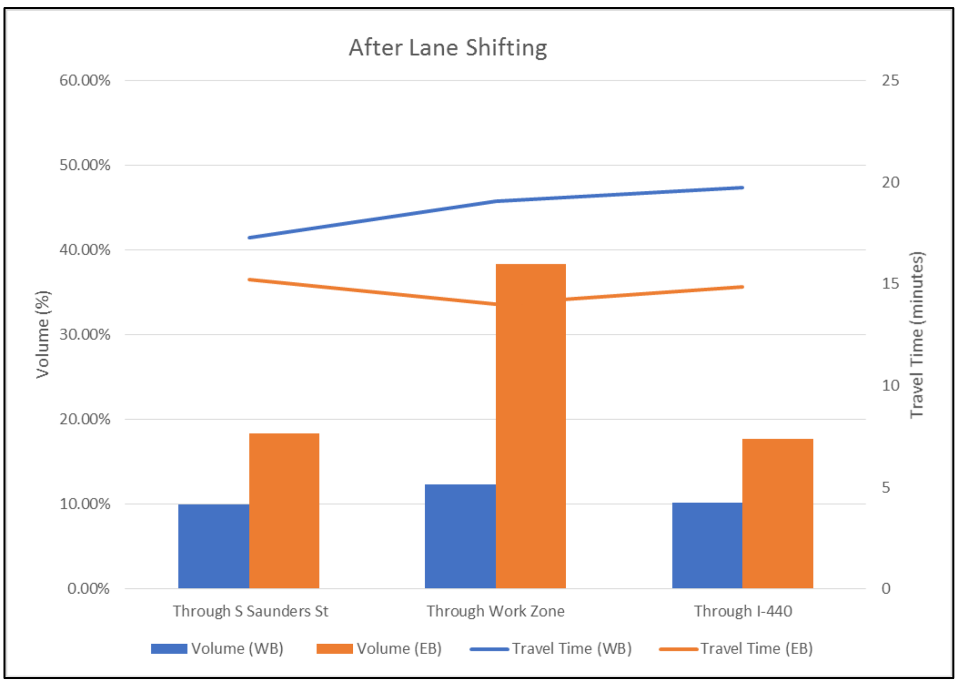
Subroute 7-8-1: trips that pass through northern side of I-440

Exhibit III - 72 shows the volume change and average travel time for vehicle sightings by the Bluetooth devices, for the two periods of deployment. It can be seen that due to the lane shifting, there was a slight decrease in the percentage of volume traveling through the work zone area in the eastbound direction and an increase in vehicles traveling taking I-440 as an alternate route in the eastbound direction. There is also a notable increase in travel time through I-440 and through the work zone in the westbound direction. It is noticeable that the before construction travel times aligns with usual expected travel times at different routes.

However, it can be seen that during the second round of data collection, the percentage volume through S. Saunders Street in both directions of travel decreases significantly. This suggests the presence of noisy data and incorrect detection of devices by the devices. Bluetooth sensors have better detection rate in proximity than in farther distances. This is an issue in trip detection at roads with a wide cross-section (e.g. freeways with a wide median). Even though the team decided to use the same deployment location, position, and angle throughout the study to ensure homogeneity in data collection across the study, low penetration rates of active Bluetooth devices in the traffic stream (usually 2% to 3% of overall volume), makes it almost impossible to get a fine temporal resolution for traffic state information from these sensors. This problem is more pertinent for route based processing, where only the devices that were sighted in common to the successive pairs of sensors are considered.

Exhibit III - 72 Volume and Travel Time for devices detected between Johnston County and RTP through predefined sub-routes in EB and WB direction for before and after lane shifting





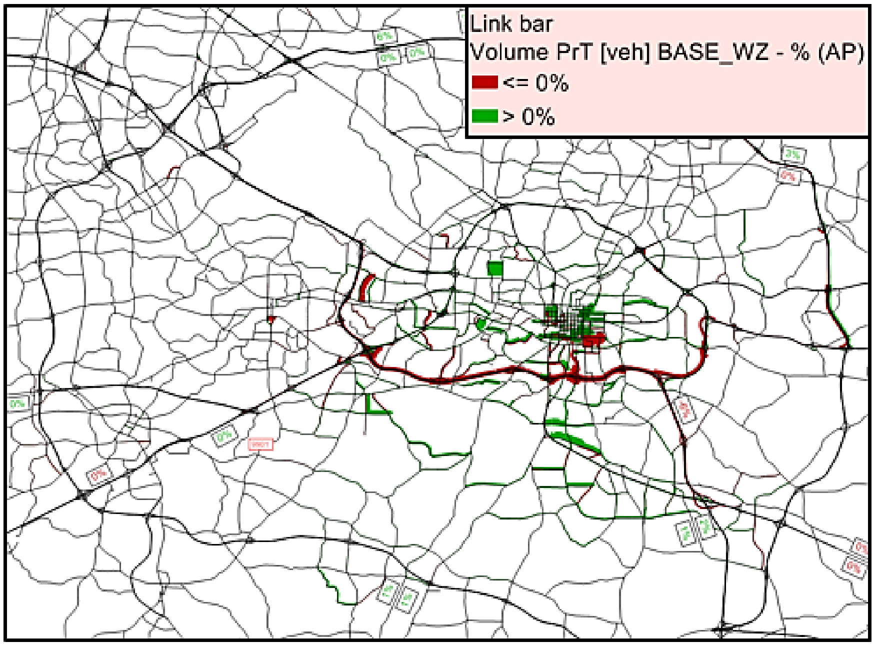
The blue bar and line represent percentage volume change and average travel time in WB direction and the orange bar and line represent percentage volume change and average travel time in EB direction.

5.0 MACROSCOPIC NETWORK LEVEL MODELING RESULTS FOR AREA 1&2: VISUM

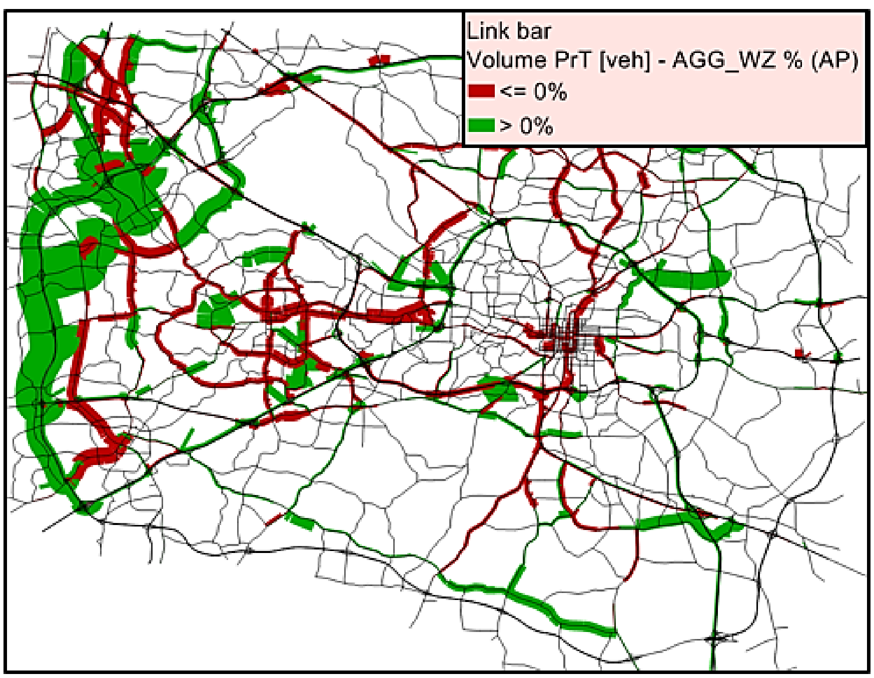
5.1 Effect of Network Complexity Reduction

The process of network reduction helps the macroscopic model in diverting traffic in a more realistic way. Exhibit III - 73 shows the percentage changes in volume in the full and reduced regional network for the AM peak period. The green bands depict an increase in volume through the links, whereas red bands depict decrease in volume. It can be noted that in the full regional network, the static user equilibrium assignment diverts traffic more evenly through the network. This is due to availability of more alternate routes in the form of local roads or minor arterials. However, once the lower category roads have been deleted in the reduced network model, more traffic is diverted through the major arterial streets. However, the reduced network models diversion results from the work zone more realistically, by assigning more traffic through the major arterial routes. This simple evaluation helps in the identification of key alternate routes that may be used for in depth analysis.

Exhibit III - 73 (a) Spreading of diversions in the full regional network macroscopic model and (b) Diversions assigned to major arterials in reduced network macroscopic model.



(a)

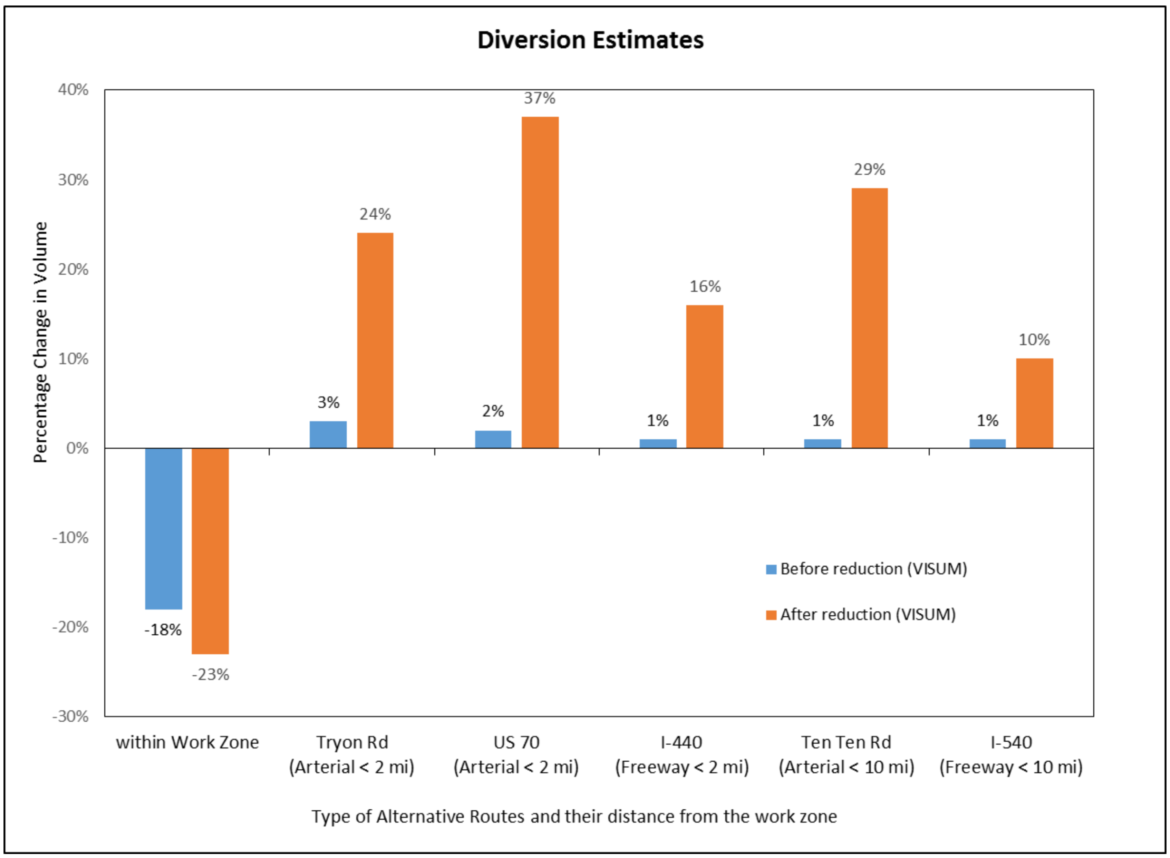


(b)

5.2 Diversion Effects on Key Alternate Routes

Exhibit III - 74 shows the change brought about by the network reduction technique in estimating diversion effects of the work zone in the AM peak period. From the results shown in Exhibit III - 73, a few key alternate routes were identified and the percentage change in the aggregate volume through those links calculated. The key routes identified were: Tryon Road, US 70, I-440, Ten Ten Road and I-540. These routes were selected as arterials and freeways within radii of 2 miles and 10 miles from the work zone. It can be seen that in the absence of local roads in the reduced network, more traffic is diverted through the arterials and freeways in the presence of the work zone. US 70 emerges as a more significant alternate route in the reduced model, which showed very little diversion in the full model. Similarly, the reduced model shows more usage of I-440 and I-540 (16% and 10% respectively) as compared to the full regional model.

Exhibit III - 74 Diversion rates estimated by the macroscopic models before and after reduction.



CHAPTER IV -

GUIDANCE DOCUMENT FOR WORK ZONE OPERATIONAL MODELING AND MONITORING

Table of Contents

1 Executive Summary

This document presents guidance for modeling and monitoring work zone operations and mobility performance in North Carolina. The guidance document is intended for analysts in the work zone and congestion management groups within the North Carolina Department of Transportation, to assist their staff in properly scoping work zone studies. The focus is on operational analysis and monitoring, which is one of the critical dimensions of work zone performance assessment. But other impacts, including safety, economic, environmental impacts, etc. should be considered as well, even if they are beyond the scope of this document.

The document presents *guidance and recommendations*, but not requirements. Any work zone analysis should therefore be carefully evaluated using engineering judgment, and under consideration of the availability of funds, staff resources, and time to conduct the recommended level of operational analysis or monitoring.

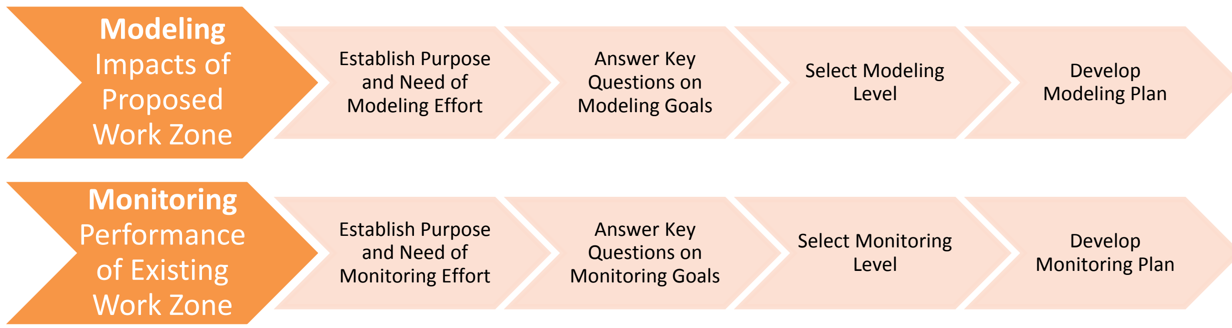
Any operational assessment or monitoring effort for a freeway work zone should have a clear purpose and goal for conducting the analysis. The guidance in this document helps inform that purpose. The analyst should keep the goals in mind when scoping a work zone evaluation, and balance the required departmental resources against the expected benefits and outcomes of the effort.

In the context of this document, *Modeling* refers to predicting the operational effects and impacts of a work zone prior to construction starting. Modeling is performed in order to predict work zone operations, compare and contrast alternatives, and support decision-making for work zone staging. The guidance discusses types of models, and presents guidance for applying different levels of analysis tools to estimate work zone effects.

Monitoring refers to evaluating and tracking performance of a work zones once it is in effect. Work zone monitoring is conducted during active construction. It captures data, applies data analytics, and provides opportunities for providing real-time decision-support. The guidance discusses types of sensing and data collection approaches to quantify operational characteristics of a work zone, and makes recommendations for what level of monitoring is appropriate for a given work zone.

In order to use this document, the analyst should have a general sense of what he or she is trying to predict or find out about a given work zone. The guidance then links these questions to different levels of modeling and monitoring, and makes recommendations for the type of tool or approach NCDOT may want to use. The following flowchart summarizes the information contained in the document.

Exhibit IV- 1: Work Zone Modeling and Monitoring Framework



Every modeling and monitoring effort should start by establishing a clear purpose and need for the analysis. Before engaging in an analysis effort, the analyst needs to define the goals and expected outcomes of the effort at hand. These goals should be weighed against the required departmental resources, before finalizing a work zone operational modeling and monitoring plan.

The guidance is presented in the form of key questions an analyst or work zone designer may have for a specific project. Those questions in turn focus on the desired outcomes of the analysis, and the guidance then presents the path or approach to get to that outcome. For example, a high-level modeling question may be “What time of day are lane closures permissible on this facility?” A more detailed modeling question may be “What alternate routes are going to be most impacted by diversion from this work zone?” These two questions require very different types of tools, and while the first can be answered with planning-level look-up charts (presented in this document), the second requires advanced network-wide modeling using a simulation tool. For monitoring, similar questions are presented to guide the analyst in selecting appropriate approaches.

From the answers to these key questions, the guidance then proposes different levels of work zone monitoring and modeling, depending on the desired level of detail and analysis outcomes. These modeling levels are the key inputs into deriving a work zone operational modeling or monitoring plan.

2 Introduction

This document provides guidance for the evaluation of work zone operations in North Carolina. The document covers both work zone modeling and work zone monitoring. **Work zone modeling** is performed prior to the construction activity to predict operational impacts of a proposed work zone, compare and contrast alternatives, and support decision-making for work zone staging. **Work zone monitoring** is conducted during active construction, and captures data collection, data analytics, and opportunities for providing real-time decision-support.

