NCDOT Project 2012-36

Work Zone Traffic Analysis & Impact Assessment

Final Project Report

Prepared for:

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Abstract:
This report documents the final results and project summary of NCDOT research project 2012-36: Work Zone Traffic Analysis & Impact Assessment. The project is tasked with assessing the estimated impact of proposed NCDOT TIP Project I-5311/I-5338, which is a pavement rehabilitation project on interstates I-40 and I-440 from Exit 293 to I-40 Exit 301 and I-440 Exit 14. The project aims to predict the network-wide impacts of this work zone during construction. The primary focus in the project and in this report is the development and calibration of a network-wide mesoscopic simulation model of the Triangle region using the DynusT and DTALite software tools, as well as a macroscopic evaluation in the FREEVAL tool. The geometric extents of the model cover the entire triangle region, with expansion to the east of the triangle to include additional sections of US264, I-40, and I-95. The model has been calibrated using field-estimated spot volume and speed data, as well as key route travel times obtained from INRIX. A variety of work zone scenarios were modeled to test the relative impacts of different lane closure configurations on route and network performance. The analysis further differentiates between no-diversion and with-diversion, where the latter relies on twenty iterations of a dynamic traffic assignment utility, which diverts traffic in an effort to minimize overall network travel time.

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Executive Summary

This document is the final report for NCDOT research project 2012-36: *Work Zone Traffic Analysis & Impact Assessment.* The project was tasked with assessing the estimated traffic impacts of the proposed NCDOT TIP Project I-5311/I-5338, a pavement rehabilitation project on interstates I-40 and I-440 from Exit 293 to I-40 Exit 301 and I-440 Exit 14. NCDOT anticipates that significant corridor and network level impacts would arise from this project during construction. Both I-40 and I-440 corridors presently carry approximate Average Annual Daily Traffic (AADT) volumes of 113,000 and 90,000 vehicles per day (vpd), respectively. Current demand levels already produce recurring peak-hour congestion in the vicinity of the proposed work zone. The capacity reduction associated with the work zone involves 24-hour, multi-day lane closures. In addition to freeway mainline congestion, this work zone is also expected to have significant congestion impacts on alternative routes and other choke points in the network.

The project aimed to predict corridor and network-wide impacts of the work zone during construction, including routes along the work zone corridor, as well as key alternative routes. The primary focus of this study was the development and calibration of a network-wide mesoscopic simulation model of the Triangle region, as well as a macroscopic representation of the work-zone corridor.

The geographical coverage of the mesoscopic simulation model includes the entire triangle region and additional sections of US264, I-40, and I-95 east of the triangle. The model was calibrated using field-estimated spot volume and speed data, as well as key route travel times obtained from INRIX. The model was initially developed and tested in the DynusT software tool, and was then transferred to the DTALite software tool. Both tools gave reasonable results for the baseline scenario, and when modeling higher-capacity work zone scenarios. However, for lower capacity (more severe) work zone scenarios DTALite performed more reasonably, while the DynusT tool yielded unrealistically high traffic densities in segments upstream of the work zone. Therefore, while both tools proved useful in this project, the DTALite results are thought to provide a more realistic assessment of the expected work zone impacts at this time.

In addition to the two mesoscopic tools, the macroscopic analysis tool FREEVAL was used to explore the estimated impacts on the work zone corridor. While FREEVAL is not able to predict diversion rates and network-wide performance, it has been proven to be a useful tool for assessing work zone impacts based on previous research conducted for NCDOT. FREEVAL is a faithful representation of the freeway facilities methodology in the 2010 U.S. Highway Capacity Manual, and as such, a benchmarked analysis tool across the U.S.

Multiple work zone scenarios were modeled in all three tools to test the relative impacts of different lane closure configurations on route and network performance. Scenarios included a reduction of the overall cross-section to only two travel lanes, from a base of three to five lanes per direction. Additional scenarios maintained more travel lanes at key bottleneck sections during construction, as well as a three-lane scenario that was thought to offer significant congestion relief during construction. The analysis further differentiates between no diversion (drivers not taking alternative routes) and with diversion (drivers taking alternative routes to travel through or around the construction) results. Traffic diversion volumes were estimated assuming drivers identified ideal alternative routes based on running

a dynamic traffic assignment (DTA) model for twenty iterations until network user equilibrium (UE) is achieved.

In interpreting the model results, several key assumptions were made. First overall traffic demand was kept unchanged before and during the work zone, without any consideration of trip reductions, additional carpooling, or telecommuting. The model further assumed that travelers only change their route between the same origin and destination, but not their departure time. In addition, no modal shift towards transit was modeled. All these travel strategies may result in further trip reduction and thus mitigate the impacts of the work zone on traffic congestion in the triangle.

FREEVAL results suggest that 30-40% of drivers must select alternative routes in the AM Peak hour to keep average travel speeds through the work zone above 20 mph with two open lane work zone pattern. With three open lanes, FREEVAL estimates that if 10-20% of drivers select alternative routes the average travel speeds will be over 40 mph. For the PM Peak, the FREEVAL analysis suggests that if 40-50% of drivers select alternative routes, the average speed will be over 10 mph with at least two travel lanes open. For the three-lane open case, it is estimated that a 40 mph average travel speed can be maintained only if 30-40% of drivers select alternative routes.

DTALite results showed optimum diversion rates of 56% and 33% for the two-lane open and three-lane open options, respectively, in the AM peak under UE conditions. With these assumed rates of traffic volume reduction through the work zone, the network model estimates I-40 westbound travel times to increase through the work zone from 8.6 to 15.1 min for the two-lane pattern, and to 12.7 minutes for the three-lane pattern. In the more constrained two-lane open pattern, the model estimates volume increases in excess of 500 vph on Wade Avenue, US64, US1, and NC55, with smaller increases for other routes in the triangle. As a result, the model estimates travel time increases over 30% for I-440 eastbound (+32%), US70 northbound (+92%), Hammond Rd. northbound (+115%), and Rock Quarry Road westbound (+43%) in the AM Peak for the two-lane. For the three-lane open case, network-wide impacts are mitigated to some extent because fewer drivers select alternative routes. The model still estimates travel time increases over 30% for US70 northbound (+44%), Hammond Road northbound (+54%), and Rock Quarry Road westbound (+32%), and other significant impacts on I-440 EB (+10%), NC55 NB (+17%) and Hammond Road northbound (+22%).

In the PM Peak, the network is generally more congested due to higher traffic volumes. The idealized UE solution in DTALite estimates I-40 eastbound travel time to increase through the work zone from 8.6 to 18.5 min for the two-lane open pattern, and to 13.9 minutes for the three-lane open pattern. These increases are determined by the model calculating an idealized 62% traffic volume reduction and 36% traffic reduction for the two-lane open and three-lane open pattern, respectively. Due to drivers self-selecting alternative routes, the model estimates volume increases in excess of 500 vph on US70, and over 1,000 vph on US64, US1, and NC55. That driver-selected diversion to alternative routes results in travel time increases over 30% for Wade Ave. EB (+59%) and Davis Drive SB (+33%), as well as significant impacts to I-440 EB (+20%), I-540 EB (+20%), and US64 WB (+30%). Similar to the AM Peak, many of these impacts are mitigated with the three-lane open option, and a travel time increase over 30% is estimated only for US64 westbound (+32%), with other significant impacts on I-440 EB (+17%), Wade Avenue EB (+21%), NC55 EB (+14%), and Davis Drive SB (=10%).

Finally, it should be noted that the contractor scenarios in the design-build contract had not been finalized at the time of this writing. As a result, the actual impacts of the work zone are expected to differ depending on how close the final contractor phases and stages are to the modeled scenarios.

In conclusion, this project provided an in-depth and comprehensive comparison and application of three software tools for evaluating corridor and network impacts of a major urban freeway work zone. All three models were calibrated and validated with a significant amount of field-measured data and local work zone capacity estimates from prior research. Further work on monitoring, measuring, and validating the actual impacts will be carried out in a follow up research project.

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1. Introduction

Major work zones can cause significant disruption to travel conditions on freeways. The magnitude of the congestion caused by construction activities is influenced by factors such as: 1) the severity and duration of resulting capacity reductions (generally lane closure plus reduced capacity of the open lanes), 2) the timing of the lane closures relative to the peak demand periods on the facility, and 3) amount of traffic diversion that can be achieved as drivers avoid the (long-term) construction zone. However, while traffic diversion can help alleviate congestion on the freeway mainline, it can simultaneously result in severe traffic pressure and congestion on signed (and unsigned) alternate routes on the surrounding traffic network.

NCDOT anticipates that such corridor and network level impacts will arise from Transportation Improvement Project (TIP) I-5311/I-5338, which is a pavement rehabilitation project on Interstates I-40 and I-440 in Raleigh, NC. The I-40 and I-440 corridors carry approximate Average Annual Daily Traffic (AADT) volumes up to 113,000 and 90,000 vehicles per day (vpd), respectively. These demand levels already produce recurring peak-hour congestion in the vicinity of the proposed work zone. The freeway capacity reduction associated with the work zone includes 24-hour, multi-week lane closures, that will likely lead to significant diversion of traffic to the surrounding road network. While some work zone activities can be completed with nighttime and weekend work (periods of lower traffic demand), construction activity during weekday peak hours (AM and PM) are required for this project. In addition to freeway mainline congestion, this work zone is therefore expected to result in significant congestion impacts on diversion routes and other choke points in the network. This research was geared to explore and quantify diversion patterns and resulting congestion and use that information to assist the NCDOT with developing informed network traffic management plans for the work zone.

Background

The Federal Highway Administration (FHWA) recently published two volumes in the Traffic Analysis Toolbox devoted to work zones (FHWA 2009). While not offering a new methodology for work zone analysis, the document summarizes existing methods and classifications of tools that are applicable to work zone analysis. Among others, the toolbox distinguishes between macroscopic traffic analysis tools, microscopic traffic simulation, and mesoscopic simulation. These alternative approaches generally differ in the level of resources required, the necessary modeling resources, and the level of technical risk resulting from poor data or user error.

Macroscopic traffic analysis tools like FREEVAL, a computational engine implementation of the freeway facilities method in the 2010 Highway Capacity Manual (HCM, TRB 2010), can be readily applied to work zone evaluation (Schroeder and Rouphail, in press). The FREEVAL tool has recently been enhanced specifically for application in North Carolina, including an improved planning- and work-zone-specific user interface in FREEVAL-WZ (Schroeder et al., 2011, Sajjadi et al., 2012). The FREEVAL methodology has been validated against field data and compared favorably to simulation-based approaches (Hall et al., 2000), and has more recently been validated to sensor-based work zone performance data in North Carolina (Schroeder et al., 2012). However, while the FREEVAL and HCM methodologies are very appropriate for the evaluation of a work zone on a single freeway facility, they are inadequate tools (when used in isolation) for studying network-wide impacts of work zones.

Per guidance in the FHWA Toolbox (FHWA 2009), a micro-simulation tool is very appropriate for evaluating network-wide impacts of work zones. A micro-simulation tool uses microscopic (agent-based) algorithms for car-following, lane-changing, and gap acceptance, etc. to explicitly model the behavior of drivers in a time-step-based simulation. By modeling the behaviors of all drivers on the network, the simulation model can then estimate congestion impacts at the network level in great detail. However, one of the limitations of a microscopic modeling approach can be the increased computational complexity and potentially difficult calibration to local conditions (Zhang 2008). Also, not all micro-simulation models include the ability to dynamically assign or re-assign traffic to routes on the network under consideration of congestion patterns. Without this *dynamic traffic assignment* (DTA) feature, alternative routes have to be user-defined, which results in the analyst having to specify all the routing assumptions with little quantitative support.

Mesoscopic simulation models provide a more computationally-efficient approach to analyzing large transportation networks, by using macroscopic traffic stream relationships (e.g. link-based speed/flow/density) to model behavior of individual vehicles. Mesoscopic models have previously been used for very large network analyses, for example for predicting traffic patterns from a downtown evacuation event (Kwon et al, 2005), as well as evaluation of Active Traffic Management Strategies in the Triangle region in North Carolina (Williams et al, 2011). Mesoscopic models implement DTA algorithms that can update routing decisions of vehicles based on capacity reductions (from work zones), congestion patterns, and even impacts of deploying various technologies for enhanced traveler information. For this research, mesoscopic tools are therefore ideally suited for modeling a large and complex network efficiently, while allowing for evaluation of diverse traffic management strategies.

Objectives

The principal objective of this research is to quantify and illustrate network-level impacts generated from the I-5311/I-5338 project work zone. In this project, the ITRE team used a combination of mesoscopic network modeling in DynusT and DTALite, and macroscopic corridor-level analysis in FREEVAL to identify the expected impacts on the projects, as well as anticipated diversion patterns across the network.

Without a robust, network-wide assessment of expected diversion rates, queuing patterns, and delay impacts, it will be challenging to develop a reasonable traffic management plan for this project and anticipate diversion patterns. The goal of this research is to estimate how severe queuing impacts on the freeway are expected to be, and more importantly, how drivers are expected to adjust their travel patterns towards alternate routes. Knowledge of diversion behavior and critical choke points in the surrounding networks will help NCDOT anticipate problems and be proactive in their approach to managing this work zone. The results of this research will inform and guide the network-wide traffic management plan for this work zone project, with the goal of minimizing the impacts of the construction activities on the quality of service of the traveling public.

Report Content and Limitations

This report is produced through NCDOT research project 2012-36, which is divided into six research tasks: 1. Project Work Plan and Schedule, 2. Mesoscopic Baseline Model, 3. Mesoscopic Work Zone Scenarios, 4. Macroscopic Base and Work Zone Scenarios, 5. Interim Project Report, and 6. Final Project Report. This report represents the deliverable of Task 6: Final Project Report.

This report provides NCDOT with results obtained from all tasks. It presents an estimate on the expected congestion impacts caused by the aforementioned work zone. Due to the extremely large scale of the modeled, caution should be taken in the interpretation of the *absolute impacts* of the work zone. While the team went through a rigorous calibration and validation effort, some errors in the calibration results remained. A partial calibration success is common in the application of mesoscopic models, as not all variability of traffic patterns in a large region-wide network can be predicted by simulation algorithms. The interpretation of the results in this report should therefore focus on the *relative impacts* of the work zone when compared to the (partially calibrated) baseline. As all work zone scenarios use the same baseline, this type of relative comparison is the most appropriate analysis approach.

The remainder of this report is organized as follows. Chapter 2 presents the research methodology, including discussions on data acquisition, DynusT model development, and model calibration and validation approach. Chapter 3 presents a summary of the macroscopic FREEVAL tool. Chapter 4 presents the results from the mesoscopic simulation tool DynusT, while Chapter 5 gives the results of the DTA-Lite tool. Chapter 6 offers conclusions and interpretation of the results, followed with a discussion of next steps and recommendations for the remainder of the project. The document concludes with a list of references in Chapter 7, as well as several detailed appendices. The body of this report is deliberately kept as at a manageable length, with detailed results deferred to various appendices. Nonetheless, these appendices represent an important component of this research, and the reader is encouraged to refer to them to supplement the body of this final report. The five appendixes to this report are as follows:

- Appendix A: Work Zone Lane Configuration Maps
- Appendix B: Field Data Details
- Appendix C: Detailed FREEVAL Results
- Appendix D: Detailed DynusT Results
- Appendix E: Detailed DTALite Results

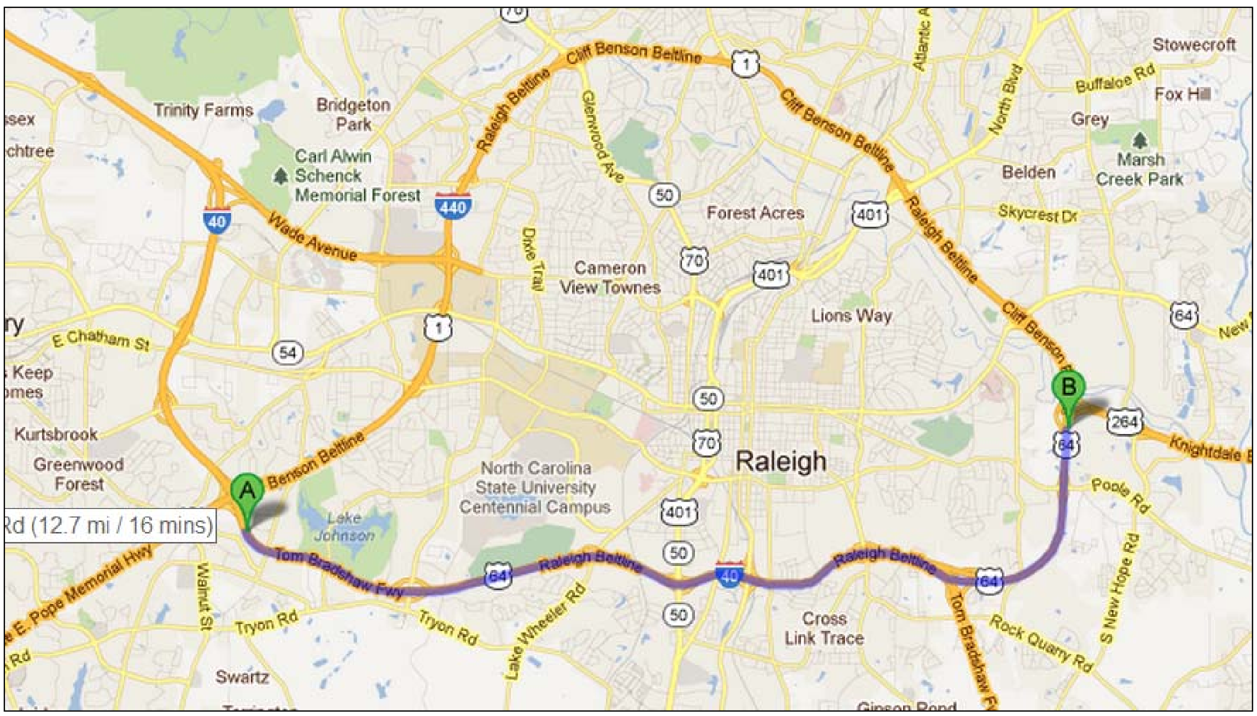
2. Methodology

This chapter presents the study methodology used in this project, including an overview of field data acquisition, model development of the DynusT and DTALite mesoscopic tools, and approach for using the macroscopic FREEVAL tool. The chapter is supplemented with significant additional details provided in the appendix.

Project Scope

The objective of this research is to quantify and illustrate network-level impacts from the I-5311/I-5338 project work zone. The work zone is scheduled to be deployed on Interstate Highway 40 from US1 interchange to I40/440 split, and continues on Interstate highway 440 from I40/440 split up to US64/264 interchange. The work zone section extends from Exit 293 on I-40 through Exit 301 at I-40 and Exit 14 on I-440, with a total length of around 11 miles. Exhibit 1 shows the work zone extent on a map of the area.

Exhibit 1: Work Zone in the Study Area (Source: Google)



The planned I-5311/I-5338 work zone will significantly reduce capacity on the I-40 and I-440 freeway facilities for an extended period of time, resulting in significant but undetermined traffic impacts on the surrounding transportation network.

The research uses a region-wide, mesoscopic traffic simulation model to predict traffic diversion patterns and estimate congestion patterns on the subject facility, as well as the surrounding road network. The study area used in the model includes the entire *Triangle Regional Model* network, which is the basis of a large regional travel demand model. The study area has further been expanded to include key links east of the Triangle area, specifically the I-95 corridor between interchanges with I-40 and US-264. The US-264, I-40, and I-95 corridors east of the triangle are expected to carry at least some diversion traffic from the work zone, especially commercial truck traffic.

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 2 and 3 show the EB and WB geometries, respectively. The exhibits 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 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 3 shows a total length of 20.2 miles with the work zone 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 2: Eastbound Lane Geometry and Work Zone Extents

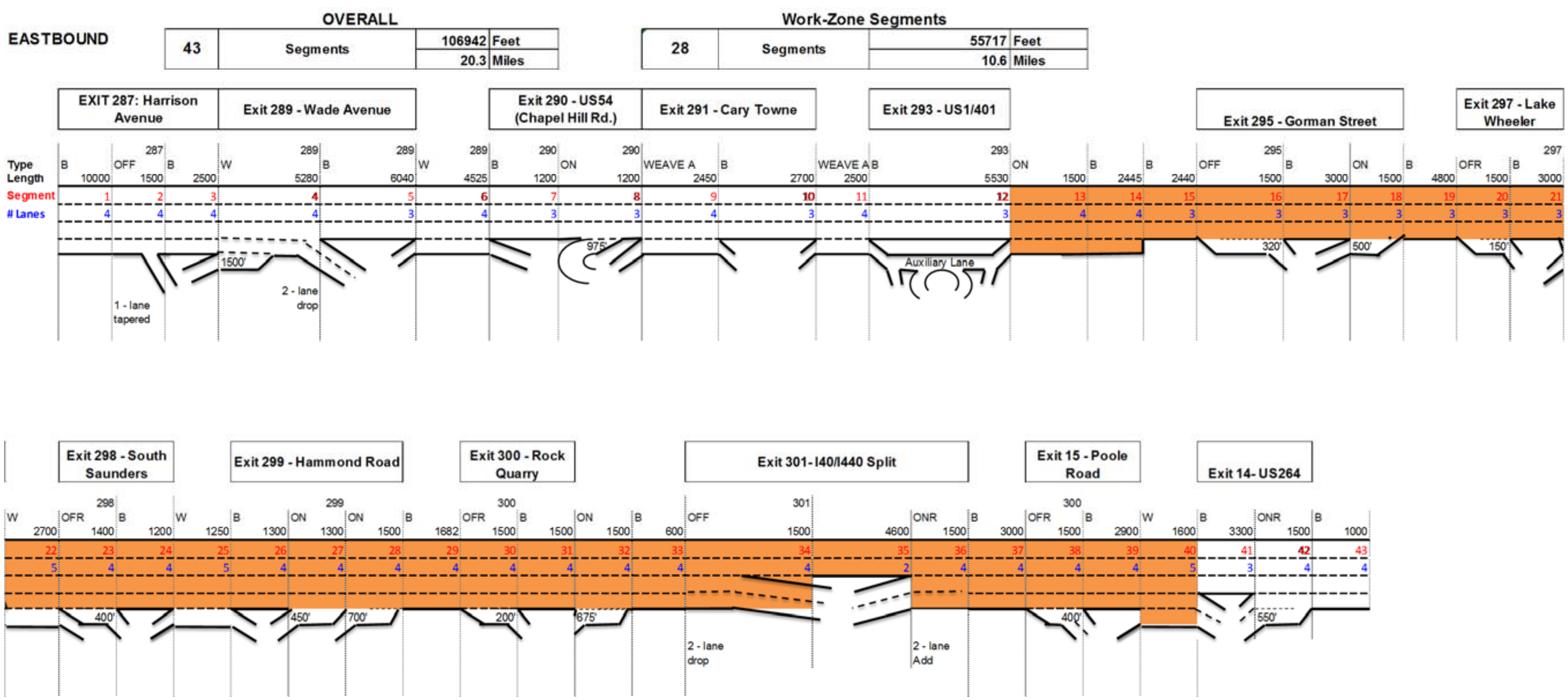
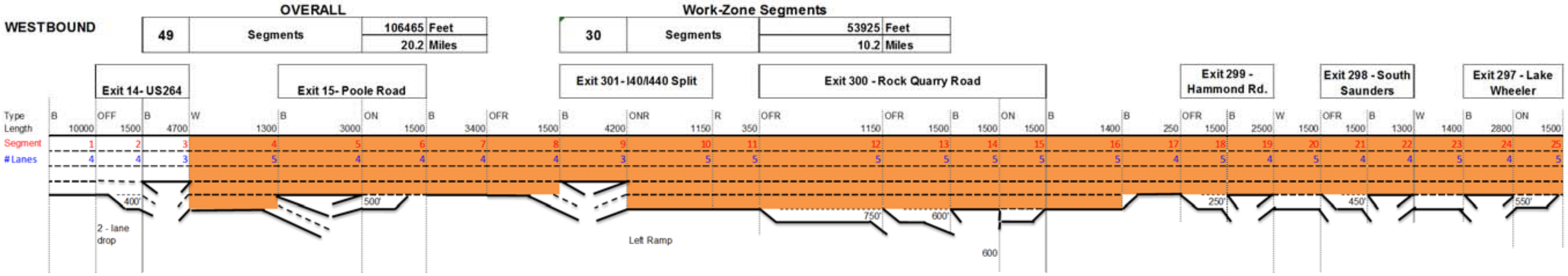
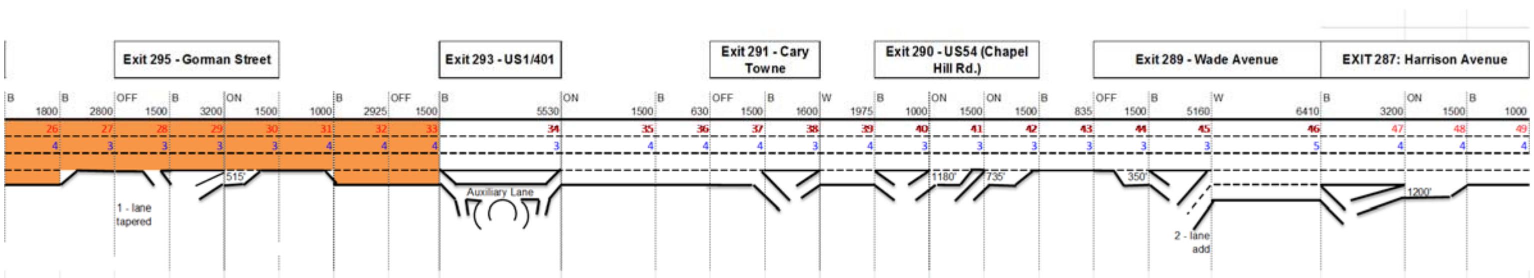


Exhibit 3: Westbound Lane Geometry and Work Zone Extents





Hypothesized Impacts

Before taking a detailed look at the model results, it is recommended to develop some hypotheses for the expected impacts of various lane closure scenarios. At a free flow speed between 65 and 70mph throughout the work zone facility, the per-lane base capacity per Highway Capacity Manual theory is about 2,400 passenger cars per hour per lane (pcphpln). This results in capacity fluctuations through the facility between 4,800 and 12,000 pcphpln. Under work zone conditions, past research has demonstrated that the remaining capacity of the open lanes under a lane closure scenario only provide approximately 1,600 pcphpln of capacity, which is a reduction of 33% over the base case. Consequently, a 5-lane to 2-lane closure work zone scenario reduces theoretical throughput from 12,000 pcphpln to 3,200, which is a 73% reduction of throughput. Exhibit 4 summarizes the percent capacity reduction when considering number of lanes and reduced per-lane capacity for a variety of lane closure configurations tested in this research.

Exhibit 4: Percentage Total Capacity Reduction for Various Lane-Closure Scenarios

Original Lanes Available*	Open Lanes During Work Zone**			
	1	2	3	4
2	-67%			
3	-78%	-56%		
4	-83%	-67%	-50%	
5	-87%	-73%	-60%	-47%

* Assumes 2,400 pcphpln base capacity

** Assumes 1,600 pcphpln work zone capacity

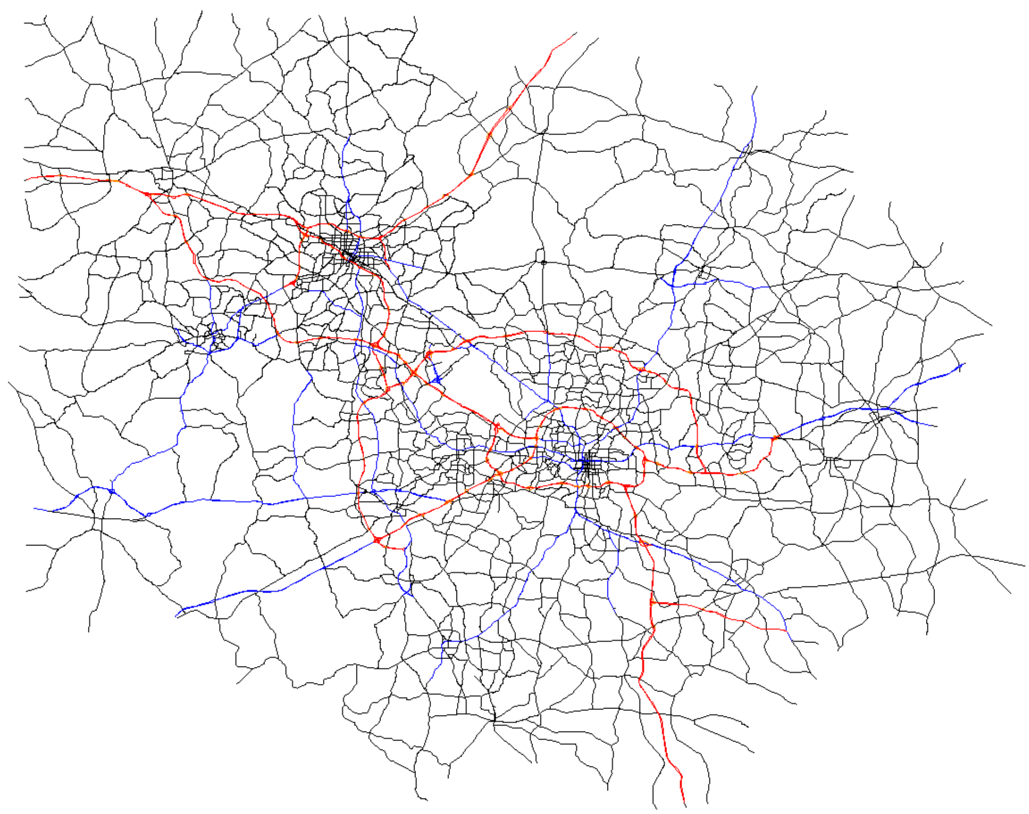
While some traffic is expected to divert from the work zone facility due to these impacts (an impact explored through the user-equilibrium dynamic traffic assignment feature in this research), these capacity reductions provide a rough approximation for expected impacts under the “no diversion” scenarios.

The work zone scenarios described in more detail below, include lane closure conditions ranging from 3-to-2 lane closures up to 5-to-2 lane closures. Consequently, capacity reductions are expected to range from 56% to 73% of the original base capacity. With a facility that is currently congested in the peak periods with demand-to-capacity (d/c) ratios exceeding 1.0, it is expected that the work zone will result in significant queuing. Assuming a base d/c ratio of 1.0, the d/c with a 56% and 73% reduction in capacity is expected to be 2.3 and 3.7, respectively.

Mesoscopic Model Development in DynusT

The DynusT network used in this project was obtained from NCDOT project HWY-2009-05 (Williams et al., 2001). The network was converted from the TRM (Triangle Regional Model), which was developed in 2010 for the planning year 2015. Exhibit 5 illustrates the original DynusT 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 DynusT network comprises 2389 traffic analysis zones, 9527 nodes, and 20,250 links.

Exhibit 5: DynusT Base Network



In this project, 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.

Since the mesoscopic simulation base model in DynusT was initially built several years ago in a prior NCDOT research project, the team had to make several modifications and additions were necessary, including:

1. *Modify the network back to year 2011* – since the original DynusT network was based on the 2015 Triangle Regional Model, several links were included that had yet to be constructed (including the I-540 southern loop for example). The team obtained a list of these construction projects to back-date the network to a 2011 base year.

2. *Expand I-40 and US-264 to the I-95 interchange* – the existing DynusT network did not cover the entire study area for this project. Specifically, several new links and zones were needed on the eastern edge of the network, to include the proposed truck detour route using US264 to I-95 to I-40.
3. *Update the demand profile for both AM and PM periods* – the Origin-Destination (O/D) Matrix for the DynusT model was obtained from the Triangle Regional Model, which is a four-hour peak period model. As a result, the team needed to estimate hourly factors from field sensors, to split the four-hour demand into four separate hourly O/D matrices with the appropriate peaking characteristics.
4. *Adjust the speed limits of all freeway and arterial links* – the link speed limit coded in the DynusT network, which represents the free flow speed in the simulation, is not consistent with the real-world traffic flow condition. Therefore, the team need go through all freeway links and adjust the speed limit if necessary.
5. *Update the traffic flow model of freeway links* – the team found that there are optimal values for the parameters of the two-regime traffic flow model in response to different speed limits. Therefore, the team updated the original traffic flow parameters for all the freeway links.
6. *Develop bottleneck traffic flow models* – several of the links in the network correspond to freeway weaving segments, which are known bottlenecks. The team developed custom traffic flow models for these segments following capacity estimates in the 2010 Highway Capacity Manual.
7. *Develop work zone traffic flow models* – with the primary objective of this project being the evaluation of work zone impacts, the team worked carefully to develop and calibrate customized work zone traffic flow models. These models are based on speed-flow model theory in the Highway Capacity Manual and calibrated to match work zone capacity estimates in North Carolina from prior research.

The process of updating the network was a very involved and time-intensive effort. Additional details are provided in the appendix.

The mescoscopic 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 (a) the travel time savings on that new route are greater than 10 minutes over the current route, OR if (b) the travel time savings are greater than 33%. Not that these rules have been customized for this project (Step 10 in the calibration process) and are more restrictive than the t in the DynusT tool.

Mesoscopic Model Development in DTALite

The DTALite network used in this project was directly obtained from the DynusT network discussed above. The data-hub system built in DTALite makes the network transfer easy and seamless. All modifications made in DynusT (relative to the Triangle Regional Model base network) are automatically transferred to DTALite except for the calibrated traffic flow models. As such, the following steps are automatically taken:

1. *Updated network back to year 2011*
2. *Expanded interchanges between I-40 and I-95 and US-264 and I-95*
3. *Updated the demand profile for both AM and PM periods*
4. *Adjusted the speed limits of all freeway and arterial links*

As discussed above, in DynusT, a two-regime model is applied to the basic freeway and on/off ramp segments; while a single-regime model is applied to highways and arterial streets. In contrast, a simplified triangular speed-density model is applied to all facility types in DTAlite with default jam density of 250 vehicles/mile/lane and wave speed of 12 mph. The team found optimal values for the parameters of the traffic flow model and made the following modifications:

- *Updated the traffic flow model of freeway links* – In the process of DTALite modeling, the research team decided to use the speed limit of 70 mph for all the links whose speed limits were code as 75 mph in DynusT and then update the original traffic flow parameters for all the freeway links. This was done because free-flow travel times were found to be too high before this adjustment relative to field data.
- *Updated bottleneck traffic flow models* – Several of the links in the network correspond to freeway weaving segments, which are well-known bottlenecks in the Raleigh metropolitan area. The team developed custom simplified triangular speed-density models for these segments following capacity estimates in the 2010 Highway Capacity Manual.
- *Developed work zone traffic flow models* – with the primary objective of this project being the evaluation of work zone impacts, the team worked carefully to develop and calibrate customized work zone traffic flow models. These models are based on speed-flow model theory in the Highway Capacity Manual and calibrated to match work zone capacity estimates in North Carolina from prior research.

Additional details of the traffic flow model modifications are provided in appendix E.

Calibration and Validation

The team went through a calibration and validation effort, using three key performance measures for validating the baseline model:

1. *Point-based traffic volumes* at key locations in the network;
2. *Point-based speed* estimates at key locations; and
3. *Route-based travel time and speed* estimates along critical network routes.

The validation includes both freeway and arterial sections, with an initial emphasis on freeways.

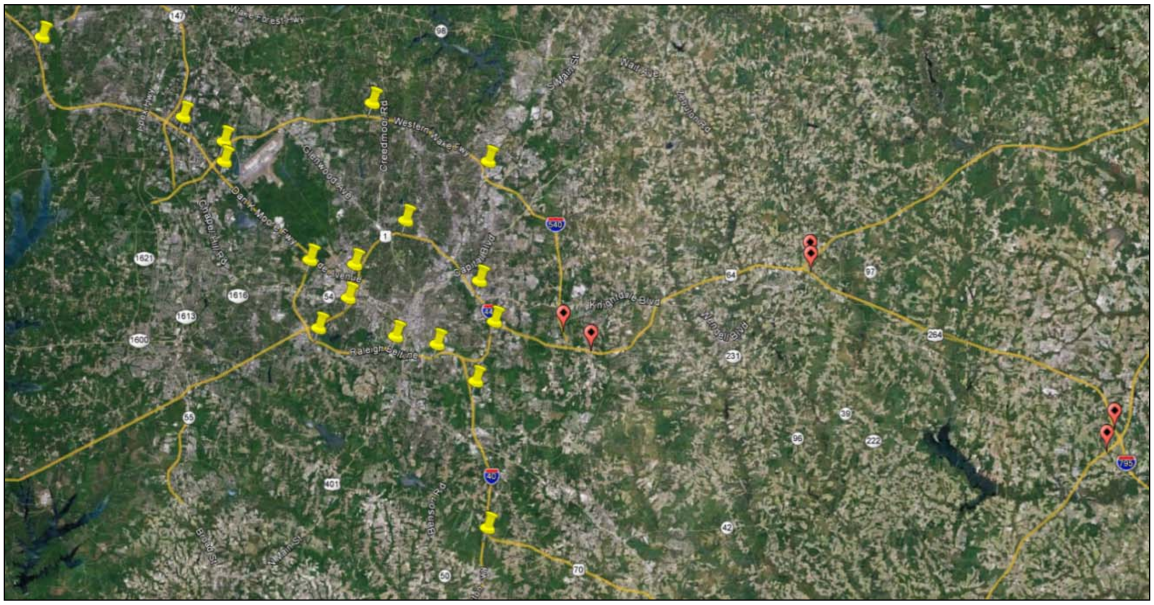
Field Data to Support Modeling

A large amount of data is necessary to support the calibration and validation of the mesoscopic baseline model. The team has relied on four different sources of data to develop the calibration and validation dataset:

1. *Sensor-based speed and volume data* from Traffic.Com side-fire radar stations across the triangle region to support volume calibration and speed validation of model results;
2. *Probe-based travel time data* from INRIX.com to support validation of modeled route travel time to field observations;
3. *Custom point volume estimates* requested from NCDOT at key locations outside of the Traffic.Com sensor coverage in the triangle; and
4. *Arterial traffic counts* on key non-freeway routes in the triangle, which are likely to serve as key diversion routes to the proposed work zone.

The traffic volume data obtained from sources 1, 3, and 4 were used with the DynusT calibration tool to modify the O/D matrix in a way that reduces the error between field-measured and modeled link volumes. These internal volumes were then also used to verify and validate the internally-modeled volumes in the network. Similarly, the point speed estimate from data source 1 were used validate point speed estimates in the network. A map showing the point sensor and count locations is shown in Exhibit 6.

Exhibit 6: Map of Point Sensor Locations for Volume Calibration



: Traffic.com Sensor Location **: Custom Count Location**

In addition to these point estimates, the team identified several key analysis routes. The team extracted INRIX travel time data for a validation of the base travel time performance in the DynusT network. All calibration and analysis routes are shown in Exhibit 7 using a start-point (green), an end-point (red), and several mid-points (blue) for each of the ten route numbers. Exhibit 8 provides a narrative and milepost of each of the routes.