The focus of this document is on operational analysis and monitoring, which is one of the critical dimensions of work zone performance assessment. Other considerations, including safety performance, economic impacts, etc. should be considered as well, even if they are beyond the scope of this document.

The document presents *guidance and recommendations*, but not requirements. Any work zone should therefore be carefully evaluated using engineering judgment, and under consideration of the availability of funds, staff resources, and time to conduct the recommended level of operational analysis or monitoring.

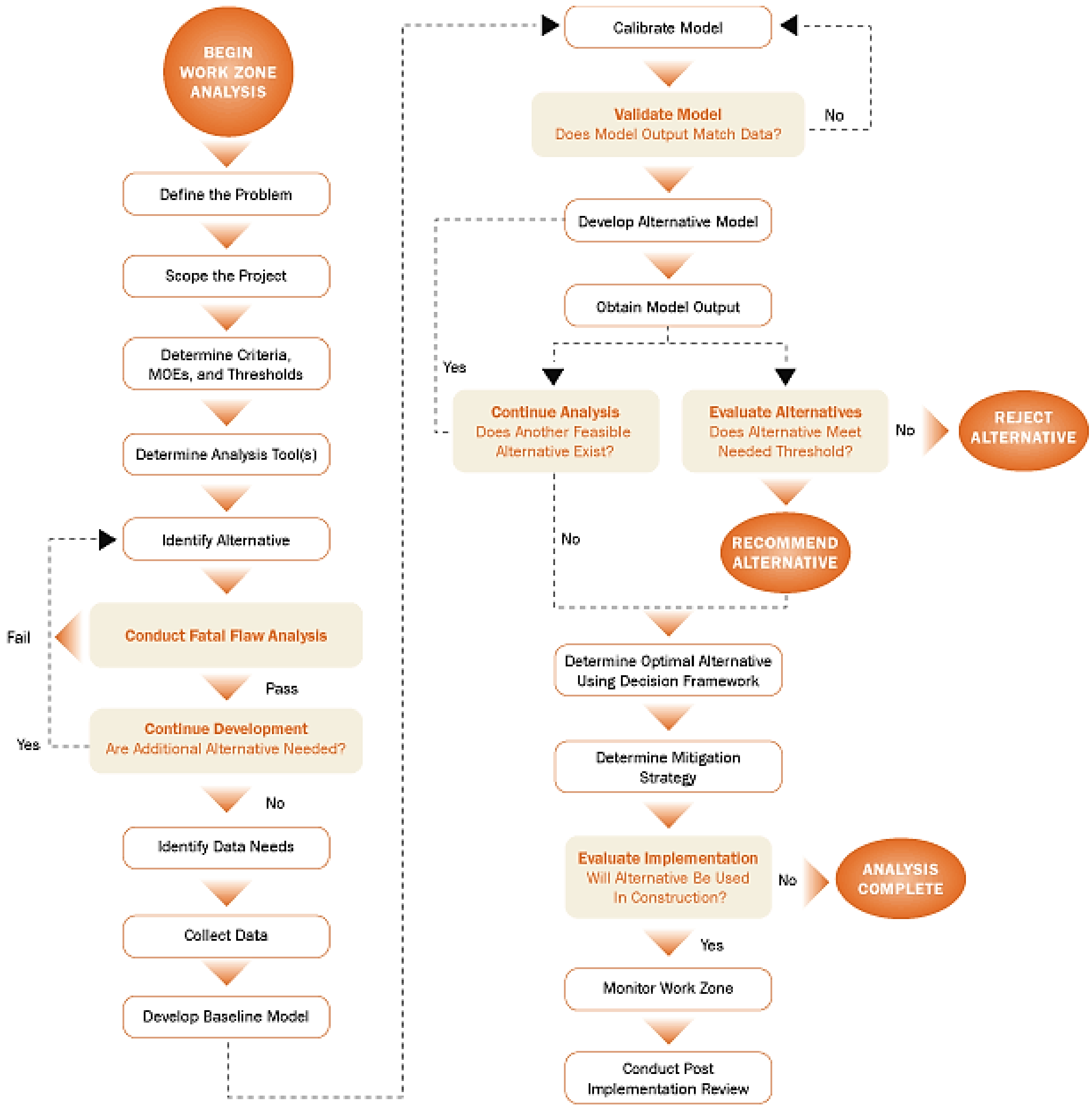
An operational assessment or monitoring effort for a freeway work zone should have a clear purpose and goal for conducting the analysis. The guidance in this document helps with informing that purpose. The analyst should keep the goals in mind when scoping a work zone evaluation, and balance the required departmental resources against the expected benefits and outcomes of the effort.

In the context of this document, *Modeling* refers to predicting the operational effects and impacts of a work zone prior to construction starting. Modeling is performed in order to predict work zone operations, compare and contrast alternatives, and support decision-making for work zone staging. The guidance discusses types of models, and presents guidance for applying different levels of analysis tools to estimate work zone effects.

Monitoring refers to evaluating and tracking performance of a work zones once it is in effect. Work zone monitoring is conducted during active construction, and captures data collection, data analytics, and opportunities for providing real-time decision-support. The guidance discusses types of sensing and data collection approaches to quantify operational characteristics of a work zone, and makes recommendations for what level of monitoring is appropriate for a given work zone.

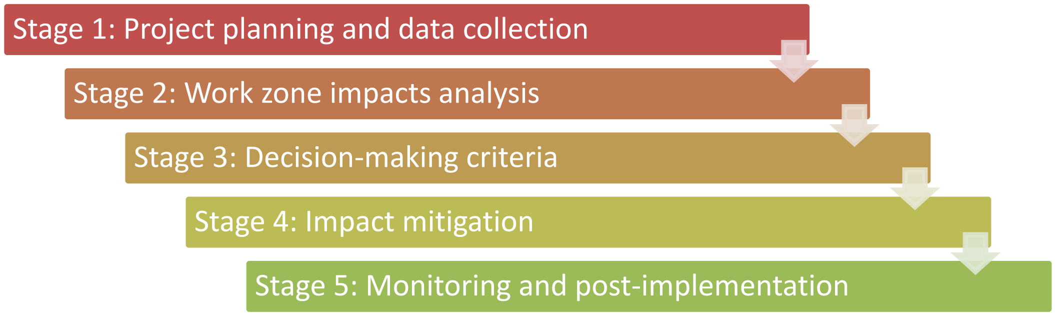
Both work zone modeling and monitoring are part of a broader work zone planning and assessment framework, and significant resources exist at the federal level to support these efforts (1). The NC-specific guidance described in this document fits within the broader application of a Maintenance of Traffic Alternatives Analysis (MOTAA) framework that is described in FHWA Toolbox Volume XII and is shown in Exhibit IV- 2.

Exhibit IV- 2: FHWA Work Zone Maintenance of Traffic Alternative Analysis (MOTAA) Framework (1)



The steps shown in Exhibit IV- 2 provide a detailed work flow for a work zone maintenance of traffic alternatives analysis. The basic steps can be adapted to various work zone configurations. The reader is encouraged to consult Volume XII of the FHWA Traffic Analysis Toolbox for additional information on this process. The work flow can also be summarized into five general stages for work zone traffic analysis as shown in Exhibit IV- 3:

Exhibit IV- 3: Five Stages of Work Zone Traffic Analysis (Source: FHWA)



The operational modeling and monitoring needs for a work zone should be considered early in the work zone planning process. Modeling and analysis results play an important role in evaluating and comparing various construction scenarios, and may be even more important in design-build projects to clearly define scope and requirements before issuing a solicitation for the work.

Similarly, data and monitoring needs should be defined and agreed-upon in advance to any construction activity, especially when it is determined that additional data collection devices may need to be deployed or analytics capabilities developed to support the desired data sources. Work zone monitoring is the key focus of Stage 5 of the work zone analysis process, but data needs for monitoring also factor into stages 1, 2, and 4 of the process.

The remainder of this document is organized as follows: The next section provides guidance for developing a work zone modeling plan, followed by a corresponding section on developing a work zone monitoring plan. Both sections also discuss data needs to support the modeling and monitoring efforts. The document then presents a summary of practical recommendations for work zone analysis, using various use cases to illustrate different levels of modeling and monitoring. The document concludes with a series of appendices that provide additional details on the work zone modeling approaches.

The guidance process is organized along key analysis and modeling questions, as well as the introduction of different levels for operational data analysis and modeling. It is assumed that this guidance will be applied by NCDOT staff or contractors, who may or may not have the technical background and expertise in actually applying the models or analyzing sensor data. As such, the *scoping questions* for a work zone analysis and modeling effort are at a relatively high level, and focus on desired outcomes of the analysis, rather than specifics on model application.

Some example **modeling questions** include:

- What times of day are lane closures permissible?
- What diversion levels are needed to keep operational performance at pre-work zone levels (or within XX%)?
- How can mitigation measures benefit operations on the work zone corridor?

Some example **data analysis and monitoring questions** include:

- What are the travel times and speeds through the work zone?

- How do travel times and speeds compare to pre work zone conditions?
- How much diversion has taken place compared to pre-work zone conditions?

Depending on the answers to these and other questions presented later, the document provides guidance and recommendations for the type of modeling tools and monitoring approaches for work zones in North Carolina.

3 Developing a Work Zone Modeling Plan

3.1 Overview and Tool Selection

In developing a work zone operational modeling plan, the analyst has access to various levels of analysis tools. Each level differs in functionality, resource needs, and types of output it can provide, and may further involve multiple commercial vendor options; each with differences in interface and functionality. While this guide cannot provide a comprehensive overview of all commercial tools that may be applicable to work zone analysis, it provides broad categories of tools, and discusses their purpose, functionality, and recommendation for application for work zones in North Carolina.

In selecting an analysis tool or level of analysis, one must consider that all models have uncertainty in their predictions. Modeling tools are intended to estimate the operational performance of different work zone configurations, but generally do not provide performance metrics on the safety of the work zone, economic impacts, and other effects that should be considered in a work zone evaluation. As such, this document provides guidance for selecting adequate levels of operational modeling, but all decisions in the work zone modeling plan should be evaluated carefully based on engineering judgment, and under consideration of the available staff resources, funds, and time to conduct the analysis.

The FHWA *Traffic Analysis Toolbox* (1, 2) provides a national resource with guidance for the use of different traffic analysis tools, including specific guidance for work zone analysis. In particular, the FHWA Toolbox documents distinguishes between seven analysis tool categories:

1. Sketch-Planning Tool
2. Travel Demand Model
3. Analytical/Deterministic Tool (HCM-Based)
4. Traffic Optimization Tool
5. Macroscopic Simulation
6. Mesoscopic Simulation
7. Microscopic Simulation.

A summary of tools with most direct application to work zone operational analysis are introduced below.

Sketch-planning tools are planning-level tools that provide high-level estimates of performance without detailed computations. The Highway Capacity Manual (HCM) for example offers *Generalized Daily Service Volume Tables*, which can be used for a quick assessment of the expected operations of a facility.

Appendix A of this document presents planning-level charts for work zone analysis based on the HCM methods, and calibrated for daily volume profiles on freeways in North Carolina. These types of tools may also provide a useful benchmark when considering the results of more complex modeling tools.

A **Travel Demand Model (TDM)** is often developed for a metropolitan areas and it can be adapted for a network level work zone analysis. The analyst must provide additional inputs to the model in order to estimate potential diversion due to work zone. The work zone effects can be estimated through the four step travel demand forecasting process in order to get a rough estimation of diversion. However, TDMs will not include detailed queuing effects or corridor-level operations, because the level of analysis is too broad. Appendix B of this document presents an example of TDM application for work zone analysis for the Fortify work zone in Raleigh, NC based on the Triangle Regional Model.

A **deterministic analysis tool** is based on equations that have been derived and calibrated from theory and field observations. The Highway Capacity Manual (HCM) is the primary resource for deterministic equations in the area of traffic operations in the US. Analytical or equation-based tools usually require less computing resources and will arrive at a unique answer from a given set of inputs. Common drawbacks of these tools are that they are less adaptable to unique geometric configurations and travel patterns, but advantages lie in their efficient application, and consistency in inputs and outputs. Example deterministic tools for work zone analysis are QUEWZ, QUICKZONE, HCS, and FREEVAL. Appendix C of this document presents a high level overview of the FREEVAL-WZ tool, and its capabilities for work zone analysis customized for North Carolina (5).

In addition to deterministic analysis tools, **traffic optimization tools** such as Synchro and Vistro are available for use in signalized arterial work zone projects. Currently there are no default work zone impacts incorporated in these tools, but there are opportunities to adjust the saturation flow rate and other inputs to account for work zone effects. Guidance for these adjustments is available in the forthcoming HCM 6th Edition, based on national research (3, 4). These tools are generally less applicable to freeway facilities but optimization is key for any work zones on arterial streets.

A **simulation-based** tool does not rely on deterministic equations, but rather uses algorithms to predict the movements of individual vehicles through the transportation system. These algorithms are stochastic in nature and multiple iterations of the simulation will all result in slightly different results. The solution of a simulation analysis is reported as an average Measure of Effectiveness (MOE) from multiple runs, along with its standard deviation. Simulation tools for work zone analysis can further be divided into microscopic and mesoscopic models (a third category, macroscopic simulation, does not have application here).

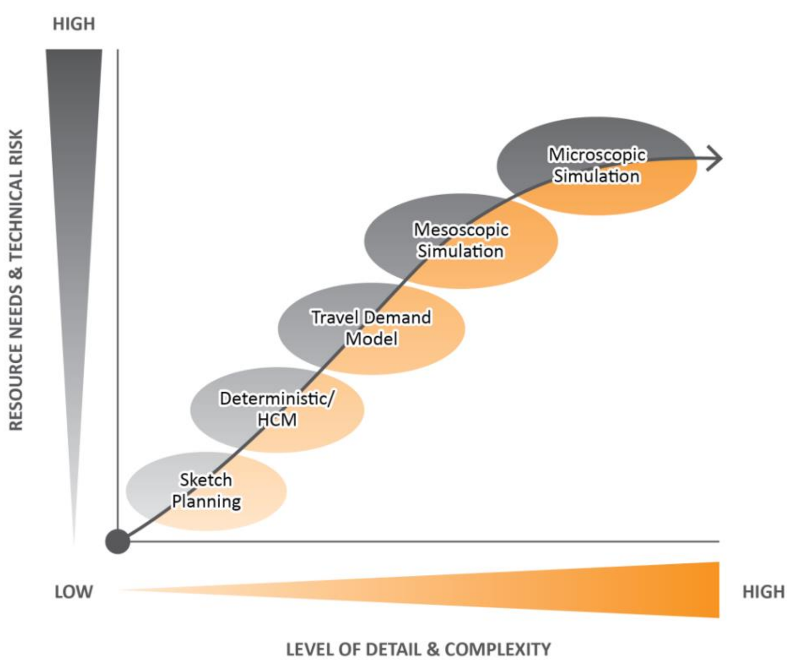
In **microscopic simulation**, individual vehicles are modeled through algorithms such as car-following, lane-changing, and gap-acceptance allowing for a high degree of analytical detail, while requiring more input data. Microsimulation algorithms can be calibrated to replicate the observed work zone performance, and guidance is available through federal research (4). Appendix D presents a high level overview of the VISSIM microscopic simulation tool for work zone analysis.

In **mesoscopic simulation**, individual vehicle movements on road links are modeled through link-based speed-flow-density relationships (vehicle speed is updated based on the traffic conditions surrounding the vehicle on a linlk). Mesoscopic tools use macroscopic speed-flow-density relationships to predict vehicle movements, and as such can be calibrated from work-zone specific speed-flow models as those contained in the HCM 6th Edition based on federal research (3, 4). Appendix E presents a high level overview of the mesoscopic simulation tool for work zone analysis.

Mesoscopic models require less vehicle-specific input data than microsimulation and the base algorithms are less computing intensive. This allows the mesoscopic model to be more quickly adapted to larger networks and to incorporate additional traffic assignment algorithms modeling traffic diversion in response to congestion or traveler information. While microsimulation allows for a basic representation of this sort of driver behavior, the mesoscopic diversion algorithms are generally more sophisticated in that respect. Example microscopic simulation tools include CORSIM, VISSIM, AIMSUN, TRANSMODELER, and PARAMICS, and example mesoscopic tools include DTA-Lite, Dynus-T, and Dynasmart-P.

In selecting different analysis tools, there is oftentimes a tradeoff between the level of detail provided by a model, and the associated resource needs to apply it. Simple sketch-planning tools can be applied with a minimum amount of resources, but are limited in their ability to reflect complex work zone geometries or produce advanced performance measures. More complex tools are required in order to model complex work zone geometries and operational strategies, as well as investigating network-wide effects. But increasing complexity is typically associated with increased resource needs, as well as increasing technical risk (due to need for more calibration, fewer available defaults, and more room for user error). This relationship is illustrated in Exhibit IV- 4.

Exhibit IV- 4: Work Zone Modeling Approaches



3.2 Key Questions to Determine Modeling Needs

The work zone modeling plan is driven by key questions the analyst is trying to answer in the evaluation of a work zone. This section introduces these basic questions, which are later linked to the various types and levels of analysis tools.

3.2.1 What times of day are lane closures permissible?

Lane closures are oftentimes the most disruptive periods during a construction project, and the question of when lanes can be closed has critical impacts on the contractor schedule, as well as impacts to the traveling public.

3.2.2 How long are the peak and off-peak queues expected to be?

Queue length is a key work zone performance measure and of key interest to the agency, as well as the traveling public. Predicting queue lengths, and comparing results for different scenarios can help with construction staging. A significant consideration for modeling queue lengths is the point at which merges occur, if a merge is located at the bottleneck or within the queued region. Many microsimulation tools may assume that the merging lane is fully utilized until the lane drop, which may underestimate the actual queue length. Model parameters may be adjusted according to engineering judgment to reflect local driving behavior.

3.2.3 What are the expected speeds and travel times through the work zone?

Speed and travel times are related performance measures that directly tie to the user experience of traveling through a work zone. Similar to queue lengths, these measures of effectiveness can provide key insights and comparison between scenarios.

3.2.4 What level of diversion is needed to keep operations at pre-work zone levels (or within XX%)?

Since work zones affect the capacity of a roadway, or the *supply side,* the question often comes up how much traffic *demand* would have to be reduced to achieve acceptable performance? Estimating the percent diversion needed to keep operations at pre-work zone levels (or alternatively within some percentage of pre-work zone conditions) can provide key insights into diversion targets and the associate need for and magnitude of public outreach campaigns.

3.2.5 What are the operational impacts of specific interchange configurations and modifications within the work zone

Some freeway work zones may involve changes to a specific interchange, including reconfiguration of access points, closure of acceleration or deceleration lanes, or other modifications.

This question involves the study of the operational effects of these modifications on freeway (and/or arterial) operations.

3.2.6 What are the potential effects of off-ramp spillback onto the freeway mainline?

For some work zones, the interaction between freeway and arterial streets are of key interest. Diversion may result in additional demand on specific off-ramps, which in turn result in spillback onto the freeway mainline. A work zone analysis may be interested in evaluating these interaction and queue spillback effects.

3.2.7 How much diversion do we expect to take place?

While the prior question conducted simple sensitivity analyses of different diversion scenarios, this question asks more specifically how much traffic will actually divert onto alternate routes in the transportation network.

3.2.8 What is the APPROPRIATE performance measure of work zone segment with non-standard geometry or work zone strategy?

Most analysis tools are not flexible enough to model very rare geometries or work zone strategies. In the case of microscopic modeling, the analyst has enough flexibility to incorporate these conditions and impacts on the simulated driving behavior.

3.2.9 How can mitigation measures benefit operations on the work zone corridor?

Knowing that work zones are expected to impact performance, it may be of interest to evaluate various work zone ITS or active travel and demand management (ATDM) strategies on the work zone corridor with the aim of improving operations.

3.2.10 How much diversion onto a parallel route do we expect to take place?

An analyst may be interested in estimating the level of diversion onto a specified parallel route, or a limited number of alternate routes.

3.2.11 What alternate routes in the Network are going to be most impacted?

Diversion away from a work zone is likely to have impact on the adjacent roadway network, and it is often of interest which routes are impacted most, and at what magnitude.

3.2.12 How can mitigation measures benefit operations on diversion routes?

If diversion is expected to take place and impact alternate route performance, it may be of interest to evaluate strategies and ITS solutions for these alternate routes.

3.3 Levels of Work Zone Modeling

Five levels of work zone modeling are defined below. The levels range from very simple, sketch-planning level analysis tools all the way to complex network-wide simulation models. The five levels are associated with an increasing level of resource needs, as well as technical risks as was introduced in Exhibit IV- 5. In general, an analyst should strive to apply the simplest analysis level that is able to address all modeling questions of interest.

Exhibit IV- 5: Overview of Modeling Levels of Analysis

Modeling Level 1: Simple Impact Assessment
- Sketch-Planning Analysis Tools
- Service Volume Tables and PLanning Charts in Appendix A

Modeling Level 2: Planning-Level Corridor Performance
- Deterministic/Analytical "Pipe" Tools
- FREEVAL-WZ, Synchro/Vistro and ARTVAL-WZ NCDOT Tools

Modeling Level 3: Detailed Corridor Performance
- Microscopic Simulation
- Evaluation of special geometries and ramp terminals

Modeling Level 4: High Level Network Assessment
- Travel Demand Model and Macroscopic Simulation
- Only models overal traffic stream without queueing

Modeling Level 5: Detailed Network Assessment
- Mesoscopic Simulation
- Evaluation of network-wide diversion and mulitple alternate routes

The next section relates the key modeling scoping questions to these five levels of analysis to guide analysts in which level of analysis may be most appropriate for the specific work zone project under study.

3.4 Selecting Work Zone Modeling Level

Exhibit IV-6 provides a linkage between the key work zone modeling scope questions and the five levels of analysis introduced above. Several questions can be answered by the simplest analysis level, while others require more complex and comprehensive modeling approaches. The analyst should strive to select the simplest level of modeling that satisfies all modeling questions identified.

Exhibit IV- 6 : Linking Work Zone Modeling Levels to Key Questions

Modeling Analysis Questions	M. Level 1	M. Level 2	M. Level 3	M. Level 4	M. Level 5
What times of day are lane closures permissible?	√				
How long are the peak and off-peak queues expected to be?		√	√		
What are the expected speeds and travel times through the work zone?		√	√		
What level of diversion is needed to keep operations at pre-work zone levels (or within XX %)?		√			
What are the operational impacts of specific interchange configurations and modifications within the work zone			√		
What are the potential effects of off-ramp spillback onto the freeway mainline?			√		
What is the performance measure of work zone segment with non-standard geometry or work zone strategy?			√		
How can mitigation measures benefit operations on the work zone corridor?		√	√	√	√
How much diversion onto a parallel alternate route do we expect to take place?				√	√
What alternate routes in the network are going to be most impacted?					√
How can mitigation measures benefit operations on the diversion routes?					√

Exhibit IV- 6 illustrates that while some questions can be answered with a level 1 or level 2 analysis, others require more advanced modeling approaches. The analyst should carefully weigh the importance of each question, especially if it pushes the analysis from one level to the next. As mentioned above, it is expected that each higher level of analysis will be associated with greater resource needs, more analysis time, and a greater level of technical risk. So in general, simpler tools and lower levels of modeling are preferred, if they can give NCDOT the same type of answer, but at reduced risk and resource needs.

3.5 Data Needs of Modeling Plan

Typical data needs for work zone modeling highly depend on the type of analysis tool used. Planning level tools may only need hourly or daily demands, while microscopic tools need time-of-day demands for all movements throughout the study period. Regardless of the tool, the network geometry and any closures need to be included. Some tools may have default effects for the impacts of various closures while others require extra inputs or calibration to model different closure types. Exhibit IV- 7 summarizes data requirements for the calibration of each modeling level.

Exhibit IV- 7: Level and Details of Data Requirements for Different Modeling Level

Modeling Level	Level of Data Requirement	Details of Data Requirements
1: Simple Impact Assessment	Low	Hourly or daily demand data (AADT) from point sensors; Daily Volume Profile
2: Planning-Level Corridor Performance	Medium	Basic Freeway Geometry characteristics; Daily AADT values; Daily Volume Profile
3: Detailed Corridor Performance	High	Detailed Geometry Information (CAD files etc.); Detailed Demand Information (traffic volumes, fleet, etc.); Traffic Control Information (ramp metering, intersection control, etc.); Field observations for model calibration (Volume Sensor data); Driver Routing (Traveler Information, etc.)
4: High Level Network Assessment	Medium	Detailed Geometry (CAD files); Static one hour peak demand information (Volume Sensor data) ; Field observations for model calibration (Sensor data)
5: Detailed Network Assessment	High	Regional Travel Demand Model (CAD files); Time dependent demand information (sensor counts); Field observations for model calibration (RTMS sensors – volume and speed data); Traffic Control Information (ramp metering, intersection control, etc.); Driver Routing (Traveler Information, etc.)

3.6 Estimated Level of Effort for Modeling Plans

There are many other factors that should be considered when deciding on a modeling plan for a particular work zone. This includes the level of modeling expertise required, cost, etc. Exhibit IV- 8 summarizes the various levels of effort needed for the different levels of modeling.

Exhibit IV- 8: Level of Detail, Data Requirements, Level of Effort, and Modeling Scope for Different Modeling Levels

Modeling Level	Modeling Level of Detail	Input Data Requirements	Level of Effort Needed	Modeling Scope (Corridor vs Network)
1: Simple Impact Assessment	Low	Low	< 1 day	Segment
2: Planning-Level Corridor Performance	Low	Low-Medium	2-3 days	Corridor
3: Detailed Corridor Performance	High	High	2-3 weeks	Corridor
4: High Level Network Assessment	Medium	Medium-High	1-2 weeks	Network
5: Detailed Network Assessment	High	Very High	> 1 month	Network

The level of detail for the five modeling levels largely translates into the data requirements to conduct the analysis. Also, higher level of detail and complexity generally translates into a higher level of effort. An increasing level of effort to conduct an analysis should be carefully evaluated in light of the following:

- Increasing cost to perform the analysis, due to increasing labor hours or contractor time for more complex analyses.
- Increasing turnaround time to complete an analysis, which may interfere with letting schedules and other project timelines.
- Increasing time for revisions to model or iterations in the analysis, which again translate into cost and turnaround time.
- Increasing technical risk, due to potential need for more calibration, fewer available defaults, and more room for user error.

It is further noted that in considering the time to budget for analysis, the estimates in the Exhibit IV- 8 are high-level estimates, and may not include time for documenting the results of the analysis and assembling a detailed assessment report. Of course, actual times will vary across work zones with different scopes and geographic extent, so the Exhibit IV- 8 is merely intended to provide high-level guidance.

4 Developing a Work Zone Monitoring Plan

4.1 Overview, Data Sources, and Performance Measures

In developing a work zone operational monitoring plan, the analyst is faced with various potential levels of monitoring and a variety of available data sources. Each level differs in resource needs, and in the types of metrics it can produce. While this guide cannot provide a comprehensive overview of all data sources that may be applicable to work zone monitoring, it does recommend broad categories of monitoring approaches, and discusses their purpose, functionality, and recommendation for application for work zones in North Carolina.

The work zone monitoring approaches discussed in this guide are focused on the operational performance of different work zone configurations. Those do not generally provide performance metrics on safety of the work zone, economic impacts, and other effects that should be considered in a work zone performance evaluation. As such, this document provides guidance for selecting appropriate levels of operational monitoring, but all decisions in the work zone monitoring plan should be evaluated carefully based on engineering judgment, and under consideration of the available staff resources, funds, and time to conduct the analysis.

4.1.1 Data Sources

NCDOT has access to a wide variety of potential data sources from both permanent and temporary data collection systems. Network geometry and AADT data are available, and there are permanent count stations located throughout the state on a variety of facilities. In addition, approximately 50 permanent side-fire microwave radar sensors are located on freeways around the Triangle that provide speed and volume data. Another permanent data source is the probe-based link speeds provided by HERE, which covers all freeways and most highways in North Carolina. When coverage of the permanent systems is not adequate for a work zone analysis, there are also many temporary data collection systems available. Point-based speeds and volumes can be collected using pneumatic tube counters or temporary side-fire radar. Additionally, Bluetooth readers can be used to collect corridor travel times in addition to more expensive floating car runs.

Exhibit IV- 9 below shows a brief descriptions of typical traffic data sources used in North Carolina in 2016. In future applications of this guidance, many new technologies and data sources may be available and used as appropriate. Specifically, as probe-based data become more prevalent, they may provide vastly enhanced data capabilities, at a marginal increase in resource needs to acquire and use them.

Exhibit IV- 9: Summary of Data Sources and Associated Performance Measures

Data Source	Manufacturer or Provider	Point or Link Based	Queue Lengths	Speed	Volume	Occupancy	Travel Time
Radar	Wavetronix/RTMS	Point		✓	✓	✓	
Loop/WIM		Point			✓	✓	
Pneumatic Tube		Point			✓		
Floating Car	(any GPS unit)	Link	✓	✓			✓
Probe Network	HERE/INRIX	Link	✓	✓			✓
Bluetooth	BlueMAC/TRAFFAX	Link		✓			✓
Video (single)	Autoscope	Point		✓	✓		
Video (ALPR*)		Link	✓	✓			✓

**Automated License Plate Reader*

4.1.2 Establishing MOEs

Various measures of effectiveness (MOEs) can help quantify mobility performance and can be utilized to make decisions about the work zone and future policies. The ability to report these MOEs depends on available data and analysis tools. FHWA has compiled a list of key measures to assess work zone performance. NCDOT may identify other key performance measures depending on its available resources. However, a work zone will have the most significant impacts in these areas. These MOEs and brief descriptions are shown in Exhibit IV- 10.

Exhibit IV- 10: Key work zone measures of effectiveness

Measure	Description
Travel Time	• Used to evaluate whether the agency is meeting goals to maintain an average travel time • Can be reported directly to road users
Delay	• Used to evaluate whether the agency is meeting goals in minimizing delay • May be measured as maximum or average
Queue Length	• Used to evaluate lane closure scenarios and locations • Used to evaluate reduction in capacity caused by queueing
Volume	• Used to evaluate the capacity of the work zone • Used to evaluate throughput
User Cost	• Used to evaluate the loss of productivity due to the work zone • May best be considered during the design phase
Incidents	• Used to evaluate the safety of the work zone • Used to identify points of high incident prevalence

4.2 Key Questions to Determine Data and Monitoring Needs

The work zone monitoring plan is driven by key questions regarding the evaluation of a work zone. This section introduces these basic questions, which are later linked to the various types and levels of analysis tools.

The work zone monitoring questions depend on the goals and objectives of the agency. Specifically, NCDOT has established a Work Zone Safety and Mobility Policy that outlines several goals, objectives, and strategies for work zones. Identification of questions should go hand in hand with NCDOT's vision and intended direction of policies. In addition, the answers to the questions can allow NCDOT to effectively direct resources to the most impactful strategies to fulfill their goals. For example, Goal D of the Work Zone Safety and Mobility Policy is "to consider mobility and access in work zones to minimize impact to users". One of the objectives in fulfilling this goal is "to minimize delays and reduce congestion in work zones". To meet this objective, understanding of how the work zone contributes to delay and congestion is required. The following data analysis questions are intended to help scope the work zone monitoring plan

4.2.1 What are the queue lengths upstream of the work zones?

Queue lengths are oftentimes of interest for construction projects, and can be inferred from probe-based data (only up to the level of a single link or TMC), from floating car runs (limited by the sample size of runs), or from video observations (subject to the video angle and camera coverage).

4.2.2 What are the travel times and speeds through the work zone?

Travel times and speeds are key performance measures for work zone performance assessment. These measures can readily be obtained from probe-based data sources, Bluetooth devices, or point side-fire radar sensors, however the various technologies differ in the level of resolution of the speed and travel time estimates, as follows:

- **Side-Fire Radar Sensors** provide speed data at point locations only, but can be used to approximate travel times if multiple sensors are available in close proximity.
- **Bluetooth Sensors** provide end-to-end travel times relative to the location of the deployed devices. With multiple devices, additional detail can be obtained.
- **Probe-based data** provides travel times and speeds at the TMC-level, which is typically for a segment from one interchange ramp gore to the next (for freeways), or from one intersection to the next (for major arterials)

4.2.3 How do travel times and speeds compare to pre work zone conditions?

A before and after assessment of travel times and speeds is possible from the same data sources identified above, with the caveat that sensors need to have been installed in the before period (probe-based data are generally available in archived format).

4.2.4 What are the travel times and speeds on major alternate routes?

Similarly, sensors or probe-based data can be used to obtain travel time and speeds on alternate routes.

4.2.5 How have traffic demands in work zone shifted over time?

Many work zones result in temporal changes in traffic patterns, which is also referred to as “peak spreading”. Traffic volume sensors can help answer the question how much earlier commuters leave home to get through the work zone, or how much later they decide to stay at work to avoid congestion.

4.2.6 How much diversion has taken place compared to pre-work zone conditions?

Traffic volumes are of principal interest to work zone monitoring, as they closely tie to diversion estimates. Volumes are most readily obtained from a point (side-fire radar) sensor, but can also be obtained from video or other sensing technologies. With the availability of archival data, volumes with and without work zone conditions can be compared to estimate diversion percentages.

4.2.7 What are the driver behavioral patterns in key bottleneck sections?

Video observations at the work zone may provide insight into specific behavioral patterns that may contribute to congestion effects, or safety problems. While sensors and probe data are useful to quantify performance, sometimes real-time or archived video feeds are highly valuable to identify problem areas and identify solutions.

4.2.8 What real-time events contribute to work zone congestion (e.g. incidents)?

Video cameras in the work zone can also help flag real-time events, such as broken down vehicles, crashes, and other incidents that may impact work zone operations. A real-time look at work activity and intensity can also be valuable in understanding traffic patterns.

4.2.9 At what point did traffic divert from the work zone corridor?

With multiple sensors upstream of the work zone, the agency may be able to determine the time periods when the traffic diverted from the mainline corridor is impacted by the work zone. This can provide insight on potential diversion routes used.

4.2.10 How did traffic on key alternate route(s) increase/change due to work zone?

If a work zone results in diversion to one or more key alternate routes, the use of additional sensors on those routes can help provide information about percentage of traffic increases, as well as temporal changes in travel patterns on the alternate routes.