For each route, the team extracted 15-minute travel time and average speed data for Tuesdays, Wednesdays, and Thursdays of the second week of each month in 2011, as well as for January 2012. These analysis periods are consistent with the point data collected. Route data were obtained from the INRIX.com online data repository. Each route includes several links, and the team summed up link travel times to yield route travel time. Similar to point-data, for most of the routes, travel time for each 15-minte time interval is the average of 39 travel time observation throughout 2011 and January 2012.

Exhibit 7: Key Route Definitions

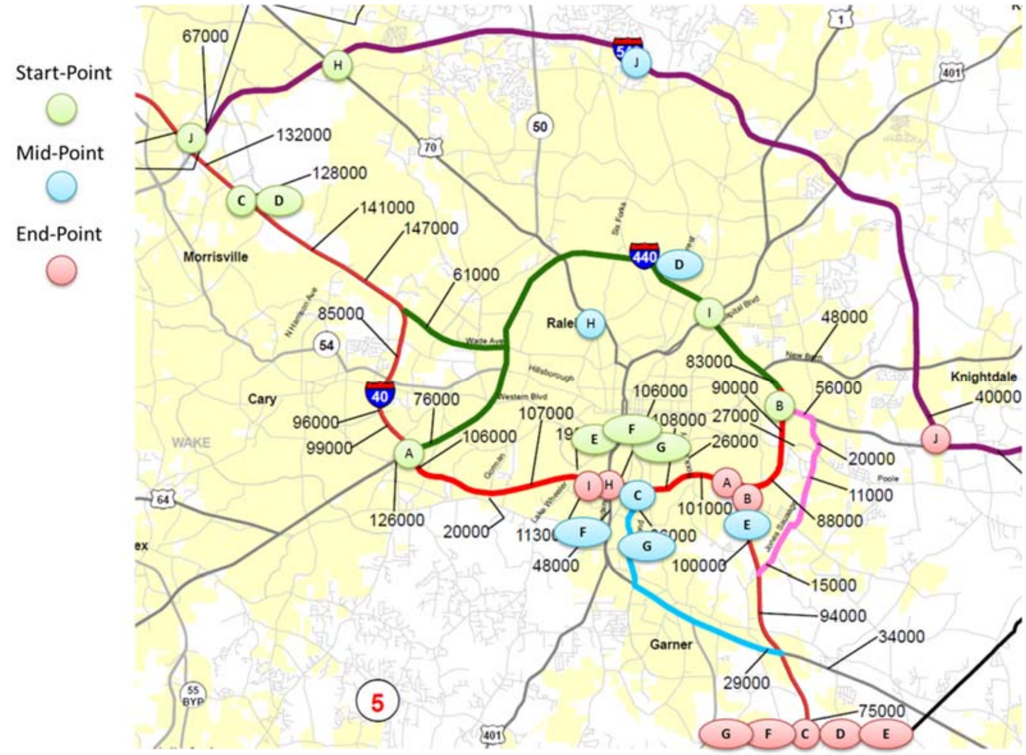


Exhibit 8: Description of Routes

#	Route Description	Start Milepost	Start Facility	End Milepost	End Facility
A	I40 WZ Section	293	I40-I440	301	I40-I440
B	I440 WZ Section	14	64/264 SPLIT	16	I40-I440
C	Triangle Route I-40	284	I-40	312	
D	Triangle Route I-440	284	I-40	312	
E	South Approach - I-40	Downtown	Saunders	312	I-40
F	South Approach - Saunders	Downtown	Saunders	312	I-40
G	South Approach - Hammond	Downtown	Saunders	312	I-40
H	US 70 Arterial	I540		I40	
I	US401 Arterial	I440		I40	
J	I540 Detour	1	I40	26	64/264

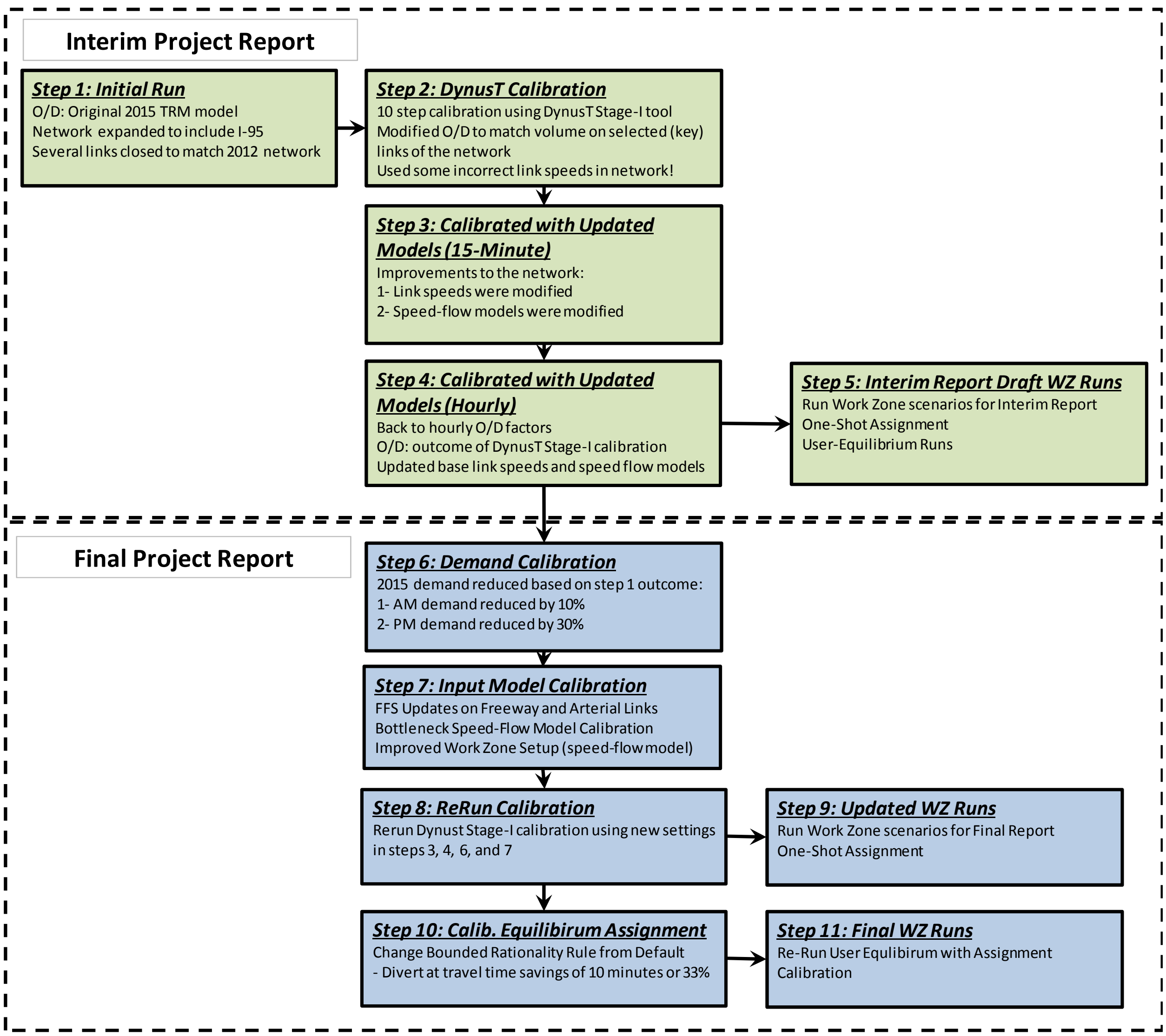
DynusT Calibration

The team initially only used the DynusT tool, and the chart below reflects the detailed calibration approach that was applied to that tool. For the DTA Lite, the final calibration results from DynusT were used as an initial approach, but were then re-calibrated using DTALite's internal calibration tool as is detailed in the next section.

Calibration and Validation Process for DynusT

The calibration and validation process for DynusT is presented in Exhibit 9 below. The DynusT calibration chart distinguishes between the calibration and validation steps that were conducted up to the time of the interim project report, as well as more recent additional calibration and validation work. Overall, the process included eleven calibration steps as outlined in the exhibit. Additional details on the calibration and validation process are provided in the Appendix, with high-level results presented below.

Exhibit 9: Calibration Flow Chart for DynusT



The calibration effort started with network and O/D volume files imported from the 2015 Triangle Regional Model (TRM), which was built in the TransCAD software. After import, several modifications to the base network were necessary, including backdating the network to 2012 geometry, and adding zones and links to the eastern edge of the network for key diversion routes. From here, the team ran the DynusT calibration tool (Step 2), updated link speed flow models (Step 3 and 4), modified the underlying hourly factors in the O/D matrix, and generated interim results (Step 5).

For the final report, the team adjusted the volume demand levels based on sensor data (Step 6), which suggested that the previous base network significantly overestimated demands. Further scrutiny was then given to the underlying speed-flow models for the work zone links, as well as key weaving bottleneck segments in the triangle (Step 7), before re-running the calibration in Step 8. Step 9 then generated updated work zone scenario results, which suggested very high diversion rates and dispersion across even very minor links in the network. Consequently, the team changed the *bounded rationality rule* in DynusT (Step 10), to where drivers will only divert if they save 10 minutes or 33% of travel time, and then generated final results (Step 11).

Calibration and Validation Results - DynusT

While the team went through an extensive calibration and validation effort, not all sensor stations could be validated against the field-measured sensor data. For a network of this magnitude a “complete” validation is very difficult to achieve, and consequently the team focused on links within the work zone, as well as key diversion routes.

The resulting network in the AM peak period was calibrated to an average error within 5% of sensor volumes, and 11% of sensor speeds. For the PM peak, all volumes on average were within 20% of field-measured sensor volumes, and within 6% of speeds in the peak hour.

The team further validated route travel times, which resulted in a match within 15% for the AM Peak period, and within 25% for the PM peak route travel times. The key routes through the work zone were validated within 9% of the travel time estimate obtained from INRIX.com probe vehicle data. For the PM peak, the key work zone routes were within 23% of the probe data, with DynusT generally estimating a higher travel time than field data.

The team concluded the calibration and validation effort with greater confidence in the AM peak period results, with the PM period showing a slight overestimation of volumes and travel times. The challenges in calibration are attributed to the large size of the network, as well as highly-variable commuting patterns across the region. A close investigation of sensor data, revealed that westbound/northbound volumes from Johnston County generally peaked about one hour earlier than the eastbound/southbound movements from Orange and Durham County. With the model requiring generalize O/D volume factors over the entire network, the team used an average volume profile across sensor stations as the best feasible estimation across the network. Additional details on the calibration are shown in the Appendix.

DTALite Calibration

The calibration process in the DTALite tool is straightforward. Starting from the final calibration results from DynusT discussed above, the demand matrices were re-calibrated using DTALite's internal calibration tool: Origin Destination Matrix Estimation (ODME). Based on the point sensor data discussed above, 200 ODME iterations were performed to calibrate the demand matrices by modifying the O/D matrices in a way that reduces the error between field-measured and modeled link volumes.

Calibration and Validation Results – DTALite

The resulting network in the AM peak period was calibrated to an average error within 2% of sensor volumes for the last three hours of peak period, and 11% of sensor speeds. The average error was 21% for the first hour of the AM peak period. This higher was deemed acceptable, as the primary performance statistics were extracted for the second hour of analysis, and the first hour was generally uncongested due to lower volumes.

For the PM peak, all volumes on average were within 4% of field-measured sensor volumes in the first three hour of the peak period, and within 9% of speeds in the peak hour. The average error was 21% for the last hour of the PM peak period.

Work Zone Scenarios

A total of seven work zone scenarios were identified for evaluation. Exhibit 10 and Exhibit 11 show these scenarios for the AM and PM Peak, respectively. The scenario description shows the lane closure configurations in parentheses. Note that westbound (WB) lane closures are generally shown as odd numbers, while eastbound (EB) lane closures have even numbers.

The scenarios in Exhibit 10 and Exhibit 11 are principally divided between westbound (WB) and eastbound (EB) lane closures. Scenarios 1 (WB) and 2 (EB) represent lane closure scenarios that maintain a *two-lane cross-section* throughout the work zone, regardless of the number of base lanes.

Scenario 3 offers a variation for the WB lane closure scenario 1, and maintains 3 open lanes in segments with four or five base lanes, thus limiting the reduction to two lanes to only those segments with 3 base lanes. Scenarios 3 was modeled for the AM Peak Hour only.

Scenario 4 mirrors scenario 3, but for the eastbound direction. Accordingly, this scenario was modeled for the PM peak hour only.

Scenario 5 represents a full three-lane cross-section in the westbound direction (regardless of the number of base lanes), and scenario 6 does the equivalent for the eastbound direction. Scenario 7 explores the feasibility of a directional crossover between I-40 exits 293 and 297. The eastbound direction between those mileposts would be reduced to two lanes and shifted into the westbound lanes. The WB lane consequently would also experience a 3-to-2 lane reduction between those mileposts. The remainder of the EB direction would maintain a three-lane cross-section.

A series of maps showing the lane configurations for the various work zones is provided in the Appendix A.

Exhibit 10: Listing of Work Zone Scenarios – AM Peak

No.	Work Zone Scenario	DynusT	DTALite	FREEVAL
1	WB lane closure, two lanes open (3 > 2, 4 > 2, 5 > 2):	Yes	Yes	Yes
1b	WB lane closure, two lanes open, (3 > 2, 4 > 2, 5 > 2, extra lane in weaves)	No	No	Yes
2	EB lane closure, two lanes open (3 > 2, 4 > 2, 5 > 2, 2 > 2*):	Yes	No	No
2b	EB lane closure, two lanes open (3 > 2, 4 > 2, 5 > 2, 2 > 2*, extra lane in weaves):	No	No	No
3	WB lane closure, two/three lanes open (3 > 2, 4 > 3, 5 > 3):	Yes	No	Yes
4	EB lane closure, two/three lanes open (3 > 2, 4 > 3, 5 > 3, 2 > 2*):	No	No	No
5	WB lane closure, three lanes open throughout (3 > 3, 4 > 3, 5 > 3):	Yes	Yes	Yes
6	EB lane closure, three lanes open throughout (2 > 3*, 4 > 3, 5 > 3):	No	No	No
7	Crossover (3 > 2, 4 > 3, 5 > 3, 2 > 2*):	Yes	No	Yes

** The "2 > 2" scenario refers to an existing two-lane cross section EB between I-40 MM 301 and I-440 MM 16, where a wide shoulder is expected to be usable as a full lane during construction*

Exhibit 11: Listing of Work Zone Scenarios – PM Peak

No.	Work Zone Scenario	DynusT	DTALite	FREEVAL
1	WB lane closure, two lanes open (3 > 2, 4 > 2, 5 > 2):	Yes	No	No
1b	WB lane closure, two lanes open, (3 > 2, 4 > 2, 5 > 2, extra lane in weaves)	No	No	No
2	EB lane closure, two lanes open (3 > 2, 4 > 2, 5 > 2, 2 > 2*):	Yes	Yes	Yes
2b	EB lane closure, two lanes open (3 > 2, 4 > 2, 5 > 2, 2 > 2*, extra lane in weaves):	No	No	Yes
3	WB lane closure, two/three lanes open (3 > 2, 4 > 3, 5 > 3):	No	No	No
4	EB lane closure, two/three lanes open (3 > 2, 4 > 3, 5 > 3, 2 > 2*):	Yes	No	Yes
5	WB lane closure, three lanes open throughout (3 > 3, 4 > 3, 5 > 3):	No	No	No
6	EB lane closure, three lanes open throughout (2 > 3*, 4 > 3, 5 > 3):	Yes	Yes	Yes
7	Crossover (3 > 2, 4 > 3, 5 > 3, 2 > 2*):	Yes	No	Yes

** The "2 > 2" scenario refers to an existing two-lane cross section EB between I-40 MM 301 and I-440 MM 16, where a wide shoulder is expected to be usable as a full lane during construction*

The exhibits further highlight which scenarios were evaluated using each software tool. It is noted here that not all scenarios were studied in each tool for various reasons. For example, DynusT was used as the initial tool for analysis of scenarios 1, 2, 3, 5 and 7 in the AM Peak, and 1, 2, 4, 6, and 7 in the PM peak.

Since DTA Lite was added as a late addition to this project, only scenarios 1 and 5 were modeled in the AM peak, and only 2 and 6 in the PM peak. At the time DTALite was added, it was determined that scenarios 3 and 4 were unlikely to ever be constructed, and were thus excluded. The modeled DTALite scenarios thus correspond to potential work zone configurations in the respective peak directions for AM and PM peak.

For the FREEVAL tool, the team initially evaluated scenarios 1, 3, 5, and 7 in the AM peak, and 2, 4, 6, and 7 in the PM peak period, each corresponding to the peak direction of travel. Two additional scenarios were later added to FREEVAL, which modify scenarios 1 and 2 to add an additional auxiliary lane in critical weaving segments on I-40 (between Lake Wheeler Road, South Saunders, and Hammond Road exits).

For all scenarios, the analysis distinguishes between a *no-diversion* and *with-diversion* scenario. The no-diversion case corresponds to a "one-shot" assignment, where all vehicles remain on their baseline paths despite the presence of the work zone. Conceptually, this corresponds to a worst-case analysis of that work zone scenario where drivers are not aware of the presence of the work zone. The with-diversion results were obtained from running mesoscopic dynamic traffic assignment (DTA) modules to (near) user-equilibrium, by repeating the network assignment twenty times. After each assignment, each simulated vehicle in the network reconsiders its routes based on its experience in the previous run. After 20 iterations, the model therefore results in a modified traffic assignment, where each vehicle minimizes its origin-to-destination travel time, under the constraints imposed by the work zone. Conceptually, this corresponds to a user equilibrium solution, under the assumption of fixed demand.

That last point needs to be treated with caution, since some traffic reduction is expected with a work zone of this magnitude. In other words, the *with-diversion* results maintain the same O/D matrix overall demand and therefore the same hourly traffic demands. In continued work following this interim report, the team plans to explore the effects of strategies like peak-spreading, car-pooling, increased transit use, or telecommuting, which would all result in an overall reduction in demand and thus the O/D matrix.

Macroscopic Model Development in 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 DynusT and DTALite are simulation tools that model 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.

FREEVAL Methodology

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 calibrated DynusT baseline files for the AM and PM peak period. The use of DynusT 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. Each lane closure was coded with the reduced number of lanes consistent with the scenario listing in Exhibit 10. 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 DynusT base volume inputs. Conceptually, these results are similar to the *one shot* results from DynusT, 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.

3. FREEVAL Macroscopic Results

FREEVAL 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.

FREEVAL Modeling Approach

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 DynusT used in this research. Exhibit 12 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.

Exhibit 12 Basic Geometric Information for FREEVAL scenario files

Route	Direction/Period	Start Point	End Point	Length (miles)	# HCM Segments
C	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
D	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 Work Zone scenarios were modeled for each route and direction. Work zone scenarios 6 and 7 were not modeled in FREEVAL since a full facility closure is not supported by the HCM freeway facilities methodology. Exhibit 13 demonstrates the list of work zone scenarios analyzed using the FREEVAL computational engine. There is a total of 16 different work zone scenarios for both routes.

Exhibit 13 List of Analyzed Work Zone Scenarios in FREEVAL

Route	Route C		Route D	
Direction/ Time Period	EB-PM	WB-AM	EB-PM	WB-AM
Work Zone Scenario	WZ-2	WZ-1	WZ-1	WZ-2
	WZ-2b	WZ-1b	WZ-1b	WZ-2b
	WZ-4	WZ-3	WZ-3	WZ-4
	WZ-6	WZ-5		
	WZ-7	WZ-7		

Scenarios WZ-1 (two lanes open on WB) and WZ-2 (two lens open on EB) represent lane closure scenarios, which maintain two lanes open to traffic through the work zone, regardless of the base number of lanes. Scenarios WZ-1b and WZ2b differ in providing one additional lane over scenarios WZ-1 and WZ-2 in the weaving segments between Exits 297, 298, and 299 (Lake Wheeler, South Saunders, and Hammond Road). In these scenarios an auxiliary lane is added to the number of open lanes, providing for a higher facility throughput.

Scenarios WZ-3 (lane closure on WB) and WZ-5 (lane closure on WB) are variations for the WB lane closure of scenario WZ-1. Scenario WZ-3 maintains 3 open lanes in all segments with four or five base lanes, and limits the reduction to two lanes only in segments with three lanes. Scenario WZ-5 maintains three lanes open in all segments, which requires any work on three lane segment to be limited to off-peak time period.

Scenarios WZ-4 (lane closure on EB) and WZ-6 (lane closure on EB) mirror scenarios WZ-3 and WZ-5, for the eastbound direction, with WZ 4 being a combination of 3 and 2-lane closures, and WZ 6 maintaining three lanes open throughout.

Scenario WZ-7 is designed for the eastbound only. This scenario explores the feasibility of a directional crossover between I-40 exits 293 and 297. The eastbound direction between those mileposts would be reduced to two lanes and shifted to the westbound direction. The westbound direction would consequently experience a 3-to-2 lane reduction between those mileposts. The remainder of the EB direction would maintain three lanes open to traffic in this scenario.

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 DynusT model. The analysis focused on Travel Time, Denied Entry Queue Length (DEQL), Queue Length, maximum demand/capacity (d/c) ratio, and Speed Contours.

FREEVAL Results

Both work zone and the base conditions’ scenarios were coded in the FREEVAL computational engine. A summary report of each scenario FREEVAL run was saved using an automated module. Exhibit 14 depicts the scenarios' key performance measures: Travel Time, Maximum Denied Entry Queue Length (DEQL), Maximum Queue Length, and Maximum Demand/Capacity (d/c) Ratio.

Exhibit 14 FREEVAL Scenarios Key Performance Measures

Route	Direction/ Time Period	Scenario	Travel Time (Minutes)	Max Queue Length (Miles)	Max DEQL (Miles)	Max d/c Ratio
C	EB / PM	Base	27.4	3.3	0.0	1.16
		WZ2	320	16.2	25.1	3.4
		WZ2b	214.2	16.2	20.9	2.8
		WZ4	122.7	11.6	30.7	2.4
		WZ6	77.8	10.4	0.0	2.3
		WZ7*	106.5	10.3	19.2	2.4
	WB / AM	Base	26.8	0.5	0.0	1.2
		WZ1	115.9	13.5	1.38	3.8
		WZ1b	58.9	8.8	0.0	2.6
		WZ3	46.9	10.9	0.0	2.5
		WZ5	47.3	10.9	0.0	1.6
		WZ7*	36.2	10.9	0.0	2.5
D	EB / PM	Base	31.7	1.0	0.0	1.2
		WZ1	68.0	8.9	0.0	3.7
		WZ1b	40.3	3.0	0.0	2.5
		WZ3	39.5	2.6	0.0	2.5
	WB / AM	Base	47.4	7.2	0.0	1.7
		WZ2	92.9	16.8	0.0	3.0
		WZ2b	67.9	14.5	0.0	2.6
		WZ4	55.6	14.0	0.0	2.0

* This scenario is designed for the EB direction, but the analysis in the WB direction considers onlooker delay impacts

Exhibit 14 shows for the westbound direction evaluation for the AM Peak period, that route C travel time for the WZ1 scenario (two lanes open throughout) increases the before travel time from 27.4 minutes to a drastic 115.9 minutes. That travel time impact is significantly offset with the provision of an additional lane in the weaving segments between Hammond Road, South Saunders Road, and Lake Wheeler Road in Scenario WZ-1b, which gives an average travel time of 58.9 minutes. Maintaining three lanes in parts of the facility (WZ 3) or the entire facility (WZ 5) further reduces the resulting travel time to 46.9 and 47.3 minutes. The direction crossover scenario WZ7 in the eastbound direction, was evaluated in the AM Peak WB direction to investigate potential onlooker impacts. With the assumptions on friction effect, FREEVAL predicts a travel time of 39.5 minutes, but this number should be treated with great caution.

In the eastbound direction, the PM peak base travel time of 27.4 minutes is predicted to increase to 320 minutes for the two-lane pattern, with some relief (214.2) minutes if maintain an additional lane in the weaving segments. The combination 3-lane and 2-lane scenario (WZ4) shows a travel time of 122.7 minutes, which is further reduced to 77.8 minutes if three lanes are maintained open throughout the work zone. The high benefit of the added three-lane segments in scenario WZ6 is explained, because these segments are in the beginning of the work zone for the eastbound PM peak direction, and therefore have a large incremental benefit. In the AM peak westbound analysis, those same segments are towards the end of the work zone, and therefore have a lesser impact. The directional crossover scenario in WZ7 is predicted to result in a travel time of 106.5 minutes.

Exhibit 14 also shows other performance measures; specifically the maximum queue lengths, and the maximum denied entry queue lengths (DEQL). The latter is an estimate of the extent of queuing beyond the facility being explicitly modeled in FREEVAL. The analysis shows that the AM queues are generally contained within the modeled facility, with exception of the two-lane pattern, where the DEQL is about 1.4 miles. The queues within the facility are on the order of 8-10 miles for the remaining scenarios, and are reduced to only 2.1 miles for the full three-lane pattern configuration.

Queuing impacts in the PM peak period westbound direction are expectedly more severe. The two-lane pattern showing a 16.2 mile queue on the modeled facility, which is estimated to extend an additional 25 miles beyond the boundary of the facility around Airport Blvd. Most of the other PM peak period scenarios show similarly high queues, and only the full three-lane pattern is able to contain the queue within the bounds of the facility at a total maximum queue length of just over 10 miles.

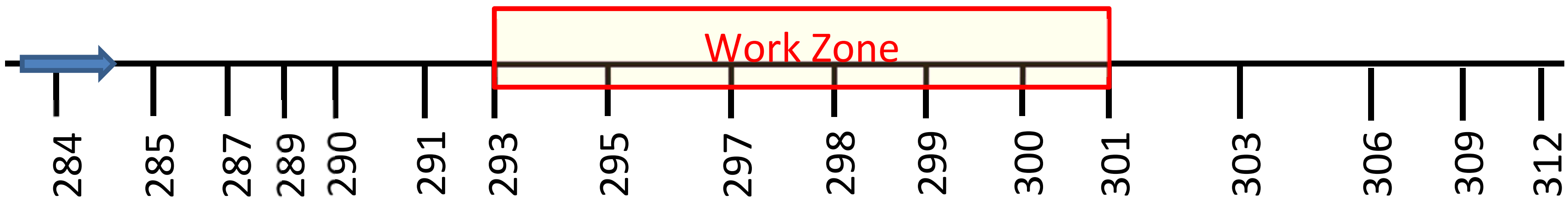
In addition to the Route C results, Exhibit 14 shows travel time impacts on Route D. While that route avoids most of the work zone, it does travel through portions of the construction on the I-440 beltline. It is emphasized here that since FREEVAL is not a network tool, the results for Route D do NOT include any spillback effects from congestion on route C. In other words, the true travel times on Route D may be significantly longer than what is shown here, as Route D traffic may be significantly delayed in Route C congestion spillback.

But even without this spillback consideration, FREEVAL estimates impacts on Route D travel in the AM peak, increasing base travel time of 47.4 minutes to 92.9 minutes for the two lane pattern. This travel time is reduced to 55.6 minutes for the full three-lane pattern. The queuing impacts of these WZ2 and WZ4 scenarios are significant in the range of 16.8 and 14.0 miles.

For the PM peak travel on Route D, WZ1 is expected to increase baseline travel time from 31.7 minutes to 68.0 minutes, while WZ 3 provides a travel time estimate of 39.5 minutes. Estimated queue lengths for these two scenarios are 8.9 and 2.6 miles, respectively.

Exhibit 15 shows speed contour plots for Route C in the eastbound direction for the PM peak for all work zone scenarios. Additional contour maps for Route C westbound AM and Route D, as well as additional FREEVAL results are given in Appendix C: Detailed FREEVAL Results.

Exhibit 15 Speed Contours for the Base and Work Zone Scenarios for Route C (EB/PM)



Base

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
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2	60	66	64	67	61	67	59	65	65	52	67	70	66	61	51	65	49	68	68	68	60	63	66	59	61	64	65	48
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9	68	66	70	70	69	70	68	64	70	57	70	60	70	64	54	70	53	70	70	70	70	63	70	62	69	64	70	51
10	68	65	70	70	69	70	68	65	70	55	70	58	70	63	52	70	51	70	70	70	67	64	69	61	66	64	68	51
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Time	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56
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12	65	69	44	68	62	63	66	66	68	61	63	51	53	53	53	63	60	57	57	52	45	41	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	74
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WZ-2

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
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2	60	66	64	67	61	67	59	65	65	52	67	54	28	23	10	7	4	12	25	29	21	17	8	15	13	13	9	27
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Time	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56
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11	4	4	4	4	8	17	15	15	11	25	25	25	70	69	69	64	70	63	69	69	70	62	65	73	63	75	68	75
12	4	3	4	4	8	16	15	15	11	25	25	25	70	69	69	64	70	63	69	69	69	61	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
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14	4	4	4	5	11	17	16	16	11	25	25	25	70	70	70	65	70	64	70	70	70	62	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
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16	5	4	5	5	13	17	16	16	11	25	25	25	70	70	70	65	70	64	70	70	70	62	66	74	66	75	68	75

WZ-2b

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
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Time	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56
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2	11	7	5	6	10	18	17	17	12	25	25	25	70	70	70	64	70	64	70	70	70	62	66	74	66	75	68	75
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4	5	4	4	5	9	16	15	15	12	25	25	25	70	69	69	65	70	63	69	69	69	61	64	69	67	75	67	75
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13	4	4	3	4	7	16	13	13	11	25	25	25	70	70	70	65	70	64	70	70	70	62	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
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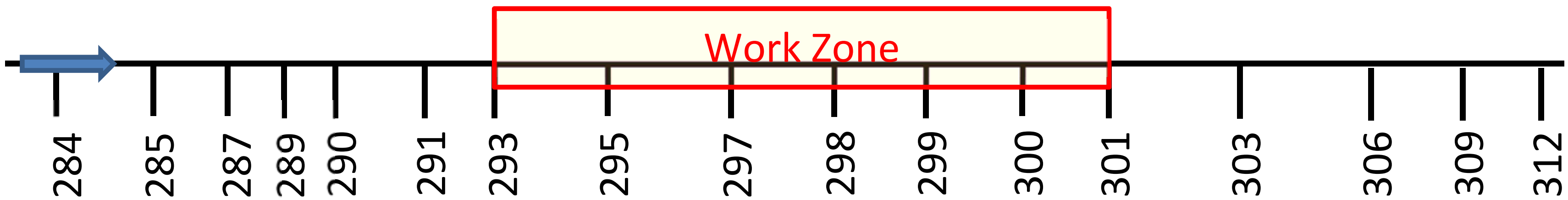
16	4	4	5	6	14	17	16	16	11	25	25	25	70	70	70	65	70	64	70	70	70	62	66	75	66	75	68	75

Exhibit 15 (Continued)



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	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56
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2	60	66	64	67	61	67	59	65	65	52	67	54	28	23	10	7	4	12	25	31	28	26	13	25	25	46	49	21	45	46	19	46	42	35	35	35	41	25	25	25	70	69	69	64	70	63	68	68	69	61	64	71	66	75	68	75
3	59	65	63	67	60	66	59	65	65	50	24	4	4	5	5	5	4	10	23	21	21	21	12	25	25	46	49	21	44	46	19	46	43	34	34	34	40	25	25	25	69	67	67	64	69	62	67	67	68	60	63	68	66	75	67	75
4	61	65	65	68	63	68	62	64	68	17	3	3	4	5	4	4	4	9	21	20	20	20	12	25	25	46	49	20	54	14	17	48	44	38	38	38	43	25	25	25	69	66	66	64	69	61	66	66	67	59	61	65	66	75	67	75
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13	3	3	2	2	1	2	3	3	2	3	3	2	3	4	3	4	4	9	19	19	19	19	12	25	25	46	48	34	15	10	19	47	43	39	39	39	45	30	30	30	70	70	70	65	70	63	70	70	70	61	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
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WZ-4

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	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56
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2	60	66	64	67	61	67	59	65	65	52	67	70	66	61	51	61	14	15	25	25	25	25	28	20	17	16	11	21	45	46	19	46	42	35	35	35	41	25	25	25	70	69	69	64	70	63	68	68	69	61	64	71	66	75	68	75
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7	60	65	64	68	62	67	60	65	66	31	5	5	6	8	5	5	6	7	14	14	14	14	9	15	15	15	11	25	11	10	18	48	40	27	27	27	32	26	26	26	70	67	67	64	68	62	66	66	67	59	60	64	65	75	67	75
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13	68	66	70	70	69	70	69	65	70	16	7	7	8	10	6	7	7	9	15	13	12	12	8	13	12	10	7	15	9	9	19	47	43	39	39	39	44	29	29	29	70	70	70	65	70	63	70	70	70	61	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
14	69	67	70	70	69	70	69	65	25	15	5	4	6	7	5	6	6	8	12	11	11	12	8	13	10	9	7	22	11	9	19	46	43	40	40	40	46	25	25	25	70	70	70	65	70	64	70	70	70	62	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
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16	69	66	70	70	69	70	69	66	66	9	5	5	6	7	5	6	6	8	13	12	12	13	8	14	11	10	8	18	10	8	19	47	45	44	44	44	46	25	25	25	70	70	70	65	70	64	70	70	70	62	66	73	66	75	68	75

WZ-6

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	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56
1	63	66	66	68	63	68	62	65	67	55	69	70	69	62	52	69	45	12	12	10	25	25	31	25	25	46	49	20	46	47	18	47	44	37	37	37	42	30	30	30	70	69	69	64	70	63	69	69	70	62	65	73	66	75	67	75
2	60	66	64	67	61	67	59	65	65	52	67	70	66	61	26	17	6	6	10	10	25	25	31	25	25	46	49	21	45	46	19	46	42	35	35	35	41	25	25	25	69	69	69	64	70	62	68	68	69	61	64	71	66	75	68	75
3	59	65	63	67	60	66	59	65	65	50	64	10	7	7	5	6	5	6	10	10	25	25	31	25	25	46	49	21	44	46	19	46	43	34	34	34	40	25	25	25	69	67	67	64	69	62	67	67	67	60	63	68	66	75	67	75
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5	61	65	65	68	63	68	62	64	67	15	5	4	6	7	6	6	5	6	10	10	25	25	31	25	25	46	49	20	53	10	18	49	44	38	38	38	44	25	25	25	70	68	68	64	69	62	67	67	69	61	64	70	66	75	67	75
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7	34	28	18	11	4	7	4	4	3	4	3	3	4	5	4	4	4	6	10	10	25	25	31	25	25	46	48	27	12	10	18	48	40	28	28	28	35	26	26	26	70	67	67	64	69	62	66	66	67	59	61	64	65	75	67	75
8	5	5	4	4	2	4	4	5	4	5	3	3	4	6	4	5	4	6	10	10	25	25	31	25	25	46	48	19	10	9	17	48	39	28	28	28	20	25	25	25	70	64	64	64	67	60	63	63	62	56	55	56	66	74	66	74
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11	12	9	7	8	4	8	7	8	6	6	4	4	5	7	5	5	5	6	9	9	25	25	31	25	25	46	55	32	54	55	23	50	45	34	34	34	53	30	30	30	70	67	67	64	70	63	68	68	70	61	65	72	63	75	68	75
12	5	5	4	4	1	4	4	5	3	5	4	4	4	7	5	4	5	5	9	9	25	25	31	25	25	46	55	22	44	21	18	48	40	31	31	31	53	27	27	27	70	68	68	64	69	62	68	68	69	61	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
13	12	9	7	7	3	7	7	8	6	6	4	3	4	5	4	4	5	7	10	10	25	25	31	25	25	46	48	21	21	10	19	47	44	39	39	39	54	31	31	31	70	70	70	65	70	64	70	70	70	62	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
14	4	3	3	3	1	3	4	4	3	5	4	4	5	7	5	5	5	6	10	10	25	25	31	25	25	46	54	42	12	10	19	46	44	41	41	41	54	32	32	32	70	70	70	65	70	64	70	70	70	63	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
15	8	6	5	6	3	6	7	7	5	6	4	4	5	6	5	5	5	6	9	9	25	25	31	25	25	46	55	41	12	11	19	46	44	41	41	41	54	37	37	37	70	70	70	65	70	64	70	70	70	62	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]
16	8	7	6	6	2	6	6	6	5	6	4	4	5	6	5	5	5	6	10	10	25	31	30	25	25	46	54	47	12	10	19	47	45	44	44	44	54	39	39	39	70	70	70	65	70	64	70	70	70	62	66	74	66	75	68	75

WZ-7

The contour maps in Exhibit 15 support the travel time and queue estimates discussed above. The color-coded cells clearly show the severe queuing impacts predicted for scenarios WZ-2, WZ-2b, WZ-4, and WZ-7 for eastbound travel in the PM peak. Only the full three-lane pattern in scenario WZ-6 is able to contain the queues within the studied facility.

Model Sensitivity to Diversion Rates

In order to assess the impact of traffic diversion on the performance of selected work zone scenarios, several diversion levels were tested. Freeway traffic diversion is a potential strategy to alleviate the work zone traffic impact. Drivers who typically travel on the work zone corridor can be encouraged to take alternative routes using Variable Message Signs (VMS), Travelers Information Systems (TIS) or media announcements. While FREEVAL cannot estimate where the diverted traffic will go (not a network tool), the purpose of the diversion analysis is to conduct a “what if” analysis of resulting operations on the corridor. The results may then be used to set diversion targets that may guide for example how aggressive an agency is on the media campaign and VMS deployment for a work zone.

The diversion rate was modeled in FREEVAL using two input variables, the Origin Demand Adjustment Factor (ODAF) and the Destination Demand Adjustment Factor (DDAF) in the FREEVAL computational engine. Since both ODFA and DDAF have identical values in this study, they will be referred to as Demand Adjustment Factor (DAF) for simplicity. The diversion conditions include the following vehicle diversion percentages on the freeway mainline:

1 - 0% Diversion, DAF = 1.0
2 - 5% Diversion, DAF = 0.95
3 - 10% Diversion, DAF = 0.90
4 - 20% Diversion, DAF = 0.80
5 - 30% Diversion, DAF = 0.70
6 - 40% Diversion, DAF = 0.60
7 - 50% Diversion, DAF = 0.50

Traffic diversion significantly impacts freeway operations and reduces the overall travel time and delay. Exhibit 16 depicts the key performance measures of travel time, Maximum DEQL, and maximum queue length for Route C in EB/PM. Results for other routes and for the AM Peak period are shown in Appendix C.

As expected, by shifting diverting traffic from the subject facility, freeway traffic operations improved significantly, although still not to acceptable levels for the very severe work zone scenarios. The WZ2 travel times of 320 minutes without diversion, is reduced to 253.5 minutes with 20% diversion and 117 minutes with 50% diversion. The latter diversion is likely overly optimistic, and 20% is considered a reasonable assumption. With 20% diversion, the queue further still spills back beyond the bounds of the facility, and at least 30% diversion is necessary to contain the queue to 15 miles and within the modeled facility.

For the full three-lane pattern in WZ6, a 20% diversion rate results in a travel time of 55.1 minutes compared to the 77.8 minutes without diversion. It also reduces the queue length from 10.4 miles to 6.9 miles.