4.2.11 What are the origin-destination travel patterns of traffic traveling through the work zone?

Origin-destination travel patterns can be obtained by deploying multiple Bluetooth readers in the work zone, and the surrounding network.

4.2.12 Where in the network did THE diverted traffic from the work zone end up?

Availability of sensors on alternate routes across the network can provide insight on where traffic may have diverted to. Bluetooth deployment can be used to provide additional information on origin-destination patterns and shifts to alternate routes.

The questions to answer as a result of monitoring the work zone should be related to the goals and objectives established by NCDOT. These questions may also be used to improve current policy, as well as revise the strategies that are used to meet objectives.

4.3 Levels of Work Zone Data and Monitoring

Similar to the work zone modeling plan, Exhibit IV- 11 below groups the various performance measures into five level of analysis with increasing level of complexity.

Exhibit IV- 11: Overview of Data Levels for Work Zone Analysis

Data Level 1: Simple Impact Assessment

- Speed and travel times from probes
- Queue lengths estimated from probes

Data Level 2: Corridor Performance

- Speed and travel times from probes
- Queue lengths estimated from probes
- Mainline volume point sensors

Data Level 3: Corridor Performance plus Real-Time

- Speed and travel times from probes
- Queue lengths estimated from probes
- Mainline volume point sensors
- Streaming video along work zone corridor

Data Level 4: Route Diversion Estimates

- Speed, travel times, and queues from probes
- Mainline volume point sensors on work zone and alternate route
- Streaming video along work zone corridor and alternate route
- Bluetooth readers on work zone and alternate route for diversion estimation

Data Level 5: Network Assessment

- Speed, travel times, and queues from probes
- Mainline volume point sensors on work zone, alternate route, and key points in network
- Streaming video along work zone corridor, alternate route, and key points in network
- Bluetooth readers in work zone, alternate, and key points in network for O/D estimation

4.4 Selecting Work Zone Monitoring Level

Exhibit IV- 12 provides a linkage between the key work zone monitoring questions and the five data levels introduced above. Several questions can be answered by the simplest data level, while others require more complex and comprehensive monitoring approaches. The analyst should strive to select the simplest level of monitoring that satisfies all data questions identified.

Exhibit IV- 12: Linking Work Zone Monitoring Levels to Key Questions

Monitoring Analysis Questions	D. Level 1	D. Level 2	D. Level 3	D. Level 4	D. Level 5
What are the queue lengths upstream of the work zones?	√	√	√	√	√
What are the travel times and speeds through the work zone?	√	√	√	√	√
How do travel times and speeds compare to pre work zone conditions?	√	√	√	√	√
What are the travel times and speeds on alternate major routes?	√	√	√	√	√
How have traffic demands in work zone shifted over time?		√	√	√	√
How much diversion has taken place compared to pre-work zone conditions?		√	√	√	√
What are the driver behavioral patterns in key bottleneck sections?			√	√	√
What real-time events contribute to work zone congestion (e.g. incidents)?			√	√	√
At what point did traffic divert from the work zone corridor?				√	√
How did traffic on key alternate route(s) increase/change due to work zone?				√	√
What are the origin-destination travel patterns of traffic traveling through the work zone					√
Where in the network did the diverted traffic from the work zone end up?					√

The exhibit above shows that different monitoring questions result in very different levels of performance monitoring. The five monitoring levels are designed to be cumulative, in that each successive level adds additional functionality. It is generally desirable and advisable to select the lowest feasible monitoring level that satisfies analysis needs in an effort to minimize resource needs.

Any decision to monitor work zone operations should serve a clear purpose and need, which should be established prior to engaging in any monitoring or data collection activity. Considerations for establishing the purpose and need include:

- What is the ability to mitigate concerns identified in monitoring? Any data collection should be tied to action items in terms of strategies or mitigation measures to improve work zone operations.
- Is there a willingness to mitigate operational concerns? For some work zones, mitigation of operational challenges may be technically possible, but infeasible in a time and resource-constraint environment.

- How can the operational monitoring data be linked to other sources? At least some congestion in the work zones is likely to come from incident and weather impacts. Isolating these non-recurring sources of congestion from the effect of the work zone can be important to adequately quantify performance and identify the correct strategy and mitigation response.
- Is before data available for the work zone corridor to establish a baseline of performance, and quantify the incremental delay impacts of the work zone? Having a baseline for operational performance is critical to capture the true effects of the work zone, as well as user costs.

The reporting process for the answers to identified questions and measures of effectiveness will depend on the policies of the agency. NCDOT may seek to inform the public and key stakeholders as often as possible during monitoring activities. In that sense, the questions above are on the one hand intended for internal performance tracking of the work zone and identification of mitigation measures, but may also be of interest for communicating work zone travel times and congestion patterns to the traveling public, as well as other stakeholders of the work zone (e.g. surrounding municipalities, the public school system, major employers in the region, special event venues, emergency responders, etc.).

Travel time is already reported continuously by NCDOT directly to road users on various routes. This is a well-established practice by many agencies and should continue. The delay in travel time compared to non-work zone conditions should also be reported at each change in the work zone configuration (or more often) so that users know what to expect. Incidents are also reported to users when they occur, but more information about detours and alternative routes for severe incidents may be reported more efficiently. Road users should be informed of expected impact on their productivity and safety before the work zone is launched. Volume and queue length may not be of as much interest to users, but NCDOT officials may wish to record and report these figures for monitoring contractor performance.

Work zone monitoring data requirements are entirely dependent on the MOEs and the reporting plan established in the previous section. These may range from reporting a change in travel time along the work zone, which may require only probe network data to detailed diversion path analysis which would require license plate recognition or an extensive Bluetooth monitoring system. Once a monitoring plan is developed, it is also important to identify if the technology is sensitive to the expected changes.

4.5 Estimated Level of Effort for Monitoring Plans

In addition to identifying the monitoring level needed for a particular project, the frequency of reports must be established in order to estimate the cost of monitoring. Exhibit IV- 13 summarizes the various levels of effort needed to create a standard report for a typical work zone, as well as the incremental additional equipment needed in order to increase monitoring from the previous level. In considering the time to budget for monitoring, the estimates below are preliminary and include data collection by an analyst (but not travel to site). Note that estimates will vary across work zones with different scopes. It is also important to note that reports on a smaller scope (i.e. Corridor performance report [level 2] when data are collected network wide [level 5]) may be completed at a higher frequency than the largest scoped report.

Exhibit IV- 13: Data Requirements and Level of Effort for Different Monitoring Levels

Monitoring Level	Potential Additional Equipment Needed	Level of Effort Needed to Report
1: Simple Impact Assessment	None (Probe Data Only)	< 1 day
2: Corridor Performance	All Level 1 Equipment, plus Mainline Point Sensors (Radar, Loop)	1-2 days
3: Corridor Performance plus Real-Time	All Level 2 Equipment, plus Video Cameras	2 days + Camera Monitoring
4: Route Diversion Estimates	All Level 3 Equipment, plus Point Sensors on Alt. Route, Bluetooth	3-4 days + Camera Monitoring
5: Network Assessment	All Level 4 Equipment, plus Network Point Sensors, Bluetooth	1-2 weeks + Camera Monitoring

5 Practical Recommendations for WZ Modeling/Monitoring

This section of the guidance document provides a set of recommendations to practitioners on modeling and monitoring work zones. Freeway work zones can span a wide range of construction activities. The spectrum of different work zone types will require different approaches for monitoring and modeling. Along with the type of work zone activity, the duration and proximity to large metropolitan areas will have an impact on the monitoring and modeling approaches selection. Therefore, the two major factor for determining a modeling and monitoring approach are 1) work zone type, and 2) proximity to a large metropolitan area.

The discussion below presents initial recommendations and guidance. Over time, it will be important to further refine this guidance and institutionalize the recommendations from this document into practice. This will require both internal structure and work flow for work zone analysis within NCDOT, as well as processes for integrating the work of consultants into the modeling and monitoring approaches. The approach should be incorporated into NCDOT's Traffic Engineering Policies, Practices, and Legal Authority (TEPPL) to provide clear and consistent guidance across divisions.

Any modeling and monitoring activity should start with the identification of a clear purpose and need. An analyst should identify the purpose of the modeling effort, why data are being collected, what the results will be used for, etc. Every work zone analysis and monitoring effort should add value to NCDOT and have a clear purpose. That purpose may be internally-driven, or may be linked to performance reporting and public engagement activities by the department.

5.1 Recommendations for Work Zone Modeling

Work zone modeling is needed to predict the operational impacts of lane closures, lane shifts, diversion impacts, etc. as part of one or more work zone staging scenarios. The various modeling packages described in earlier sections require different levels of data, effort and time for calibration and validation. The guidance process above is geared at using a series of key questions to help the analyst determine the appropriate level of modeling for a particular work zone. It is recommended that analysts follow the process above whenever feasible.

In an effort to tie the recommendations above to some typical work zone analysis scenarios, Exhibit IV- 14 presents a few common types of work zones and provides recommendation for the type of modeling that is suggested for those scenarios. It is emphasized that these are just examples, and that the more detailed, question-driven process above should be applied to the specific work zone in question.

One thing to stress in the interpretation of Exhibit IV- 14 is that modeling Level 1 is included for all work zones. The reasoning behind this is that the sketch-planning lookup charts are extremely easy and fast to apply, and therefore do not add significant time or burden to even higher-level analyses. Furthermore, the sketch-planning charts serve as a good benchmark against which other analyses can be compared. Clearly, more detailed analyses are needed and recommended for most of the work zone scenarios. But developing a general sense for lane closure schedules and expected impacts can be very useful for analysts, and the planning-level charts are geared at serving that purpose.

Exhibit IV- 14: Practical Recommendations for level of Modeling based on type and location of work zone

Work Zone Scenario	Recommended Level of Modeling*
Minor work zones that are of very short duration, up to a few hours hour, in off-peak periods and that are outside of major metropolitan areas	Level 1
Minor work zones that are of very short duration, up to a few hours hour, in off-peak periods and that are within a major metropolitan area	Level 1 and 2
Intermediate work that occupies a location for a few hours a day, including peak periods, for up to 3 days and is outside of major metropolitan areas	Level 1 and 2
Intermediate work that occupies a location for a few hours a day, including peak periods, for up to 3 days and is within a major metropolitan area	Level 1 and 2
Longer term work zones with multi-day lane closures on a freeway facility outside of major metropolitan areas	Level 1, 2 and 4
Reconstruction or extension of off-ramp lanes on a freeway	Level 1 and 3
Longer term work zones with multi-day lane closures on a freeway facility within a major metropolitan area	Level 1, 2 and 4
Major work zones that span over a large area in a metropolitan region that sees high daily travel and require longer time for completion	Level 1, 2, and either 4 or 5
Full Facility closure on a smaller stretch of road, requiring diversions and mandatory detours, for longer than 3 days	Level 1, 2, and either 4 or 5

**See Exhibit IV-7 for modeling level descriptions*

5.2 Recommendations for Work Zone Monitoring

Work zone monitoring plays a crucial role for NCDOT to observe traffic conditions while the work zone activity is in process. The work zone monitoring effort relies on empirical data that can be collected in a variety of ways, as was described in earlier sections. With access to more data sources, the work zone monitoring process can be conducted more precisely and comprehensively. However, for some work zone activities, access to multiple data sources may be limited, as can be the case for rural freeways. But even at sites with readily available data, there are cost and resource needs to extract data and conduct the analysis. As such, the work zone monitoring plan needs to be scaled appropriately to balance resources and expected return.

The question-driven process above is the preferred way to develop an adequately-scaled work zone monitoring plan. But, in an effort to tie the recommendations above to some typical work zone analysis scenarios, Exhibit IV- 15 presents a few common types of work zones and provides recommendation for the type of monitoring that is suggested for those scenarios. It is emphasized that these are just examples, and that the more detailed, question-driven process above should be applied to the specific work zone in question.

Exhibit IV- 15 recommends some level of monitoring for all scenarios, given that probe-based travel time data are readily available for all freeways and major arterials in North Carolina. The use of probe-based and real-time speed and travel time data can allow NCDOT to readily monitor any work zone in the state, while further saving time and resources for custom deployment of data collection. But even with probe data readily available, the analyst should start each analysis with identifying a clear purpose and need for the analyst, and lay out clear objectives and goals for engaging in the monitoring effort. Also, it is critical to have a good understand of "before" or non-work zone conditions for the facility under study. Archival probe data is typically available to establish a baseline of performance, against which the work zone impacts and associated user costs can be compared.

Exhibit IV- 15: Practical Recommendations for level of Monitoring based on type and location of work zone

Work Zone Scenario	Recommended Level of Monitoring *
Minor work zones that are of very short duration, up to a few hours hour, in off-peak periods and that are outside of major metropolitan areas	Level 1
Minor work zones that are of very short duration, up to a few hours hour, in off-peak periods and that are within a major metropolitan area	Level 1
Intermediate work that occupies a location for a few hours a day, including peak periods, for up to 3 days and is outside of major metropolitan areas	Level 1 or 2
Intermediate work that occupies a location for a few hours a day, including peak periods, for up to 3 days and is within a major metropolitan area	Level 2 or 3
Longer term work zones with multi-day lane closures on a freeway facility outside of major metropolitan areas	Level 2 or 3
Reconstruction or extension of off-ramp lanes on a freeway	Level 2 or 3
Longer term work zones with multi-day lane closures on a freeway facility within a major metropolitan area	Level 3, 4, or 5
Major work zones that span over a large area in a metropolitan region that sees high daily travel and require longer time for completion	Level 4 or 5
Full Facility closure on a smaller stretch of road, requiring diversions and mandatory detours, for longer than 3 days	Level 4 or 5

**See Exhibit IV-11 for Data Monitoring Levels*

6 References

1. Lin Zhang, Dorothy Morallos, Krista Jeannotte, Jennifer Strasser, *"Traffic Analysis Toolbox Volume XII: Work Zone Traffic Analysis – Applications and Decision Framework"*, April 2012
2. Matthew Hardy Karl Wunderlich, Ph.D, *"Traffic Analysis Tools Volume IX: Work Zone Modeling and Simulation—A Guide for Analysts"*, March 2009
3. Hajbabaie, Ali, Chunho Yeom, Nagui M. Rouphail, William Rasdorf, and Bastian J. Schroeder. *"Freeway Work Zone Free-Flow Speed Prediction from Multi-State Sensor Data."* In Transportation Research Board 94th Annual Meeting, no. 15-2004. 2015.
4. Yeom, Chunho, Ali Hajbabaie, Bastian J. Schroeder, Christopher Vaughan, Xingyu Xuan, and Nagui M. Rouphail. *"Innovative Work Zone Capacity Models from Nationwide Field and Archival Sources."* Transportation Research Record: Journal of the Transportation Research Board 2485 (2015): 51-60.
5. Aghdashi Behzad, Bastin Schroeder, Joseph L. Trask, Chunho Yeom, Nagui M. Rouphail, "Planning Level Extensions to NCDOT Freeway Analysis Tools", March 2015

Appendix IV - A: Sketch-Planning Approach to Work Zone Performance Assessment

This section presents a sketch-planning level approach to evaluate operations of a freeway work zone. The approach uses a series of simple charts that can be used as a quick look up to decide whether a particular lane closure scenario is feasible for a given freeway. The charts are presented for varying freeway cross-sections (two-lane, three-lane, four-lane), as well as for different underlying daily traffic volume patterns (urban AM, urban PM, and rural profiles). This appendix first presents the method used to develop these charts, then provides the planning-level charts themselves, and then gives an illustrative example for how to use the charts.

6.1 Methodology and Approach

The underlying goal for this planning-level methodology was to produce readily-usable work zone operations guidance, that is anchored in the Highway Capacity Manual, as well as sensitive to specific volume profiles observed on freeways in North Carolina.

According to the new work zone capacity method in the 6th Edition Highway Capacity Manual (developed through NCHRP 03-107), work zone segment capacities can be affected by a number of conditions like barrier type, area type, work zone speed limit, ramp density, lane closure severity, lateral clearance, and day vs. nighttime conditions. That was used in this section to quantify the effects different types of lane closures have on the capacity of a 4 lane, 3 lane or 2 lane urban and rural freeways during different times of the day. Our calculations for Urban AM Peak, Urban PM Peak and Rural freeways include the assumptions described in Exhibit IV - A 1 below.

Exhibit IV - A 1 Table of factors and assumptions in calculating segment capacity for Urban AM Peak, Urban PM peak and Rural freeways

Variable	Description	Urban PM	Urban AM	Rural
f_{br}	Barrier Type, o: concrete, 1: cone or plastic drum	1	1	1
f_a	Area type, 0: urban, 1: rural	0	0	1
f_{sr}	Ratio of non-work zone speed limit (urban: 65 mph, rural: 70 mph) to work zone speed limit (55 mph)	1.182	1.182	1.273
f_{nr}	Number of ramps within three miles upstream and downstream of the work zone area	6	6	6
f_s	Work Zone Speed Limit (mph)	55	55	55
f_{lat}	Lateral Distance	6	6	6
f_{dn}	Daylight or night, 0:day, 1: night	6 AM to 6 PM: 0, 7PM to 5 AM: 1	6 AM to 6 PM: 0, 7PM to 5 AM: 1	6 AM to 6 PM: 0, 7PM to 5 AM: 1
α	Queue discharge capacity reduction following breakdown (pc/h/l)	0.134	0.134	0.134
d	Directional demand factor	0.6	0.6	0.6

The steps for calculating and plotting these capacity reductions against time of day are listed below.

1. First, the Lane Closure Severity Index is calculated as follows:

$$LCSI = \frac{1}{OR \times N_o}$$

Where

LCSI = Lane Closure Severity Index,

OR = Open Ratio, the ratio of the number of open lanes during construction to the total number of lanes, and

N_O = Number of open lanes during construction.

2. The work zone queue discharge rate is calculated as

$$QDR_{wz} = 2{,}093 - 154 \times f_{LCSI} - 194 \times f_{Br} - 179 \times f_A + 9 \times f_{LAT} - 59 \times f_{DN}$$

Where

QDR_{wz} = average fifteen-minute queue discharge rate, and all other parameters are listed in Table A -1 above.

3. The pre – breakdown capacity is calculated as follows:

$$c_{WZ} = \frac{QDR_{WZ}}{100 - \alpha} \times 100$$

Where:

c_{wz} = capacity or pre-breakdown flow rate in pc/h/l, and

α = pre-breakdown capacity drop due to queuing conditions (Refer to Table A-1).

4. The pre- breakdown capacity is then converted into total directional demand under lane closure, depending on time of day factor (k) as follows:

$$AADT_{LC} = \frac{(c_{WZ} * 0.75)}{(k * N_o)} * 100 * d$$

Where:

$AADT_{LC}$ = Annual Average Daily Travel under Lane Closure

c_{wz}=capacity or pre-breakdown flow rate in pc/h/l,

N_o = Number of open lanes during construction

d = Directional Demand factor, and

k = Time of Day factor. It is a distribution, specific to the state of North Carolina and listed in Exhibit IV - A 2.

The time of day factor (k) was obtained from previously-completed research for NCDOT, which gathered volume data for all available freeways in North Carolina, and derived three default volume profiles" Urban-AM, Urban-PM, and Rural. For this project, the original data were used to estimate the 95th percentile volume split by hour of day, as opposed to the average profiles. The use of the 95th percentile provides a more conservative estimate, and means that the planning-level work zone lane closure guidance is adequate for 95% of freeways in NC. The resulting hourly factors are shown in Exhibit IV - A 2. Note that since 95th percentiles were used, the total of all entries in the table does not add up to 100% if aggregated over a day.

Exhibit IV - A 2 Distribution of Time of Day factor (k) for Urban AM Peak, Urban PM Peak and Rural freeways, specific to North Carolina

Time of Day	Urban AM Peak	Urban PM Peak	Rural
12:00 AM	1.37	1.21	2.15
1:00 AM	1.07	0.78	1.84
2:00 AM	0.96	0.69	1.70
3:00 AM	1.04	0.77	1.73
4:00 AM	1.46	1.59	2.01
5:00 AM	3.16	3.64	2.66
6:00 AM	6.40	5.82	3.66
7:00 AM	8.58	7.57	5.04
8:00 AM	8.49	7.39	5.48
9:00 AM	6.44	6.19	5.93
10:00 AM	6.25	6.24	6.67
11:00 AM	6.50	6.34	6.90
12:00 PM	6.55	6.44	6.68
1:00 PM	6.73	6.93	6.92
2:00 PM	7.18	7.59	7.33
3:00 PM	7.72	8.44	7.98
4:00 PM	7.95	10.59	8.40
5:00 PM	8.24	11.75	8.74
6:00 PM	6.40	8.29	6.36
7:00 PM	5.40	5.35	4.98
8:00 PM	4.34	4.10	4.31
9:00 PM	3.75	3.58	3.97
10:00 PM	2.95	2.71	3.62
11:00 PM	2.19	2.24	2.91

6.2 Planning-Level Work Zone Charts

The resulting planning-level work zone assessment charts are shown in Exhibit IV - A 3 through Exhibit IV - A 11. The charts show the effects of different types of lane closure for freeways with 4-lane, 3-lane and 2-lane cross-sections (per direction). Charts are provided for urban freeways (AM and PM peak time travel) and rural freeways. The charts plot time of day on the x-axis, and AADT on the y-axis. The resulting profile lines show when a specific lane closure scenario is feasible (below the line), and when the scenario is likely to result in queuing (above the line).

For each graph, various scenarios are shown, ranging from a shoulder closure to a multi-lane closure. Intuitively, it can be seen that the daily travel capacity is affected less by a shoulder closure than a lane closure. These graphs can be used for a quick analysis of a freeway facility to determine the number of lanes that may be closed during a certain time of day without reducing the segment capacity below a critical level.

For example, while analyzing a 4 lane urban freeway segment with an AADT of about 100,000 vehicles/day and a significant AM peak time travel, the graph in Exhibit IV - A 3 may be used to determine the number of lanes that can be closed for a certain work zone. It is evident that shoulder closure will have minimum to no impact on the capacity of this facility. A one lane closure is not recommended for this facility between the hours of 6:30AM and 8:30AM. A 2-lane closure is not recommended between the hours of 5:30AM and 9:30AM, as well as between 3:00PM and 6:00PM. A 3 lane closure for such a facility should only be considered for very short duration, during late night to early morning, between 10:00PM and 4:30AM. Not that these estimates were all rounded to the nearest 30 minutes (rounded to be conservative).

Exhibit IV - A 3 AADT under different types of lane closure on a 4 lane urban freeway facility during AM peak period

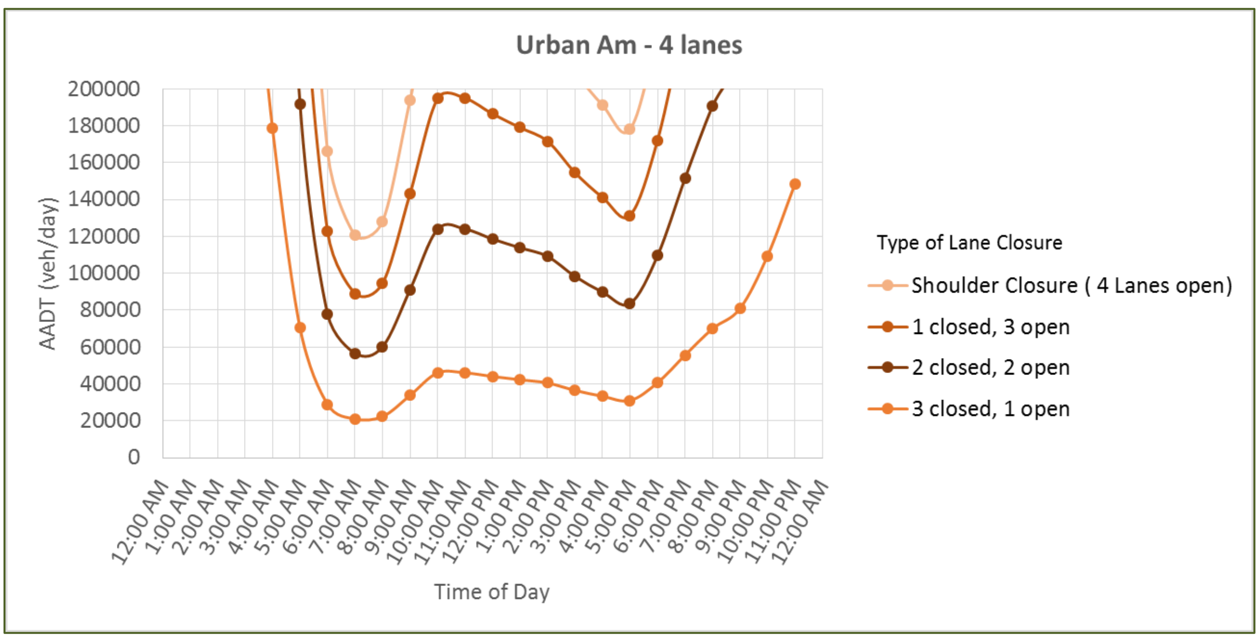


Exhibit IV - A 4 AADT under different types of lane closure on a 4 lane urban freeway facility during PM peak period

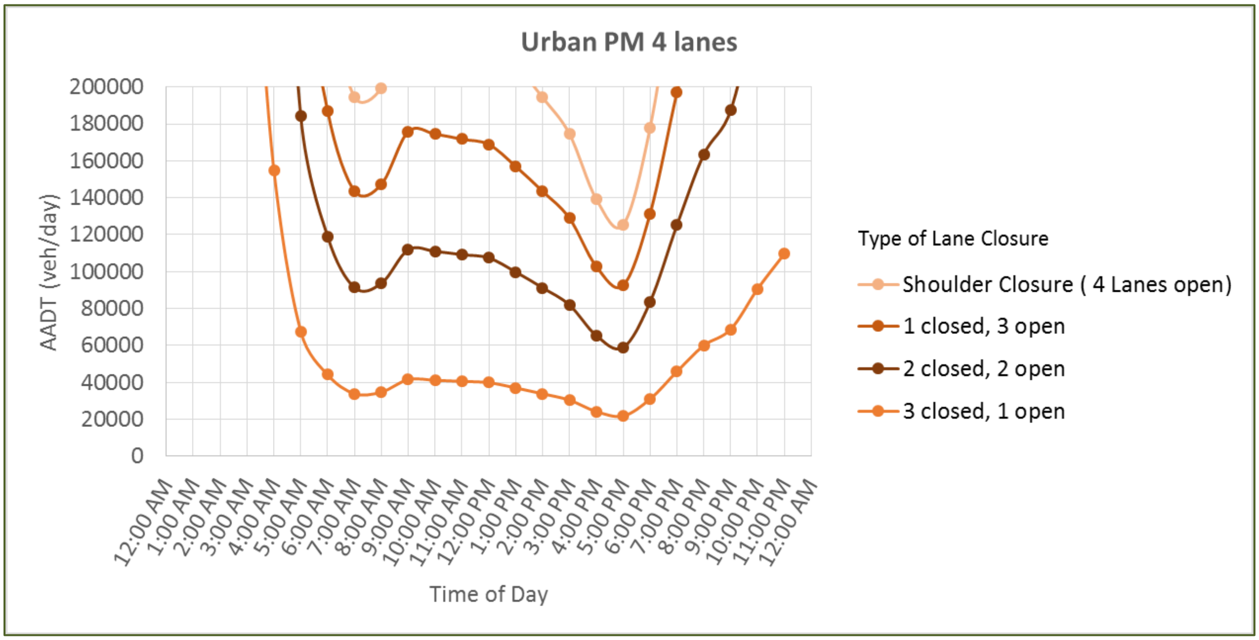


Exhibit IV - A 5 AADT under different types of lane closure on a 4 lane rural freeway facility

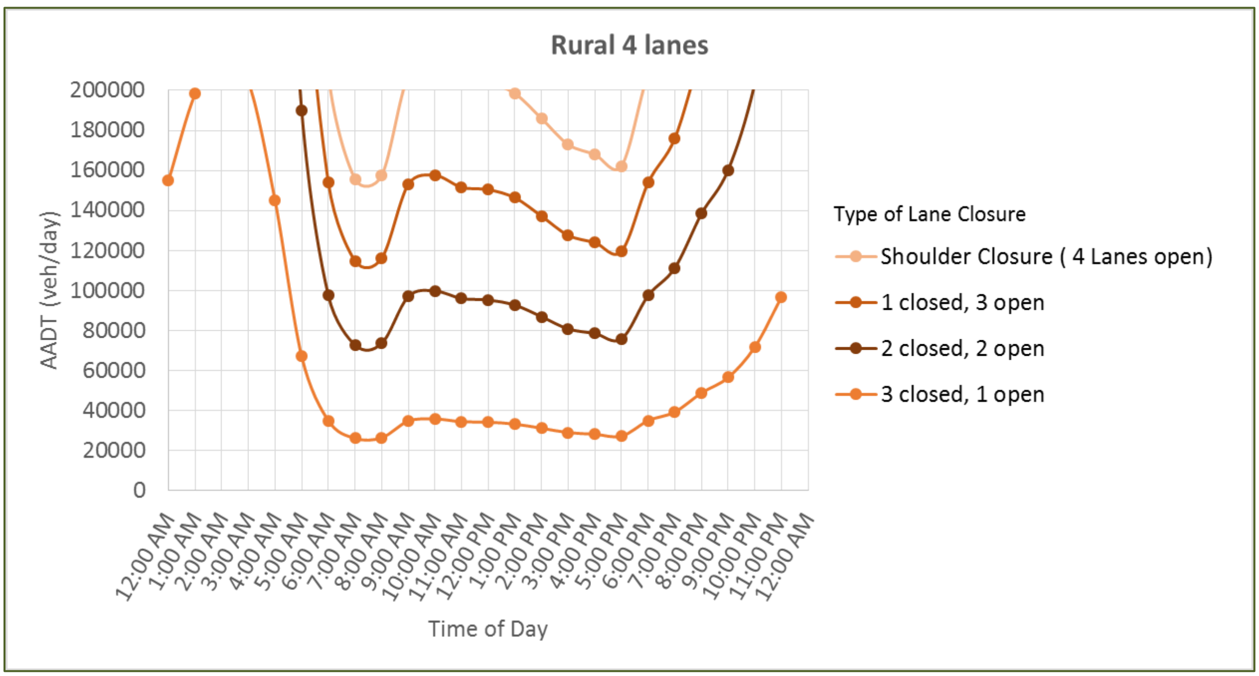


Exhibit IV - A 6 AADT under different types of lane closure on a 3 lane urban freeway facility during AM peak period

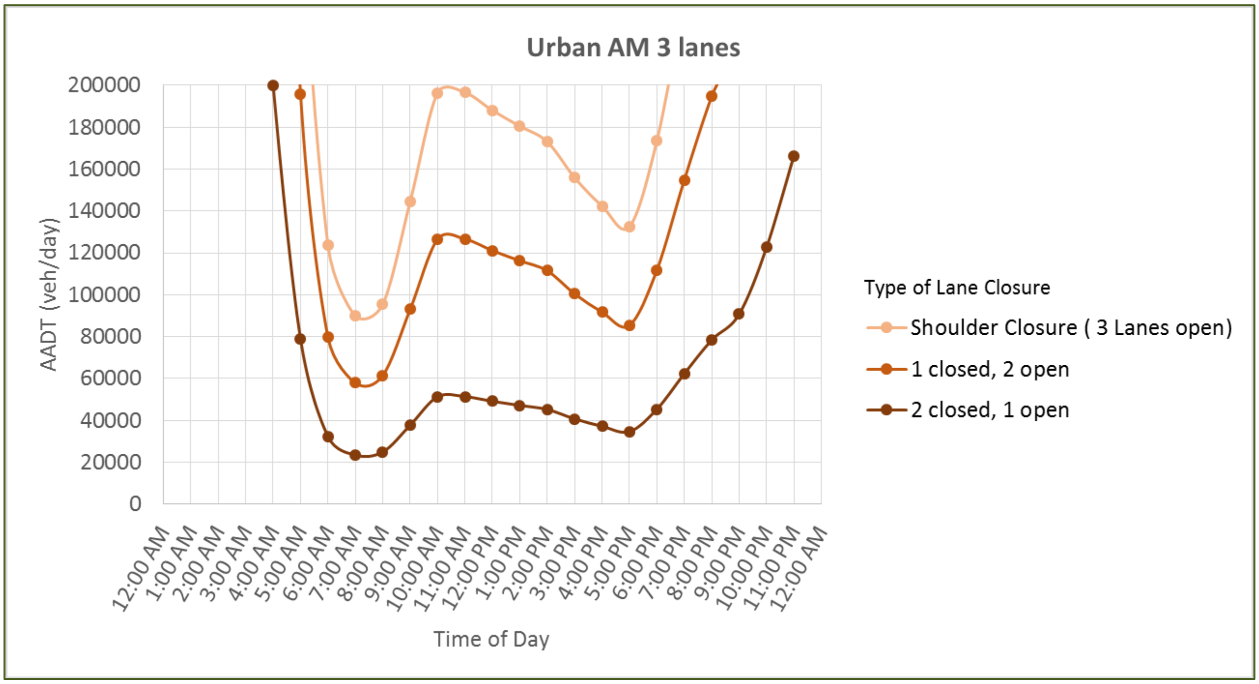


Exhibit IV - A 7 AADT under different types of lane closure on a 3 lane urban freeway facility during PM peak period