Exhibit 16 Sensitivity Analysis to Diversion Rates on Work Zone Traffic Impact (Route C EB/PM)

Scenario	DAF	Travel Time (Minutes)	Max DEQL (Miles)	Max Queue Length (Miles)	Max d/c Ratio
Base (No WZ)	1.0	27.4	0.0	0.0	1.2
WZ2	0.50	117.2	0.0	9.8	1.7
	0.60	171.3	0.0	13.1	2.0
	0.70	216.3	0.0	15.0	2.4
	0.80	253.4	4.3	16.2	2.7
	0.90	279.2	16.4	16.2	3.0
	0.95	303.7	11.8	16.2	3.2
	1.00	320.0	25.1	16.2	3.4
WZ2b	0.50	50.8	5.7	8.0	1.4
	0.60	89.2	5.7	13.5	1.7
	0.70	138.2	5.7	15.8	2.0
	0.80	176.8	8.3	16.2	2.2
	0.90	200.1	16.0	16.2	2.5
	0.95	209.2	18.7	16.2	2.7
	1.00	214.2	20.9	16.2	2.8
WZ4	0.50	35.4	10.7	3.0	1.2
	0.60	52.8	10.7	5.9	1.5
	0.70	75.9	10.7	10.9	1.7
	0.80	105.6	10.7	11.3	2.0
	0.90	116.7	19.0	11.6	2.2
	0.95	115.8	21.0	11.6	2.3
	1.00	122.7	30.7	11.6	2.4
WZ6	0.50	29.0	0.0	0.1	1.1
	0.60	34.0	0.0	2.7	1.3
	0.70	47.6	0.0	6.0	1.5
	0.80	55.1	0.0	6.9	1.8
	0.90	62.7	0.0	8.1	2.0
	0.95	72.4	0.0	9.8	2.1
	1.00	77.8	0.0	10.4	2.3
WZ7	0.50	33.8	0.0	1.0	1.2
	0.60	43.2	0.0	1.7	1.5
	0.70	55.6	0.0	4.6	1.7
	0.80	73.5	8.8	9.1	1.9
	0.90	93.2	8.8	10.3	2.2
	0.95	100.9	14.5	10.3	2.3
	1.00	106.5	19.2	10.3	2.4

Exhibit 17 depicts average and maximum travel time for different diversion conditions of work zone scenario 2 (WZ-2), which maintains only two lanes open in the construction area. The exhibit shows that the maximum travel time reduces significantly, as more drivers are encouraged to take the alternative route. Similarly, the average travel time reduces but the rate is lower compared to the maximum travel time. The exhibit makes clear that traffic diversion has potential to alleviate the work zone impact in severely congested time periods.

Exhibit 17 WZ-2 Average and Maximum Travel Time by % Traffic Remaining on the Freeway

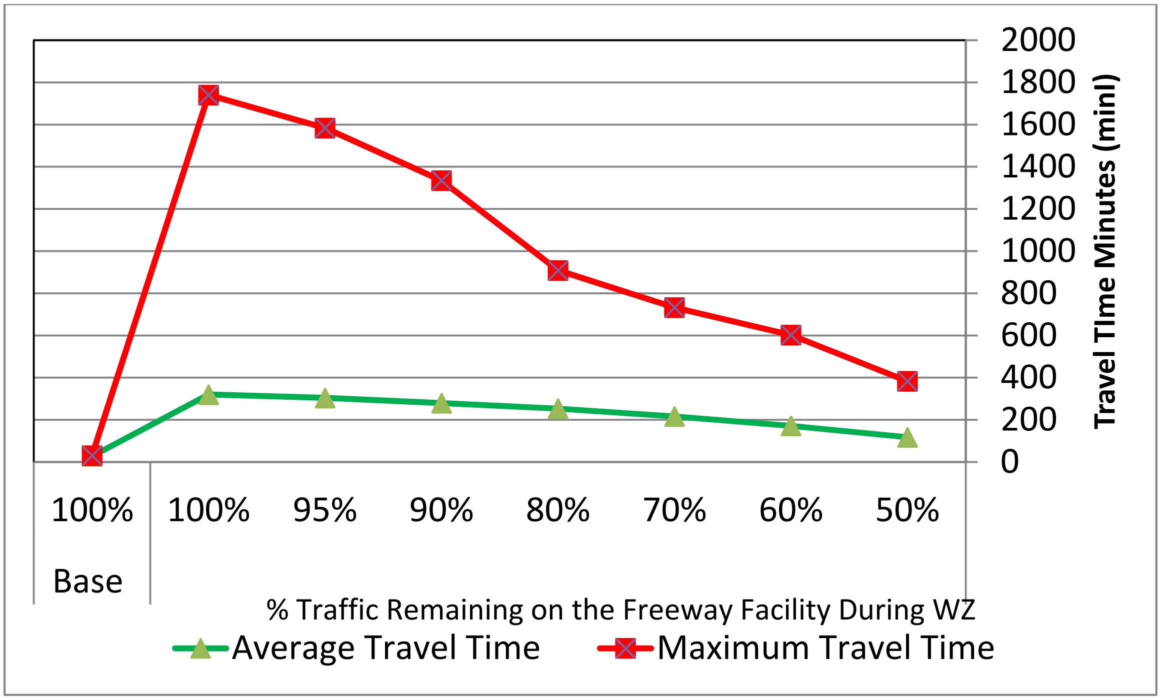
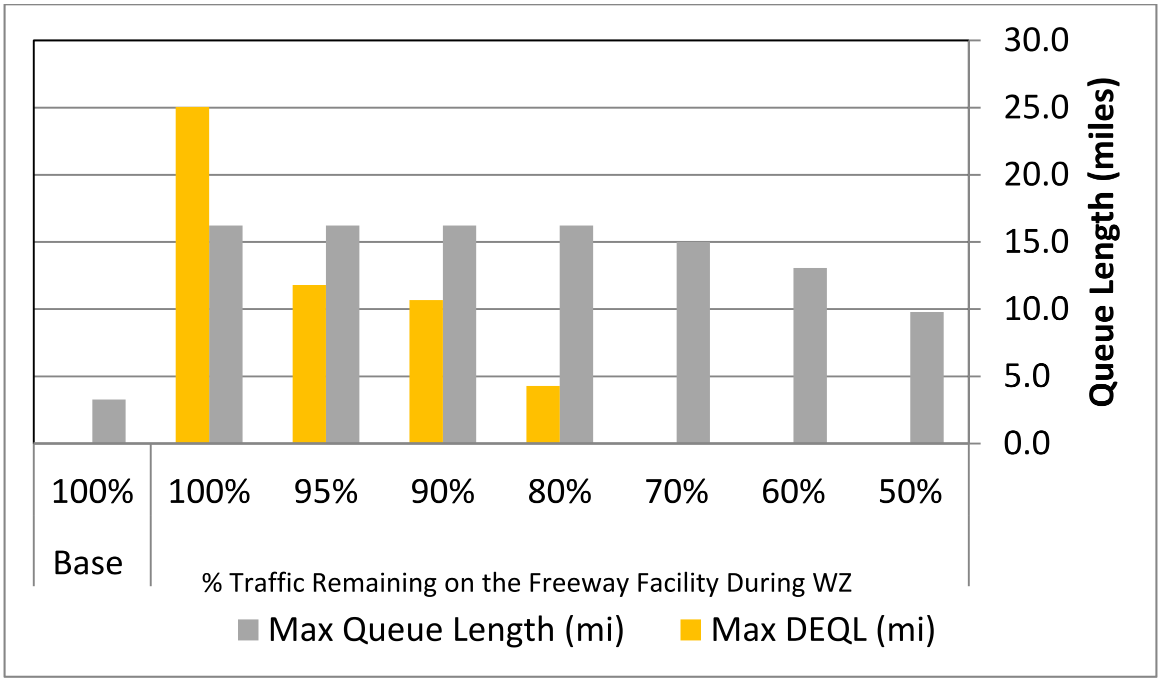


Exhibit 18 depicts the maximum DEQL and the maximum mainline queue length of work zone scenario 2. As expected, the queue length drops as the number of vehicles remaining on the mainline freeway is reduced. The exhibit makes evident that a 30% diversion is necessary to contain the queue within the extents of the modeled facility (DEQL equal zero), but that significant queuing on the facility remains even for this diversion percentage.

Exhibit 18 WZ-2 Denied Entry Queue Length (DEQL) and Mainline Queue Length



In comparison, Exhibit 19 and Exhibit 20 show the predicted travel times and queue lengths when maintaining three lanes of travel in the peak direction (Scenario WZ6).

Exhibit 19 Route C EB/PM: WZ-6 (Maintain Three Lanes Open) Average and Maximum Travel Time by % Traffic Remaining on the Freeway

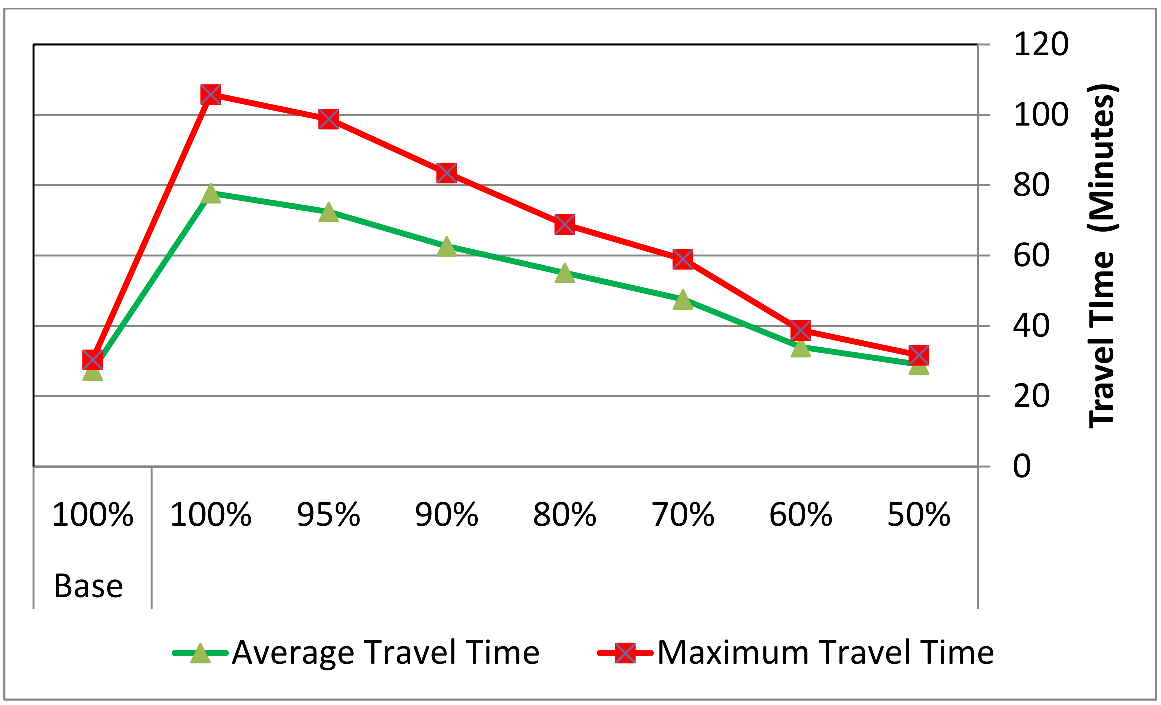
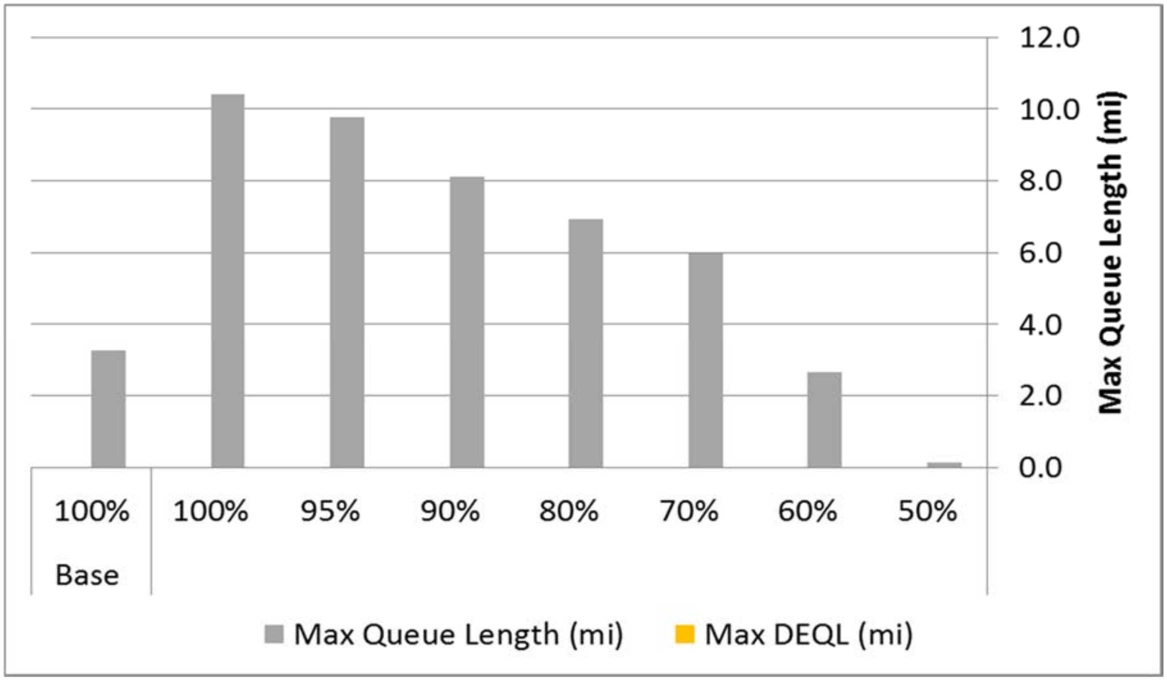


Exhibit 20 Route C EB/PM: WZ-4b (Maintain Three Lanes Open) Denied Entry Queue Length (DEQL) and Mainline Queue Length



The average and maximum travel times are significantly lower than for the two-lane pattern of WZ2 (note different y-axis scale). Diversion is predicted to have a large effect on the facility performance, reducing average travel time from about 78 minutes to about 55 minutes with 20% diversion. Similarly, the queue lengths are reduced drastically over the WZ2 results with no DEQL for WZ6 even without diversion. With 20% diversion, the maximum queue length of over 10 miles is reduced to about 7 miles on the facility.

The results very clearly show the benefit of maintain three lanes open in the PM peak period. The exhibits presented in this chapter have focused on the results for Route C in the EB/PM condition. Please refer to Appendix C for summary results of other routes and directions.

Incident Scenarios

Incidents impose large delays on the freeway transportation system. The impact of incidents occurring during the work zone construction period is assessed in this section. Seven incident scenarios were evaluated in this analysis (five scenarios on route C and two scenarios on route D). Exhibit 21 provides the details of the incident scenarios.

Exhibit 21 Incident Scenario Details

Route	Run #	WZ Scenario/ Time Period	Incident Location	Lanes Open in Incident	Incident Duration	Incident Segment Number *	Incident CAF
C	**I1**	WZ2/PM	I-40 EB @ mm 293	2→1	2 hours (4-6 PM)	18	0.44

	I1b	WZ6/PM	I-40 EB @ mm 293	3→2	2 hours (4-6 PM)	18	0.47
	I2	WZ2/PM	I-40 EB @ mm295	2→1	2 hours (4-6 PM)	23	0.44
	I2b	WZ6/PM	I-40 EB @ mm 295	3→2	2 hours (4-6 PM)	23	0.47
	I3	WZ2/PM	I-40 EB @ mm 299	2→1	2 hours (4-6 PM)	35	0.44
	I3b	WZ6/PM	I-40 EB @ mm 299	3→2	2 hours (4-6 PM)	35	0.47
	I4	WZ3/AM	I-40 WB @ mm 297	2→1	2 hours (4-6 PM)	44	0.44
	I4b	WZ5/AM	I-40 WB @ mm 297	3→2	2 hours (6-8 AM)	44	0.47
	I5	WZ3/AM	I-40 WB @ mm 301	2→1	2 hours (6-8 AM)	21	0.44
	I5b	WZ5/AM	I-40 WB @ mm301	3→2	2 hours (6-8 AM)	21	0.47
D	**I6**	WZ2/PM	I-440 EB @ mm 10	3→2	1 hour (5-6 PM)	41	0.74
	I7	WZ1/AM	I-440 WB @ mm 5	3→2	2 hours (6-8 AM)	48	0.74

The Capacity Adjustment Factors (CAF) for incidents in work zones are calculated using HCM 2010 suggested values in Exhibit 10-17. It is assumed that the capacity reduction due to incidents and work zones are independent, therefore the two adjustment factors were simply multiplied.

For example, the suggested CAF for a freeway segment, which has two lanes and where the number of lanes is reduced to one due to an incident is 0.35. Please note that this adjustment factor accounts for two lanes and in order to use this value in FREEVAL computational engine, we need to convert it to a lane by lane CAF, which is 0.70. On the other hand the suggested work zone CAF is 0.63 for such segment. The combinatorial CAF is calculated by multiplying the two values, which is 0.70*0.63 = 0.44. Route D incidents (I6 and I7) occur outside the work zone construction site and its CAF is 0.74, which just accounts for a capacity reduction due to an incident. Exhibit 22 depicts the incident locations on the map of the work area.

Exhibit 22 Incident Locations on the Map

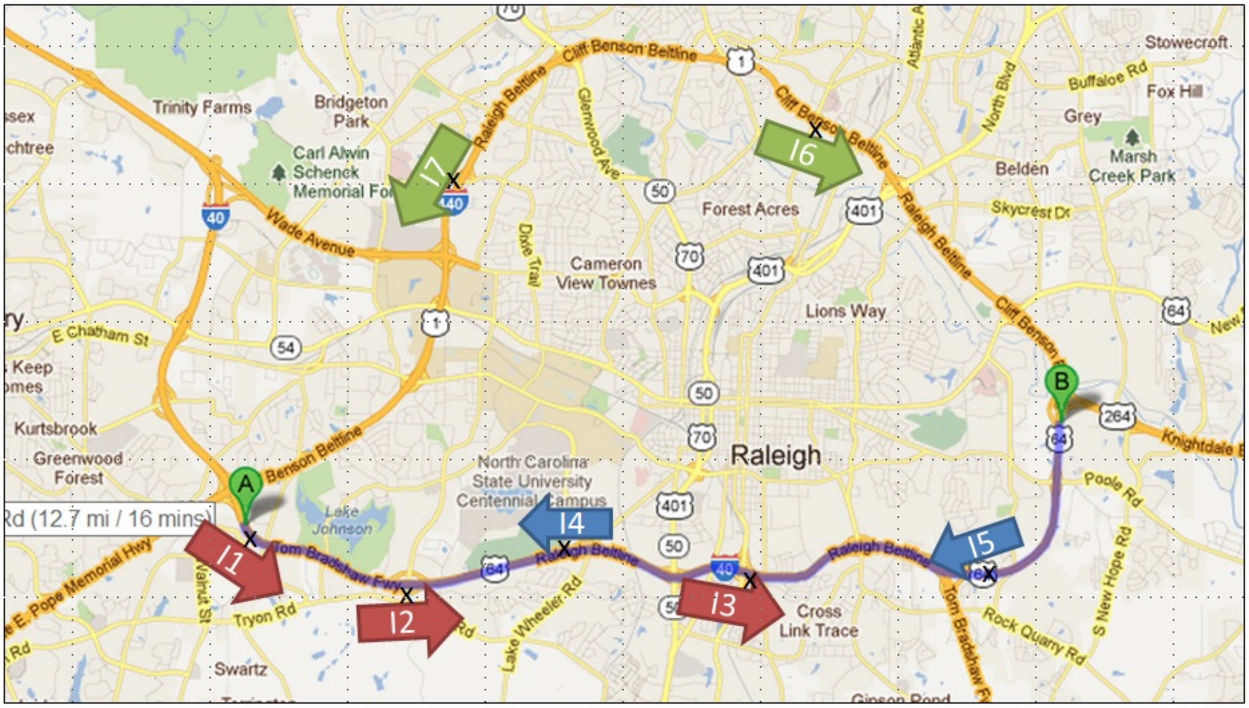


Exhibit 23 summarizes incident scenarios results.

Exhibit 23 Incident Scenario Results

Route	Run #	WZ Scenario/ Time Period	Average Travel Time (min)*	Max DEQL (miles)*	Max Queue Length (miles)*	Max d/c Ratio*
C	**I-1**	WZ-2/PM	304 (320)	25.2 (25.1)*	16.2 (16.2)*	5.3(3.4)
	I-1b	WZ-6/PM	93 (77.8)	47.6 (0)	14.2 (10.4)	2.5(2.3)
	I-2	WZ-2/PM	326 (320)	15.5(25.1)	16.2 (16.2)	5.7(3.4)
	I-2b	WZ-6/PM	84 (77.8)	0 (0)	11.8 (10.4)	2.3(2.3)
	I-3	WZ-2/PM	380 (320)	22.2(25.1)	16.2(16.2)	7.7(3.4)
	I-3b	WZ-6/PM	126 (77.8)	9.1 (0)	15.8 (10.4)	3.6(2.3)
	I-4	WZ-1/AM	132 (115.9)	3.4(1.38)	17.8(13.5)	5.6(3.8)
	I-4b	WZ-5/AM	50.3(47.3)	0 (0)	8.8 (2.1)	2.6 (1.6)
	I-5	WZ-1/AM	158(115.9)	7.5(1.38)	13.5(13.5)	6.3(3.8)
	I-5b	WZ-5/AM	78(47.3)	0.4 (0)	11.2(2.1)	3.4(1.6)
D	**I-6**	WZ-2/PM	70(92.9)	0 (0)	8.8 (16.8)	3.7(3.0)
	I-7	WZ-1/AM	93(68.0)	0 (0)	16.9 (8.9)	3.0 (3.7)

** The values in the parenthesis represent the average travel time for work zone scenario without incident.*

It should be noted that FREEVAL is not capable to evaluate highly congested conditions effectively, which some of the incident scenarios produce. However, it can provide an estimate of how poor the operating conditions are likely to be. In the following Exhibit 24, the base condition and work zone scenario are compared to incident scenarios in term of maximum demand/capacity ratio.

Exhibit 24 Maximum Demand/Capacity Ratio for Incident Scenarios Compared to Base Case and Work Zone Scenario (Maintain 2 or 3 Lanes Open During Construction)

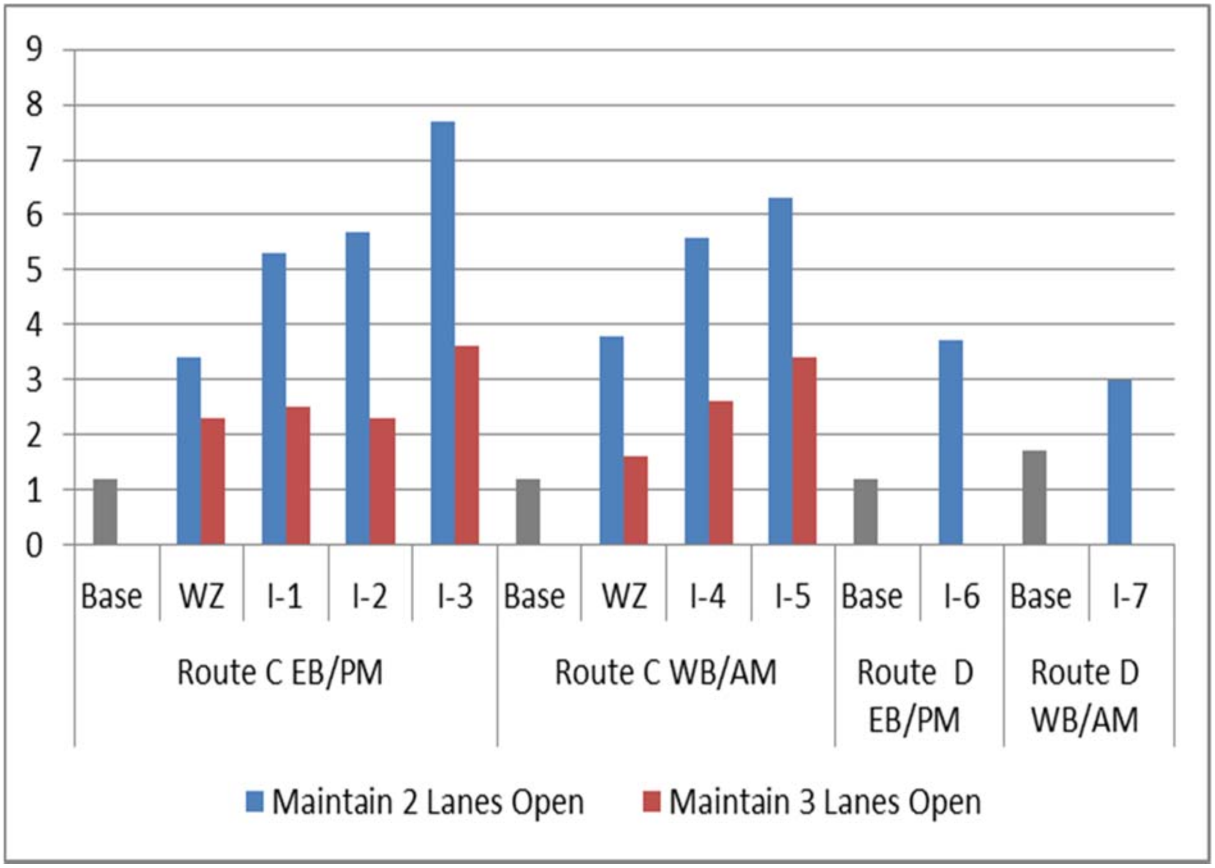


Exhibit 24 depicts that the magnitude of the incident impacts is severely higher in work zone scenarios with two lanes open. The incident scenario 3 is the worst scenario among all the incident scenarios. The analysis shows another advantage of maintaining three lanes open over just keeping two lanes open. There is no work zone scenario which maintains three lanes open during construction in route D.

FREEVAL Summary

Multiple work zone scenarios were analyzed using the FREEVAL computational engine, for routes C and D. Also, several incident scenarios were modeled on both routes in the computational engine. For route C, both two and three lanes open work zone scenarios were analyzed. For route D, only two lanes open work zone scenarios were analyzed. The result of the analysis showed that maintaining three lanes open on route C is highly advisable, especially with the likelihood of incidents. The analysis also generated promising results on the impact of effective traffic diversions for different routes. Supplementary results for all other routes and scenarios have been documented in Appendix C.

4. DynusT Mesoscopic Results

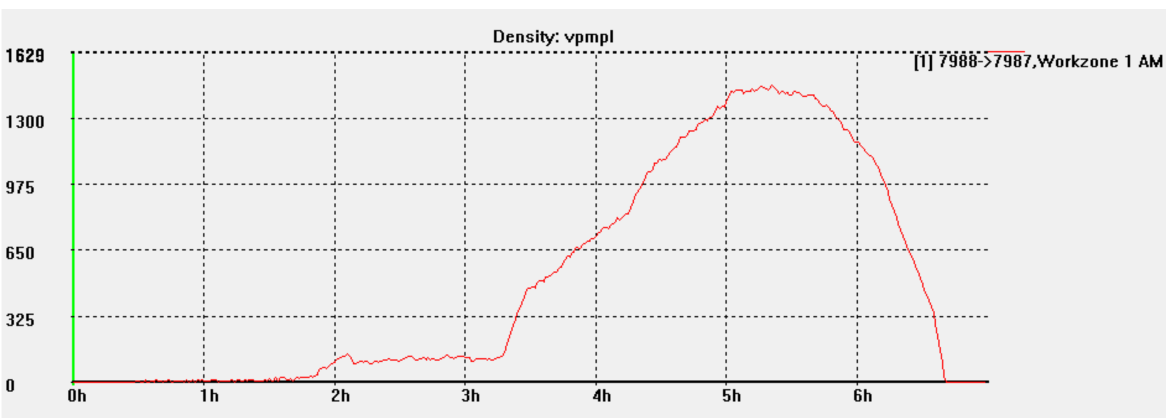
Overview

This section presents the work zone impact results from the DynusT mesoscopic simulation analysis. The results are demonstrated in terms of network-wide impacts of the work zone, the impacts of the work zone on the key routes, on one key O/D pairs, and on the other diversion routes through the network.

The research team started this project using the DynusT tool for network wide analysis of the impact of the work zone. However, results for heavily congested scenarios showed that the DynusT tools in some cases does not seems to accurately model queue spillback and propagation to upstream links. Instead, the tool appears to vertically stack the queues in cases of very severe d/c ratios (this problem was not evident in the base model for example). The result is a segment with very high densities just upstream of the bottleneck, with too-low densities in segments further upstream where the queue should be.

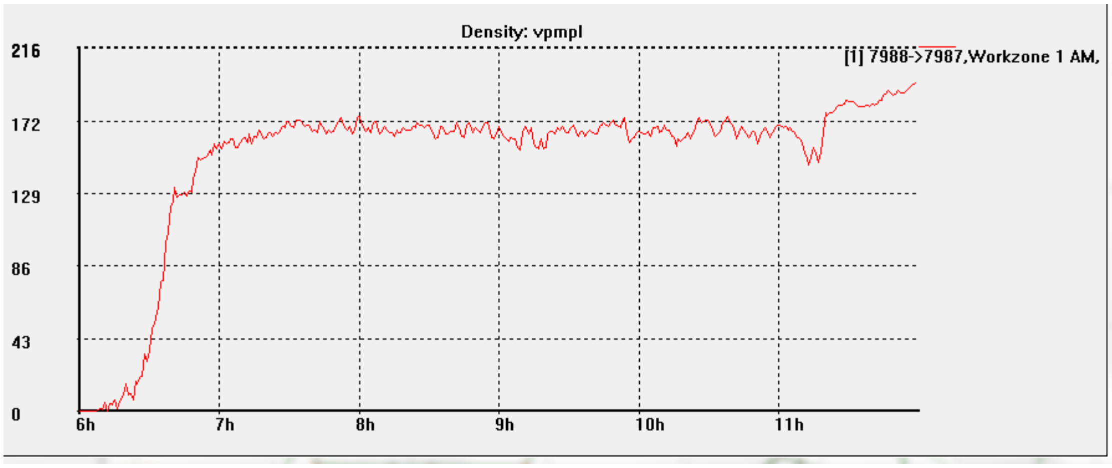
To further illustrate this point, Exhibit 25 shows very high densities in the AM peak period measured in the two-lane segment just upstream of the I-40/440 merge in the westbound direction of I-40, which is the segment immediately upstream of the work zone. A typical jam density on a freeway is expected to be on the order of 170 to 220 passenger cars per mile per lane (pcpmipln). However, the segment in question shows densities increasing to over 1,400 pcpmipln, which is indicative of the vertical queue problem and a lack of adequate propagation of congestion to other upstream segments.

Exhibit 25: High segment density observed in the DynusT tool



In comparison, Exhibit 26 shows the corresponding density plot for the same segment and time interval in the DTA Lite tool. The exhibit shows that the segment density more appropriately maxes out at approximately 170 pcpmipln, with additional unserved demand propagating to other segments upstream.

Exhibit 26: Segment density in DTALite tool



Based on these results, the research team feels that the results obtained from DTALite are more realistic than DynusT – at least for scenarios with severe levels of congestion. As a result, the findings in the rest of this chapter should be treated with some caution.

Network-Wide Impacts

Exhibit 18 shows four network-wide performance measures (average travel time, average travel distance, average stop time, and total number of unserved vehicles) for the Baseline and different work zone scenarios in the AM peak period. The number of unserved vehicles refers to those drivers who were unable to reach their desired destination within the simulated time period. The AM and PM analysis periods in the DynusT models contained approximately 1.1 million and 2.1 million vehicles respectively. The number of unserved vehicles needs to be interpreted as a fraction of that overall modeled demand to draw conclusions about the percentage of demand unserved. In addition, the percent difference for each performance measure from the Baseline scenario is presented. As expected, the Baseline scenario has the lowest average travel time, highest average travel distance, and lowest average stop time and number of unserved vehicles. This indicates that all tested work zone scenarios have resulted in a deteriorated network performance in the AM peak period, which was anticipated.

All no-diversion work zone scenarios, as expected, resulted in longer average travel time, shorter average travel distance, longer average stop time, and greater number of unserved vehicles when compared to the with-diversion work zone scenarios (in the AM peak period). This was expected since in the no-diversion work zone scenarios, vehicles were not allowed to change their routes in response to the congestion resulting from the work zone. On the other hand, in work zone scenarios with diversion, vehicles may switch their routes to those with lower travel time and consequently improve overall network performance.

The labeling of work zone scenarios was presented in an earlier section, but is repeated here for quick reference:

- WZ 1 – Westbound lane closure, two lanes open throughout
- WZ 2 – Eastbound lane closure, two lanes open throughout

- WZ 3 – Westbound lane closures, maintain three lanes for sections with 4 or 5 base lanes
- WZ 4 – Eastbound lane closures, maintain three lanes for sections with 4 or 5 base lanes
- WZ 5 – Westbound lane closures, maintain three lanes throughout
- WZ 6 – Eastbound lane closures, maintain three lanes throughout
- WZ 7 – Eastbound two-lane cross-over scenario in three lane section, with three lanes open throughout rest of the facility.

Exhibit 27: Network-wide Work Zone Impacts: Absolute and Relative to Baseline in AM Peak

Scenario		Average TT		Average Travel Distance		Average Stop Time		# of Unserved Vehicles	
		Min.	% Diff	Min.	% Diff	Min.	% Diff	Veh.	% Diff
Baseline		30.14	n/a	11.92	n/a	4.01	n/a	40168	n/a
WZ 1	No-Diversion	36.65	21.6%	11.65	-2.3%	10.07	151.1%	64088	59.5%
	With-Diversion	**31.58**	**4.8%**	**11.72**	**-1.7%**	**4.39**	**9.5%**	**44871**	**11.7%**
WZ 2	No-Diversion	35.12	16.5%	11.73	-1.6%	9.64	140.4%	57435	43.0%
	With-Diversion	**31.12**	**3.3%**	**11.73**	**-1.6%**	**4.07**	**1.5%**	**44815**	**11.6%**
WZ 3	No-Diversion	34.44	14.3%	11.75	-1.4%	9.17	128.7%	53325	32.8%
	With-Diversion	**31.17**	**3.4%**	**11.72**	**-1.7%**	**4.12**	**2.7%**	**44672**	**11.2%**
WZ 5	No-Diversion	33.06	9.7%	11.85	-0.6%	9.08	126.4%	46548	15.9%
	With-Diversion	**31.14**	**3.3%**	**11.73**	**-1.6%**	**4.08**	**1.7%**	**44606**	**11.0%**
WZ 7	No-Diversion	34.65	15.0%	11.83	-0.8%	9.43	135.2%	46868	16.7%
	With-Diversion	**31.26**	**3.7%**	**11.7**	**-1.8%**	**4.12**	**2.7%**	**44729**	**11.4%**

For the no-diversion work zone scenarios, the average network travel time increased from 9.7% to 21.6%. This is a significant increase in average travel time in the network; however, it should be noted that no-diversion scenarios represent worst-case scenarios that are highly unlikely to occur in real-world conditions. However, they could also be viewed as a second baseline by which to gauge the ability of the existing diversion routes to carry the diverted traffic load. Scenarios with fewer open lanes (scenarios WZ-1 and WZ-2) yielded longer average delay than those with more open lanes (scenarios WZ-3, WZ-5, and WZ-75).

The average travel time increased from 3.3% to 4.8% for the work zone scenarios with diversion (compared to the base line). As mention before, the WB direction carries heavier traffic in the AM peak period than the EB direction. Therefore, scenario WZ-1 (with WB lane closure) resulted in slightly higher network-wide average travel times than scenario WZ-2 as well as for the rest of the scenarios. Scenarios WZ-3, WZ-5, and WZ-7 maintained one more open lane than scenario 1 and resulted in shorter network-wide average travel time. It should be emphasized that the overall percent increase in travel time includes links across the network, including many that are quite far away from the work zone itself, including the City of Durham and the Town of Chapel Hill to the west, as well as areas north, east, and south of Raleigh. The fact that the lane closures result in a roughly 3-5% increase across the entire network is therefore a very significant impact.

The number of unserved vehicles across the network are relatively constant across the various work zone scenarios at 46,000 to 64,000 trips in the no-diversion cases, and around 45,000 vehicles in the with diversion cases. With a total of roughly 1.1 million trips modeled in the AM analysis period, the with-diversion cases therefore result in roughly 4% unserved trips, which is acceptable – especially given that the unserved trips for the base-case scenario was very similar.