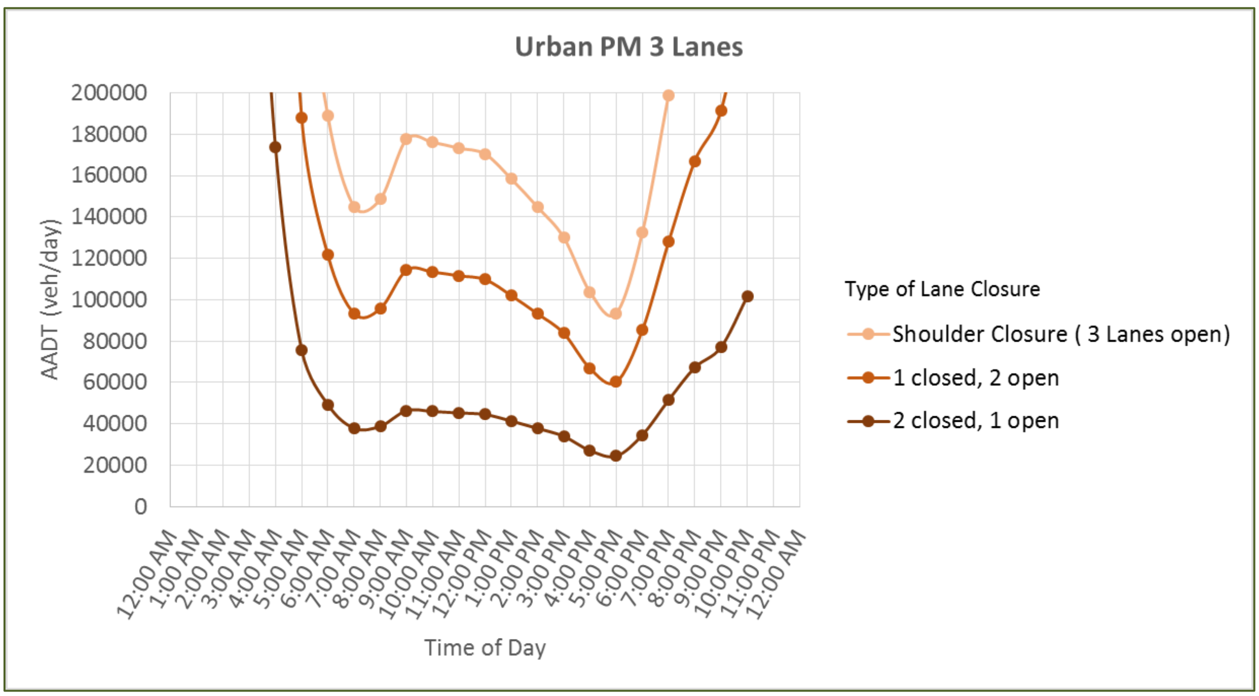


Exhibit IV - A 8 AADT under different types of lane closure on a 3 lane rural freeway facility

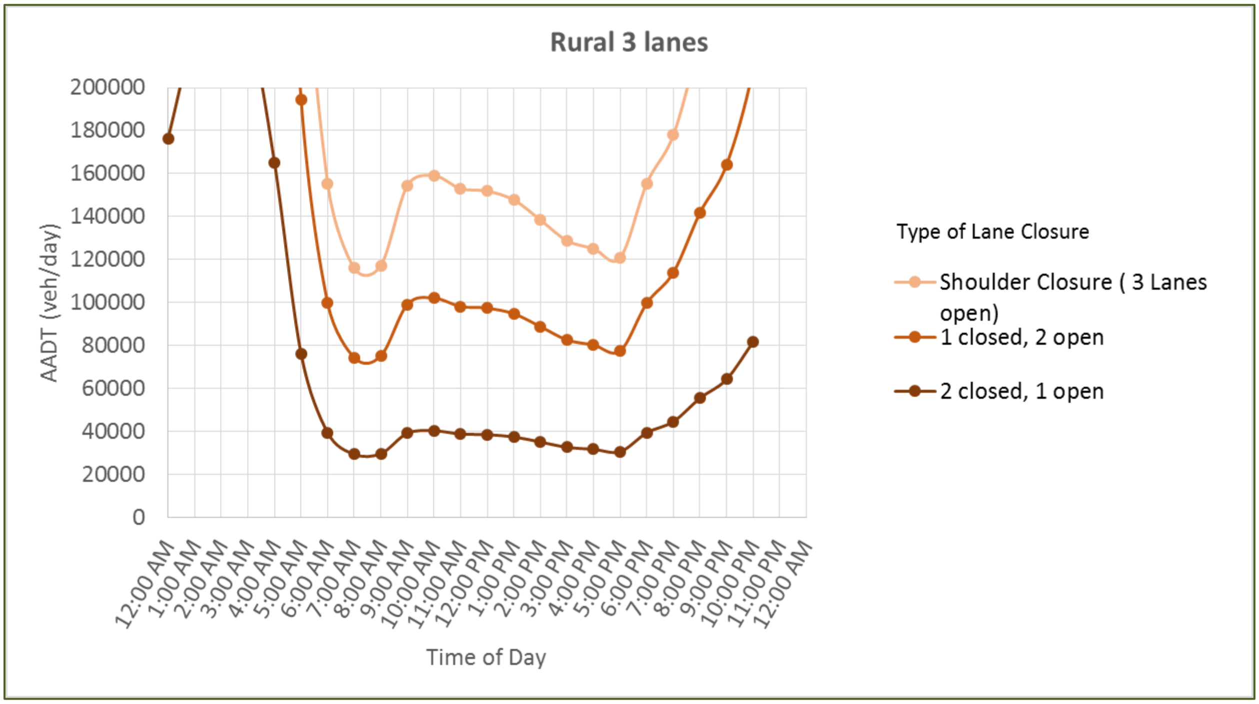


Exhibit IV - A 9 AADT under different types of lane closure on a 2 lane urban freeway facility during AM peak period

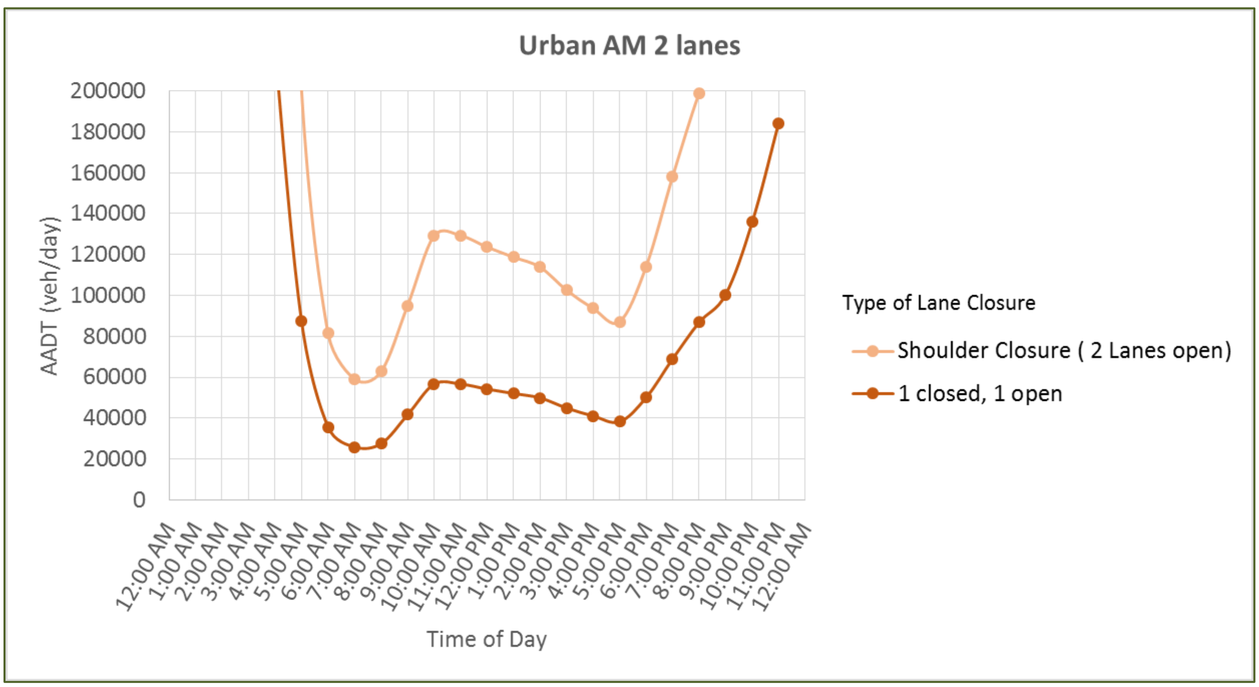


Exhibit IV - A 10 AADT under different types of lane closure on a 2 lane urban freeway facility during PM peak period

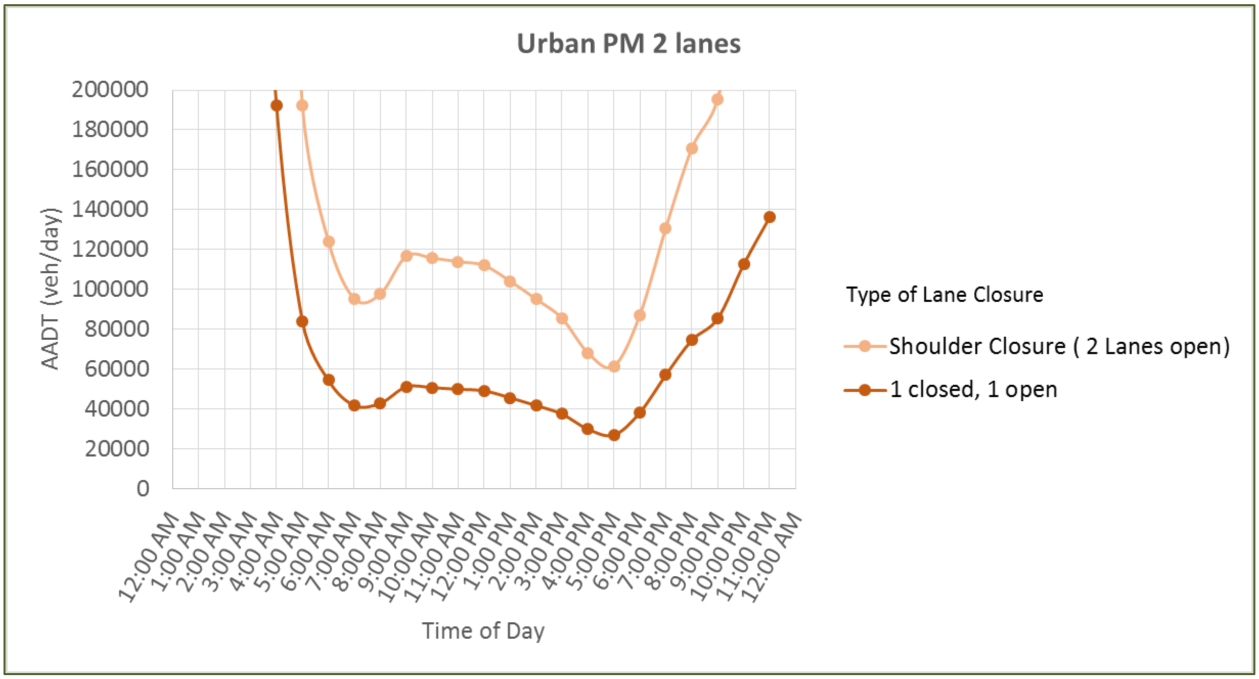
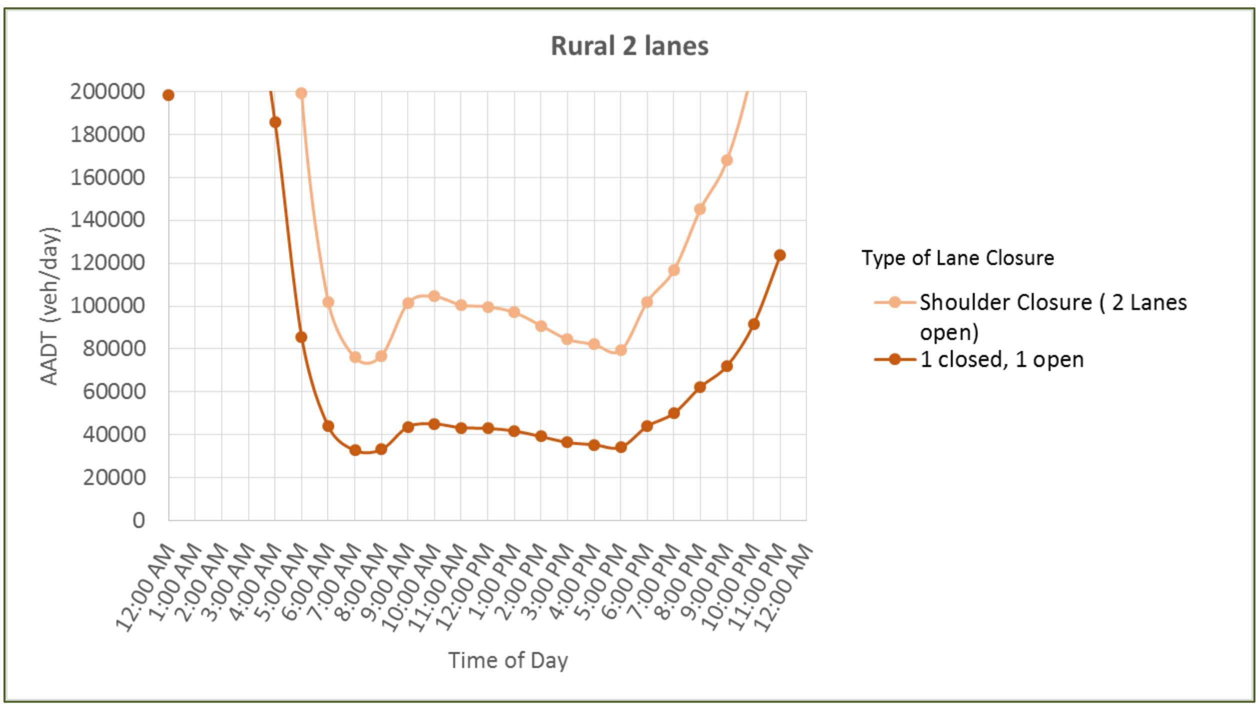


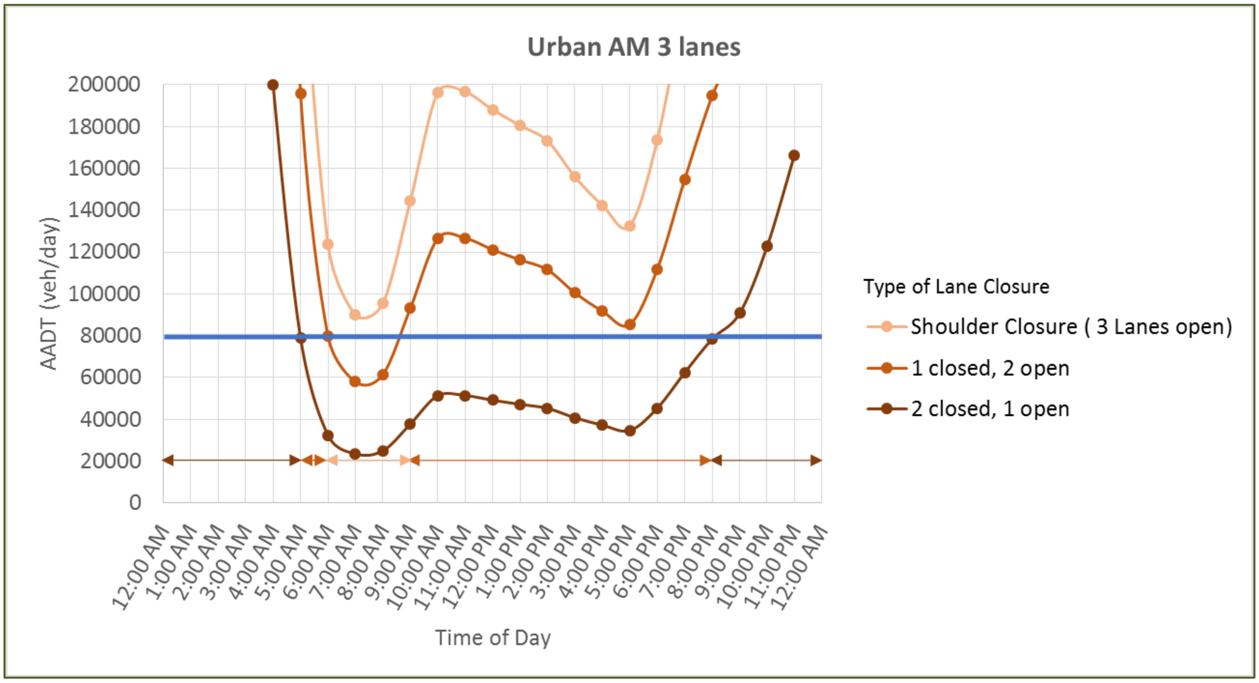
Exhibit IV - A 11 AADT under different types of lane closure on a 2 lane rural freeway facility



6.3 Illustrative Example

Resurfacing is required on a 6-lane interstate with three lanes in both directions. Geometry is consistent throughout the work zone, so the planning level analysis is performed on the first Basic segment where closures will begin. The segment is located in an urban area with a dominant AM peak period and an AADT of 80,000. In order to quickly identify the hours over which lanes can be closed, a line is drawn across at 80,000 shown in blue in below. Based on this line, a two lane closure may be considered from 8PM to 5AM, a one lane closure can be considered between the hours of 9 am to 6 am, while a shoulder closure is permissible throughout the day.

Exhibit IV - A 12 Case Study- 3 lane Urban AM Peak Freeway with 80,000 AADT



Appendix IV - B: Travel Demand Model

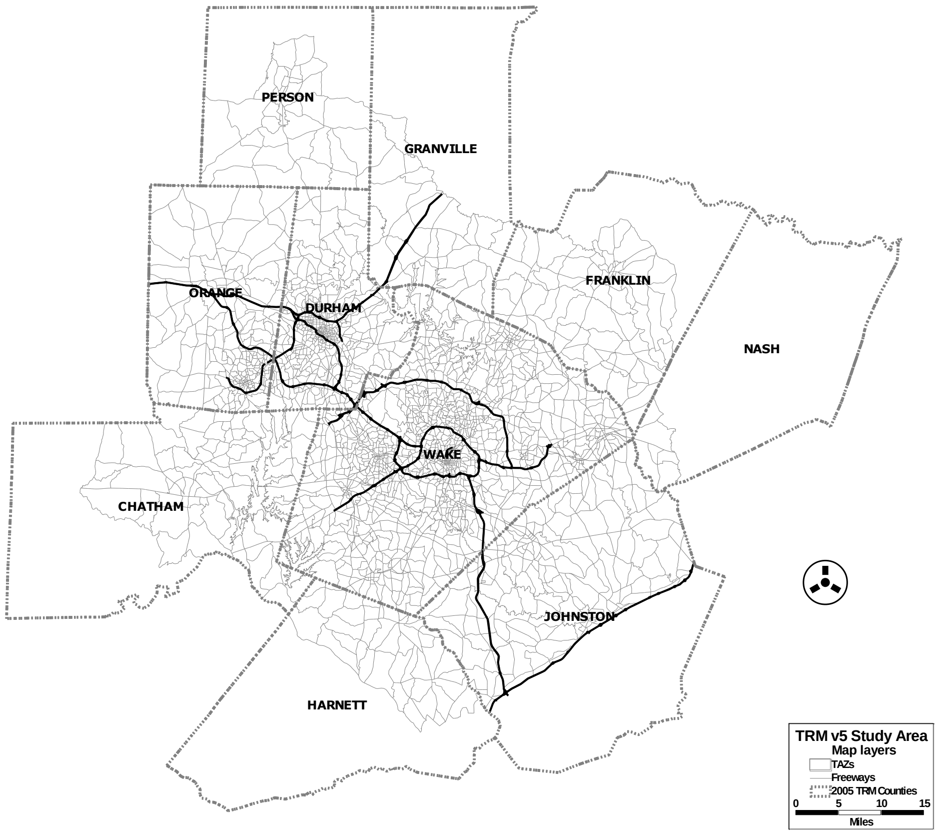
Travel Demand Modeling assists in decision-making for regional transportation planning activities and analyzing impacts of activities such as work-zones. The strength of modern travel demand forecasting is the ability to ask critical “what if” questions about proposed plans and policies. Regional transportation analysis usually involves four basic steps, which are trip generation, trip distribution, mode choice, and trip assignment.

A geographic unit called a transportation analysis zone (TAZ) and a number of pre-existing or projected characteristics within these TAZs are used to create trip generation rates in a regional model. For example, the Triangle Regional Model (TRM) is used as an analytical tool to support the policy decision making process and the development of the Metropolitan Transportation Plan (MTP). The TRM is the travel demand forecasting tool for the Triangle region of North Carolina. Trip distribution is the process by which the generated trips from each TAZs are assigned a zone to travel to, leading to an origin-destination demand matrix. The analysis involves a sophisticated process for weighting the “attractiveness” of each TAZ based on the number of attractions it has and the travel time from other TAZs. Mode choice shows which mode people use to travel between their origins and destinations. For example, the traffic demand data used to model the TRM recognizes three traffic modes: single occupancy vehicle (SOV), high occupancy vehicle (HOV) and trucks. Trip assignment determines the routes that will be selected for each trip in the region. This step requires careful calibration using information regarding actual or predicted congestion levels, road conditions, transit schedules and fares, traffic signal systems, etc. Validation of the model is a very important step and requires detailed data collection to ensure that model is able to predict accurately.

The results from the model may vary depending on the ideas and information used and the sophistication of the particular model. Small models generally provide users with forecasted highway volumes for roadways with functional classes of minor arterial and above. Large model regions generally provide users with everything included in small models and transit forecasts. Some more sophisticated models also provide users with information on truck forecasts, college/university travel, HOV travel, and the effects of toll strategies on travel behavior.

Exhibit IV-B 1 shows the travel demand model for the RTP region, which is composed of all of Orange, Wake and Durham counties, and parts of Chatham, Person, Granville, Franklin, Nash, Johnston, and Harnett counties. The model region covers 3,380 square miles. The model was developed using population and employment data for 2005. The region had a population of 1,388,231 and 716,417 employees in 2005. The model region is divided into 2,579 Traffic Analysis Zones (TAZs) and there are ninety nine external stations.

Exhibit IV-B 1 Map of TRM v5 Region Showing Traffic Analysis Zones



Appendix IV - C: Overview of FREEVAL-WZ tool for WZ analysis

ITRE **PLANNING-LEVEL EXTENSIONS TO NCDOT FREEWAY ANALYSIS TOOLS**

Overview

- The particular focus of this project was on implementing a series of planning-level analysis extensions to the freeway facilities methodology of the Highway Capacity Manual (HCM).
- Planning-level work-zone analyses are often performed in a "data poor" analysis context, where the available data is limited basic freeway geometry characteristics and daily traffic demand patterns.
- The main products of this research are new empirical results on default traffic volume distributions, in addition to methods and a software tool **(FREEVAL-WZ)** to support 24-hour freeway analysis.

Planning Level Demand Inputs

- The software allows the user to populate a facility's demands using a daily AADT value and corresponding daily volume profile.
- The research developed a set of "default" distributions through a statistical analysis of 99 permanent and temporary count stations.
- These profiles fall into 3 distinct types: Unimodal, Bimodal-AM Peak, and Bimodal-PM Peak.
- The user has the ability to create, save, and share custom facility specific volume profiles.
- The software also includes a set of NC specific profiles.

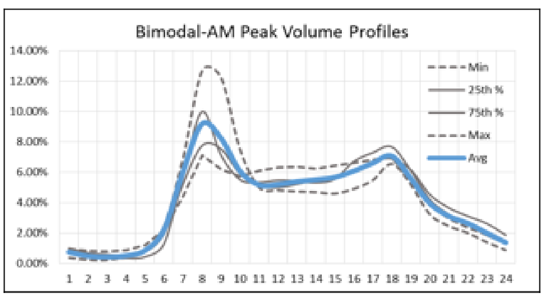
Default Distributions

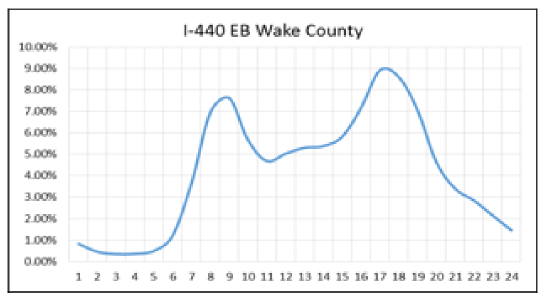
Profile Type	Description
Unimodal	Volume profile with a single peak, representing traffic on rural roads or weekend traffic.
Bimodal-PM Peak	Volume profile with two peaks, with the larger peak occurring in the afternoon rush hours. Represents typical weekday commuter traffic.
Bimodal-AM Peak	Volume profile with two peaks, with the larger peak occurring in the morning rush hours. Represents typical weekday commuter traffic.

North Carolina Distributions

- The volume profiles were developed with traffic counts collected from 26 permanent count stations in North Carolina.
- Each station included bi-directional volume data, which resulted in a total of 52 facility specific volume profiles.

#	County	Route #
1	Buncombe	I-240
2	Buncombe	I-40
3	Burke	I-40
....		
24	Wake	I-540
25	Wake	I-440
26	Wake	I-40/440

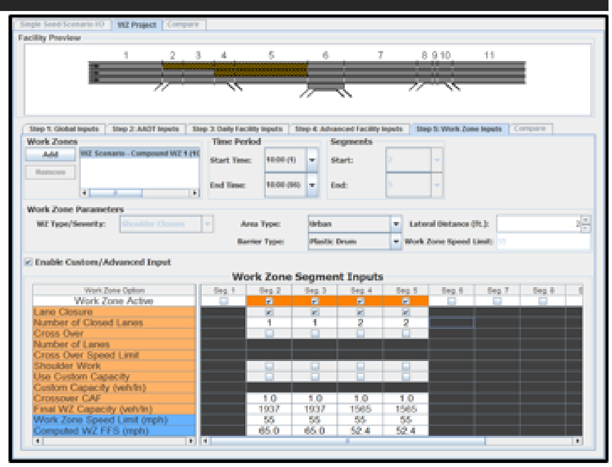




FREEVAL-WZ Analysis Process Flow

The process of creating a project is done is six steps:

- **Step 1: Facility Creation and Global Inputs**
  - Initial inputs of spatial and temporal facility properties and global parameters (Terrain, Truck %, etc.)
- **Step 2: Select AADT Inputs and Volume Distribution**
  - Specification of daily bidirectional AADT and pick or create AADT volume distribution.
- **Step 3: Daily Facility Inputs**
  - Configuration of segment types, lengths, weave characteristics and unidirectional ramp AADTs.
- **Step 4: Advanced Facility Inputs (Optional)**
  - Optional step for operational level calibration and customization of the facility.
- **Step 5: Work Zone Design and Parameters**
  - Creation and configuration of up to three distinct work zone scenarios to analyze and compare.
- **Step 6: Comparison Analysis and Report Generation**
  - View and compare performance measures of base scenario and each work zone scenario. Outputs include travel time, delay, speed, and user cost.

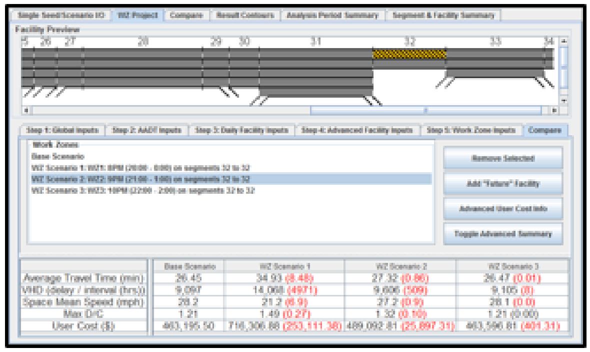


Work Zone Scenario Builder for Step 5

Institute for Transportation Research and Education (ITRE) at North Carolina State University (NCSU) – http://itre.ncsu.edu

Results and Work Zone Scenario Comparison

- The sixth step of the analysis allows the user to compare performance on the facility between the base scenario and each work zone.
- A comparison table displays the values of key performance measures for the base scenario and each work zone in the project.
- For each work zone, the differences between values for each measure are displayed to the right of the value.
- Performance measures included are: average travel time, delay, speed, max demand-to-capacity ratio (D/C), max volume-to-capacity ratio (V/C), total user cost, and maximum hourly user cost.
- The user can toggle between a basic and an advanced summary.
- The user also has the option to view an expanded set of user cost outputs as well as specify custom values used in the computation of these costs.

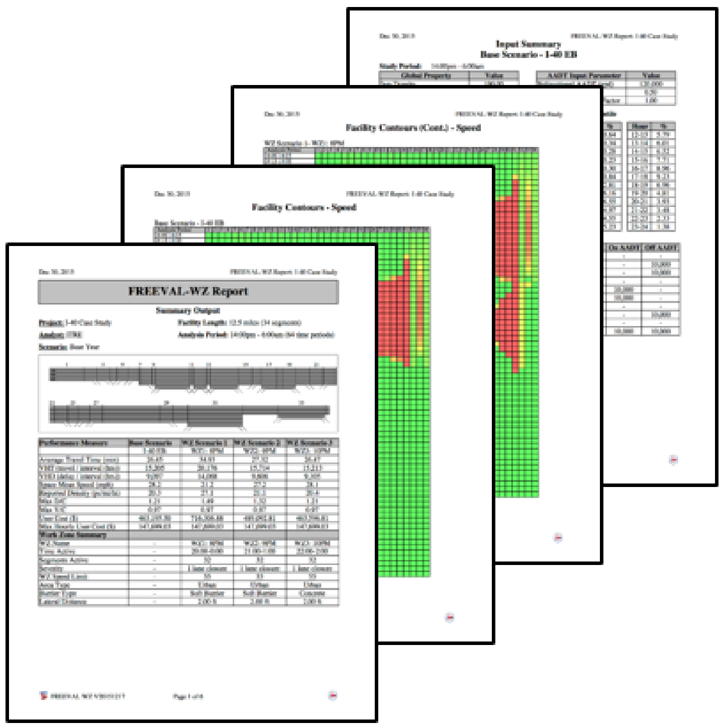


Analysis Summary and Comparison for an Example Facility

Customizable PDF Report Generation

- After completing a work zone analysis, the user can choose to generate a PDF summary report.
- Due the wide ranging scope of analysis possible in FREEVAL-WZ, the report generator was designed to be fully customizable with a large number of options.
- Default report includes facility geometry and demand information, and comparison summaries of performance measures for the base scenario and all work zone scenarios.
- The report can include up to three customizable result contours for speed, density, D/C, V/C, or level of service.

Available PDF Report Content
Facility Graphic
All Scenarios Comparison
Work Zone Scenarios Summary
Segment Information
Facility Contours
Base Facility Details
Work Zone Scenario Details



Example PDF Report with Facility Contours and Scenario Summary

Contact Information

- **Behzad Aghdashi, Ph.D.**
  Research Associate, Institute for Transportation Research and Education
  919-515-8580 , saghdas@ncsu.edu
- **Bastian Schroeder, Ph.D., PE,**
  Kittelson and Associates Inc.
  910-399-5570 , bschroeder@kittelson.com

Acknowledgements

The research team acknowledges the North Carolina Department of Transportation for supporting and funding of this project. We would like to thank all members of the Steering and Implementation Committee for their continued support and insight in this effort.

Institute for Transportation Research and Education (ITRE) at North Carolina State University (NCSU) – http://itre.ncsu.edu

Appendix IV - D: Microscopic Modeling Analysis Process

When complex geometry, work zone strategies or detailed outputs are of interest for work zone modeling, microsimulation is typically the tool of choice. In addition to the standard work flow of modeling any freeway or arterial facility in a microsimulation tool, additional calibration is required in order to make sure the simulation will accurately reflect real work operations. NCHRP Project 3-107, titled *Work Zone Capacity Methods for the Highway Capacity Manual*, focused a major effort on utilizing microscopic modeling in VISSIM for developing the models that are implemented in the methodology found in Appendix A. Prior to running the input simulations to these macroscopic models, the team first calibrated VISSIM parameters for work zone conditions using a sensitivity analysis. These calibrated parameters are found in the project report and summarized in the tables below for freeway modeling in VISSIM. Exhibit IV-D 1 shows the car following and lane changing parameters used in 3-107 that are recommended for all freeway WZ models, while Exhibit IV-D 2 shows the specific range of values for the VISSIM car following parameters cc1 and cc2. Finally, Exhibit IV-D 3 shows regression equations that can be used to find an ideal value for cc1 if a queue discharge rate (QDR) is known or assumed.

Exhibit IV-D 1 VISSIM Freeway Work Zone Parameters

Parameters		VISSIM default	Recommend WZ setting
Car following [1]	cc0 (ft)	4.92	4.92
	cc1 (s)	0.90	work zone configuration specific
	cc2 (ft)	13.12	work zone configuration specific
	cc3 (s)	-8.00	-8.00
	cc4 (ft/s)	-0.35	-0.35
	cc5 (ft/s)	0.35	0.35
	cc6	11.44	11.44
	cc7 (ft/s^2)	0.82	0.82
	cc8 (ft/s^2)	11.48	11.48
	cc9 (ft/s^2)	4.92	4.92
Lane changing	Lane change distance (ft)	656.20	3281.00
	Necessary lane change -1 ft/s^2 per distance (ft)	200.00	100.00
	Maximum deceleration for cooperative lane braking (ft/s^2)	-9.84	-20.00

[1] *Default car following VISSIM values except specific setting for cc1 and cc2*

Exhibit IV-D 2 VISSIM Freeway Work Zone Parameters- Range of values for cc1 and cc2

Lane configuration	LCSI	NCHRP 3-107 QDR (pc/h/ln)		cc1[1] (s)	cc2[2] (ft)	QDR in VISSIM (pc/h/ln)	Difference (%)[3]
4 to 3	0.44	Minimum	1486	1.80	39.36	1467	-1.3
		Maximum	2025	0.90	39.36	2049	1.2
3 to 2	0.75	Minimum	1438	1.80	26.24	1525	6.1
		Maximum	1978	1.08	26.24	1949	-1.5
4 to 2	1.00	Minimum	1400	1.80	26.24	1459	4.2
		Maximum	1939	1.26	26.24	1845	-4.8
2 to 1	2.00	Minimum	1246	1.80	23.62	1478	18.6
		Maximum	1785	1.26	23.62	1763	-1.2
3 to 1	3.00	Minimum	1092	2.70	26.24	1195	9.4
		Maximum	1631	1.44	26.24	1551	-4.9
4 to 1	4.00	Minimum	938	2.70	39.36	947	1.0
		Maximum	1477	1.62	39.36	1390	-5.9

[1] *VISSIM default: 0.9 s*
[2] *VISSIM default: 13.12 ft*
[3] *Between VISSIM and 3-107 model*

Exhibit IV-D 3 VISSIM Freeway Work Zone Parameters- Regression for cc1

Lane configuration	LCSI	cc2 (ft)	cc1 (s) Estimation Regression Model	R-square
4 to 3	0.44	39.36	-0.0015 × Avg QDR + 3.9346	0.9950
3 to 2	0.75	26.24	-0.0020 × Avg QDR + 5.0041	0.9807
4 to 2	1.00	26.24	-0.0019 × Avg QDR + 4.7155	0.9245
2 to 1	2.00	23.62	-0.0023 × Avg QDR + 5.3146	0.9913
3 to 1	3.00	26.24	-0.0041 × Avg QDR + 7.7741	0.9937
4 to 1	4.00	39.36	-0.0022 × Avg QDR + 4.7177	0.9694

Similar effort is needed to calibrate VISSIM parameters for modeling work zones on arterials in order to simulate realistic operations such as a lowered saturation flow rate. Other microsimulation tools such as Transmodeler or Corsim may also be of use to model work zones, but require calibration to field data prior to modeling any strategies.