In the PM peak period, all work zone scenarios yielded longer average travel time, shorter average travel distance, and greater number of unserved vehicles in the network, as shown in Exhibit 19. The number of unserved vehicles needs to be interpreted in relation to roughly twice as many trips modeled in the PM peak analysis, which corresponds to an overall percent unserved trips of roughly 2.8%, which is actually less than the AM period. Similar to the AM peak period, the work zone scenarios with diversion resulted in more efficient network performance compared to the ones without diversion. In addition, scenarios with more open lanes (WZ-4, WZ-6, and WZ-7) yielded shorter average travel time and average stop time than scenarios with fewer open lanes (WZ-1 and WZ-2)

Exhibit 28: Network-wide Work Zone Impacts - PM Peak

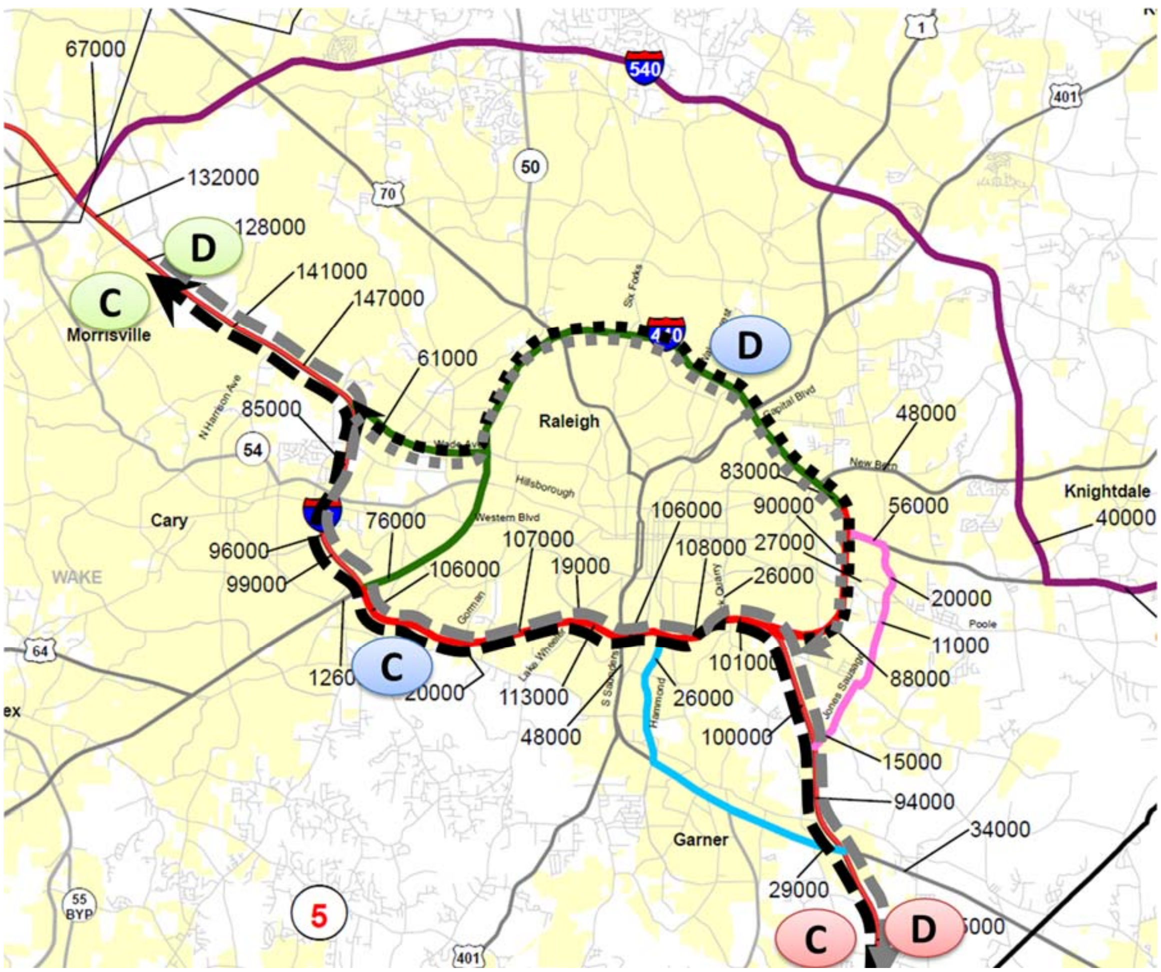
Scenario		Average TT		Average Travel Distance		Average Stop Time		# of Unserved Vehicles	
		Min	% Diff	mi	% Diff	min	% Diff	Veh.	% Diff
Baseline		26.4	n/a	9.71	n/a	3.9	n/a	55166	n/a
WZ 1	No-Diversion	30.74	16.4%	9.54	-1.8%	7.93	103.3%	82360	49.3%
	With-Diversion	27.36	3.6%	9.53	-1.9%	3.91	0.3%	61601	11.7%
WZ 2	No-Diversion	30.12	14.1%	9.5	-2.2%	7.87	101.8%	80045	45.1%
	With-Diversion	27.29	3.4%	9.54	-1.8%	3.89	-0.3%	61465	11.4%
WZ 4	No-Diversion	27.73	5.0%	9.61	-1.0%	5.98	53.3%	65380	18.5%
	With-Diversion	27.16	2.9%	9.54	-1.8%	3.79	-2.8%	61438	11.4%
WZ 6	No-Diversion	27.67	4.8%	9.69	-0.2%	6.12	56.9%	58904	6.8%
	With-Diversion	27.14	2.8%	9.53	-1.9%	3.81	-2.3%	61352	11.2%
WZ 7	No-Diversion	29.01	9.9%	9.63	-0.8%	7.21	84.9%	63574	15.2%
	With-Diversion	27.29	3.4%	9.52	-2.0%	3.86	-1.0%	61555	11.6%

The increase in network-wide average travel time ranged from 4.8% to 16.4% for the various no-diversion scenarios. Again these scenarios represent the worst-case conditions and are very unlikely to happen in the real-world. In the diversion scenarios, the average travel time increased only by 2.8% to 3.6%, considerably lower than the no-diversion scenarios travel times. In the PM peak period, all with-diversion work zone scenarios resulted in approximately similar average network travel time, average travel distance, average stop time, and number of unserved vehicles.

Peak Hour Route Performance

The network-wide analysis indicated increases in travel time ranging from 3.3% up to 4.8% in the AM peak period and from 2.8% up to 3.6% in the PM peak period. These figures indicate slightly longer average travel time in the entire network; however, it is equally important to investigate travel time changes inside the work zone and other alternative routes in its vicinity. Here, the average travel times along different routes in the network are calculated for different work zone scenarios and are compared to those in the Baseline scenario. Two key "triangle routes" are used in this analysis, which are shown in Exhibit 20. Route C represents a trip from Exit 312 on Interstate I-40 to Exit 284 (and vice versa) traveling through the work zone. Route D represents the alternate trip between the same starting and end points, but using the I-440 northern loop of the Beltline.

Exhibit 29: Triangle Route Performance Analysis - Route Definitions



AM Peak Period

Exhibit 21 summarizes travel times along Routes C and D for the peak hour of AM peak period. As a reminder, westbound traffic constitutes the peak direction during the AM peak for Route C, with eastbound peak occurring in the PM.

Exhibit 30: Peak Hour Work Zone Impacts for Selected Routes - AM Peak

Scenario		Route C (in work Zone)				Route D (alternate)			
		TT EB		TT WB		TT EB		TT WB	
		min	% Diff	min	% Diff	min	% Diff	Min	% Diff
Baseline		24.6	n/a	26.79	n/a	27.54	n/a	31.31	n/a
WZ 1	No-Diversion	24.79	0.8%	110.27	311.6%	65.66	138.4%	69.58	122.2%
	With-Diversion	24.64	0.2%	49.87	86.2%	28.49	3.4%	33.34	6.5%
WZ 2	No-Diversion	99.93	306.2%	62.19	132.1%	27.67	0.5%	95.31	204.4%
	With-Diversion	32.07	30.4%	26.87	0.3%	27.89	1.3%	34.21	9.3%
WZ 3	No-Diversion	24.8	0.8%	104.95	291.8%	62.04	125.3%	58.91	88.2%
	With-Diversion	24.62	0.1%	37.03	38.2%	28.02	1.7%	33.78	7.9%
WZ 5	No-Diversion	24.8	0.8%	96.46	260.1%	38.31	39.1%	69.71	122.6%
	With-Diversion	24.61	0.0%	34.17	27.5%	28.11	2.1%	33.41	6.7%
WZ 7	No-Diversion	68.25	177.4%	78.1	191.5%	50.06	81.8%	57.26	82.9%
	With-Diversion	28.78	17.0%	34.84	30.0%	28.21	2.4%	34.83	11.2%

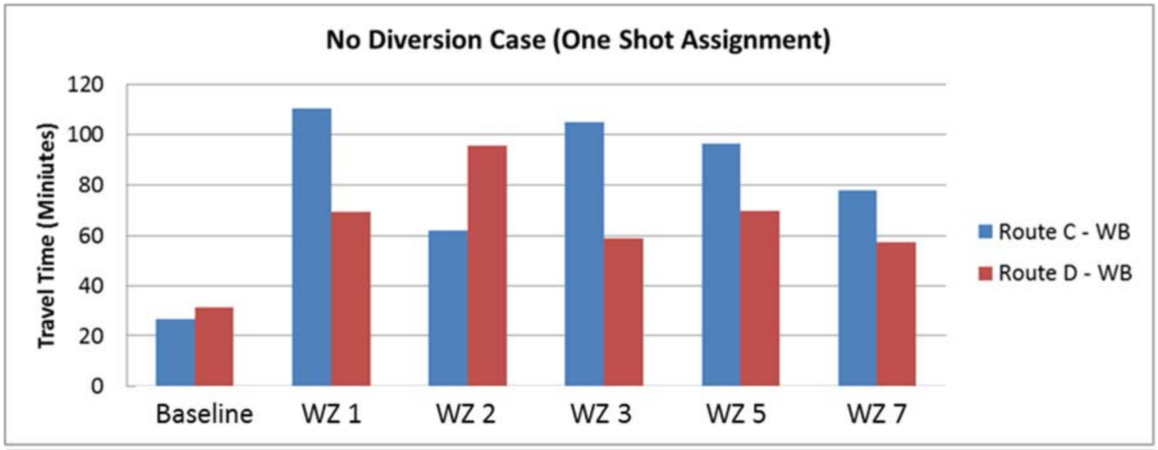
As expected, scenarios with diversion yielded lower average travel times than scenarios without-diversion. In addition, work zone scenarios with greater number of open lanes (WZ-3, WZ-5, and WZ-7) resulted in lower travel time than scenarios with fewer open lanes (WZ-1 and WZ-2). Maintaining only two open lanes yielded an 86.2% increase in travel time in the WB direction of Route C in the AM peak period. Maintaining three lanes open throughout the work zone increased travel time by 27.5%, while the combination of 2 and 3 lanes depending on starting cross-section (3) showed a 38.2% increase.

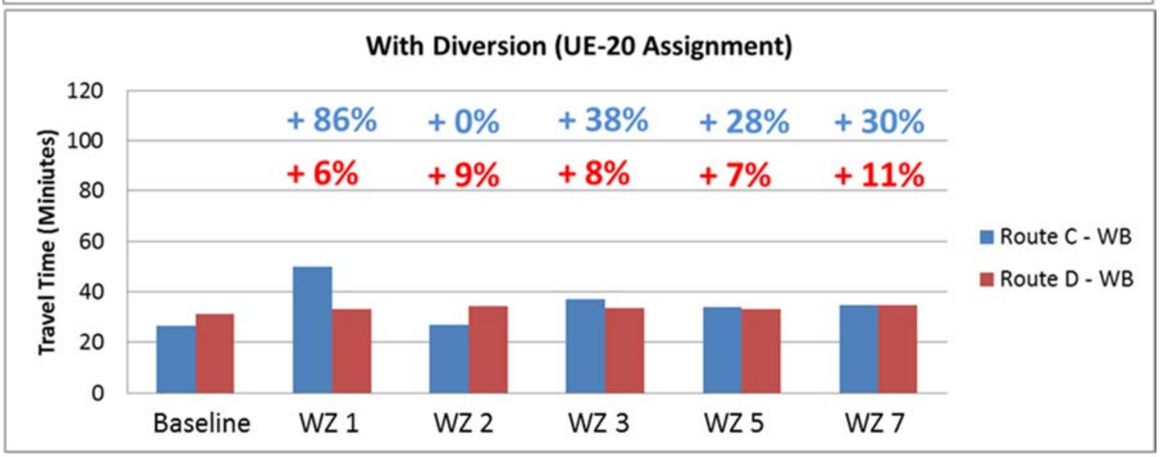
When scenario WZ-1 is in effect (maintaining only two lanes open in the WB direction) average travel times significantly increase in the WB direction on both Routes C and D in the AM peak period. For the no-diversion scenario, average travel time increased by 311% and 122% in the WB direction of routes C and D, respectively. The increase in average travel time in Route D may not seem reasonable since vehicles were not allowed to change their routes. However, it should be noted that Routes C and D share portions of the I-40 freeway from mile marker 312 to 300. When several lanes of I-40 freeway are closed due to the presence of the work zone, traffic congestion spills back to this section of I-40 (from MM 312 to 300 WB) and consequently, travel time in the WB direction of Route D are impacted.

Travel time also significantly increased in the EB direction of Route D for the scenario without diversion (by 138%). This was also expected since the work zone includes some portions of Routes C and D. In fact, three miles of the work zone in the WB direction serve as the EB direction of Route II, as shown in Exhibit 5. As such, when several lanes are closed in the WB direction of the work zone, several lanes are also closed along the EB direction of route D, and consequently travel time increases on this route.

A comparison of the no-diversion and with-diversion scenarios are provided in Exhibit 22 below, which visualizes the data in Exhibit 21 in a bar chart. The top portion of the exhibit shows the no-diversion travel times in the westbound (peak) direction for routes C and D; the bottom portion shows corresponding results for the with-diversion results.

Exhibit 31: Travel Time Results - Routes C and D - AM Peak



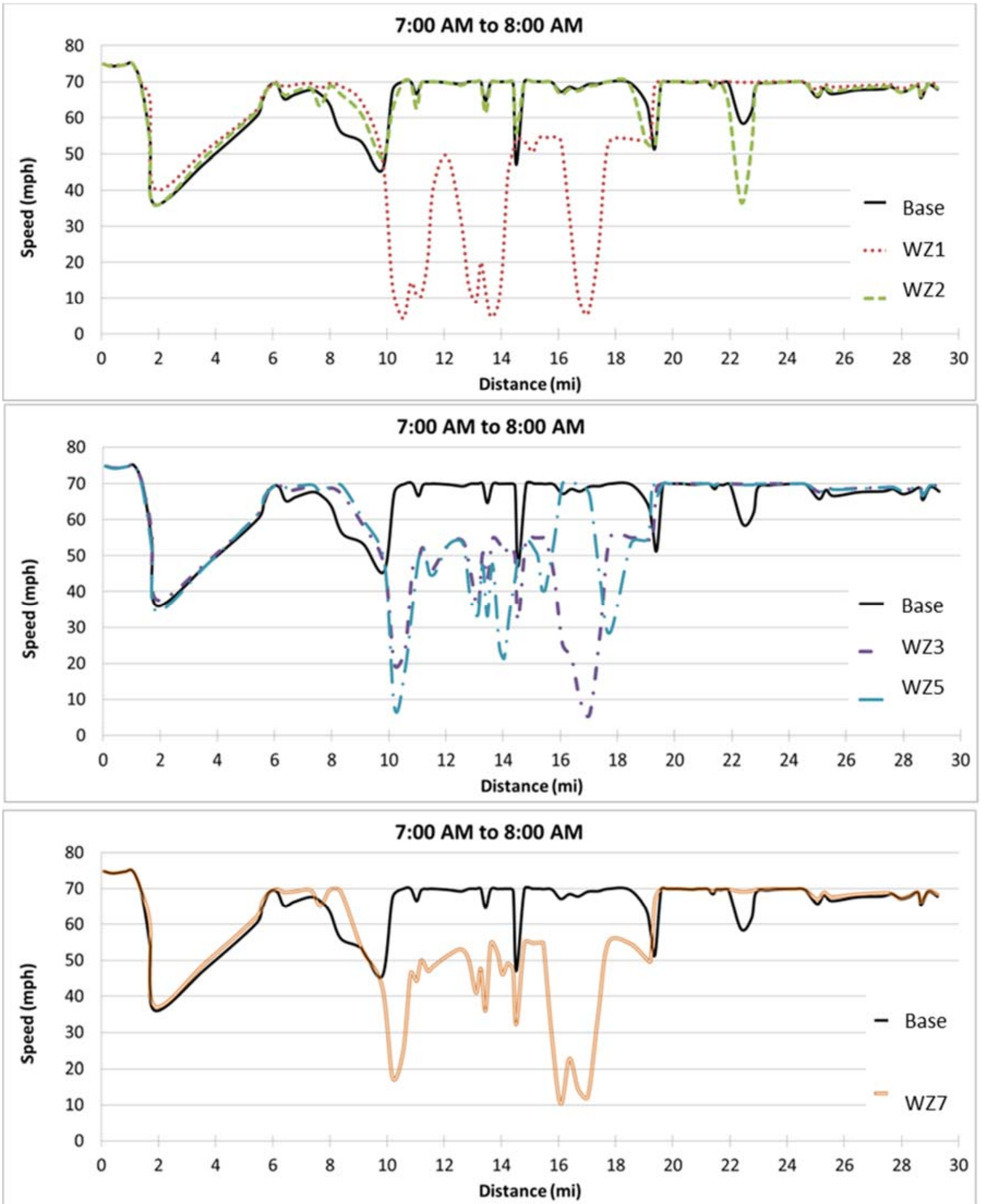


The exhibit clearly shows the high travel time impacts of the no-diversion cases on both routes C and D. It is again emphasized that without traffic diversion, increase in routes travel times without construction (e.g. Route D in WZ 1 or Route C in WZ 2) are likely attributable to congestion spillback on links common to both routes, which in this case is the portion of I-40 between Exit 301 and Exit 312, which is impacted by spillback from either I-40 or I-440 depending on the scenario. After considering traffic diversion, the construction impacts are reduced considerably, but remain high especially for Route C in the westbound work zone scenarios.

In order to get a closer look at the contributing factors to these travel times, Exhibit 38 shows speed profiles measured along route C in the westbound direction for the AM peak hour. As points of reference, westbound exits 309, 301, 297, 293, and 289 are approximately 2.0, 10.0, 14.5, 19.5, and 23.0 miles into the route. Corresponding speed contours for the eastbound direction are shown in the Appendix E.

Exhibit 23 shows baseline slow-downs around Exits 309, 301, 297, 293, and 289, with speeds dropping from a free-flow speed of 70-75 miles per hour to reduced speeds between 40 and 60 mph. The WZ 1 scenario results in additional slowdowns between exits 301 and exits 293, as speed drop down to 5mph in some segments. WZ 2 shows little impact in the westbound direction, as all lane closure are limited to eastbound. Work zone scenarios 3 and 5 show the discussed improvements over the two-lane cross-section in WZ 1, by reducing the magnitude and extent of the low-speed zone in the work zone. The crossover scenario WZ7 appears to perform similarly to WZ 5, which is intuitive in the westbound direction as both scenarios have similar lane configurations. WZ scenarios 2 and 7 are expected to result in higher impacts in the eastbound direction, as those scenarios include lane closures in that direction.

Exhibit 32: AM Peak Route Speed Profile for Work Zone Scenarios - Route I Westbound



PM Peak Period

Exhibit 24 summarizes travel times along Routes C and D for the peak hour of PM peak period. The peak travel direction in the PM peak is the eastbound direction.

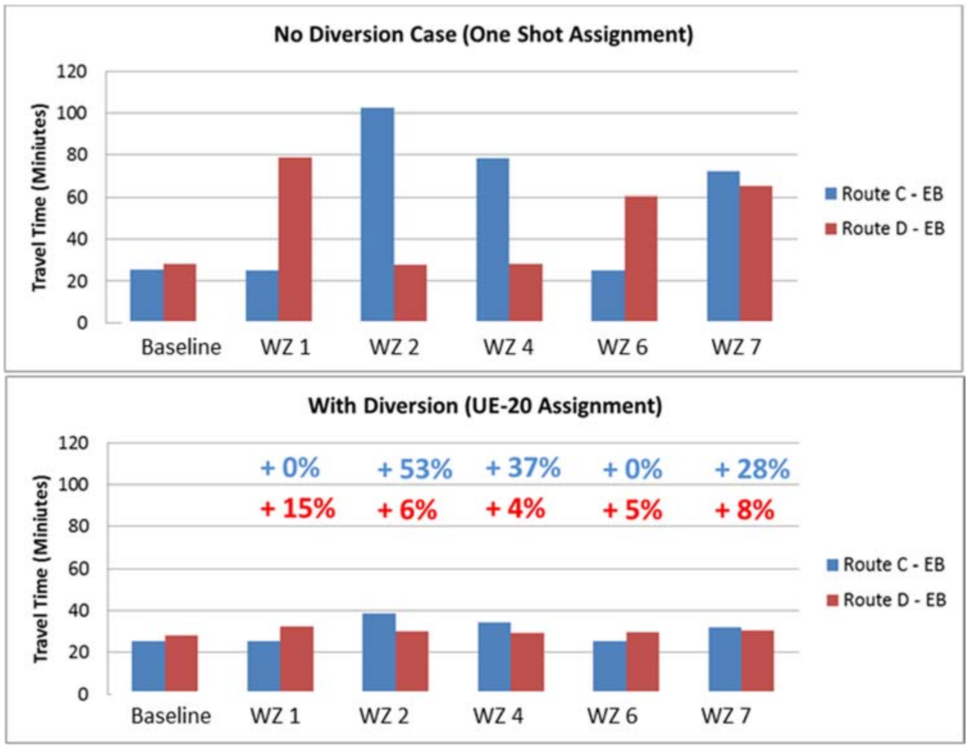
Exhibit 33: Peak Hour Work Zone Impacts for Selected Routes - PM Peak

Scenario		Route C (Work Zone)				Route D (Alternate)			
		TT EB		TT WB		TT EB		TT WB	
		min	% Diff	min	% Diff	min	% Diff	min	% Diff
Baseline		25.2	n/a	25.7	n/a	28.1	n/a	28.9	n/a
WZ 1	No-Diversion	25.1	-1%	106.6	314%	78.8	180%	52.1	81%
	With-Diversion	25.3	0%	52.4	104%	32.5	15%	31.4	9%
WZ 2	No-Diversion	102.5	306%	27.3	6%	27.9	-1%	59.1	104%
	With-Diversion	38.6	53%	25.6	0%	30.0	6%	32.4	12%
WZ 4	No-Diversion	78.5	211%	26.4	2%	28.0	-1%	31.6	9%
	With-Diversion	34.5	37%	26.0	1%	29.2	4%	29.5	2%
WZ 6	No-Diversion	25.2	0%	84.5	228%	60.4	115%	52.2	81%
	With-Diversion	25.3	0%	31.6	23%	29.6	5%	30.3	5%
WZ 7	No-Diversion	72.0	185%	59.7	132%	65.1	131%	34.8	20%
	With-Diversion	32.2	28%	32.5	26%	30.5	8%	31.0	7%

Exhibit 24 shows average travel time for different work zone scenarios and the percentage difference to the baseline travel time for Routes C and D in the PM peak period during which the majority of traffic travels in the EB/SB direction. As such, lane closures on the EB direction yielded more significant increases in travel time. Similar to the AM peak period, the scenarios without diversion resulted in higher travel times compared to the scenarios with diversion. In addition, scenarios with more open lanes resulted in shorter travel times than scenarios with fewer numbers of open lanes. Travel time was increased by 56.9% for scenario WZ-2 (two open lanes) on EB direction of route C after diversion. When maintaining three lanes open throughout (WZ-6) the travel time increase is negligible, while the three-lane and two-lane combination scenario (WZ-4) shows a 37% increase. The cross-over scenario does have an impact in the eastbound travel direction, since the travel lanes are reduces to two lanes to accommodate the eastbound crossover. The expected impact on route C travel times is 28%.

Exhibit 25 shows the no-diversion and diversion results for the peak directions of routes C and D in the PM peak period. The highest impacts on eastbound Route C are evident in scenarios WZ2, WZ4, and WZ7 as discussed above. Similar to the AM peak, the no-diversion impacts are much higher than the with diversion cases. The latter suggests that PM peak travel times stabilize at up to a 53% increase over base-year conditions in scenario WZ2. In the interpretation of these results, it should be considered that the route travel time validation for the pm peak direction didn't show as good a fit as the AM peak. As a result, the full base-year congestion was underestimated for the eastbound route, and it is expected that this error perchlorates through these work zone results. So while the relative percentage still have merit, the actual travel time numbers may change once some additional calibration has been completed in the eastbound direction.

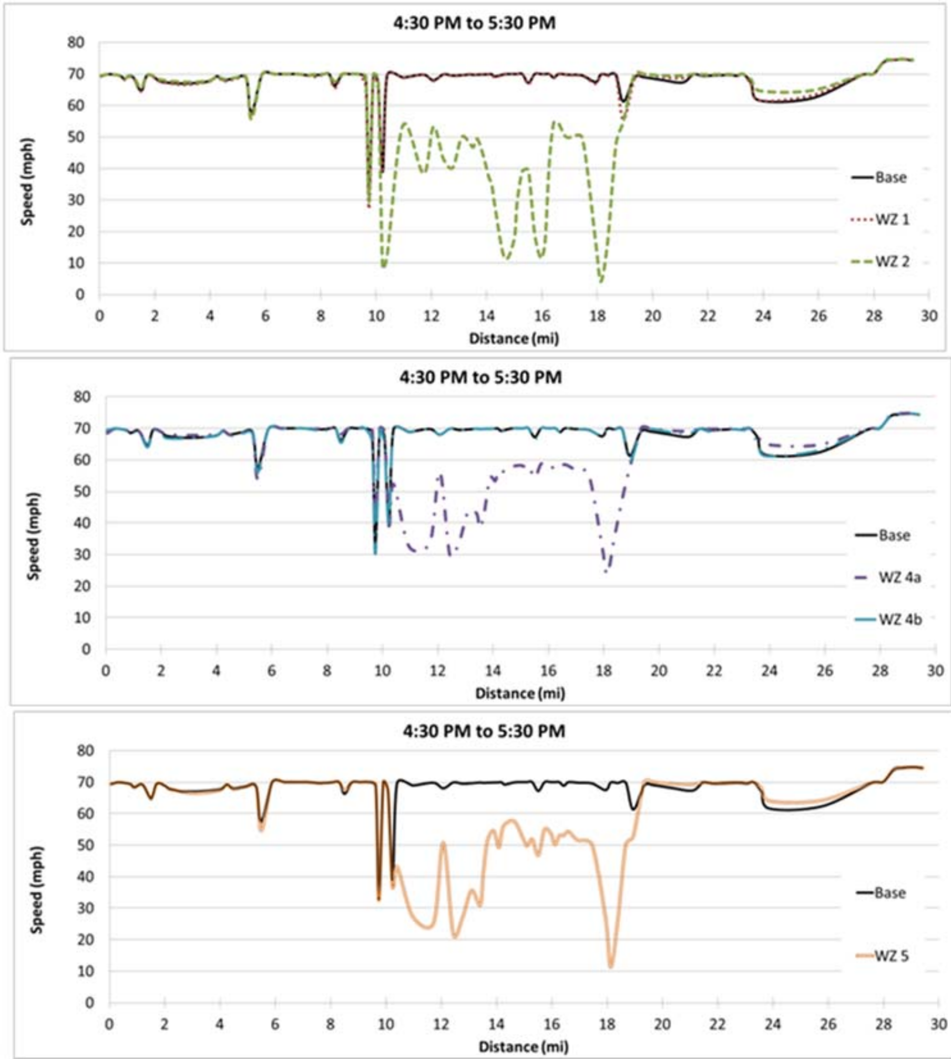
Exhibit 34: Travel Time Results - Routes C and D - PM Peak



Similar to the AM Peak, Exhibit 26 shows the speed profiles along Route C in the PM peak period in the eastbound direction. Results for the westbound direction are shown in the Appendix E. The graph again shows the peak hour speed in each DynusT segment along the distance of Route C. For reference, exits 289, 293, 298, 301, and 309 are located approximately 5.5, 9.5, 15.0, 18.5, and 25.0 miles into the route.

The speed profiles show base-year congestion approximately around the Exit 293 interchange with US1, but surprisingly doesn't show much congestion at the Wade Avenue split (Exit 289) or the I-40/440 split (Exit 301). The westbound WZ1 shows no impacts into this direction as expected, but eastbound WZ 2 drops speed to below 10 mph in some segments in the work zone. When maintaining three lanes open for the wider base sections, WZ4 shows a reduced speed impact, while WZ6 shows essentially the same performance as the base case as discussed previously. The WZ7 crossover case results in comparable performance to WZ4, although it should be considered that this scenario will also cause delay in the westbound section (see Appendix E).

Exhibit 35: PM Peak Route Speed Profile for Work Zone Scenarios - Route C Eastbound



5. DTALite Mesoscopic Results

This section presents the work zone impact results from the DTALite mesoscopic simulation analysis. The impact of different work zone scenarios on the network and on several key routes are discussed for both AM and PM peak periods. Detailed analyses are presented in Appendix F. The results are demonstrated in terms of network-wide impacts of the work zone and the impacts on the key routes.

Network-Wide Impacts

The impact of different work zone scenarios on the network average travel time, average travel distance, and number of unserved vehicles are elaborated in AM and PM peak periods. The number of unserved vehicles refers to those drivers who were unable to reach their desired destination within the simulated study period. The AM and PM analysis periods in the DTALite models contained approximately 1.1 million and 2.1 million vehicles, respectively. The number of unserved vehicles needs to be interpreted as a fraction of the overall modeled demand to draw conclusions about the percentage of demand unserved.

It shall be noted that not all work zone scenarios were modeled by DTALite mesoscopic simulation tool, because at the stage in the project when DTALite was included in the analysis, several scenarios were deemed as infeasible or unlikely. Also, in each peak period, only the scenarios that reduced the number of lanes in the peak direction were modeled. As such, the following scenarios are considered:

1- AM peak (peak direction: westbound)
   - a- WZ 1: two lanes open on westbound across the work zone, all lanes open on eastbound
   - b- WZ 5: three lanes open on westbound across the work zone, all lanes open on eastbound

2- PM peak (peak direction: eastbound)
   - a- WZ 2: two lanes open on eastbound across the work zone, all lanes open on westbound
   - b- WZ 6: three lanes open on eastbound across the work zone, all lanes open on westbound

For all work zone scenarios, in addition to average values for the network performance measures, percent difference from the baseline is presented as well. For all scenarios, the analysis distinguishes between a *no-diversion* and an *optimum-diversion* scenario. The no-diversion case corresponds to a "one-shot" assignment, where all vehicles remain on their paths from the user-equilibrium baseline condition despite the presence of the work zone. Conceptually, the one-shot assignment corresponds to a worst-case analysis of that work zone scenario where drivers are not aware of its presence.

The with-diversion results were obtained from running DTALite's dynamic traffic assignment modules to achieve (near) user-equilibrium, by repeating the traffic assignment for twenty times (iterations). After each iteration, a certain number of simulated vehicles in the network reconsider their routes based on their travel experience in the previous runs. After twenty iterations, the model therefore results in a modified traffic assignment, where each vehicle minimizes its origin-to-destination travel time, under the constraints imposed by the work zone. Conceptually, this corresponds to a user equilibrium solution, under the assumption of fixed demand and departure time.

AM Peak

Exhibit 36 shows average travel time, average travel distance, and number of unserved vehicles in the network for the AM peak period. The numbers are presented for the base case when all available lanes on the freeway are open to the traffic as well as two work zone scenarios: WZ1 with two lanes open in the westbound, and WZ 5 with three lanes open in the same direction. For each work zone scenario, two assignments strategies are used: no-diversion and with-diversion.

For the baseline scenario, when no work zone is present on the freeway, network-wide average travel time is 17.4 minutes in the AM peak. Maintaining only two lanes open in the work zone with no diversion significantly increases average network travel time to 47.0 minutes. This indicates a considerable 169.9% increase in the average travel time. For the with-diversion scenario, maintaining two open lanes in the peak direction increases network travel time by 6.5% to 18.5 minutes. The apparently small one-minute increase in network travel time should be interpreted very cautiously. The average travel time tends to mask the travel time increase at the vicinity of the work zone by averaging it with the travel time on links that are miles apart from the work zone and possibly have not been affected at all. This is the main reason for looking at route travel times in the vicinity of the work zone in the following section.

Maintaining three open lanes in the work zone increases network average travel time to 37.5 minutes with no-diversion. The additional open lane significantly reduced travel time compared to the strategy with only two open lanes (almost 10 minutes reduction). For with diversion scenario the average travel time was slightly reduced (by 1.2%) compared to the base case.

Exhibit 36: Network-wide Work Zone Impacts: Absolute and Relative to Baseline in AM Peak

Scenario		Average TT (minutes)		Average Travel Distance (mile)		# of Unserved Veh	
		Min.	% Diff	Mile	% Diff	Veh	% Diff
Baseline		17.40	n/a	12.76	n/a	46261	n/a
WZ 1	No-Diversion	46.95	169.85	12.67	-0.67	169989	267.46
	With-Diversion	**18.53**	**6.50**	**12.77**	**0.07**	**63401**	**37.05**
WZ 5	No-Diversion	37.51	115.58	12.69	-0.55	145932	215.45
	With-Diversion	**17.19**	**-1.19**	**12.52**	**-1.88**	**54916**	**18.71**

Maintaining two lanes open in the work zone increased the number of unserved vehicles by 267.5% and 37.1% for no-diversion and with-diversion scenarios, respectively. However, the average travel distance in the network was changed by a maximum of 0.7%. This indicates that while WZ 1 significantly increased the number of unserved vehicles, the average length of trips remained unchanged. The same trend was observed for scenarios maintaining three lanes open in the work zone with a lesser extent, as expected. Expectedly, for both work zone scenarios (WZ 1 and WZ 5) diversion scenarios resulted in significantly fewer number of unserved vehicles as drivers chose alternative routes to reach their destinations.

PM Peak

Average Travel time, average travel distance, and the number of unserved vehicles for the research triangle network are presented in Exhibit 37. The table summarizes the impacts of maintaining two or three lanes open on the eastbound direction of the freeway in the PM peak period.

Exhibit 37: Network-wide Work Zone Impacts - PM Peak

Scenario		Average TT		Average Travel Distance		# of Unserved Veh	
		Min.	% Diff	Mile	% Diff	Veh	% Diff
Baseline		16.43	n/a	10.03	n/a	71400	n/a
W Z 2	No-Diversion	84.70	415.63	9.95	-0.74	461846	546.84
	With-Diversion	**21.52**	**31.03**	**10.20**	**1.78**	**127231**	**78.19**
W Z 6	No-Diversion	82.30	400.98	9.96	-0.61	453177	534.70
	With-Diversion	**21.78**	**32.57**	**10.20**	**1.76**	**125534**	**75.82**

When all lanes are open on the freeway (baseline scenario), the average network travel time is 16.4 minutes. Maintaining two lanes open with no diversion increases the travel time to 84.7 minutes. This is a significant 415.6% increase. When the drivers are allowed to change their routes (with-diversion scenario), the average network travel time reduces to 21.5 minutes. This still is a considerable 31.0% increase in the travel time when compared to the baseline scenario. Maintaining three lanes open in the work zone results in average network travel time that are similar to the scenarios with two lanes open. This trend is not similar to what observed in the AM peak period and may look counterintuitive. This pattern us explained due to the much higher volumes in the PM and averaging over the network. The volumes are about twice as high in the PM as they were in the AM peak. Consequently, there are fewer diversion options for the additional demand to go.

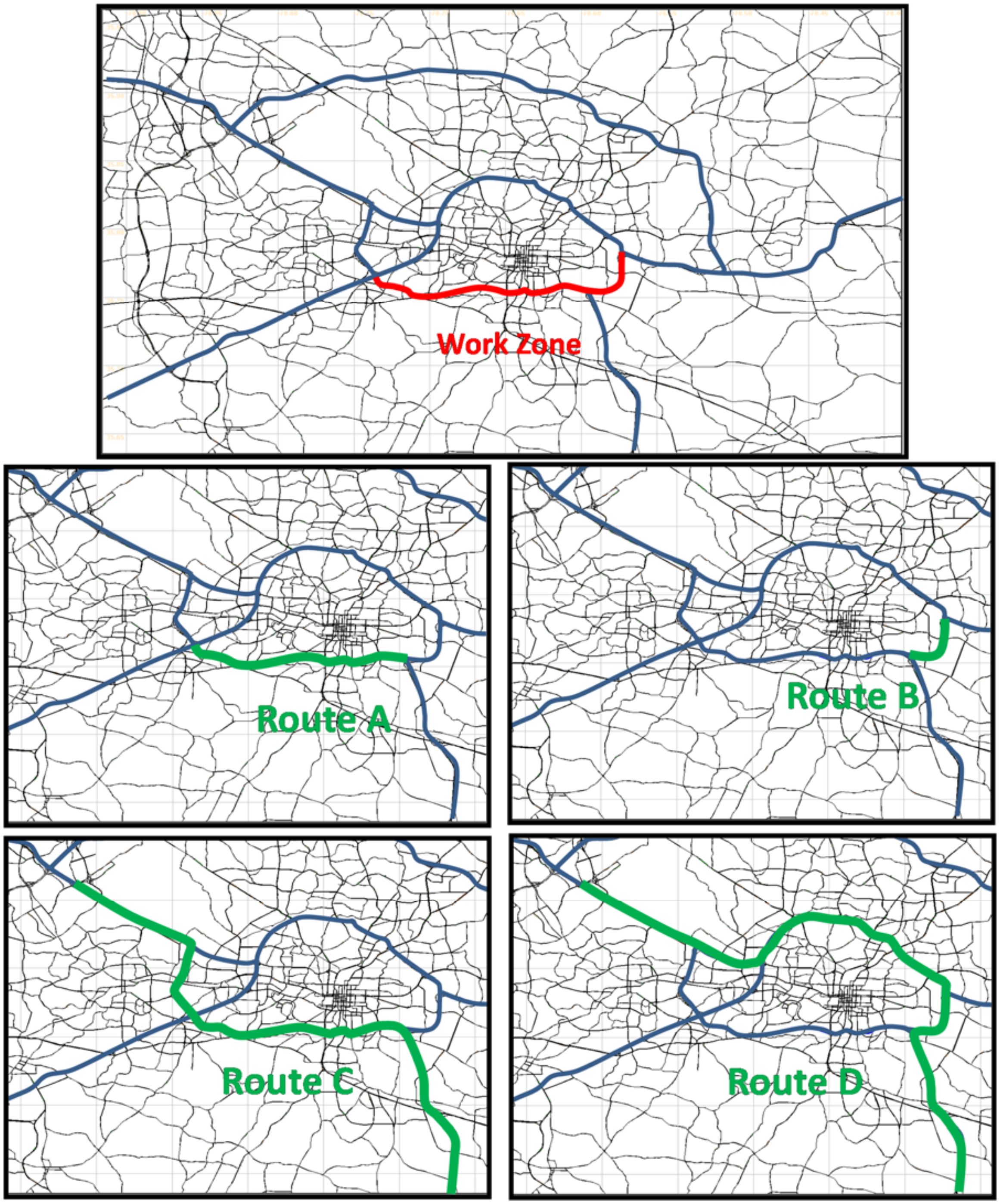
The number of unserved vehicles shows a five-fold increase for both work zone scenarios with no diversion. However, when the drivers are allowed to change their routes, the increase is limited to a maximum of 80%. In scenarios with diversion, average travel distance increases by a maximum of 1.8% indicating that drivers choose slightly longer routes to get to their destinations.

Peak Hour Travel Time and Traffic Volume for Key Routes

In this section, the impacts of different work zone scenarios on the average travel time and average volume of four key routes of the network are presented. Similar to the previous section on network-wide impact, the analysis is performed separately for the AM and PM peak hours. Average travel time and average volume are presented for pre-construction condition or the baseline scenario, and work zone scenarios with and without diversion. Average travel time is found by summing up the average travel time on all links of a route while average volume is the average of the volumes of all links of a route. It is noted that averaging volumes across a (long) route may result in some counterintuitive results in some cases, especially for routes where a bottleneck meters downstream traffic.

Exhibit 38 shows the work zone along with the four key routes of the network. Route A includes the portion of the work zone that is on Interstate 40 from milepost 293 to 300. Route B includes the portion of the work zone that is on Interstate 440 from milepost 14 to 16. Route C represents a trip from Exit 312 on Interstate 40 to Exit 284 (and vice versa) traveling through the work zone. Route D represents the alternate route between the same starting and end points but, using the I-440 northern loop of the Beltline.

Exhibit 38: Route Definition



AM Peak Period

The route analysis in the AM peak is carried out from 7:00 AM to 8:00. Exhibit 39 presents travel time and volume for the baseline scenario and work zone scenarios with and without diversion. In addition, the estimated diversion percentage (a with-diversion work zone scenario vs. baseline scenario) is shown. This percentage correspond to the proportion of traffic volume that needs to be added (positive sign) or subtracted (negative sign) from the baseline scenario to achieve user-equilibrium condition.

In the AM peak hour, WZ1 and WZ5 have minimal impacts on the eastbound direction of routes A, B, and C. This is expected since these scenarios do not include any lane closure on the eastbound. However, they significantly increase travel time on eastbound route D for no-diversion scenario. This is also expected since both work zone scenarios reduce the number of open lanes on eastbound direction of route D (from milepost 14 to 16 on I-440) in the morning.