Appendix IV - E: Mesoscopic Modeling Analysis Process

Modeling a work zone and analyzing its impacts is very challenging due to its dynamic nature. Roadways have stochastic capacity due to recurrent (known to many as “rush-hour” traffic) and non-recurring congestion due to accidents, construction, or emergencies. There are also within day and day-to-day changes in both demand and supply domains. The behavior of a work zone at varying stages of construction have different short-term and long-term implications.

A detailed modeling approach is required when the work zone creates significant impact on the overall network traffic and considerations of traffic operational characteristics on the alternate routes are important for the overall analysis. Often, a demand origin-destination pattern must be estimated. These potentially time-varying demand patterns are input into the simulation model to more realistically capture diversion effects and queue spillbacks. The use of dynamic traffic assignment (DTA) is more relevant in modeling urban freeway work zones where demand and supply show frequent fluctuations. Among the DTA based models, mesoscopic versions are more efficient in processing network traffic compared to microscopic models and more detailed compared to the macroscopic ones. Since DTA based mesoscopic models simulate network behavior at high spatial and temporal resolution, detailed field data is required for adequate calibration and validation of these models.

It is necessary to decide on the spatial extent and details of the network as this can significantly cut down the cost of developing the model. The baseline model for a work zone may be developed using information transferred from a regional travel demand model (e.g. Triangle Regional Model or TRM). The model is then calibrated in the mesoscopic tool using a built-in origin-destination matrix estimator (ODME) and point based sensor counts. The work zone is then simulated as an addition to the calibrated baseline model, by changing link-parameters such as link capacity, free-flow speed and jam density for the affected links.

In the design stage, the work zone is simulated on a set of assumed behavior regarding route choice (traffic assignment algorithm) and network parameters such as diversion sensitivity, information availability and freeway bias factor. These assumptions are developed through experience gained from similar models implemented at similar network type transportation management plan, work zone schedule and configuration. Simulation results are also sensitive to the number of iterations performed depending on the network configuration and extent of the work zone.

A rich data set is required to validate the results of the model and capture the impacts of the work zone more realistically. Model validation should be performed at network, route and link levels. Work zone operational models are traditionally assessed on how realistically they can model route travel times. Use of only route based validation can cause undetected inconsistencies in the link or point level statistics. On the other hand, biased selection of sensors for calibration data in the vicinity of the work zone can result in valid route and link statistics, but may cause invalid network wide statistics such as high number of unserved agents and unrealistic bottlenecks at other parts of the network.

The methodology adopted in modeling network-wide impacts of work zone is shown in Exhibit IV-E 1.

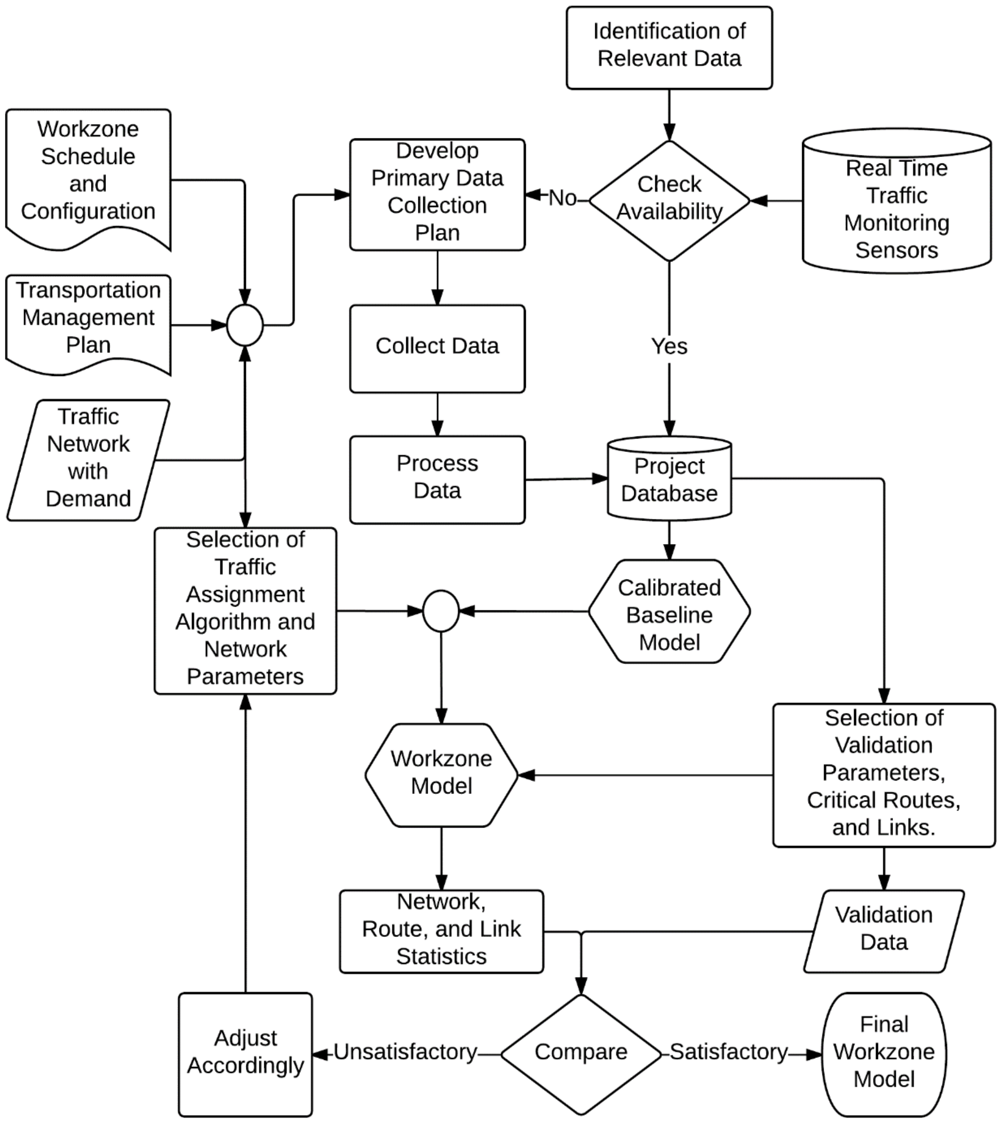


Exhibit IV-E 1 Methodology to validate mesoscopic dynamic traffic models.

CHAPTER V -

INFORMATIONAL BRIEF SUMMARY OF WORK ZONE GUIDANCE

NCDOT Work Zone Operations Monitoring and Assessment Guidance

The North Carolina Department of Transportation (NCDOT) developed a guidance document for modeling and monitoring work zone operations and mobility performance in North Carolina. The guidance document is intended to help NCDOT analysts and consultants properly scope work zone studies. While the focus is on operational analysis and monitoring, other considerations outside the scope of the document (such as safety performance and economic impacts) should be considered when evaluating work zone performance.

Modeling versus Monitoring

The document distinguishes guidance for work zone modeling prior to construction versus monitoring of performance during construction. There should be a clear purpose and need for conducting any operational analysis or monitoring of a freeway work zone. The guidance provides information that an analyst can use, when scoping a work zone evaluation, to balance the required departmental resources against the expected benefits and outcomes of the effort.

Modeling – Predict the operational effects and impacts of a work zone prior to construction starting. Modeling can be used to evaluate work zone operations, compare and contrast alternatives, and support decision-making for work zone staging. The document discusses types of models and presents guidance for applying different levels of analysis tools to estimate work zone effects.

Monitoring – Evaluate and track performance of a work zone during active construction. Monitoring involves data collection, data analytics, and providing real-time decision support. The guidance discusses types of sensing and data collection approaches and makes recommendations for the level of monitoring required for different work zones.

Modeling Impacts of Proposed Work Zone → Establish Purpose and Need of Modeling Effort → Answer Key Questions on Modeling Goals → Select Modeling Level → Develop Modeling Plan

Monitoring Performance of Existing Work Zone → Establish Purpose and Need of Monitoring Effort → Answer Key Questions on Monitoring Goals → Select Monitoring Level → Develop Monitoring Plan

Photos by Lee Rodegerdts

NCDOT
NORTH CAROLINA DEPARTMENT OF TRANSPORTATION
ITRE
KITTELSON & ASSOCIATES, INC.
TRANSPORTATION ENGINEERING/PLANNING

The guidance is developed from key questions that an analyst or work zone designer may have for a specific project. Using those questions, the guidance helps an analyst identify the appropriate level of work zone monitoring and modeling based on the desired level of detail and analysis outcomes.

Modeling Questions

The guide defines five levels of work zone modeling. The levels range from very simple, sketch-planning-level analysis tools to complex network-wide simulation models. In general, an analyst should strive to apply the simplest analysis level that is able to address all modeling questions of interest. Sample modeling questions include:

- What times of day are lane closures permissible?
- What level of diversion is needed to keep operations acceptable?
- How can mitigation measures benefit operations on the work zone corridor?

Modeling Level 1: Simple Impact Assessment

- Sketch-Planning Analysis Tools
- Service Volume Tables and Planning Charts

Modeling Level 2: Planning-Level Corridor Performance

- Deterministic/Analytical "Pipe" Tools
- FREEVAL-WZ, Synchro/Vistro and ARTVAL-WZ NCDOT Tools

Modeling Level 3: Detailed Corridor Performance

- Microscopic Simulation
- Evaluation of special geometries and ramp terminals

Modeling Level 4: High Level Network Assessment

- Travel Demand Model and Macroscopic Simulation
- Only models overal traffic stream without queueing

Modeling Level 5: Detailed Network Assessment

- Mesoscopic Simulation
- Evaluation of network-wide diversion and mulitple alternate routes

Data Analysis and Monitoring Questions

The guide defines five levels of work zone monitoring. The levels range from a simple impact assessment to a comprehensive network-wide study of operational impacts. In general, an analyst should strive to apply the lowest monitoring approach that meets the project's purpose and need. Sample monitoring questions include:

- What are the travel times and speeds through the work zone?
- How do travel times and speeds compare to pre-work zone conditions?
- How much diversion to alternate routes has taken place?

Data Level 1: Simple Impact Assessment

- Speed and travel times from probes
- Queue lengths estimated from probes

Data Level 2: Corridor Performance

- Speed and travel times from probes
- Queue lengths estimated from probes
- Mainline volume point sensors

Data Level 3: Corridor Performance Plus Real-Time

- Speed and travel times from probes
- Queue lengths estimated from probes
- Mainline volume point sensors
- Streaming video along work zone corridor

Data Level 4: Route Diversion Estimates

- Speed, travel times, and queues from probes
- Mainline volume point sensors on work zone and alternate route
- Streaming video along work zone corridor and alternate route
- Bluetooth readers on work zone and alternate route

Data Level 5: Network Assessment

- Speed, travel times, and queues from probes
- Mainline volume point sensors on work zone, alternate route, and key points in network
- Streaming video along work zone corridor, alternate route, and key points in network
- Bluetooth readers in work zone, alternate, and key points in network for O/D estimation

Any modeling and monitoring activity should…

1
Have a clear PURPOSE and NEED.
An analyst should identify the purpose of the modeling or monitoring effort, why data are being collected, what the results will be used for, and how it will impact decision-making.

2
Add VALUE to the North Carolina Department of Transportation.
That value may be internally-driven or may be linked to performance reporting and public engagement activities by the department.

In an effort to tie recommendations to typical work zone analysis scenarios, the table below presents modeling and monitoring recommendations for common types of work zones. It is emphasized that these are ***examples***; the more-detailed, question-driven process described previously should be applied to specific work zones in question.

Example Work Zone Scenarios	Recommended Level of Modeling	Recommended Data Monitoring Level
Minor work zones that are of very short duration, up to a few hours, in off-peak periods and that are outside of major metropolitan areas	Level 1	Level 1
Minor work zones that are of very short duration, up to a few hours, in off-peak periods and that are within a major metropolitan area	Level 1 and 2	Level 1
Intermediate work that occupies a location for a few hours a day, including peak periods, for up to 3 days and is outside of major metropolitan areas	Level 1 and 2	Level 1 or 2
Intermediate work that occupies a location for a few hours a day, including peak periods, for up to 3 days and is within a major metropolitan area	Level 1 and 2	Level 2 or 3
Longer term work zones with multi-day lane closures on a freeway facility outside of major metropolitan areas	Level 1, 2, and 4	Level 2 or 3
Reconstruction or extension of off-ramp lanes on a freeway	Level 1 and 3	Level 2 or 3
Longer term work zones with multi-day lane closures on a freeway facility within a major metropolitan area	Level 1, 2, and 4	Level 3, 4, or 5
Major work zones that span over a large area in a metropolitan region that sees high daily travel and require longer time for completion	Level 1, 2, and either 4 or 5	Level 4 or 5
Full facility closure on a smaller stretch of road, requiring diversions and mandatory detours, for longer than 3 days	Level 1, 2, and either 4 or 5	Level 4 or 5

Modeling Level 1 is included for all work zone scenarios because the sketch-planning approach is easy and fast to apply, and serves as a benchmark against which other more-detailed analyses can be compared.

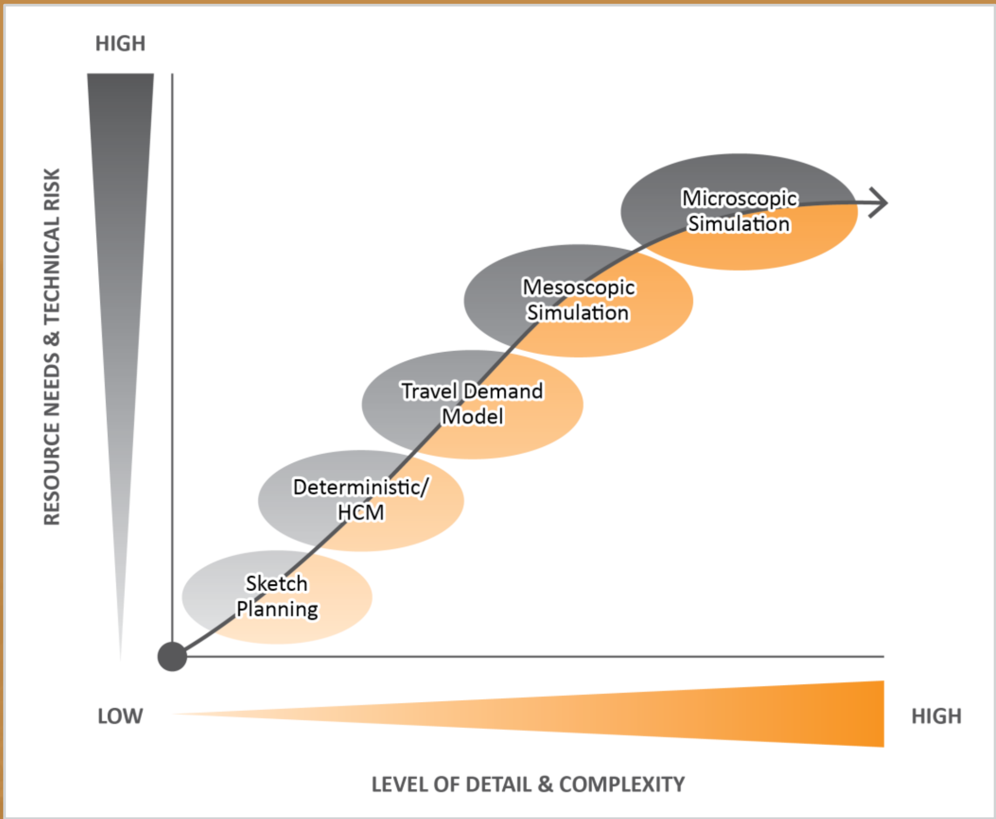
Some level of monitoring is recommended for all scenarios because probe-based travel time data is readily available for all freeways and major arterials in North Carolina.

Resource Needs and Technical Risk Associated with Modeling Levels

The level of detail for the five modeling levels largely translates into data requirements to conduct the analysis. Higher levels of detail and complexity in turn translate into higher levels of effort, as well as increasing technical risk.

An increasing level of effort to conduct an analysis should be carefully evaluated in light of the following:

- Increased labor hours or contractor time.
- Impacts on schedule and other project timelines.
- Revisions and iterations in the analysis, leading to cost and time impacts.
- Increased technical risk due to the potential need for more calibration, fewer available defaults, and more room for user error.



The document presents *guidance and recommendations* but not requirements. Any work zone analysis should therefore be carefully evaluated using engineering judgment, considering the availability of funds, staff resources, and time to conduct the recommended level of operational analysis or monitoring.

This tech brief, the full research project report, and additional information can be found at the following website:

https://connect.ncdot.gov/projects/planning/pages/ProjDetails.aspx?ProjectID=2014-33