Exhibit 39: Peak Hour Work Zone Impacts for Selected Routes – AM Peak

Route	Work Zone	Direction	Pre-Construction Travel Time (min)	No-Diversion Travel Time (min)	Optimum-Diversion Travel Time (min)	Pre-Construction Volume (vph)	No-Diversion Volume (vph)	Optimum Diversion Volume (vph)	Estimated Diversion
Route A (I-40 Milepost 293 through 300)	WZ 1	EB	8.0	8.0	7.9	3333	3254	3173	-5%
		WB	8.4	39.7	12.7	4541	1875	2078	-54%
	WZ 5	EB	8.0	8.0	8.0	3333	3314	3167	-5%
		WB	8.4	22.1	10.7	4541	3060	3037	-33%
Route B (I-440 Milepost 14 through 16)	WZ 1	EB	2.0	2.0	2.0	5045	2490	5623	11%
		WB	1.7	33.2	2.0	2755	803	1627	-41%
	WZ 5	EB	2.0	2.0	2.0	5045	3709	5377	7%
		WB	1.7	3.9	2.0	2755	2117	1796	-35%
Route C (I-40 Milepost 284 through 300 via I-40)	WZ 1	EB	25.9	25.9	25.9	2996	2873	2854	-5%
		WB	27.5	349.2	33.3	4426	2112	3086	-30%
	WZ 5	EB	25.9	26.0	26.0	2996	2968	2850	-5%
		WB	27.5	126.5	29.7	4426	3248	3668	-17%
Route D (I-40 Milepost 284 through 300 via I-440)	WZ 1	EB	29.3	139.6	29.5	2938	2684	2745	-7%
		WB	30.1	319.0	30.3	4146	2437	4288	3%
	WZ 5	EB	29.3	36.4	29.5	2938	2872	2745	-7%
		WB	30.1	98.9	30.0	4146	3374	4228	2%

Maintaining two lanes open on the peak direction in the AM peak hour significantly increases the travel time on all routes with or without diversion compared to the baseline scenario. As expected, allowing drivers to change their routes diverts a considerable proportion of traffic volume from the key routes and results in travel times that are considerably lower than those observed in the no-diversion scenario.

Maintaining three open lanes on the peak direction in the AM peak significantly increases travel time when drivers do not change their routes. However, the extent of this increase in travel time is considerably lower than that of the scenario with two open lanes, as expected. When drivers are allowed to change their routes, maintaining three lanes open only slightly increases the travel time.

Traffic assignment reroutes a significant portion of traffic on routes A, B, and C due to the delays caused by the work zone. As expected, a higher proportion of traffic is diverted from routes A, B, and C when two lanes are open. It shall be noted that the same diversion trend is not observed for route D. The main reason is that the average volume includes many links on the network that may not be affected in the same way by the work zone presence. As a result, diversion effects in the immediate vicinity of the work zone are washed out by many other links on this long route.

PM Peak Period

The route analysis in the PM peak is carried out from 4:30 PM to 5:30 PM. Exhibit 40 presents travel time and average volume for the baseline, work zone scenario with two lanes open, and work zone scenario with three lanes open.

Maintaining two lanes open in the peak direction of the freeway significantly increases travel time for no-diversion scenarios. Allowing drivers to change their routes yields a slight increase in the travel time of the peak direction of all routes and requires diverting a significant amount of the traffic.

Exhibit 40: Peak Hour Work Zone Impacts for Selected Routes – PM Peak

Route	Work Zone	Direction	Pre-Construction Travel Time (min)	No-Diversion Travel Time (min)	Optimum-Diversion Travel Time (min	Pre-Construction Volume (vph)	No-Diversion Volume (vph)	Optimum Diversion Volume (vph)	Estimated Diversion
Route A (I-40 Milepost 293 through 300)	WZ2	EB	8.2	110.0	12.1	4533	974	2022	-55%
		WB	8.1	8.1	8.1	3259	2835	2981	-9%
	WZ 6	EB	8.2	50.7	11.9	4533	2420	3067	-32%
		WB	8.1	8.1	8.0	3259	3051	2965	-9%
Route B (I-440 Milepost 14 through 16)	WZ2	EB	2.0	7.9	2.4	3309	2101	2027	-39%
		WB	1.7	1.7	1.7	3671	2530	4136	13%
	WZ 6	EB	2.0	2.4	2.4	3309	2887	2357	-29%
		WB	1.7	1.7	1.7	3671	2513	3795	3%
Route C (I-40 Milepost 284 through 300 via I-40)	WZ2	EB	26.9	281.3	32.0	4474	1578	3119	-30%
		WB	26.4	36.9	26.2	2990	2697	2861	-4%
	WZ 6	EB	26.9	94.4	31.2	4474	3000	3723	-17%
		WB	26.4	29.2	26.3	2990	2877	2848	-5%
Route D (I-40 Milepost 284 through 300 via I-440)	WZ2	EB	30.6	119.7	30.5	4434	2979	4413	0%
		WB	36.7	93.5	29.6	2890	2367	2773	-4%
	WZ 6	EB	30.6	29.7	30.3	4434	3696	4446	0%
		WB	36.7	31.5	29.4	2890	2576	2825	-2%

A similar trend is observed for the work zone scenario maintaining three lanes open however, to a lesser degree for routes A, B, and C. On route D, maintaining three lanes open did not significantly improve the route travel time and as such, no significant diversion is needed.

6. Summary and Recommendations

This document is the final report for NCDOT research project 2012-36: *Work Zone Traffic Analysis & Impact Assessment.* The project was tasked with assessing the estimated traffic impacts of the proposed NCDOT TIP Project I-5311/I-5338, a pavement rehabilitation project on interstates I-40 and I-440 from Exit 293 to I-40 Exit 301 and I-440 Exit 14. NCDOT anticipates that significant corridor and network level impacts would arise from this project during construction. Both I-40 and I-440 corridors presently carry approximate Average Annual Daily Traffic (AADT) volumes of 113,000 and 90,000 vehicles per day (vpd), respectively. Current demand levels already produce recurring peak-hour congestion in the vicinity of the proposed work zone. The capacity reduction associated with the work zone involves 24-hour, multi-day lane closures that are expected to lead to significant diversion of traffic to the surrounding road network. In addition to freeway mainline congestion, this work zone is also expected to have significant congestion impacts on potential diversion routes and other choke points in the network.

The project aimed to predict corridor and network-wide impacts of the work zone during construction, including routes along the work zone corridor, as well as key diversion routes. The primary focus of this study was the development and calibration of a network-wide mesoscopic simulation model of the Triangle region, as well as a macroscopic representation of the work-zone corridor.

The geographical coverage of the mesoscopic simulation model includes the entire triangle region, expanded east of the triangle to include additional sections of US264, I-40, and I-95. The model was calibrated using field-estimated spot volume and speed data, as well as key route travel times obtained from INRIX. The model was initially developed and tested in the DynusT software tool, and was then transferred to the DTALite software tool. Both tools gave reasonable results for the baseline scenario, and when modeling higher-capacity work zone scenarios. However, for lower capacity (more severe) work zone scenarios DTALite performed more reasonably while the DynusT tool yielded unrealistically high traffic densities, resulting from a lack of queue propagation across the network. So while both tools proved useful in this project, the DTALite results are thought to provide a more realistic assessment of the expected work zone impacts.

In addition to the two mesoscopic tools, the macroscopic analysis tool FREEVAL was used to explore the estimated impacts on the work zone corridor. While FREEVAL is not able to predict diversion rates and network-wide performance, it has been proven to be a useful tool for assessing work zone impacts based on previous research conducted for NCDOT. FREEVAL is a faithful representation of the freeway facilities methodology in the 2010 U.S. Highway Capacity Manual, and as such a benchmarked analysis tool across the U.S. Ultimately, the comparison of all three tools was expected to provide NCDOT with valuable insights about the advantages, benefits, and tradeoffs of different analysis tools.

Multiple work zone scenarios were modeled in all three tools to test the relative impacts of different lane closure configurations on route and network performance. Scenarios included a reduction of the overall cross-section to only two travel lanes, from a base of three to five lanes per direction. Additional scenarios maintained more travel lanes at key bottleneck sections during construction, as well as a three-lane scenario that was thought to offer significant congestion relief during construction. The analysis further differentiates between no-diversion and with-diversion results. Diversion rates were produced based on running a dynamic traffic assignment (DTA) model for twenty iterations until a network user equilibrium (UE) is achieved.

Baseline Model Calibration and Validation

The project used a combination of point-based sensor speed and volume data, and segment-based travel time estimates to compare the predictions of the DynusT and DTA Lite models to empirical data. The AM Peak period was modeled from 6am to 10am, while the PM peak period was modeled from 3:30pm to 7:30pm. The calibrated DynusT model achieved an average percent volume error within 5% across all sensor stations in the network, with the exception of the first AM and last PM hours. Both of those periods showed higher volume estimates in the model than the field data. Point-based speed estimates of the DynusT model yielded an overall error between 5% and 9% on freeway stations (no arterial speed data was available) and an error of 6 to 11% along sensor stations in the work zone. In all cases, the speed prediction error was positive, indicating roughly 10% higher speeds (less congestion) in the model compared to the field data.

For DTALite the AM peak period network was calibrated to an average error within 2% of sensor volumes for the last three hours of the peak period, and 11% of sensor speeds. The average error was 21% for the first hour of the AM peak period. This higher error was deemed acceptable, as the primary performance statistics were extracted for the second hour of analysis, and the first hour was generally uncongested due to lower volumes. In the PM peak, all volumes on average were within 4% of field-measured sensor volumes in the first three hours of the peak period, and within 9% of speeds in the peak hour. The average error was 21% in the last hour of the PM peak period.

The team further validated route travel times for several freeway and arterial routes. The route travel time error was less than 10-15% for most freeway routes, including the work zone. For arterial streets, the validation error was higher with some errors in the 20%-50% range. The arterial error is attributed to the form of the mesoscopic simulation model, which has traditionally been used for freeway analyses, including past research for NCDOT.

Impacts on Key Triangle Routes

DTALite results showed optimum diversion rates of 56% and 33% for the two-lane open and three-lane open options, respectively, in the AM peak under UE conditions. With these assumed rates of traffic volume reduction through the work zone, the network model estimates I-40 westbound travel times to increase through the work zone from 8.6 to 15.1 min for the two-lane pattern, and to 12.7 minutes for the three-lane pattern. In the more constrained two-lane open pattern, the model estimates volume increases in excess of 500 vph on Wade Avenue, US64, US1, and NC55, with smaller increases for other routes in the triangle. As a result, the model estimates travel time increases over 30% for I-440 eastbound (+32%), US70 northbound (+92%), Hammond Rd. northbound (+115%), and Rock Quarry Road westbound (+43%) in the AM Peak for the two-lane. For the three-lane open case, network-wide impacts are mitigated to some extent because fewer drivers select alternative routes. The model still estimates travel time increases over 30% for US70 northbound (+44%), Hammond Road northbound

(+54%), and Rock Quarry Road westbound (+32%), and other significant impacts on I-440 EB (+10%), NC55 NB (+17%) and Hammond Road northbound (+22%).

In the PM Peak, the network is generally more congested due to higher traffic volumes. The idealized UE solution in DTALite estimates I-40 eastbound travel time to increase through the work zone from 8.6 to 18.5 min for the two-lane open pattern, and to 13.9 minutes for the three-lane open pattern. These increases are determined by the model calculating an idealized 62% traffic volume reduction and 36% traffic reduction for the two-lane open and three-lane open pattern, respectively. Due to drivers self-selecting alternative routes, the model estimates volume increases in excess of 500 vph on US70, and over 1,000 vph on US64, US1, and NC55. That driver-selected diversion to alternative routes results in travel time increases over 30% for Wade Ave. EB (+59%) and Davis Drive SB (+33%), as well as significant impacts to I-440 EB (+20%), I-540 EB (+20%), and US64 WB (+30%). Similar to the AM Peak, many of these impacts are mitigated with the three-lane open option, and a travel time increase over 30% is estimated only for US64 westbound (+32%), with other significant impacts on I-440 EB (+17%), Wade Avenue EB (+21%), NC55 EB (+14%), and Davis Drive SB (=10%).

Model Limitations

This research has provided valuable insights onto the expected impacts of the I-5311/I-5338 work zone on Interstates I-40 and I-440. Those will be useful in weighing trade-offs and relative operational performance of different work zone staging strategies.

However, it should be emphasized that the current approach assumes no travel demand changes in response to the presence of the work zone. Thus, the results assume no trip reduction in the form of car-pooling, transit, telecommuting, peak-spreading, discretionary trip cancellation or other demand-reducing strategies. In reality, some demand reduction, spatial, temporal and/or modal shifts can be expected in response to a work zone of this magnitude. Findings from this analysis are important for public outreach as it relates to this project, which may also include the exploration of suggested (or mandatory) detours routes.

One other important consideration of all results put forth in this report is that the contractor scenarios in the design-build construction contract had not been finalized at the time of this writing. Thus, the actual impacts of the work zone can be expected to differ from our estimates, depending on how close the final contractor phases and stages are to the modeled scenarios.

Despite these caveats, the project has carried out an in-depth and comprehensive comparison and application of three software tools for evaluating corridor and network impacts of a significant freeway work zone. All three models were calibrated with a considerable amount of field volume data and local work zone capacity estimates (from prior research). The base models were validated with empirical speed and travel time data for various key routes in the Triangle region.

Value of Diversion

The study highlighted the critical need to divert traffic away from the work zone during construction, especially when the number of lanes closed to traffic is high. Some diversion is likely to be self-induced while the balance must be assisted using various forms of traveler information systems. Of course, one must realize that the modeled WZ scenarios presented in this report assume no change in departure times or mode shift; only route choice is allowed to be altered.

The evidence at the network level as well as within the work zone area is quite compelling. For the no-diversion work zone scenarios, network-wide average travel time increased from roughly 17 minutes up to 47 and 37 minutes in the AM peak period for two-lane and three-lane pattern, respectively. For the PM peak, the travel time increased from 16 to about 21 and 22 minutes for two and three lanes open during construction.

Assuming user-equilibrium conditions, work zone scenarios had considerably less impact on network congestion. Those scenarios resulted in network-wide average travel time of 18.5 and 17.1 minutes in the AM peak period, and 31 and 33 minutes in the PM peak period. In addition, they yielded smaller increases in travel times on a 30-mile commuter route through the triangle region, compared to the no-diversion work zone scenarios. Therefore, providing travelers with alternative routes (and hoping that they will use them) can significantly mitigate the congestion caused by the work zone.

Improvements by Maintaining a Three-Lane Pattern

While it may seem intuitive that maintaining three lanes open to traffic (as opposed to two) in the work zone results in better operational performance, the magnitude of the difference between these two scenarios was striking and definitely non-linear.

For example, FREEVAL results suggest that a 30-40% diversion is necessary in the AM Peak hour to keep average travel speeds for a route through the work zone over 20 mph with a two-lane work zone pattern. With a three-lane pattern, FREEVAL estimates that only a 10-20% diversion rate will keep average travel speed above 40mph. For the PM Peak, the FREEVAL analysis suggests that a 40-50% diversion is necessary to keep the average speed over 10mph with the two-lane work zone pattern. With the three-lane pattern, it is estimated that a 40mph average travel speed can be maintained with approximately a 30-40% diversion rate.

The results obtained from DTALite mirror these findings. They suggest that a diversion of 56% and 62% would be required for the AM and PM Peak period with the two-lane pattern, which may be an unrealistically high diversion goal. For the three-lane pattern, the model produces 33% and 36% diversion rates, which is still high, but likely more readily achievable with an intensive pre-trip and en route traveler information campaign. Another benefit of the three-lane pattern is that it would lessen the severe impacts on alternate routes, as a result of the lower required diversion estimates.

7. References

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Appendix

Appendix A: Work-Zone Lane Configuration Maps

Exhibit 41: Lane Configuration - Work Zone Scenario 1

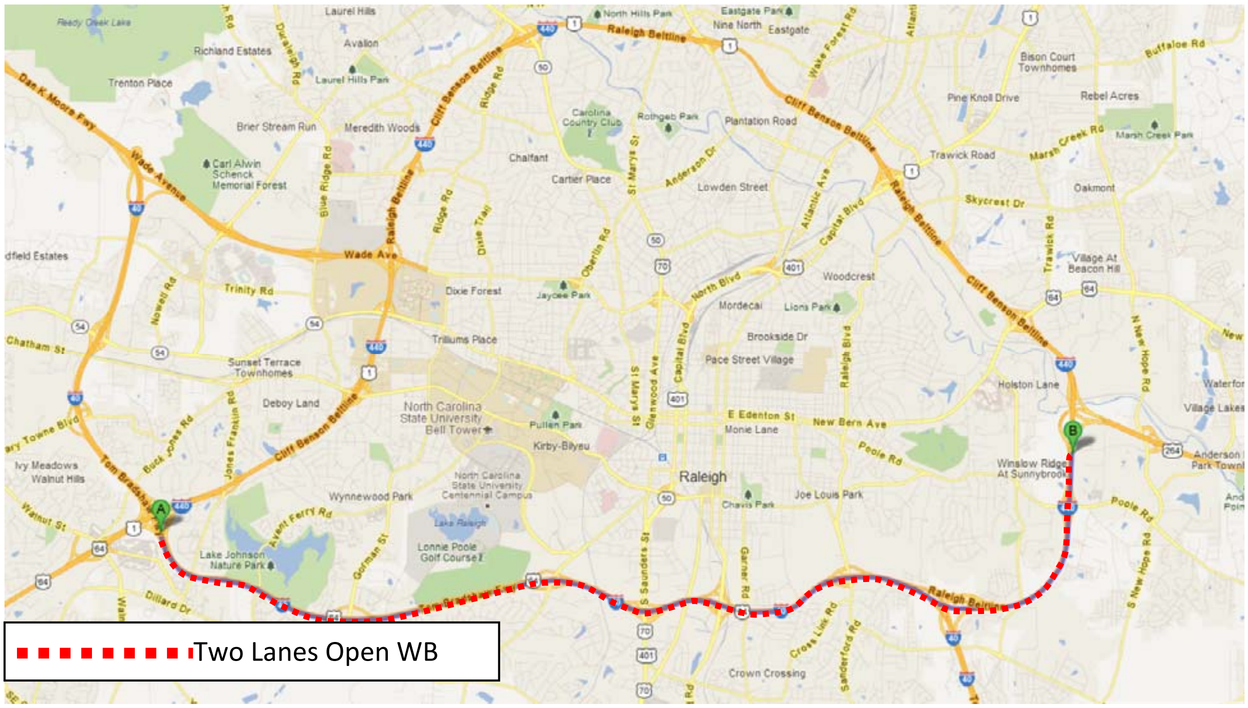


Exhibit 42: Lane Configuration - Work Zone Scenario 2

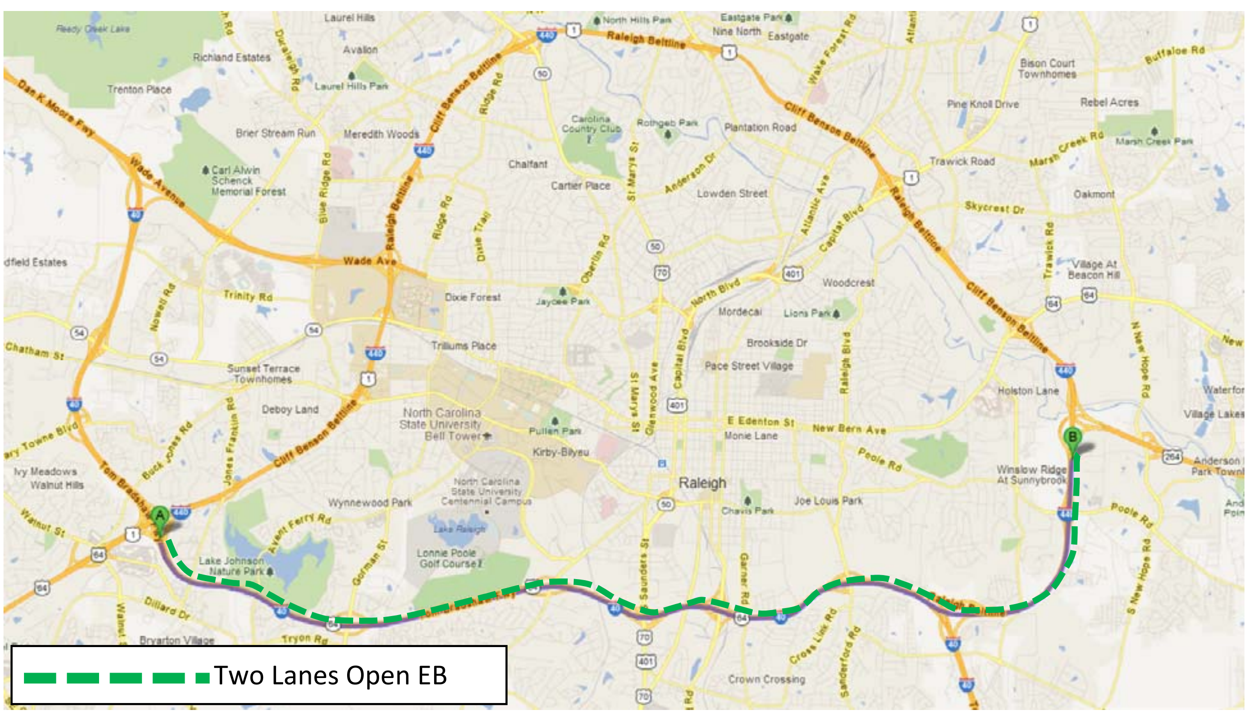


Exhibit 43: Lane Configuration - Work Zone Scenario 3

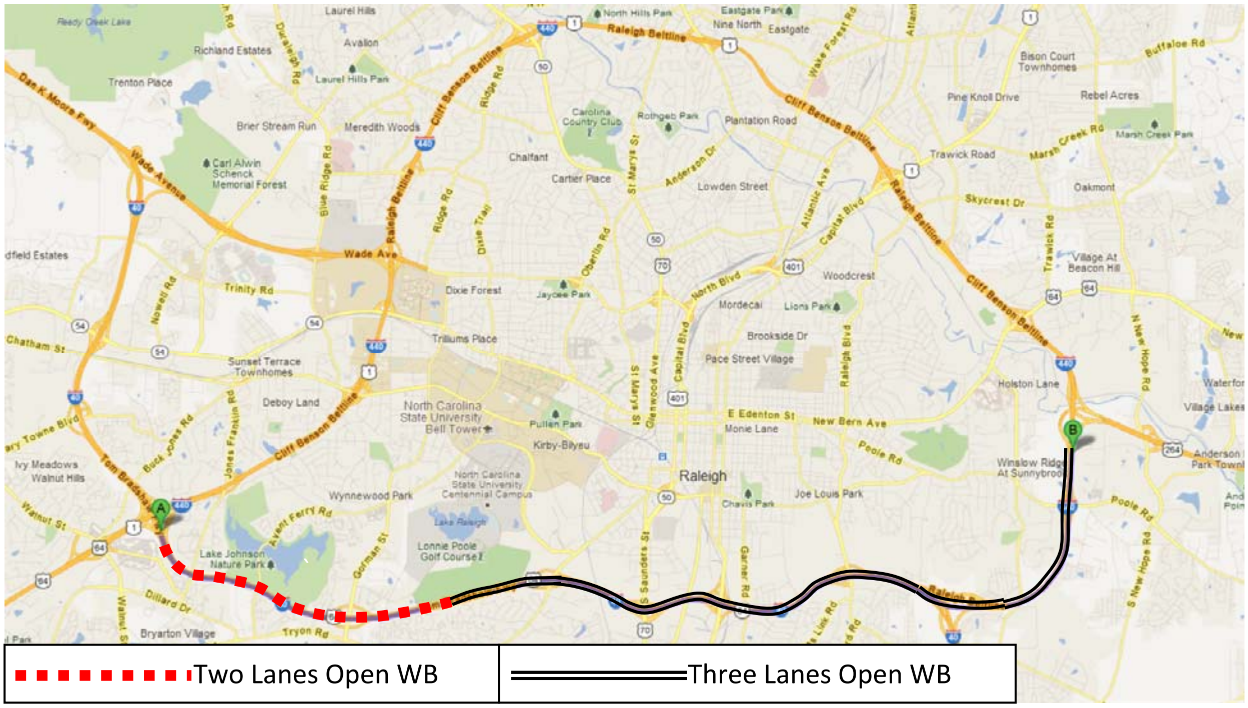


Exhibit 44: Lane Configuration - Work Zone Scenario 4

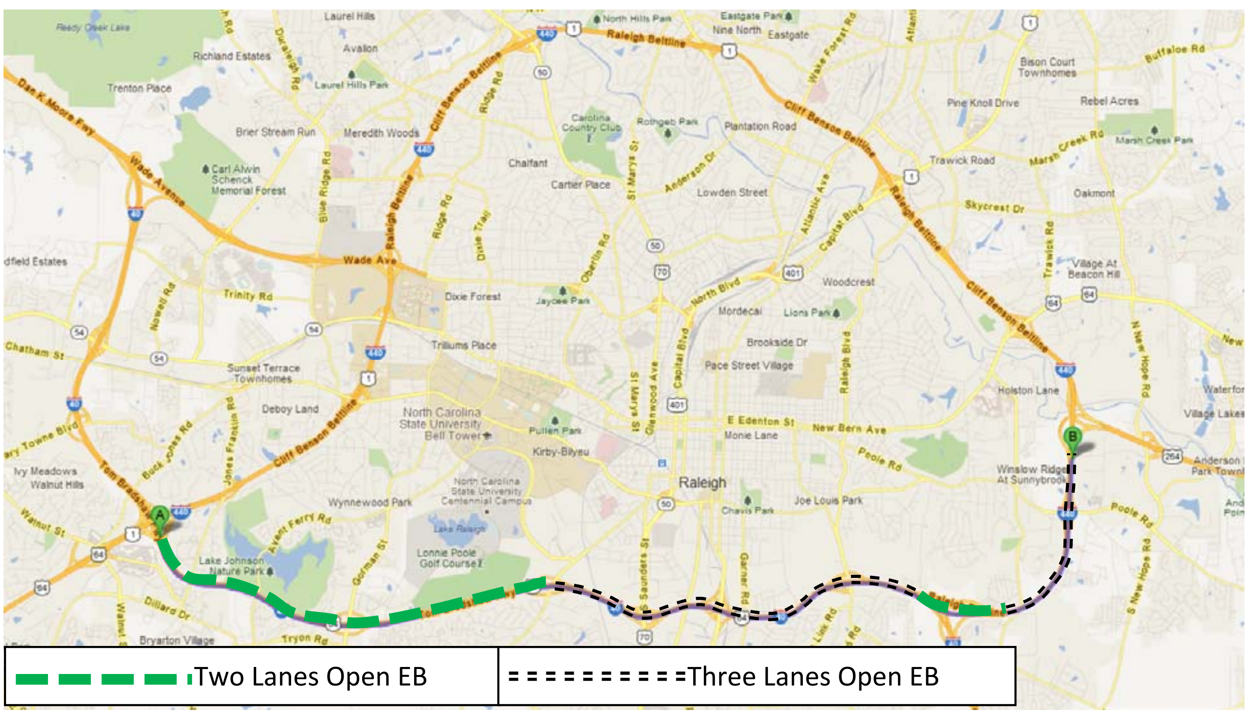


Exhibit 45: Lane Configuration - Work Zone Scenario 5

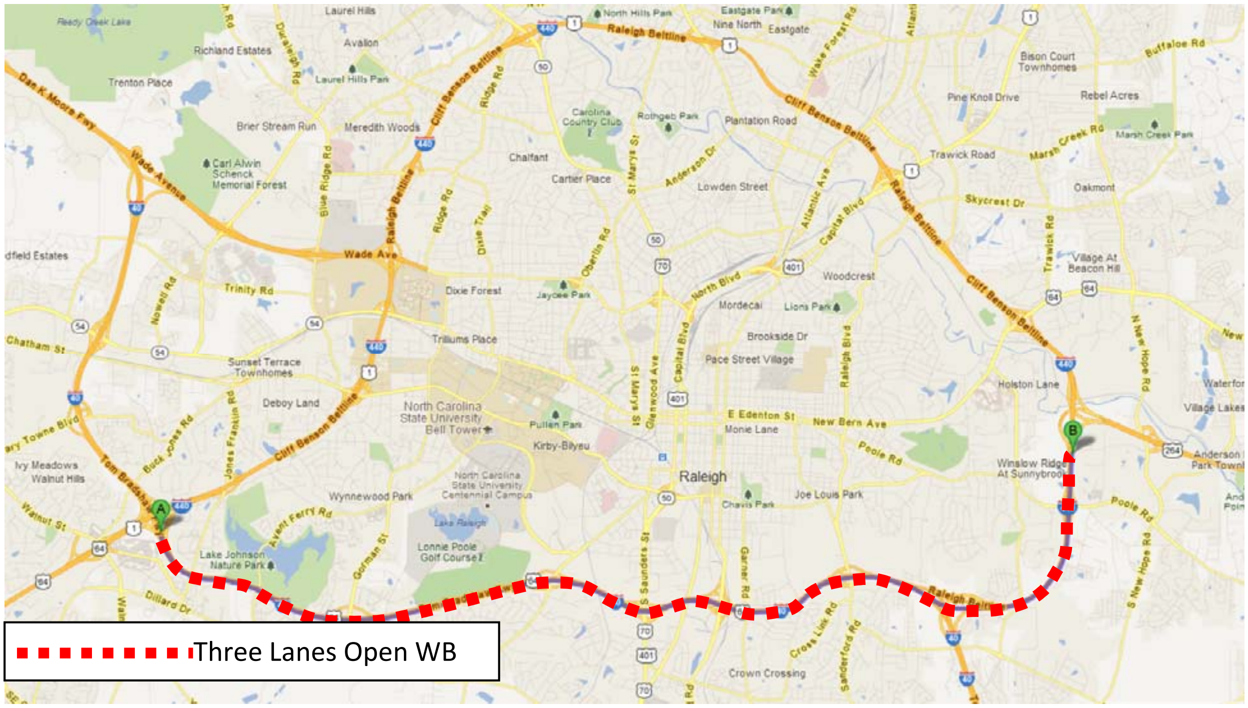


Exhibit 46: Lane Configuration - Work Zone Scenario 6

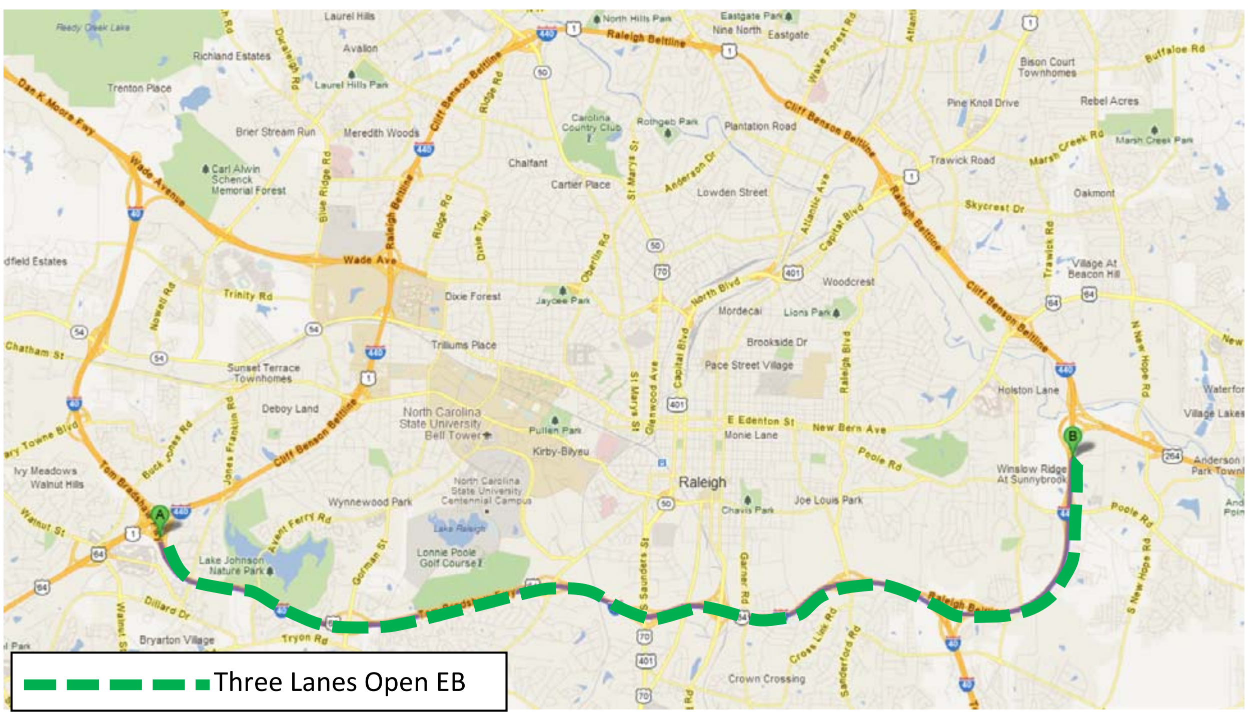
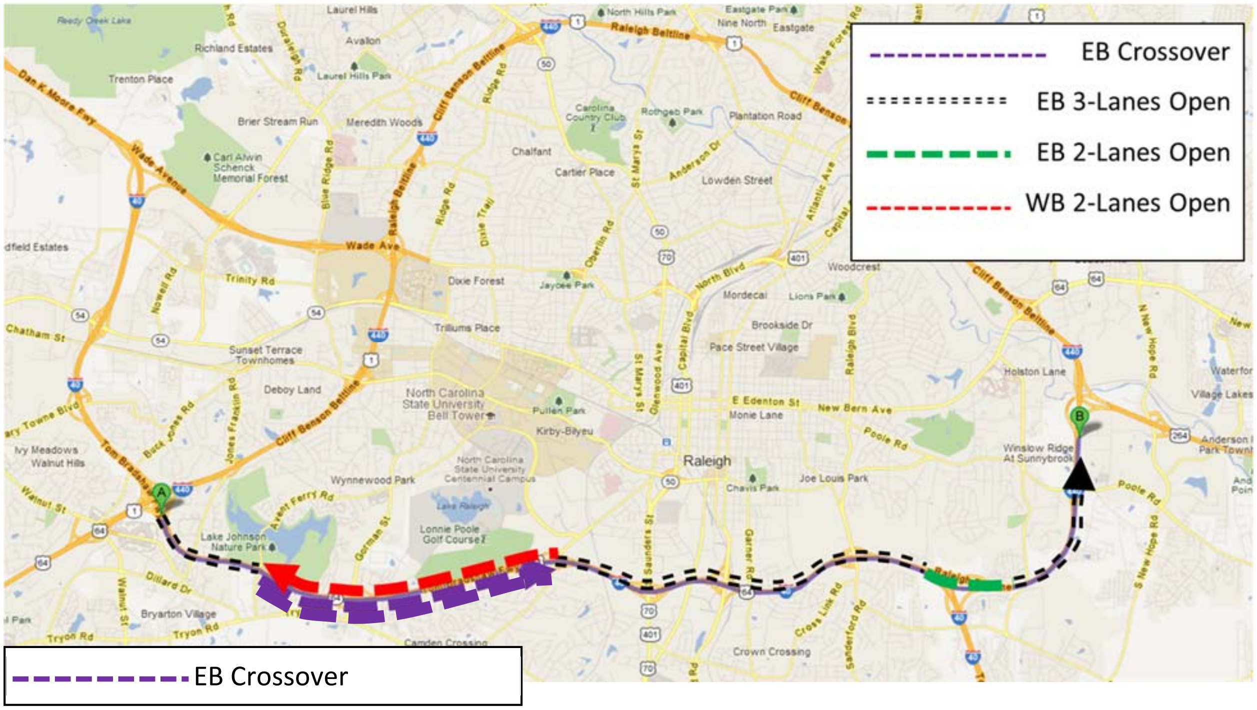


Exhibit 47: Lane Configuration - Work Zone Scenario 7



Appendix B: Field Data Details

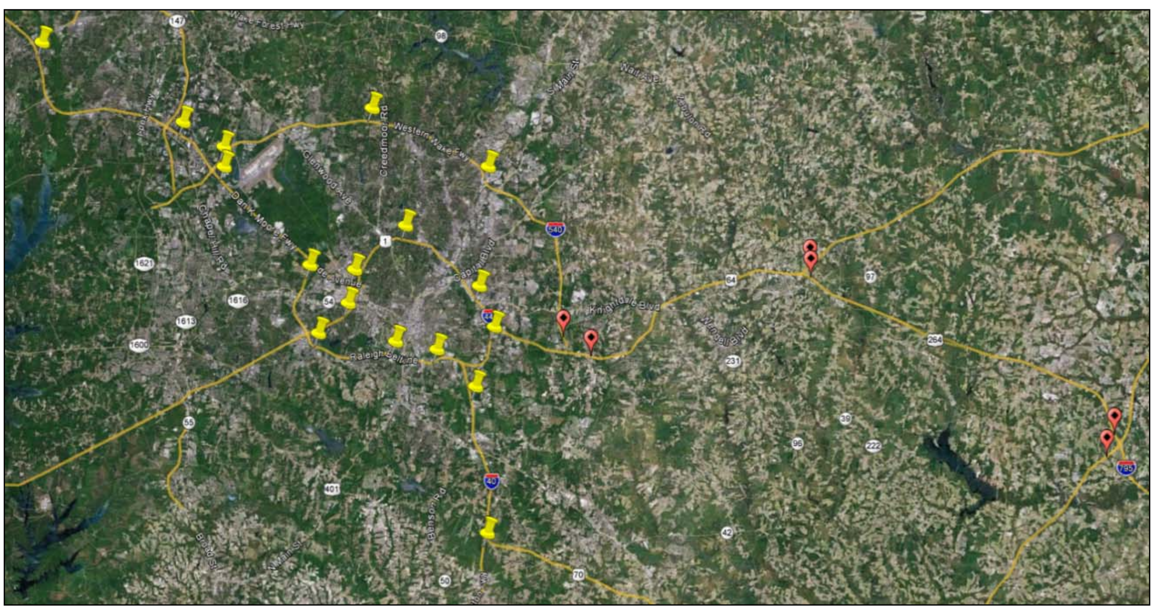
Introduction

Two types of field data were collected to be use in calibration process of the mesoscopic dynamic traffic assignment model: (a) point data and (b) link data. Point data was collected at certain locations of the network and typically included 15 minute average speed and 15 minute volume. The team used two main sources to gather point data: 1) traffic.com sensors and 2) custom data collection. Link data mainly includes 15 minute average travel time and average speed along a link. Link data was downloaded from INRIX.com website that covers all freeways and most of the arterial streets of the interest of this project. In the remainder of this chapter, details on data collection and base year performance according to the field data will be provided.

Point Data (Freeway Volumes and Speed Data)

Point data was collected at 23 locations in the study area. Seventeen locations were covered by Traffic.com sensors. Traffic.com uses side-fire radar technology to continuously record speed and volume data, which are archived online in different aggregation levels. At the remaining six locations with no sensors, a request for counts was submitted to NCDOT and traffic counts were collected for a period of two days at each location. At these locations, only 15-minute traffic counts were collected and speed data was not available. All point data collection locations are shown in Exhibit 48.

Exhibit 48: Point Data Collection Sites (Source: Google)

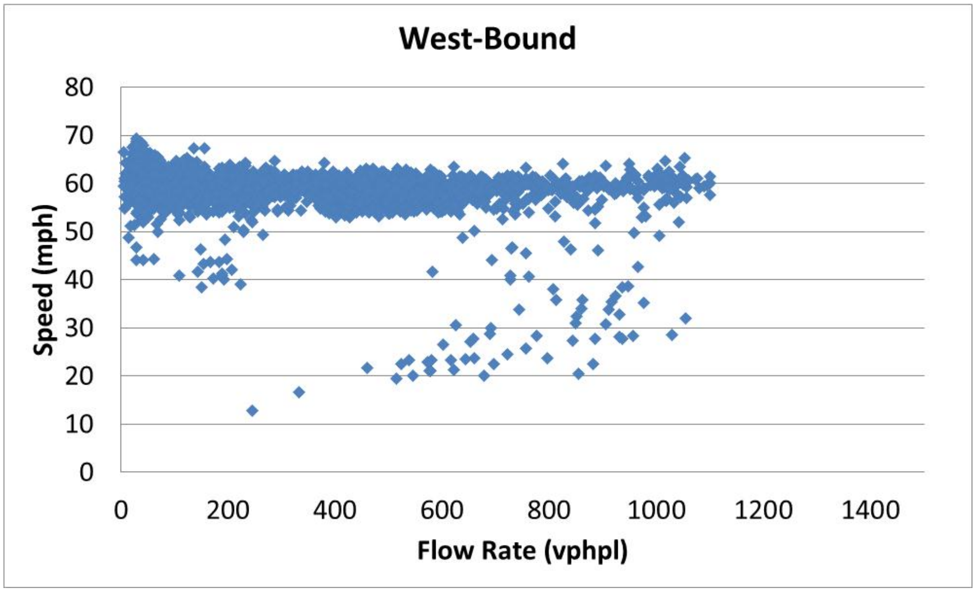


: Traffic.com Sensor Location **: Custom Count Location**

Traffic.com sensors collect speed and volume data aggregated over 5 min, 15 min, 1 hour, or 24 hour time intervals. In this study, a 15-minute aggregation level was used. Data were collected on Tuesdays, Wednesdays, and Thursdays of the second week of each month in 2011, as well as for January 2012.

Therefore, at each sensor location, $13 * 3 = 39$ observations were available for speed and volume that were used to estimate the average speed and volume for each time interval. Speed-flow curves and speed and volume profiles were obtained for all traffic.com sensors. Exhibit 49 presents speed-flow relationship for sensor 040100on I-40 Westbound.

Exhibit 49: Speed-Flow Curve for Sensor 040100 on I-40 Westbound



Speed and volume profiles for westbound and eastbound of all sensors (where data collected) are shown in Exhibit 50 through Exhibit 66.

Exhibit 50 Speed-Volume Profile for Sensor 040100 on I-40

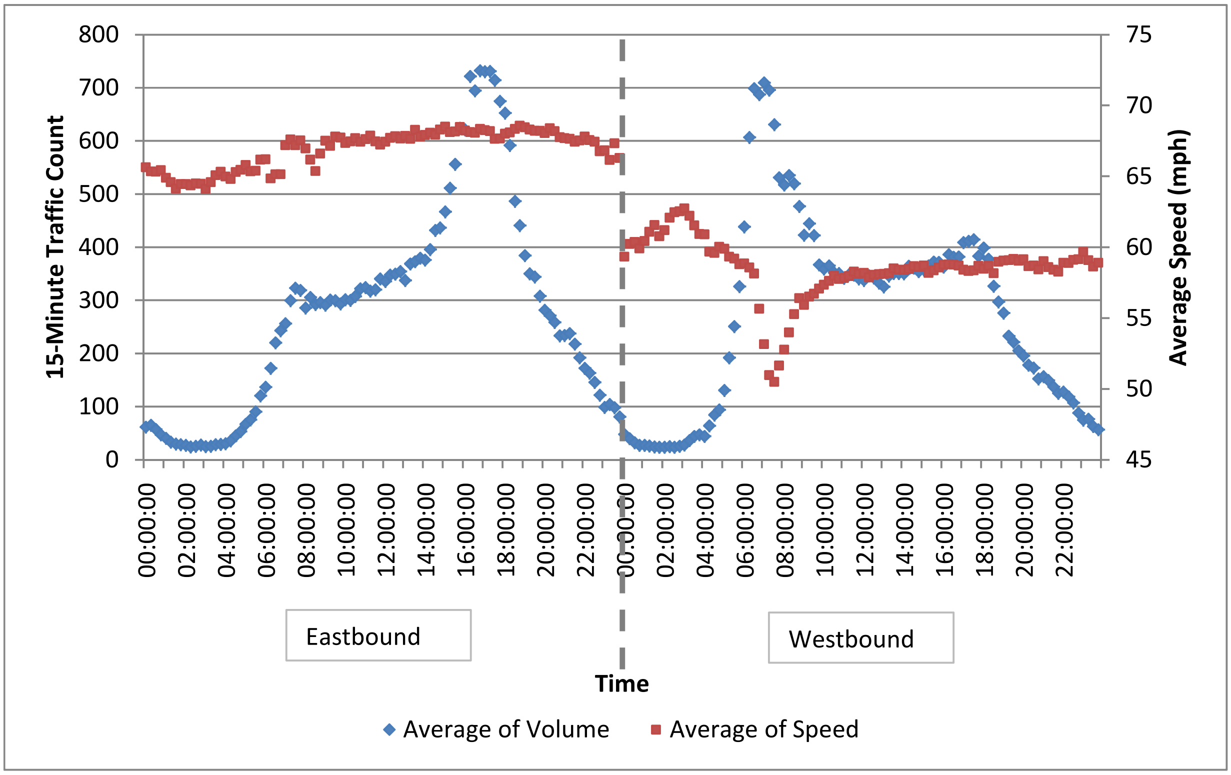


Exhibit 51 Speed-Volume Profile for Sensor 040160 on I-40

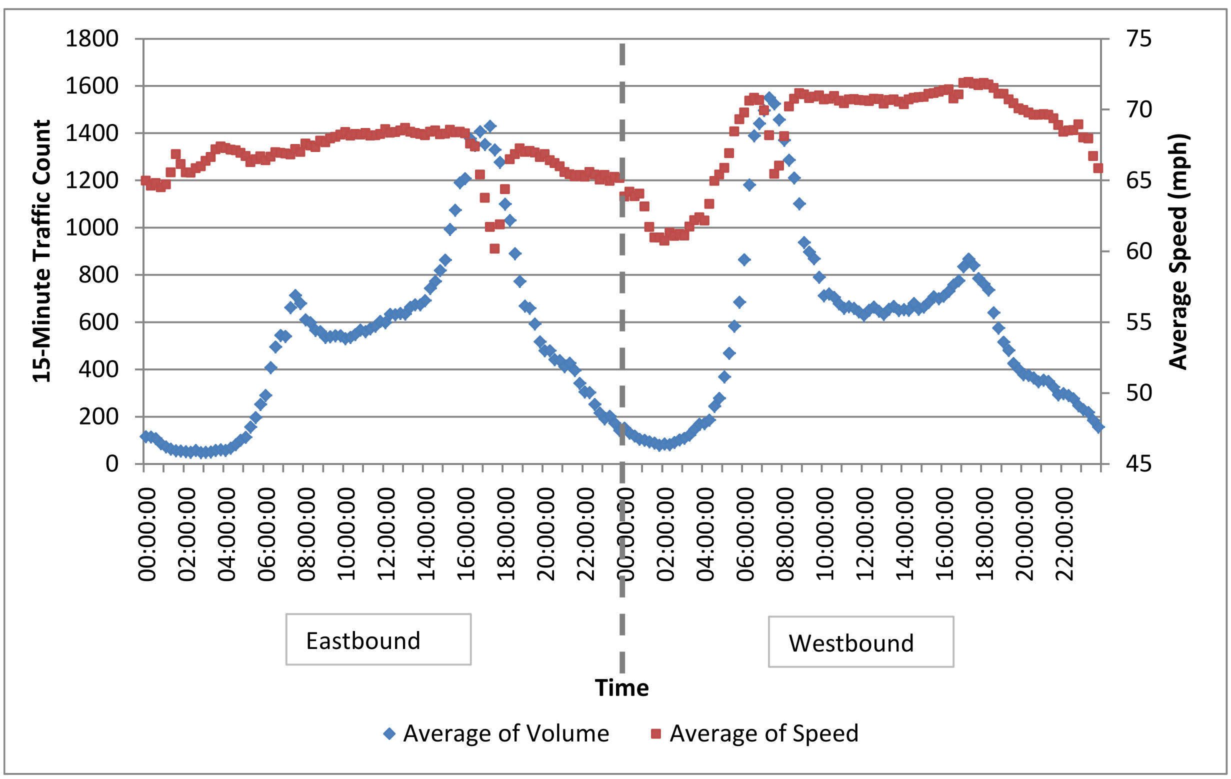


Exhibit 52 Speed-Volume Profile for Sensor 040190 on I-40

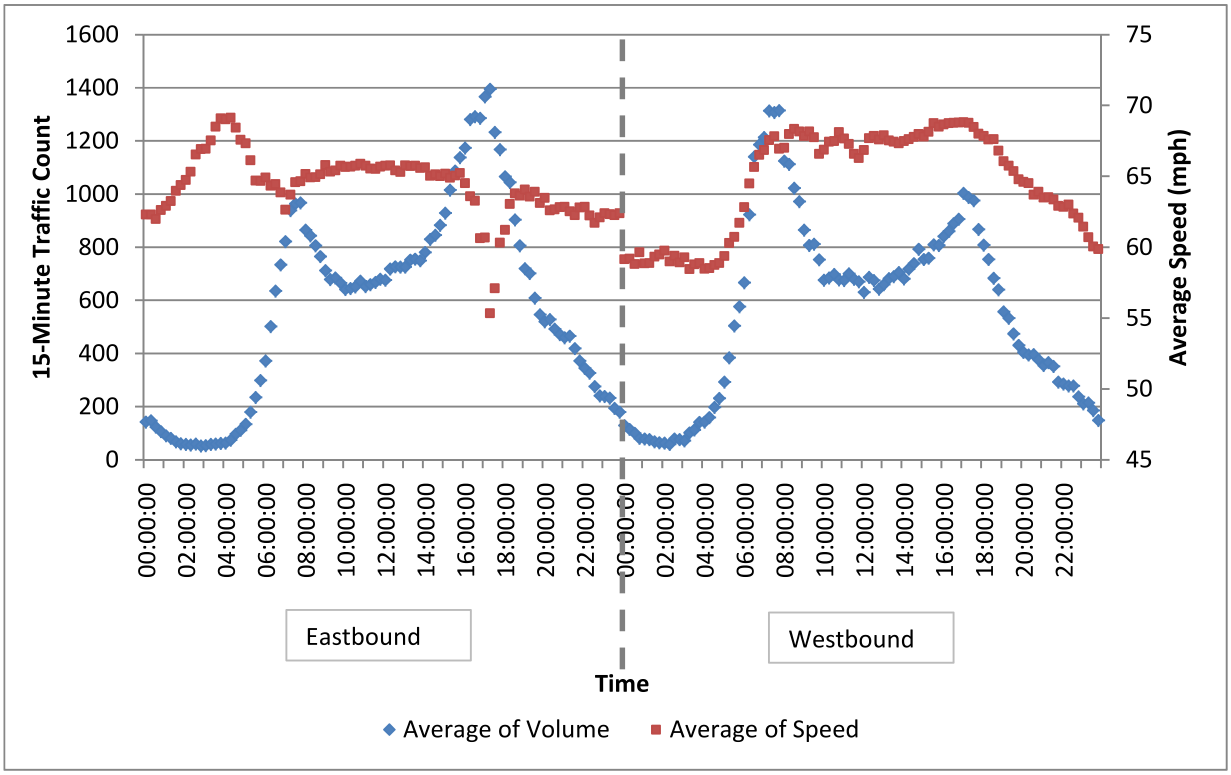


Exhibit 53 Speed-Volume Profile for Sensor 040210 on I-40

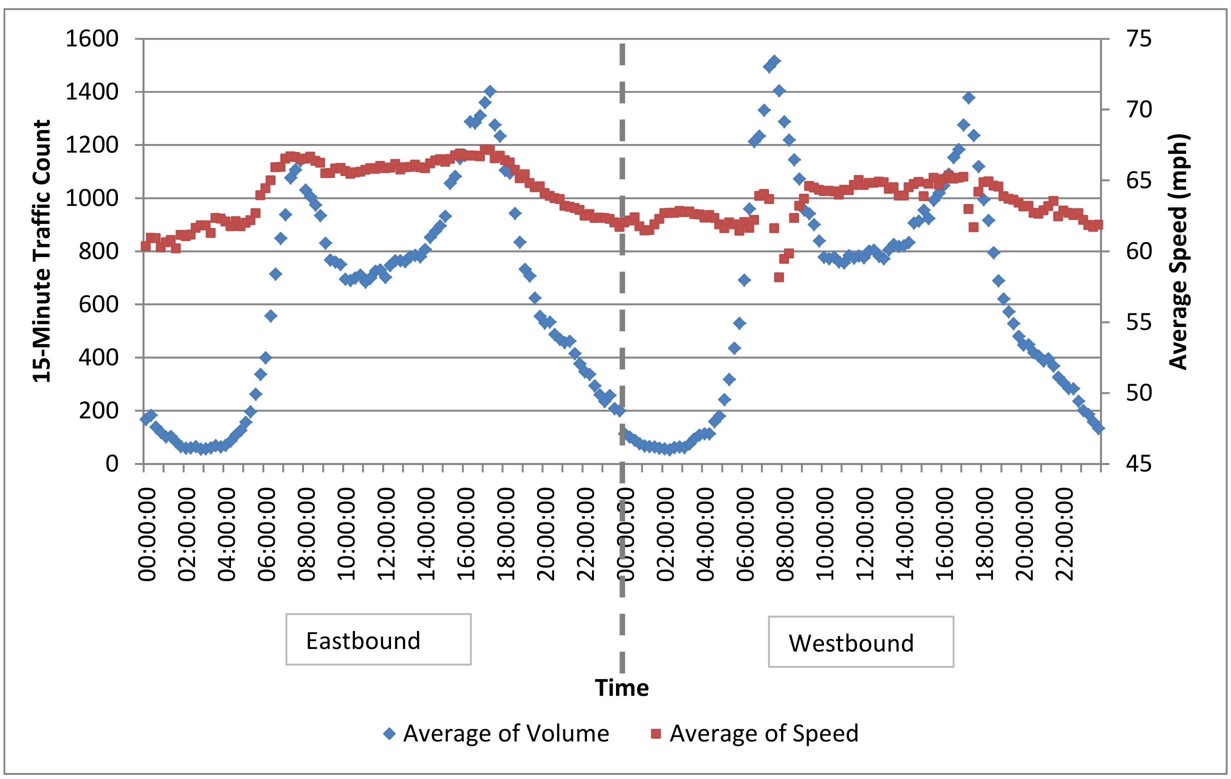


Exhibit 54 Speed-Volume Profile for Sensor 040240 on I-40

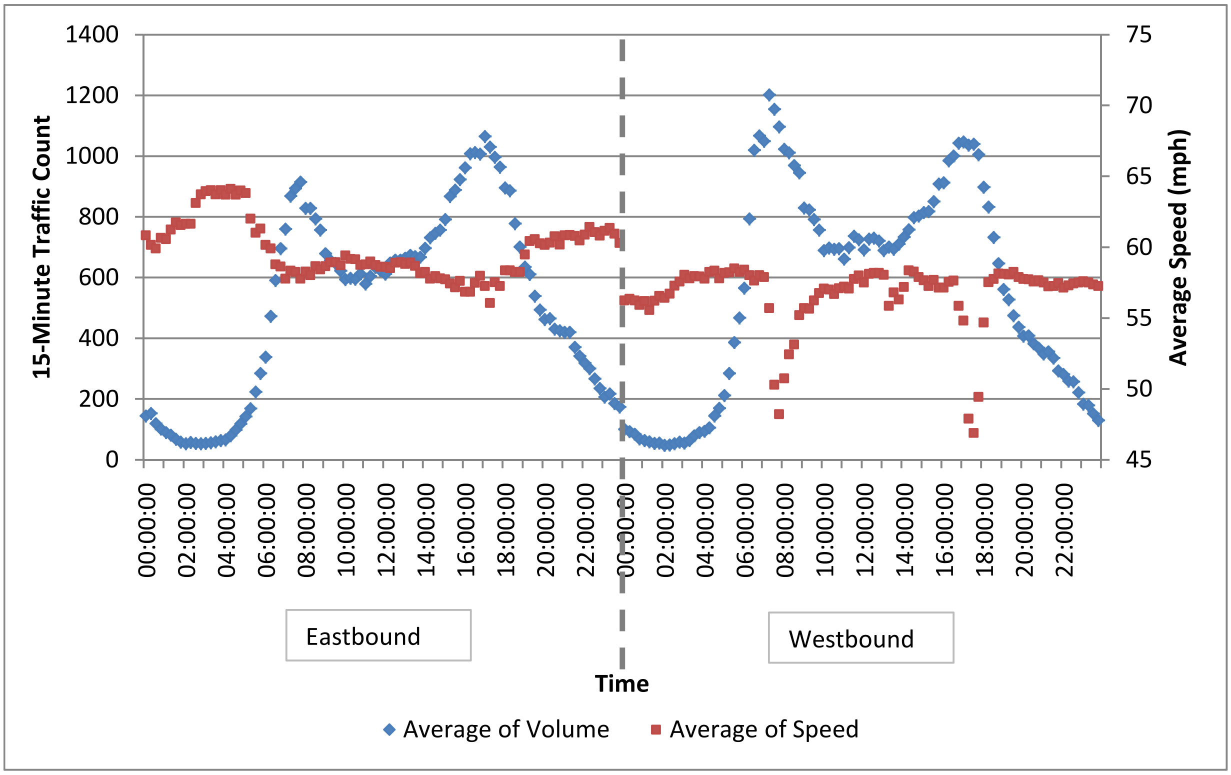


Exhibit 55 Speed-Volume Profile for Sensor 040270 on I-40

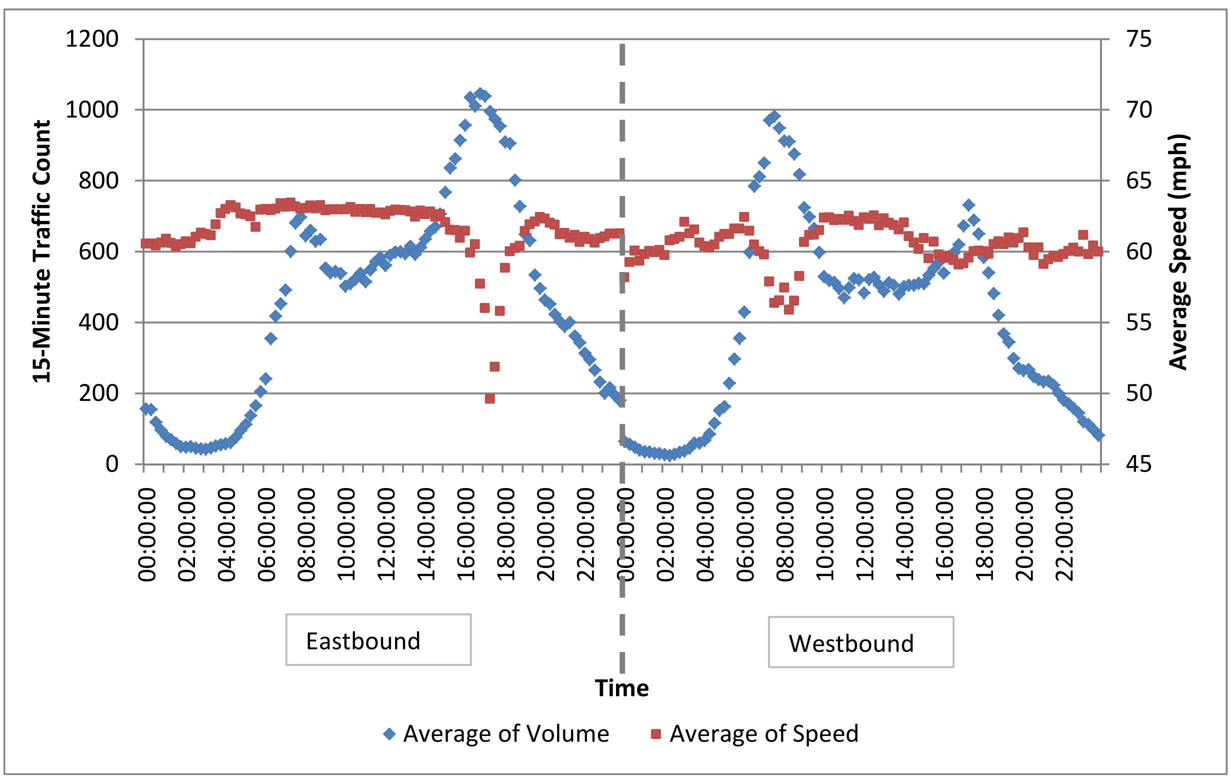


Exhibit 56 Speed-Volume Profile for Sensor 040320 on I-40

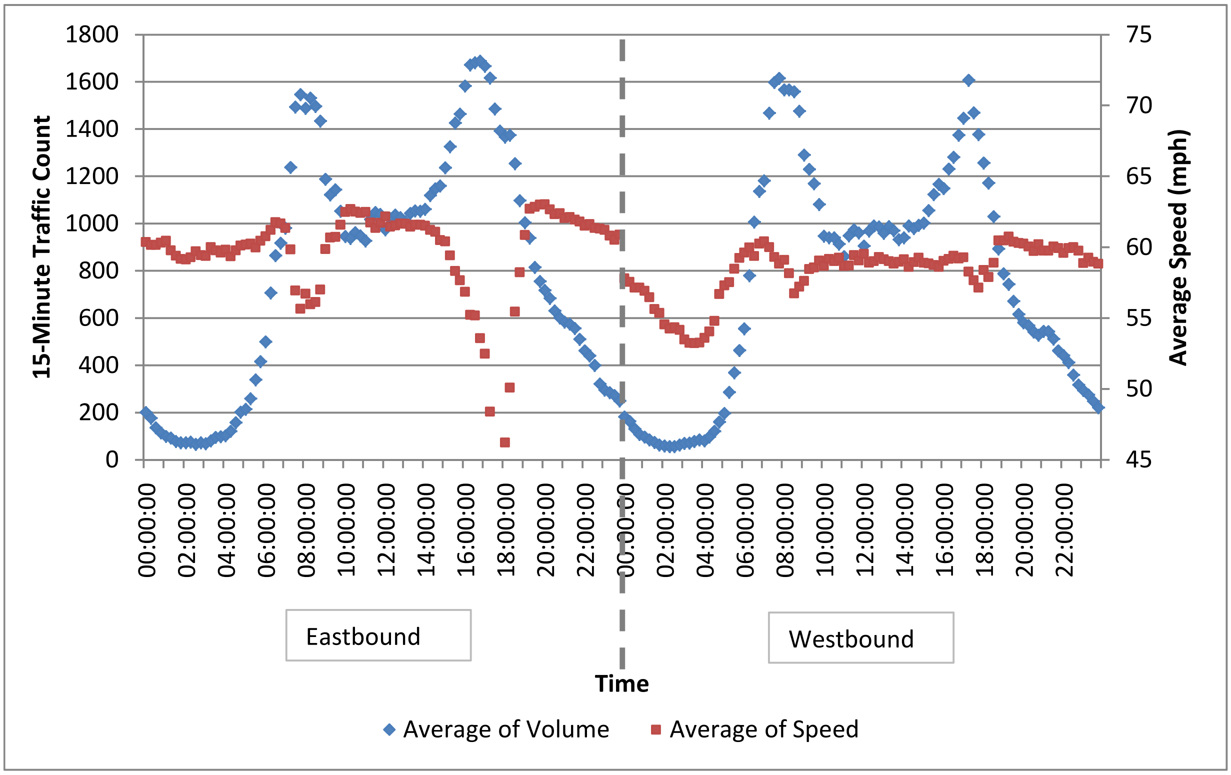


Exhibit 57 Speed-Volume Profile for Sensor 040340 on I-40

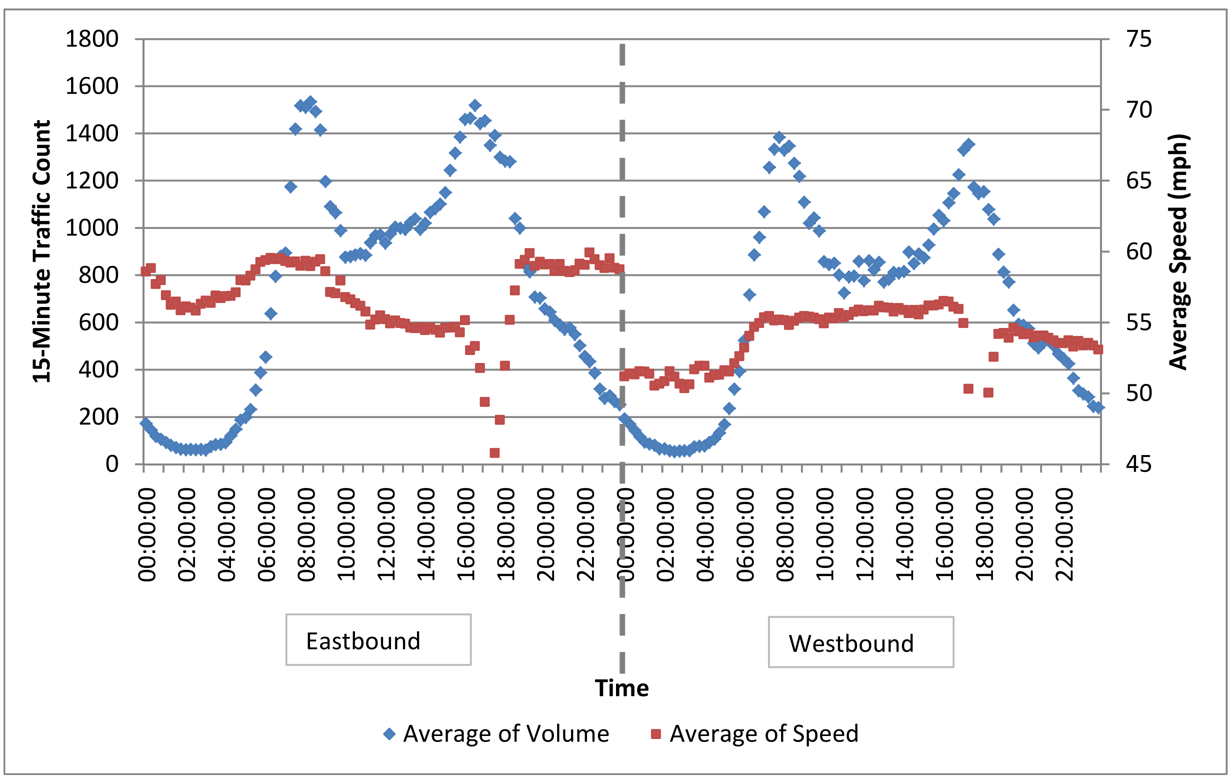


Exhibit 58 Speed-Volume Profile for Sensor 040410 on I-40

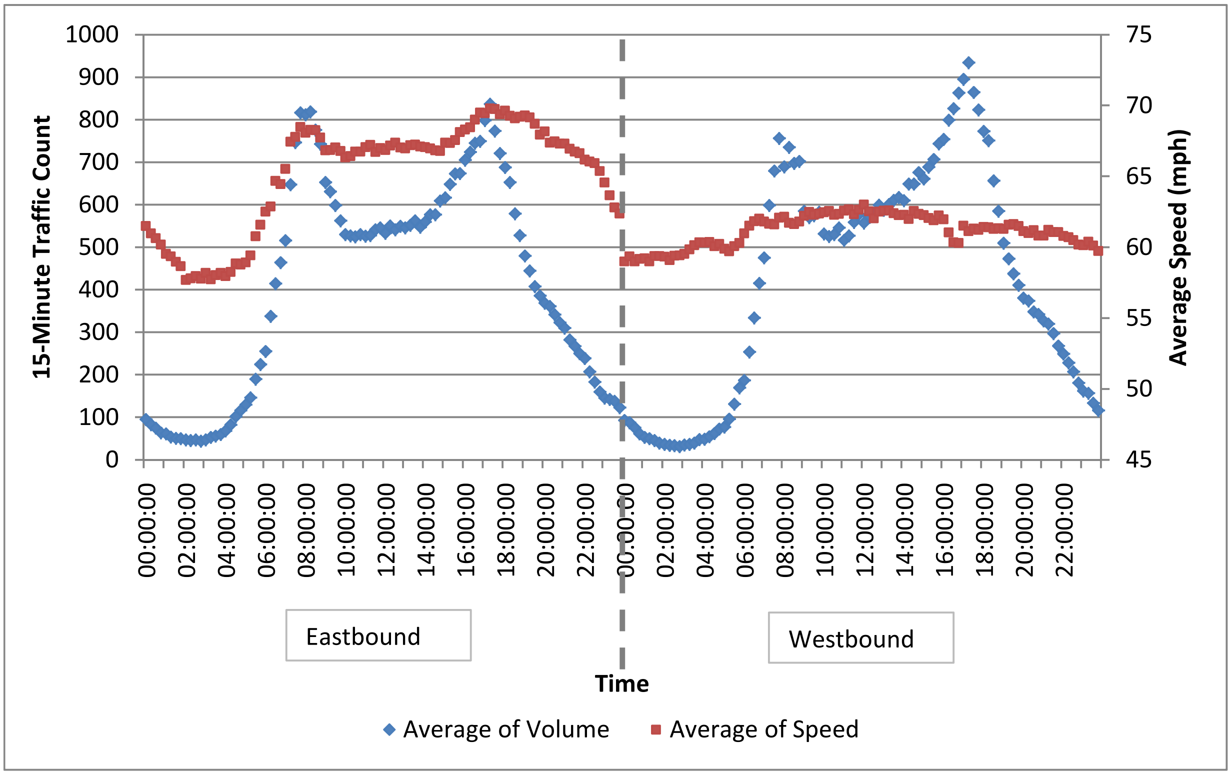


Exhibit 59 Speed-Volume Profile for Sensor 440110 on I-440

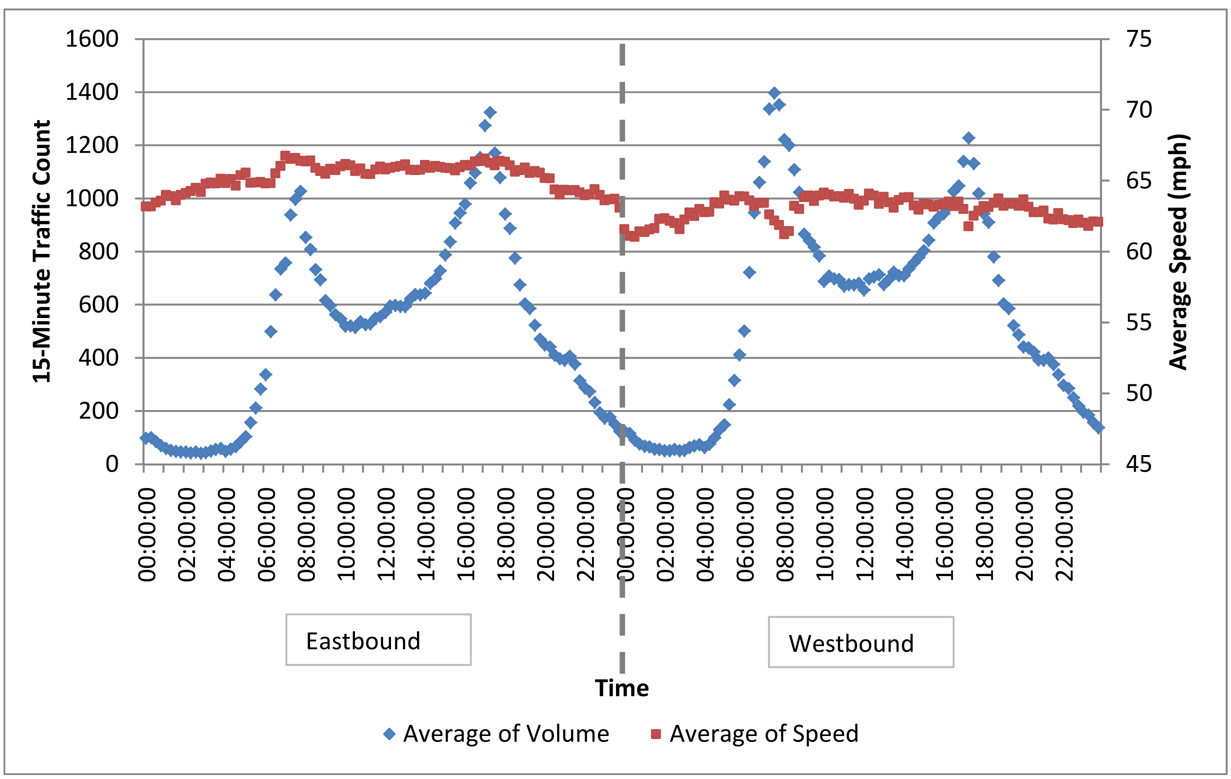


Exhibit 60 Speed-Volume Profile for Sensor 440130 on I-440

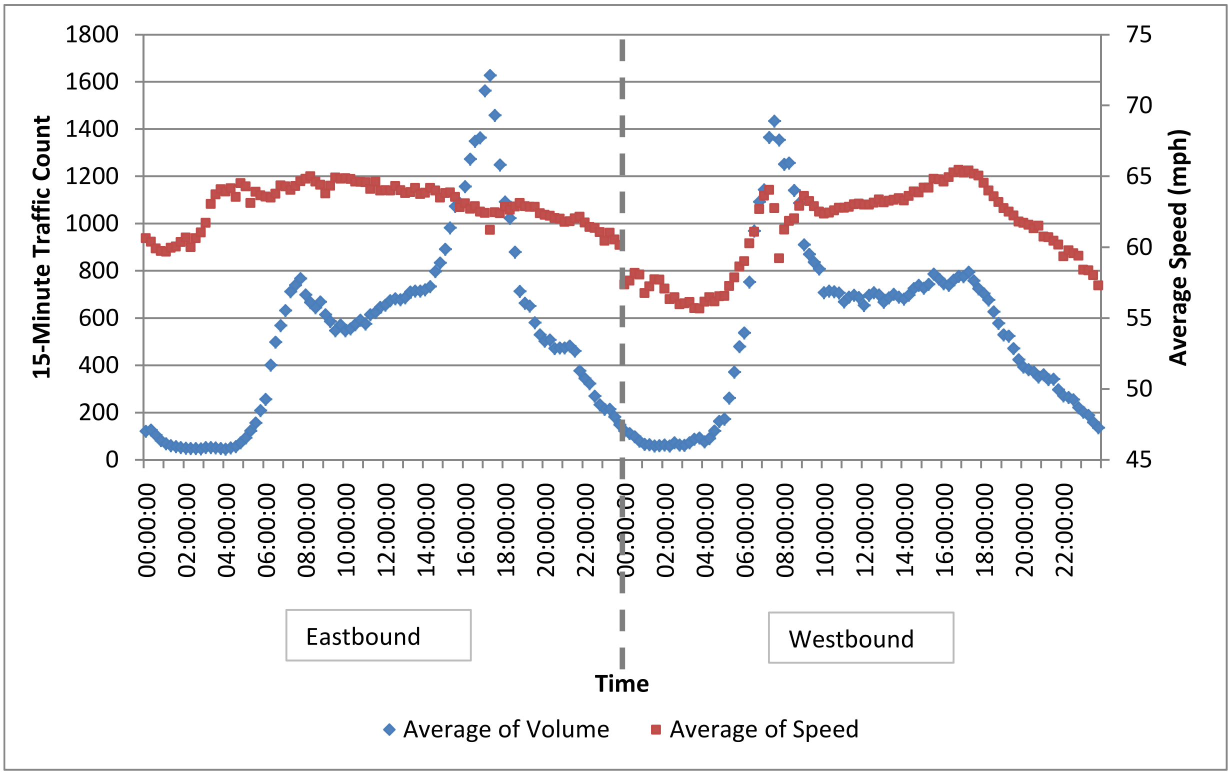


Exhibit 61 Speed-Volume Profile for Sensor 440160 on I-440

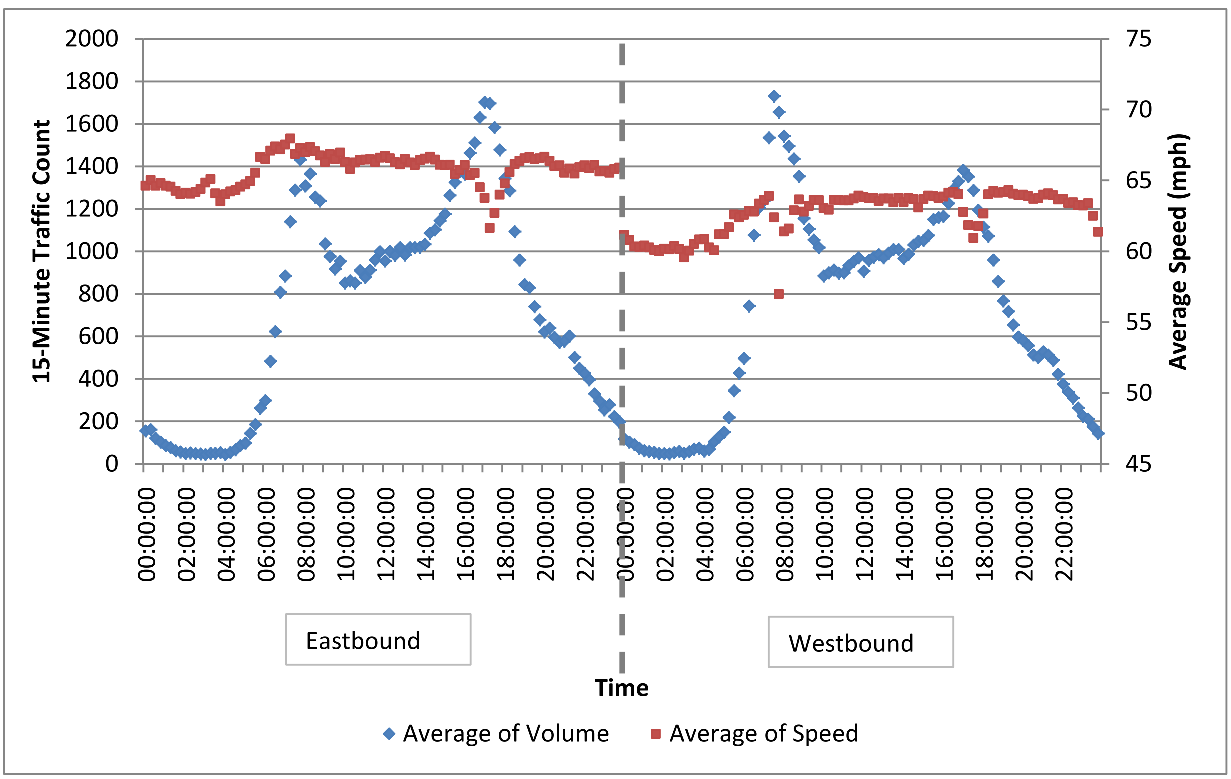


Exhibit 62 Speed-Volume Profile for Sensor 440200 on I-440

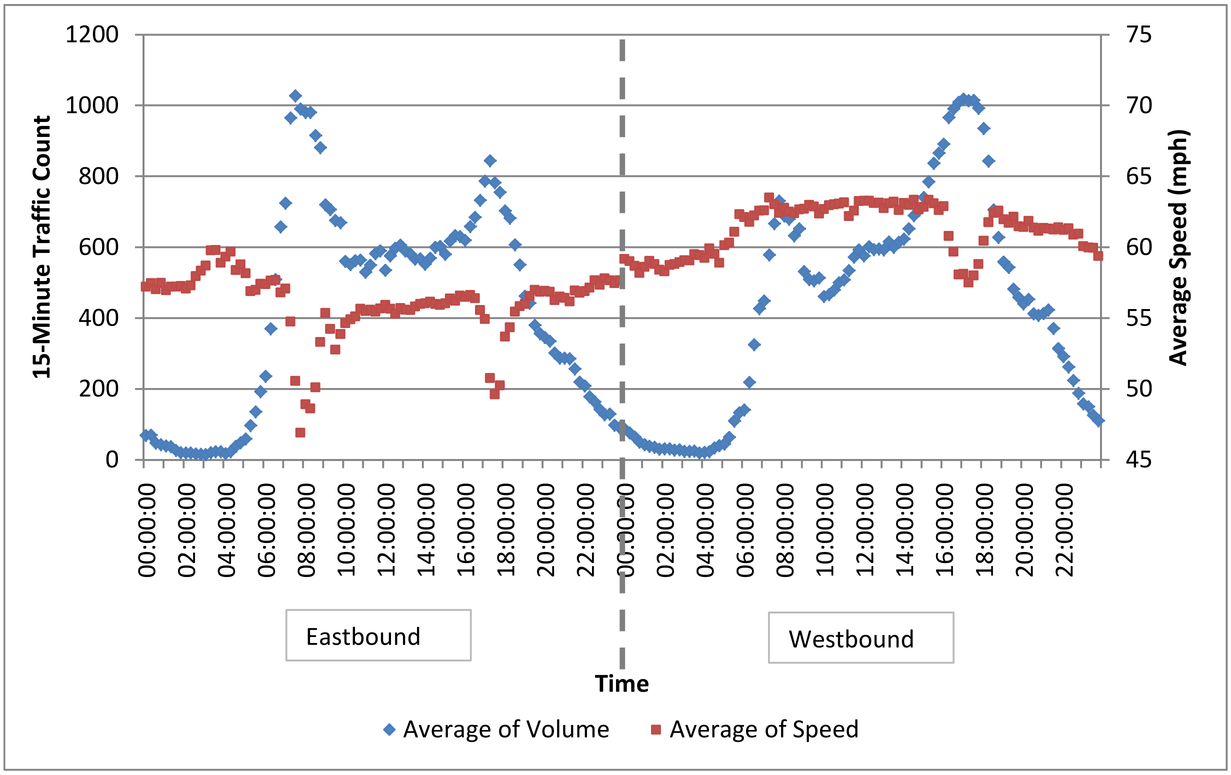


Exhibit 63 Speed-Volume Profile for Sensor 540200 on I-540

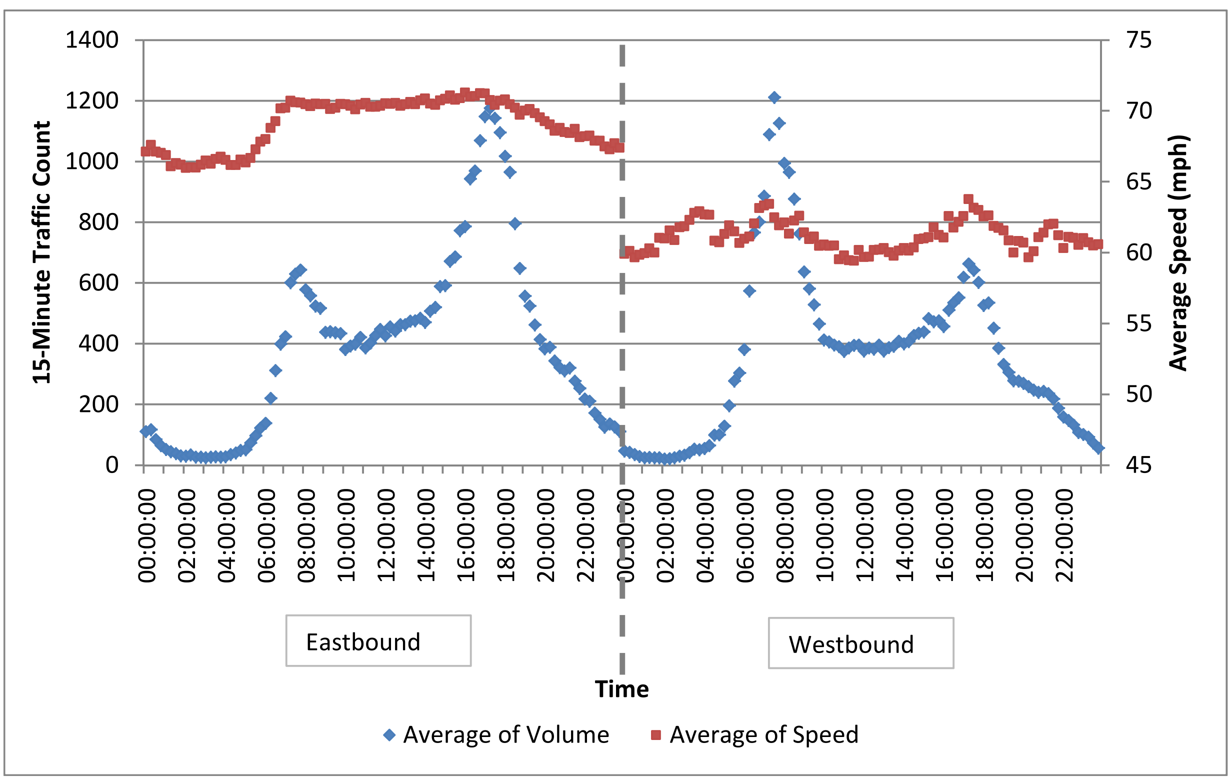


Exhibit 64 Speed-Volume Profile for Sensor 540250 on I-540

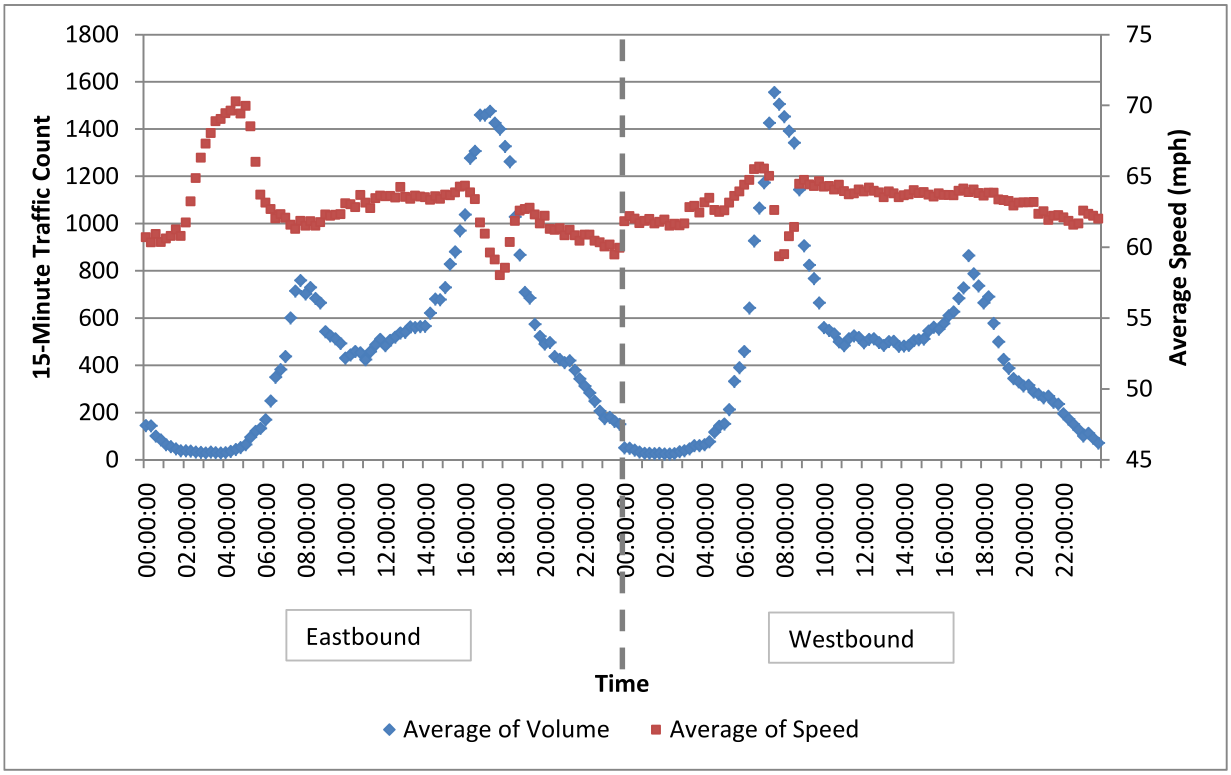


Exhibit 65 Speed-Volume Profile for Sensor 540310 on I-540

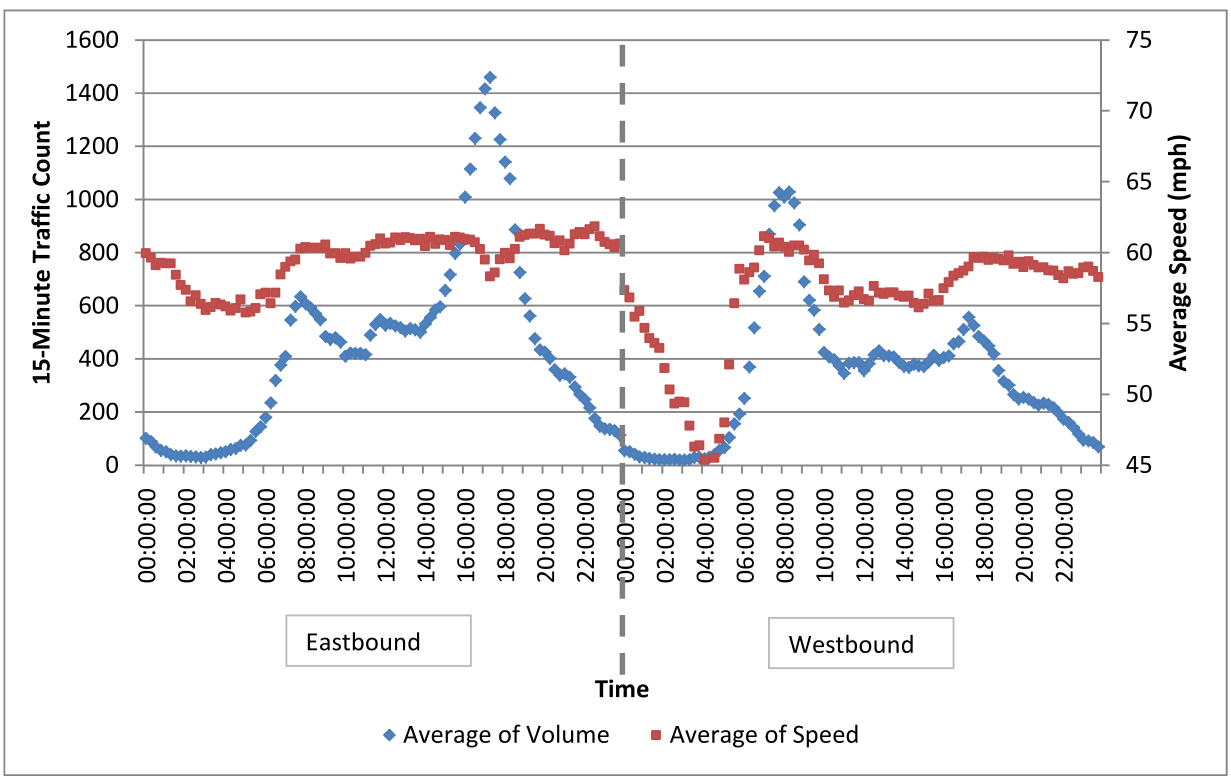
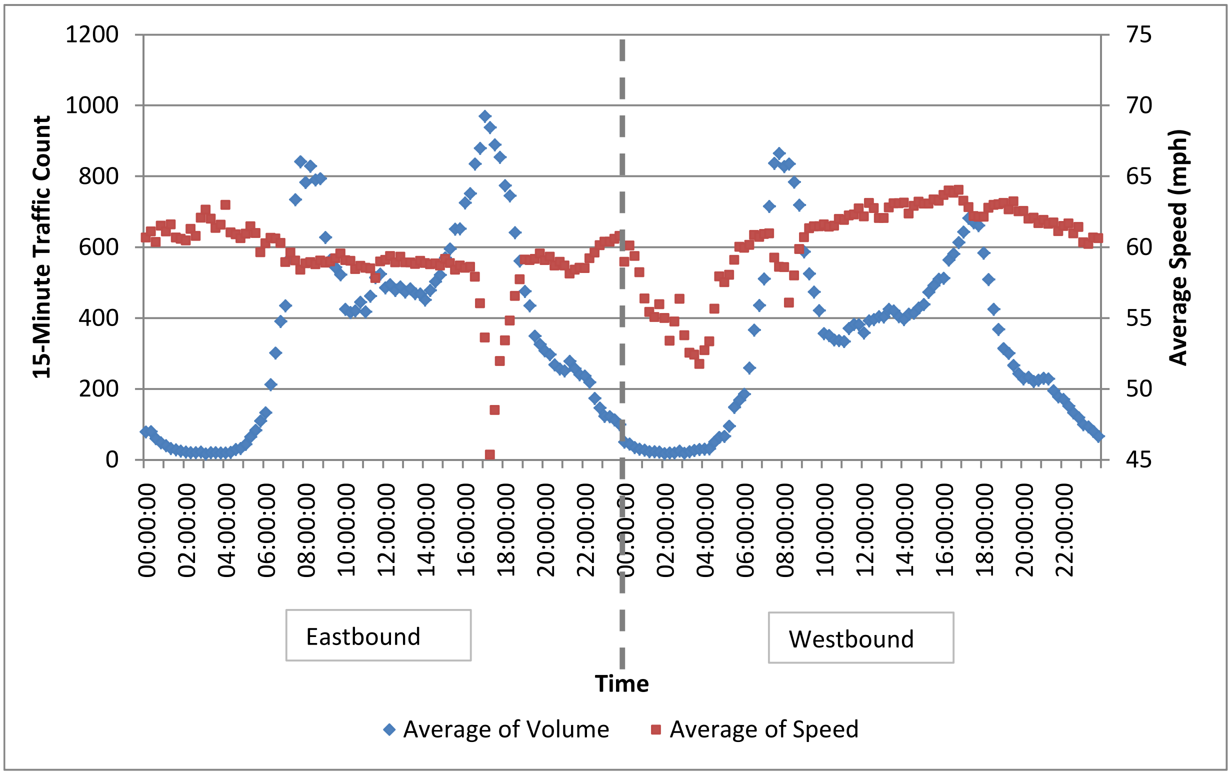


Exhibit 66 Speed-Volume Profile for Sensor WAD100 on Wade Avenue



All point data were used to calibrate current traffic demands and to validate the region-wide DynusT and DTALite simulation models.

Some additional traffic count data were needed outside the NCDOT sensor coverage in the triangle region, which were requested from and obtained by NCDOT for this project. The custom data collection included the following key locations in the study area, needed for calibration of the mesoscopic baseline model:

1- I-540 north of US64/264 interchange
2- US64/264 east of I-540 interchange
3- US64 north of US64/264 split
4- US264 east of US64/264 split
5- US264 northwest of I-95 interchange
6- I-95 southwest of US264 interchange

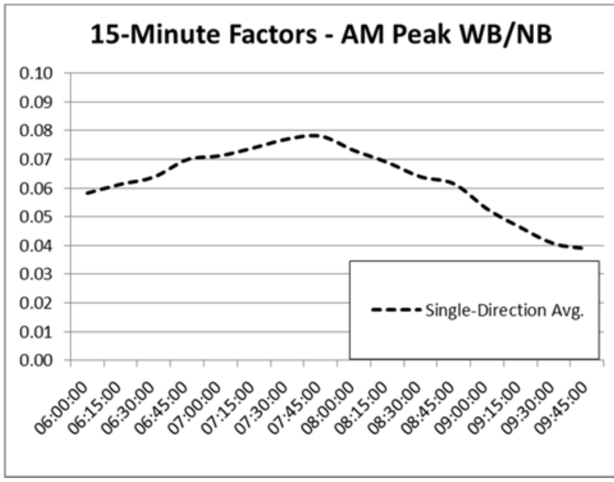
At these six locations, 15-minute traffic count data were collected for a period of two days. For each 15-minue time interval, the average of the two readings was used.

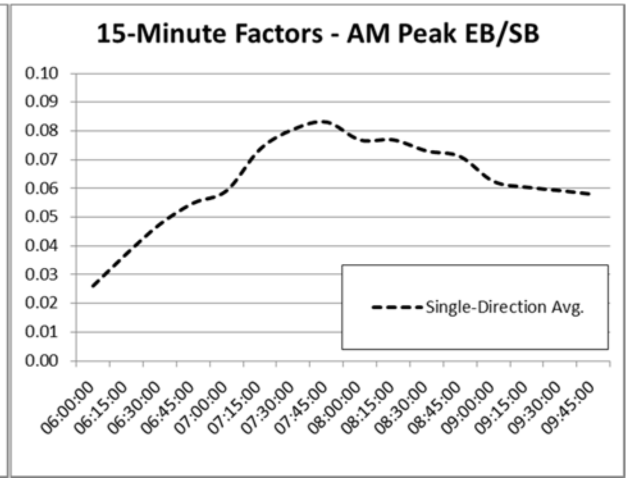
Hourly Factors

The Origin-Destination (O/D) Matrix for the DynusT model was obtained from the Triangle Regional Model, which is a four-hour peak period model. As a result, the team needed to estimate hourly factors from field sensors, to split the four-hour demand into four separate hourly O/D matrices.

For each sensor in each direction in each peak period, the hourly factors were determined by dividing the hourly volume by the sum of 4-hour volume. This yielded four hourly factors for each peak period per direction per sensor. The network wide hourly factors for each direction were computed by averaging all hourly factors in that direction. These hourly factors are shown in Exhibit 67.

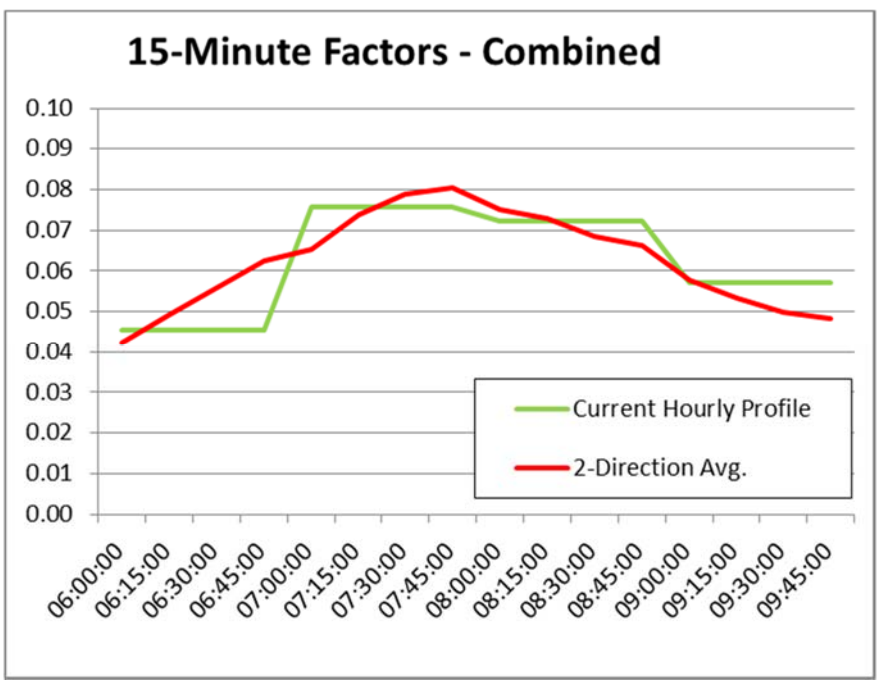
Exhibit 67 Average Directional Hourly Factor for AM Peak





As shown in Exhibit 67, hourly factors do not match between different directions due to differences in peaking patterns. As such, to recreate a more realistic peaking pattern, one needs to use different hourly factor for the different directions. Although this is possible in DynusT, it requires one to distinguish all origin-destination pairs feeding each direction, which is unfeasible. Therefore, the team used an average of the directional hourly factors as the network-wide hourly factors, see Exhibit 68.

Exhibit 68 Network Wide Hourly Factor for AM Peak



Link Data (Route Travel Times)

In addition to the point data, ten key *calibration routes* (A through J) were identified in the study area for data collection. These ten routes were defined to include the work zone, key alternate routes (I-440, I-540, etc.), and key urban arterials that could be used to carry some of work zone traffic. The calibration routes will be used to compare results of the DynusT base model to real-world data. Calibration routes were selected to provide a representative sample of key routes in the triangle region.

All calibration and analysis routes are shown in Exhibit 69 using a start-point (green), an end-point (red), and several mid-points (blue) for each of the ten route numbers. Exhibit 9 provides a narrative and milepost of each of the routes.

Exhibit 69: Key Route Definitions

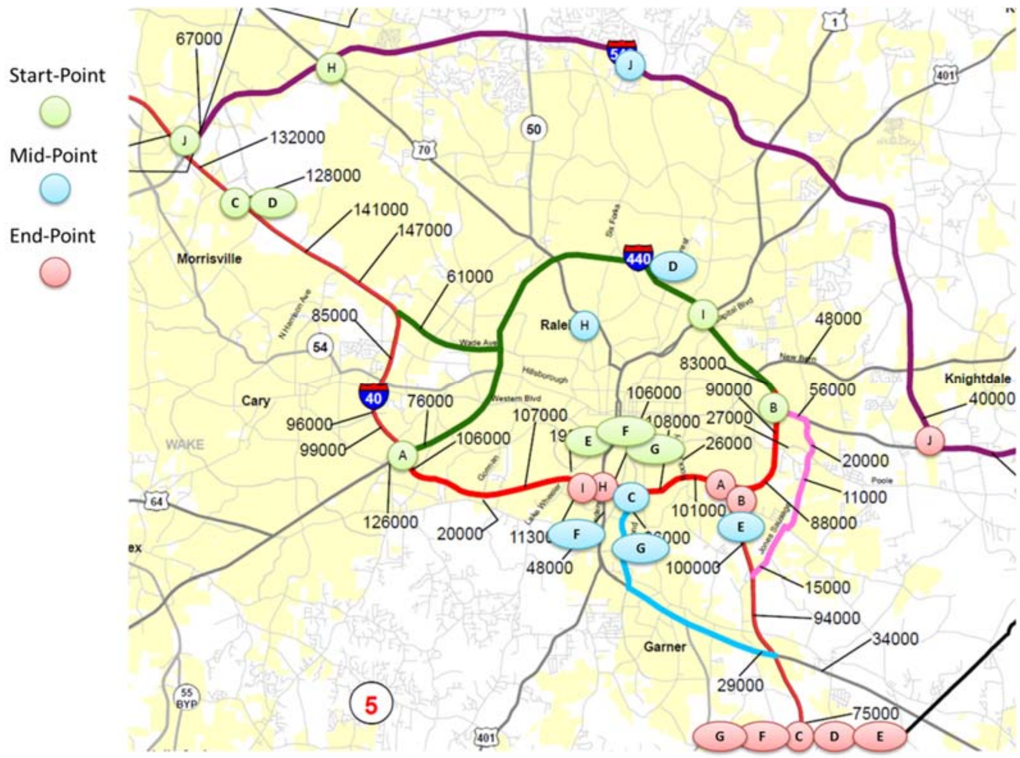


Exhibit 70: Description of Routes

#	Route Description	Start Milepost	Start Facility	End Milepost	End Facility
A	I40 WZ Section	293	I40-I440	301	I40-I440
B	I440 WZ Section	14	64/264 SPLIT	16	I40-I440
C	Triangle Route I-40	284	I-40	312	
D	Triangle Route I-440	284	I-40	312	
E	South Approach - I-40	Downtown	Saunders	312	I-40
F	South Approach - Saunders	Downtown	Saunders	312	I-40
G	South Approach - Hammond	Downtown	Saunders	312	I-40
H	US 70 Arterial	I540		I40	
I	US401 Arterial	I440		I40	
J	I540 Detour	1	I40	26	64/264

For each route, the team extracted 15-minute travel time and average speed data for Tuesdays, Wednesdays, and Thursdays of the second week of each month in 2011, as well as for January 2012. These analysis periods are consistent with the collected point data. Route data were obtained from the INRIX.com online data repository. Each route includes several links, and the team summed up link travel times to yield route travel time. Similar to point-data, for most of the routes, travel time for each 15-minte time interval is the average of 39 travel time observation throughout 2011 and January 2012.

For each route, the team estimated average travel time, average travel time plus standard error, and average travel time minus standard error profiles. Travel Time profiles for all routes are shown in Exhibit 71 through Exhibit 86. It should be noted that travel time data was not available for Route G.

Exhibit 71: Average Travel Time Profile for Route A, Westbound Direction

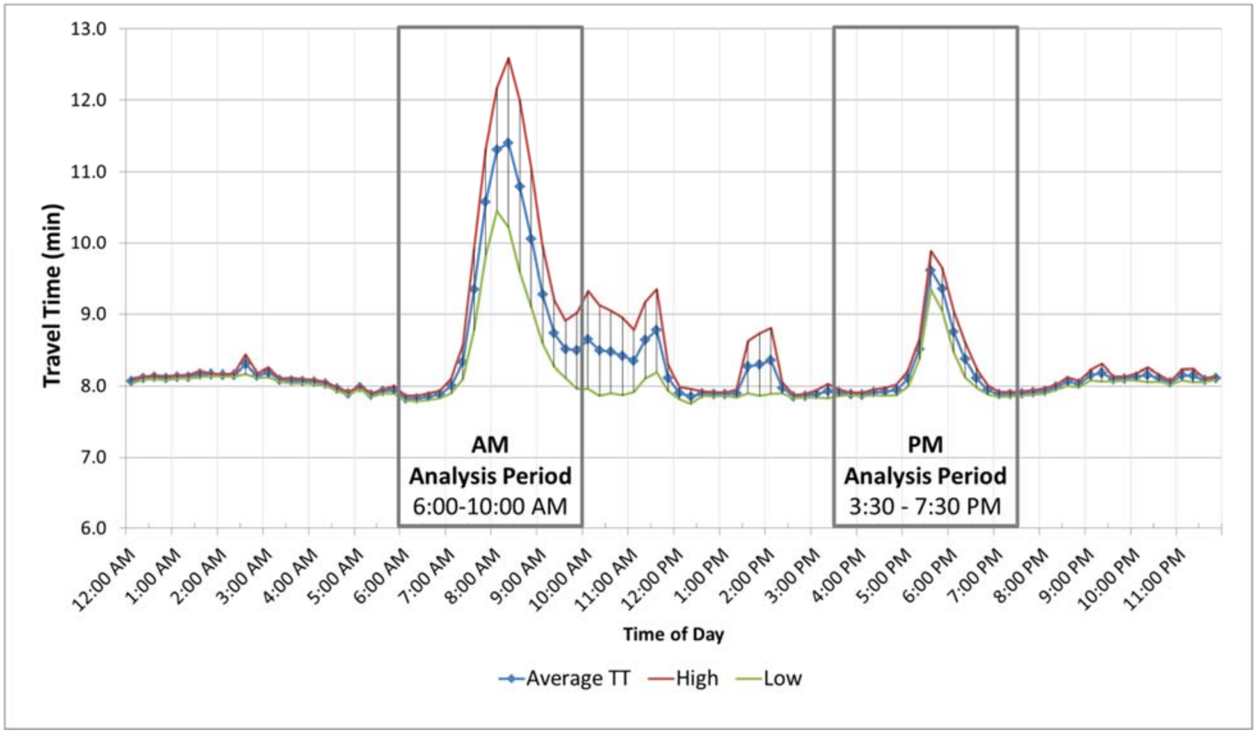


Exhibit 72: Average Travel Time Profile for Route A, Eastbound Direction

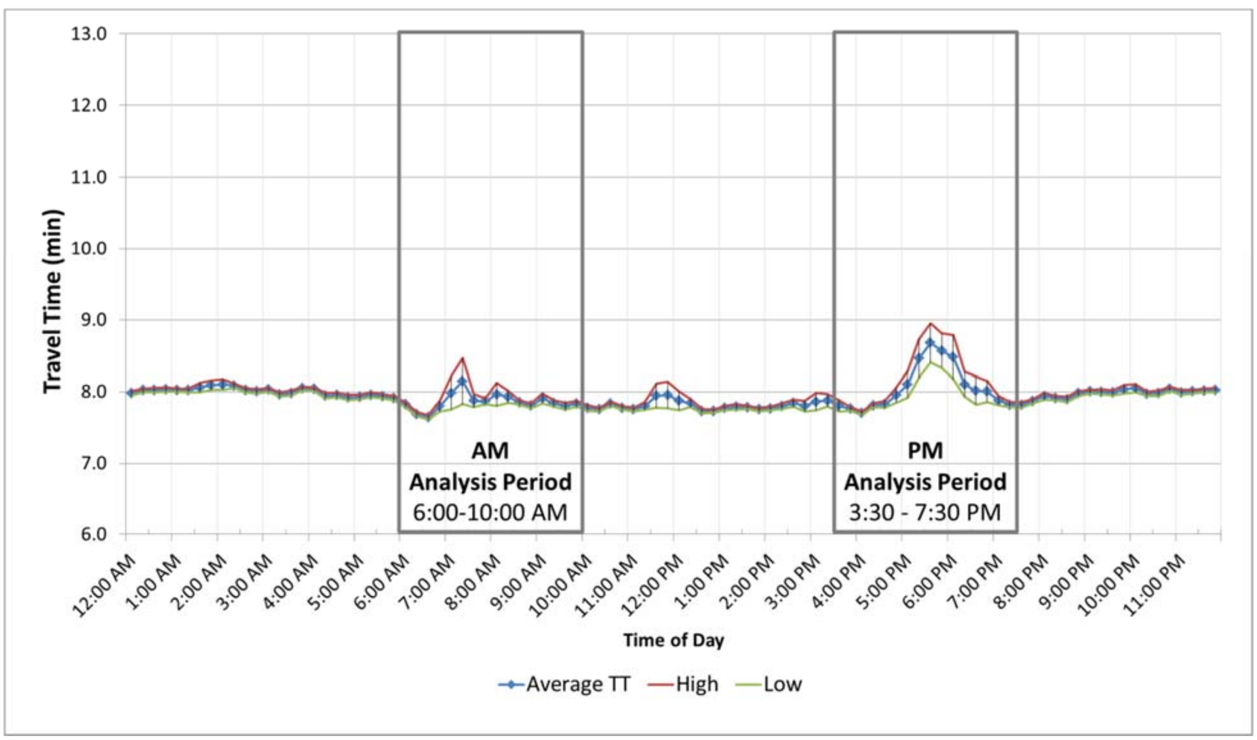


Exhibit 73 Average Travel Time Profile for Route B, Northbound Direction

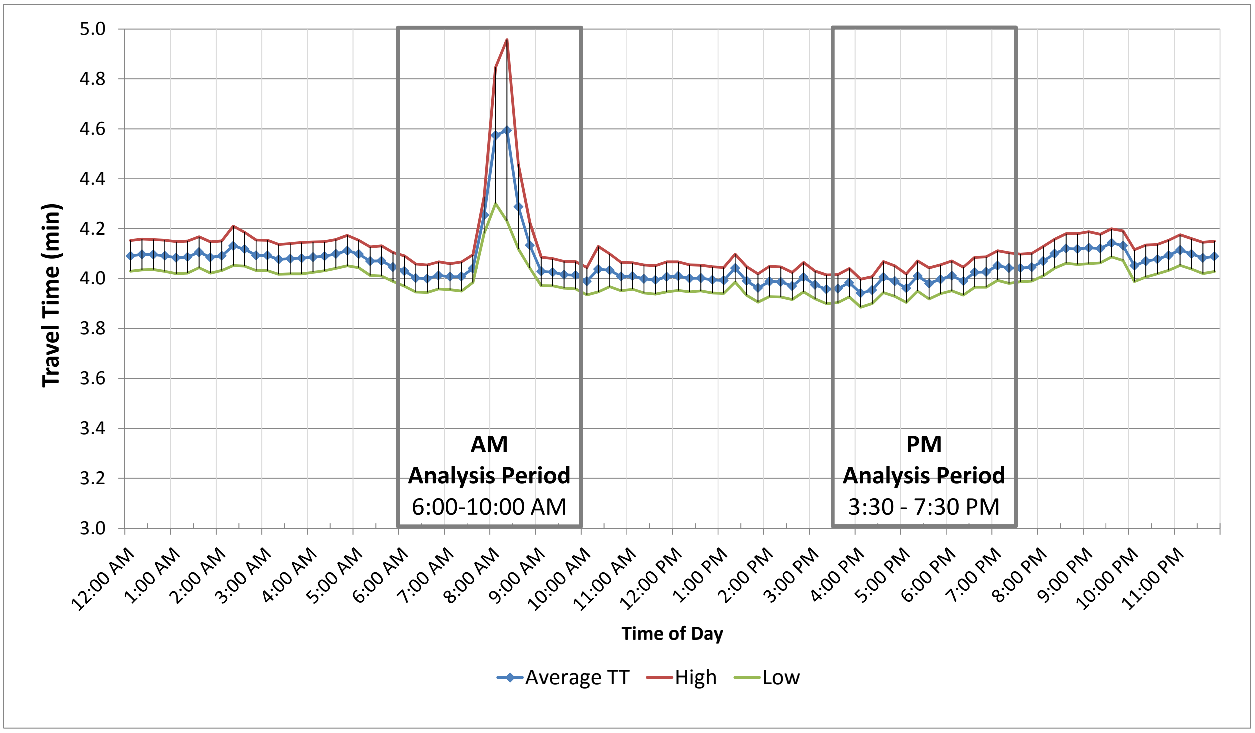


Exhibit 74 Average Travel Time Profile for Route B, Southbound Direction

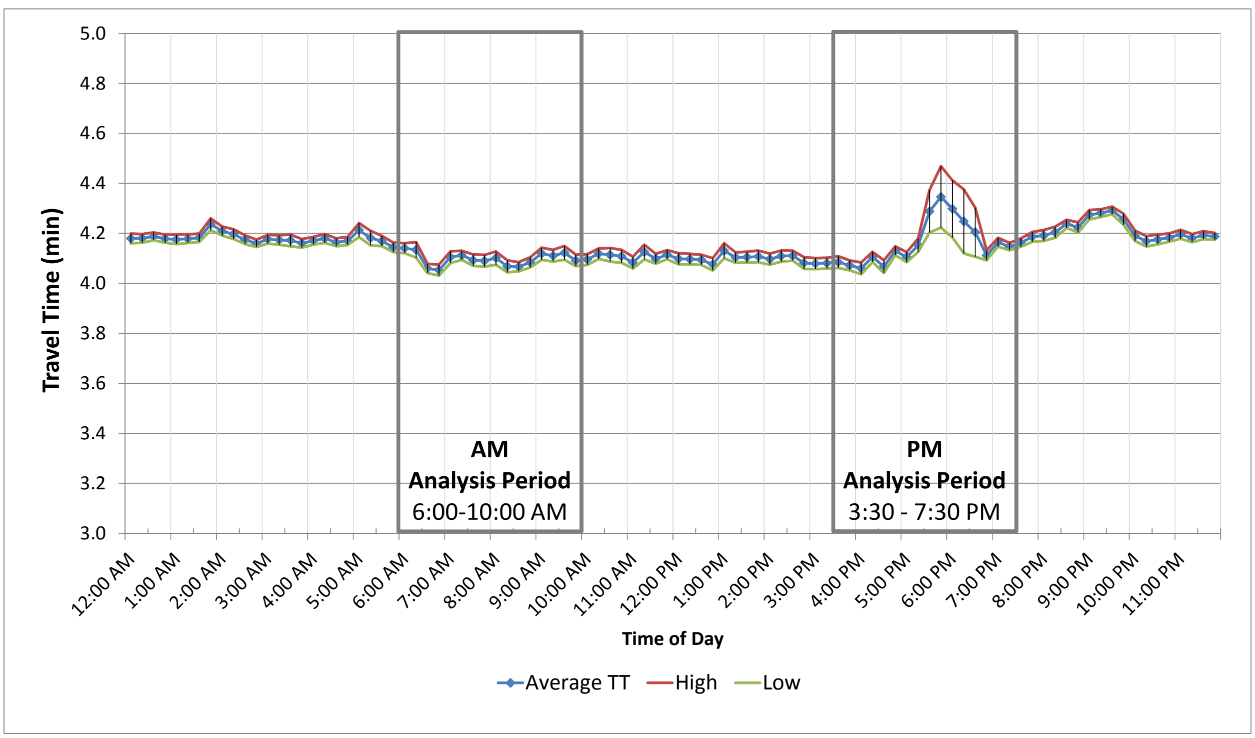


Exhibit 75 Average Travel Time Profile for Route C, Westbound Direction

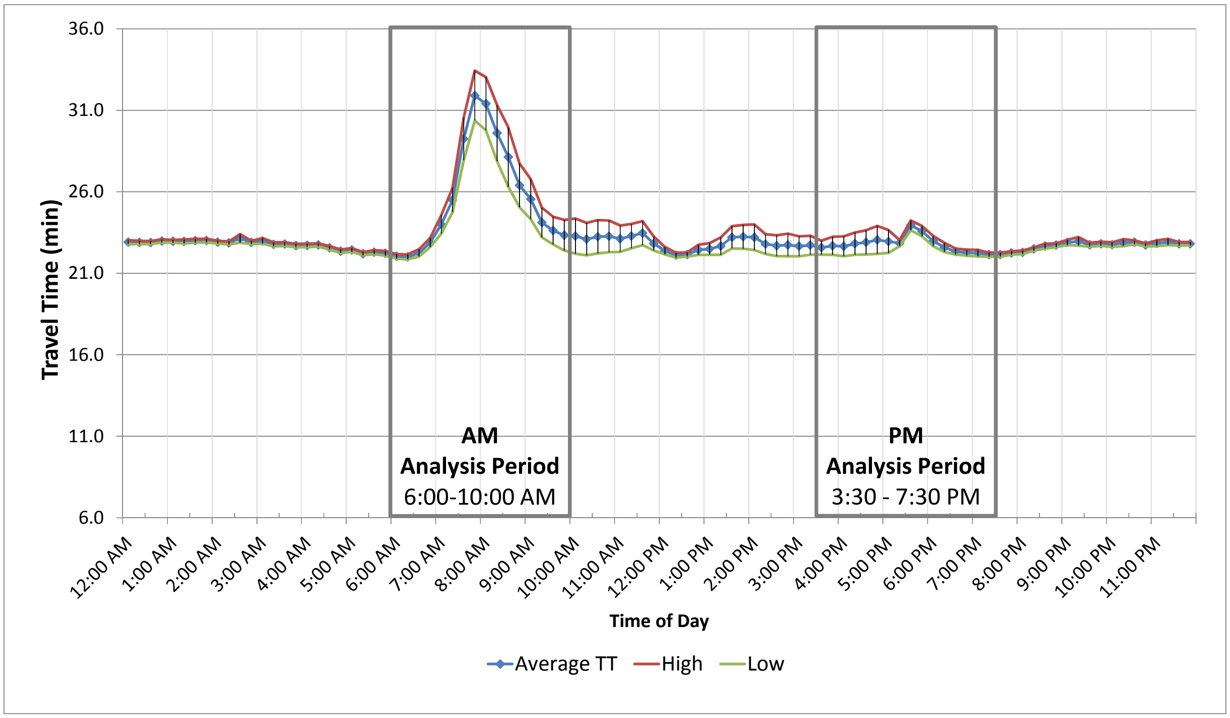


Exhibit 76 Average Travel Time Profile for Route C, Eastbound Direction

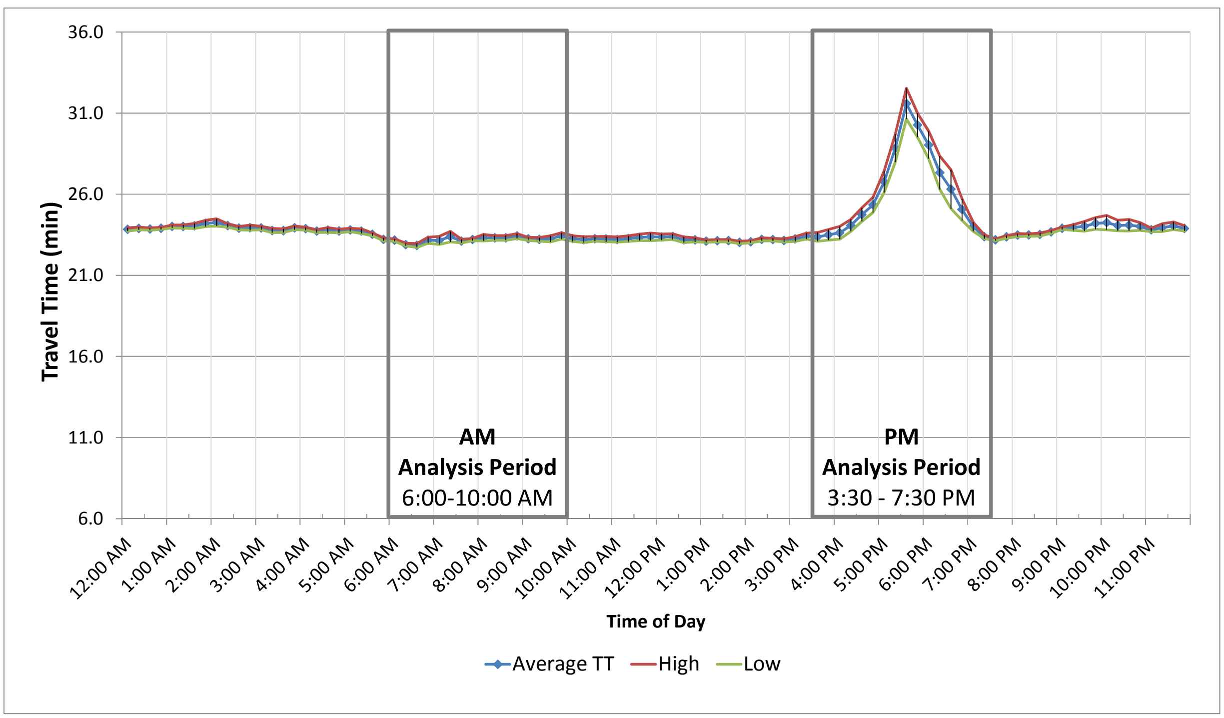


Exhibit 77 Average Travel Time Profile for Route D, <u>Westbound</u> Direction

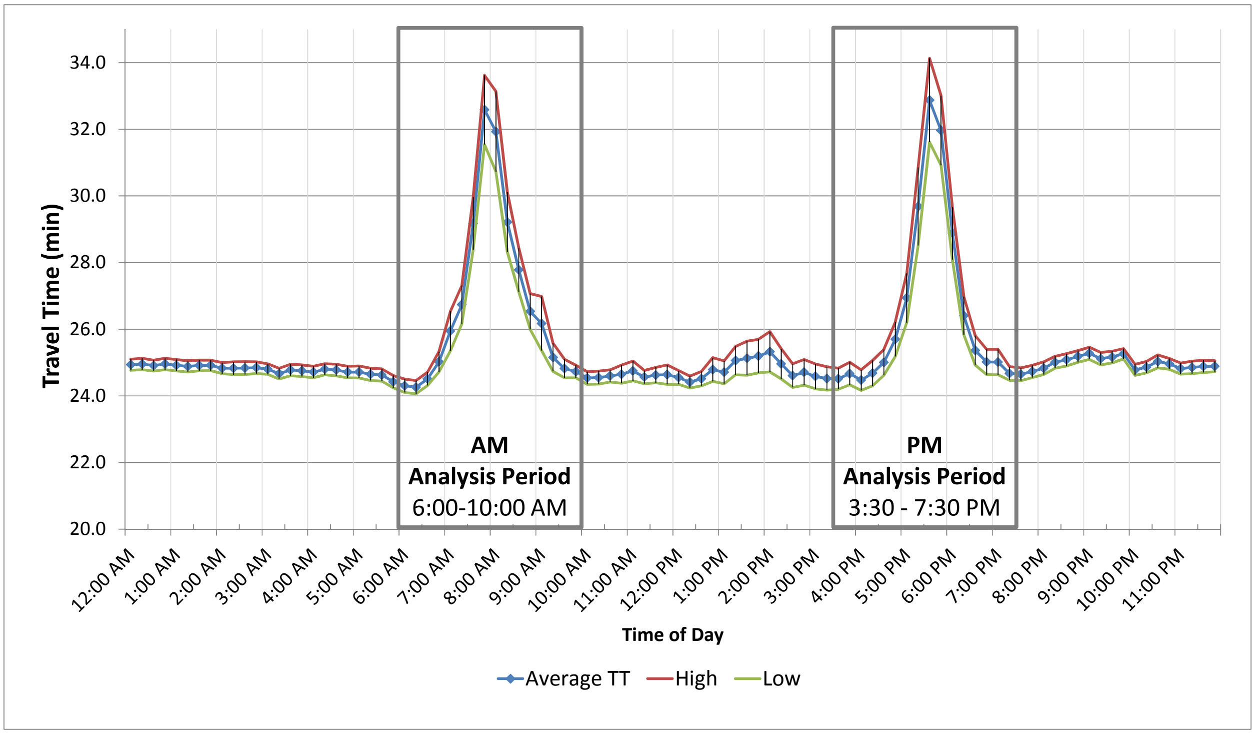


Exhibit 78 Average Travel Time Profile for Route D, <u>Eastbound</u> Direction

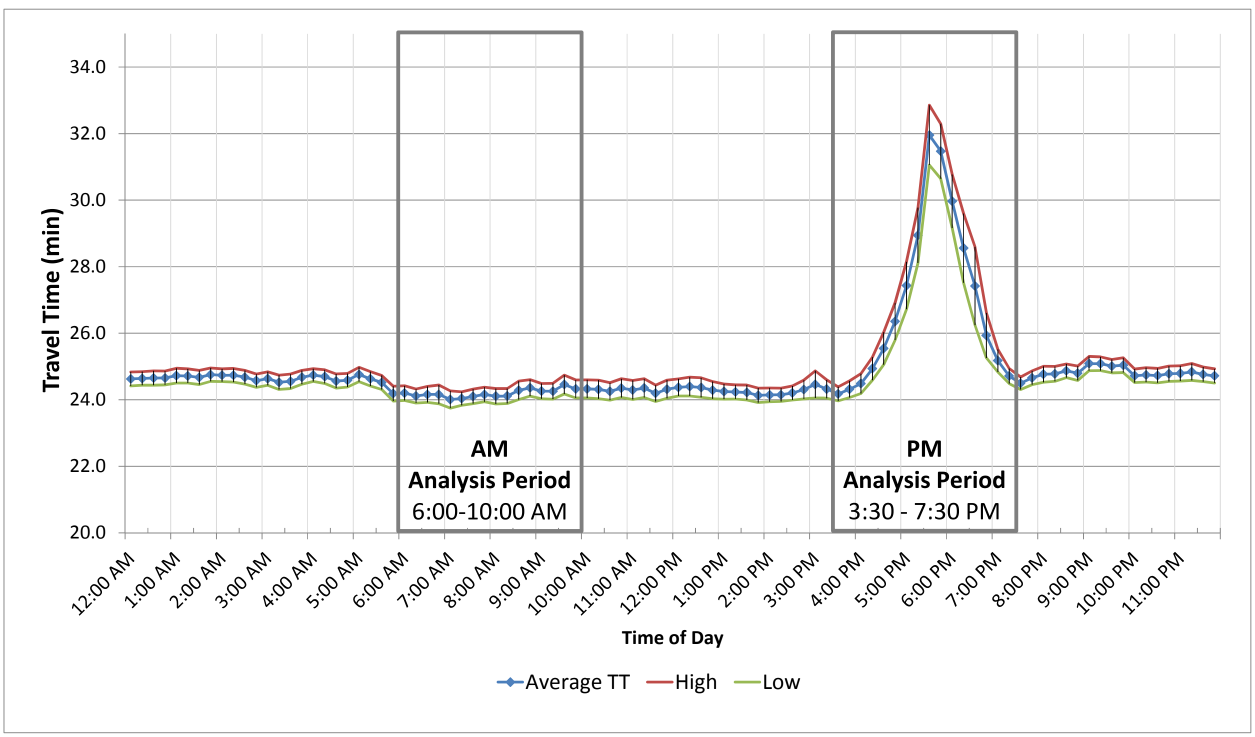


Exhibit 79 Average Travel Time Profile for Route F, <u>Westbound</u> Direction

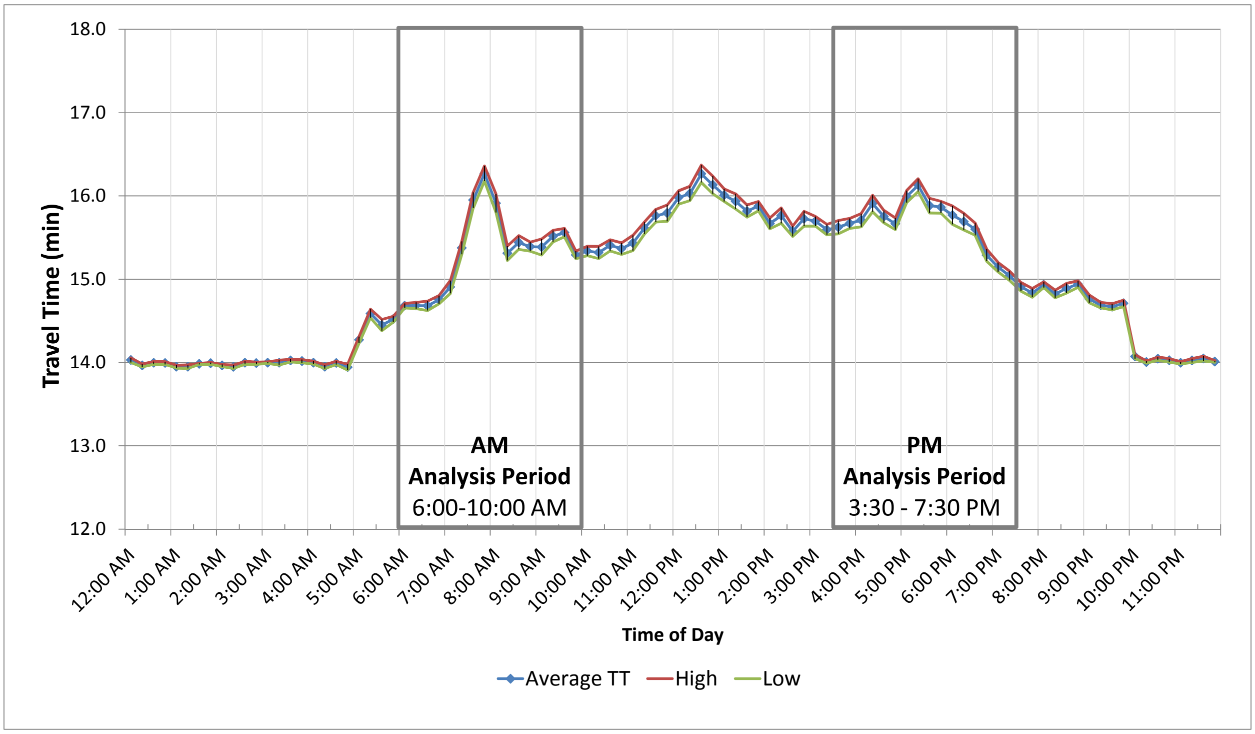


Exhibit 80 Average Travel Time Profile for Route F, <u>Eastbound</u> Direction

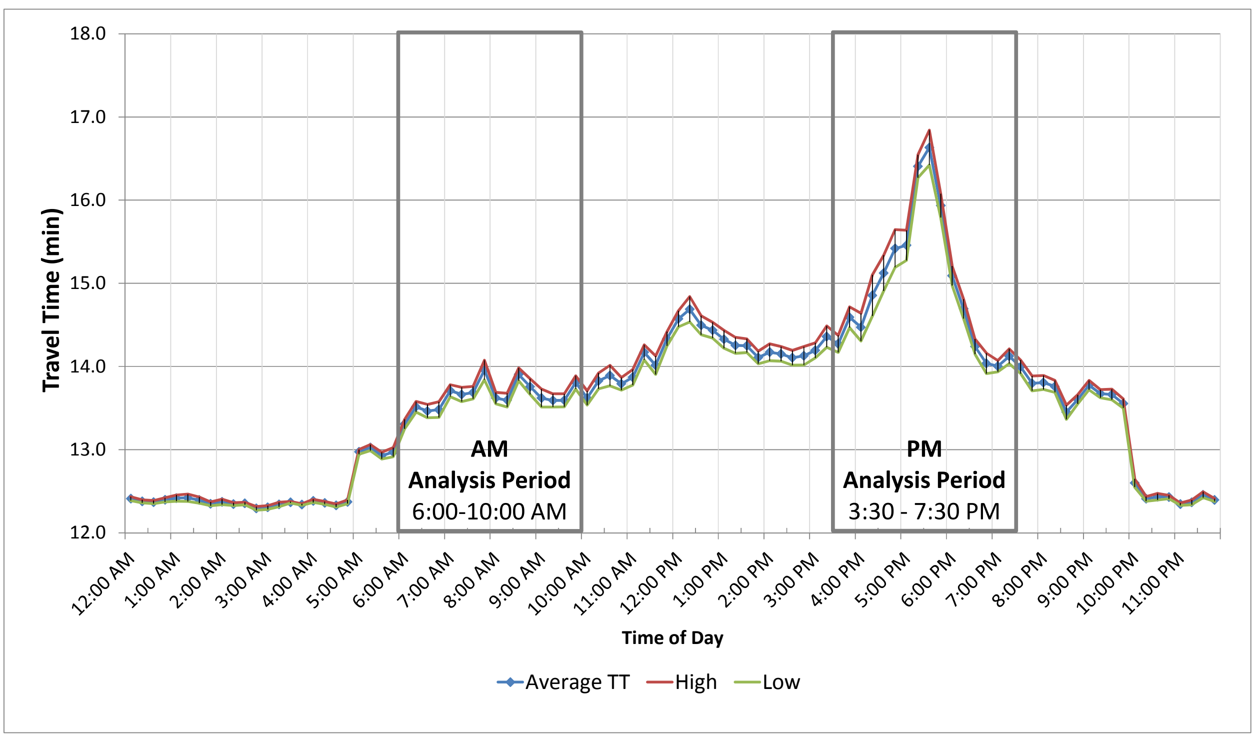


Exhibit 81 Average Travel Time Profile for Route H, Westbound Direction

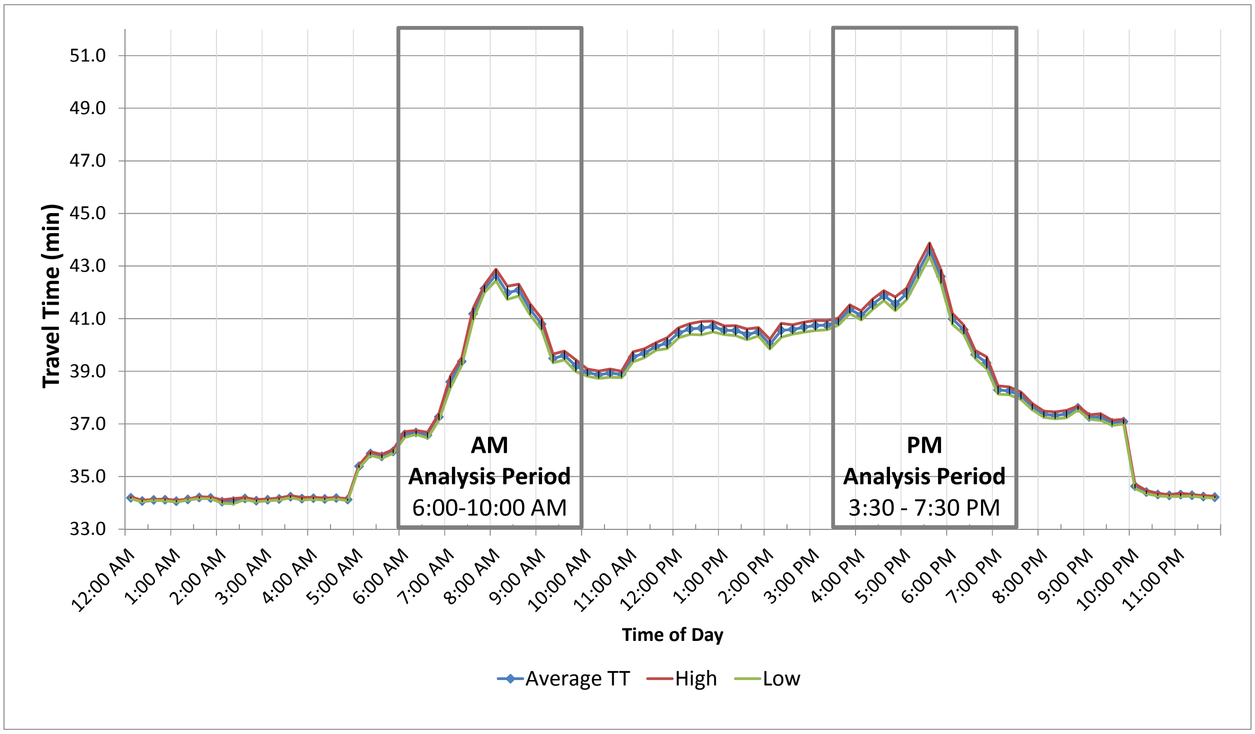


Exhibit 82 Average Travel Time Profile for Route H, Eastbound Direction

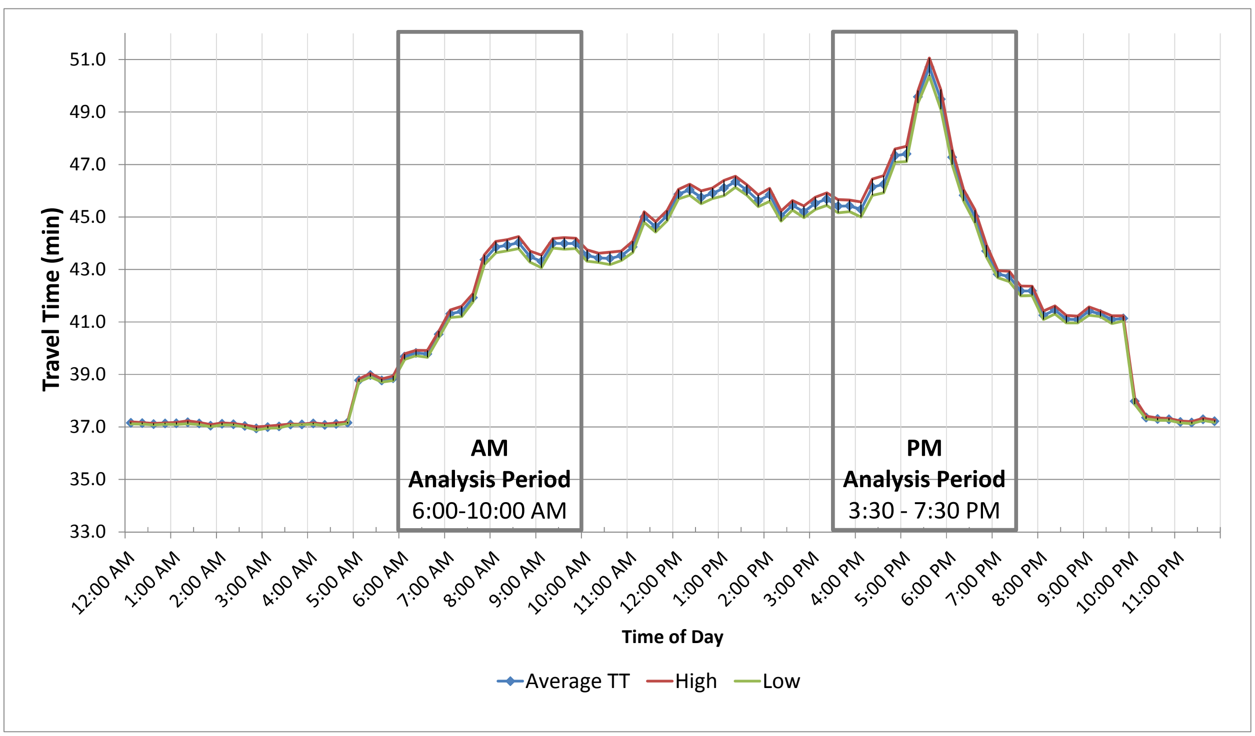


Exhibit 83 Average Travel Time Profile for Route I, Northbound Direction

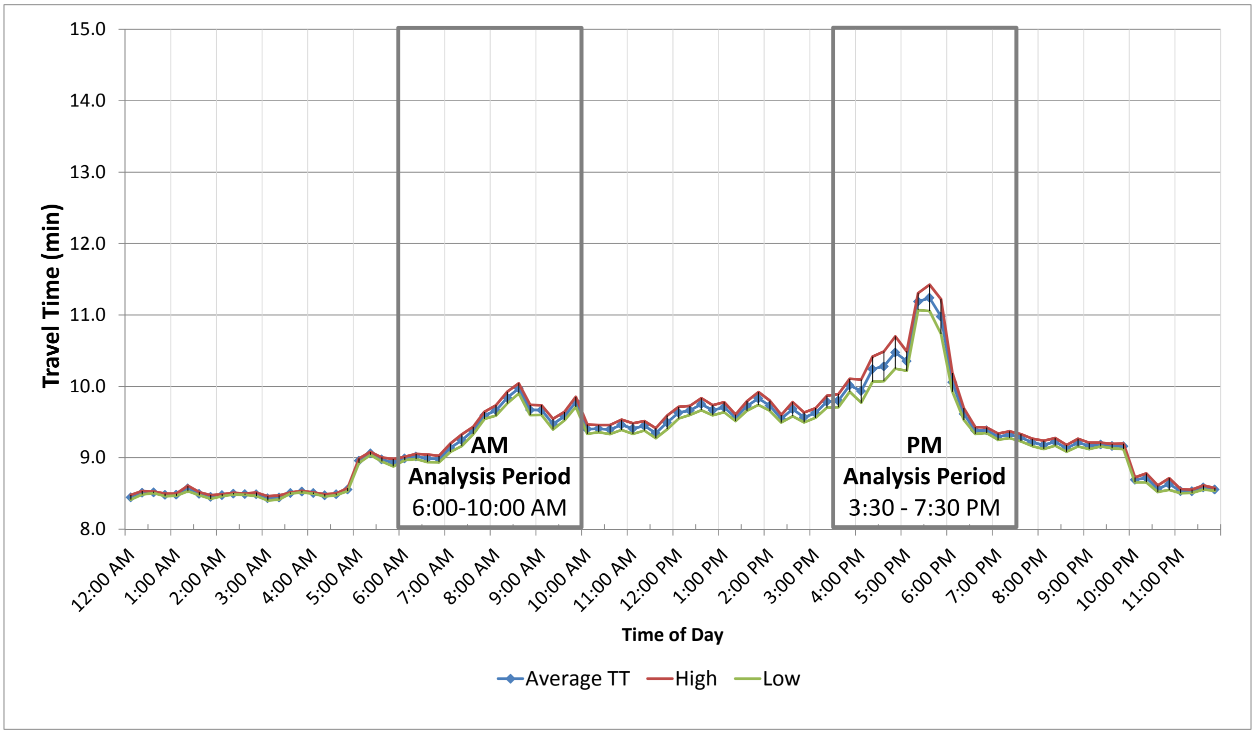


Exhibit 84 Average Travel Time Profile for Route I, Southbound Direction

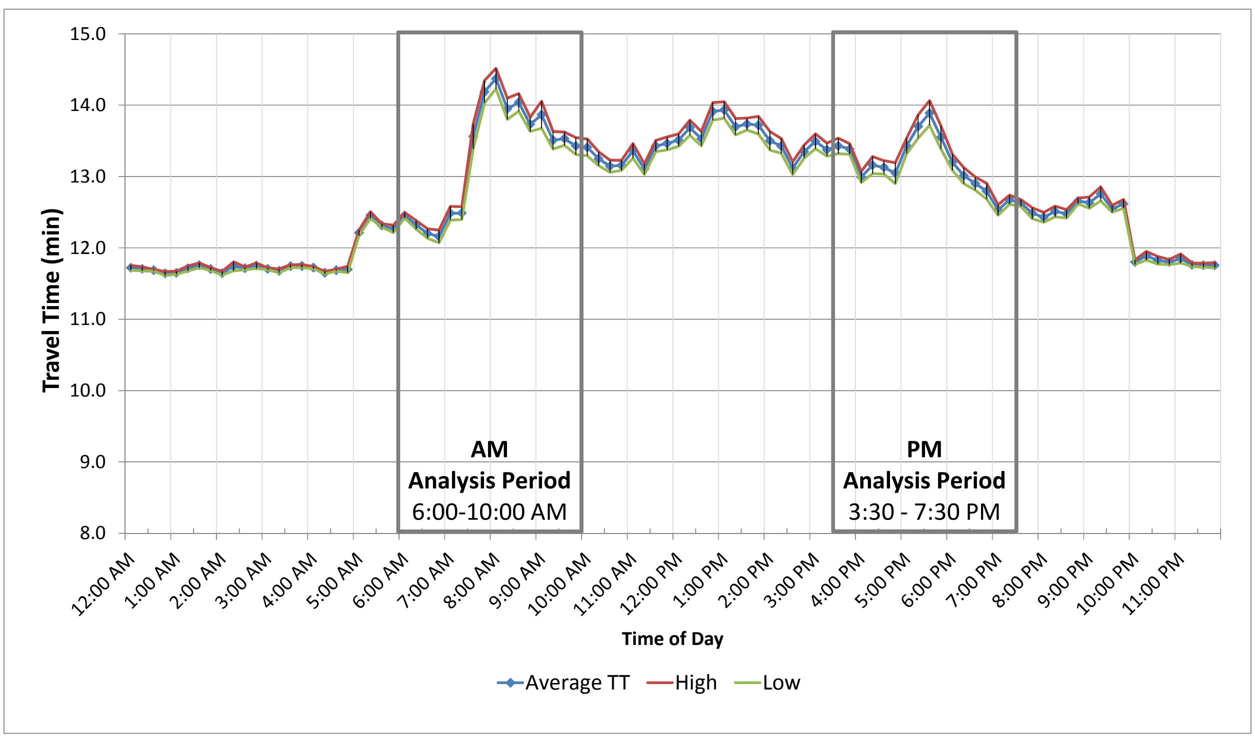


Exhibit 85 Average Travel Time Profile for Route J, Westbound Direction

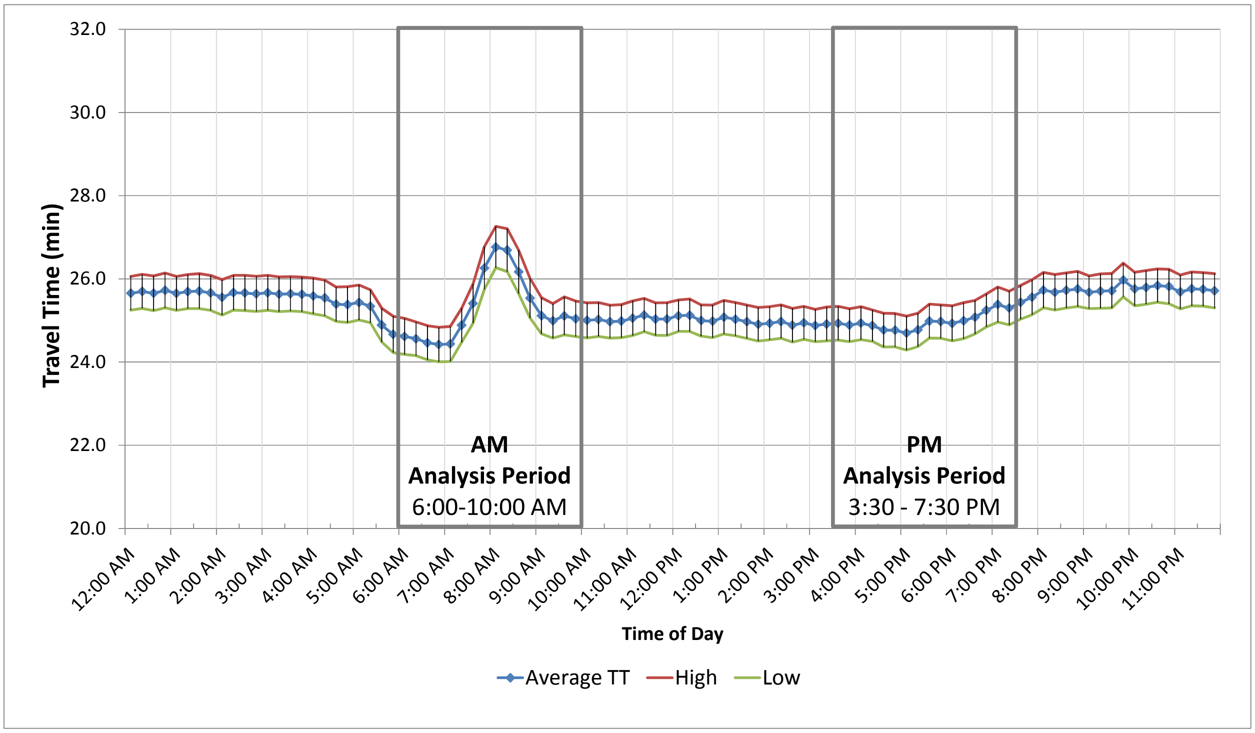
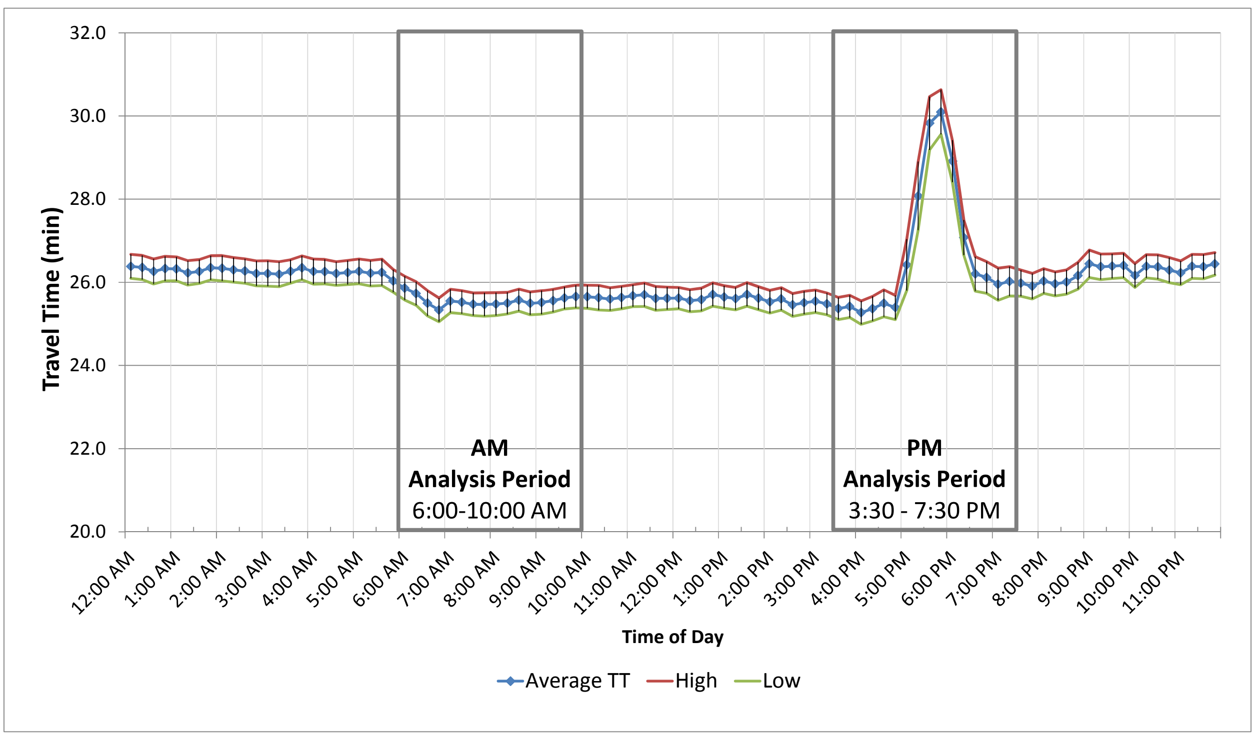


Exhibit 86 Average Travel Time Profile for Route J, Eastbound Direction



Appendix C: Detailed FREEVAL Results

Exhibit 87 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 88 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 89 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

FREEVAL Charts

Exhibit 90 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

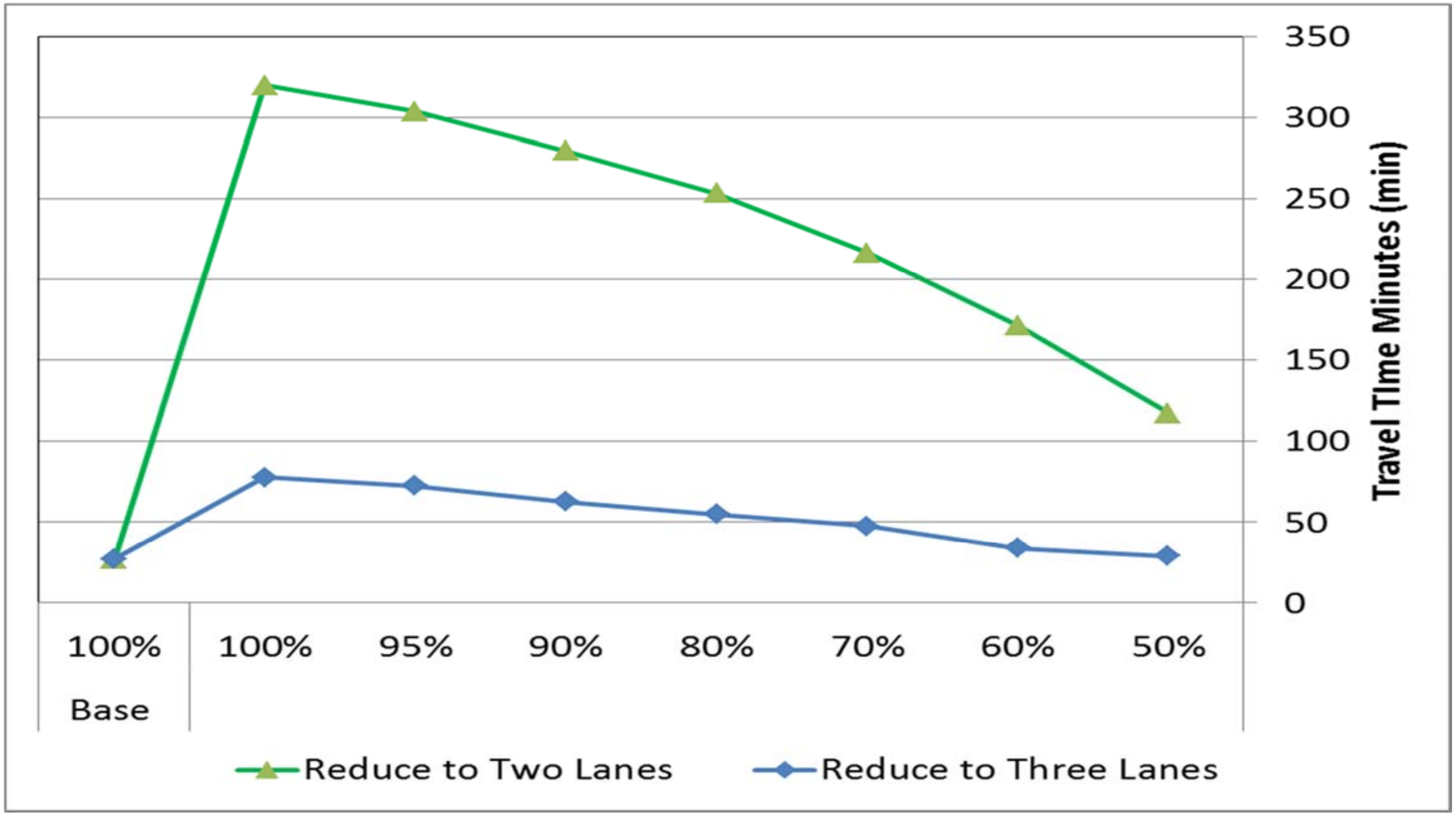


Exhibit 91 Route C WB/AM: WZ-1 (Maintain Two Lanes Open) Average and Maximum Travel Time by % Traffic Remaining on the Freeway

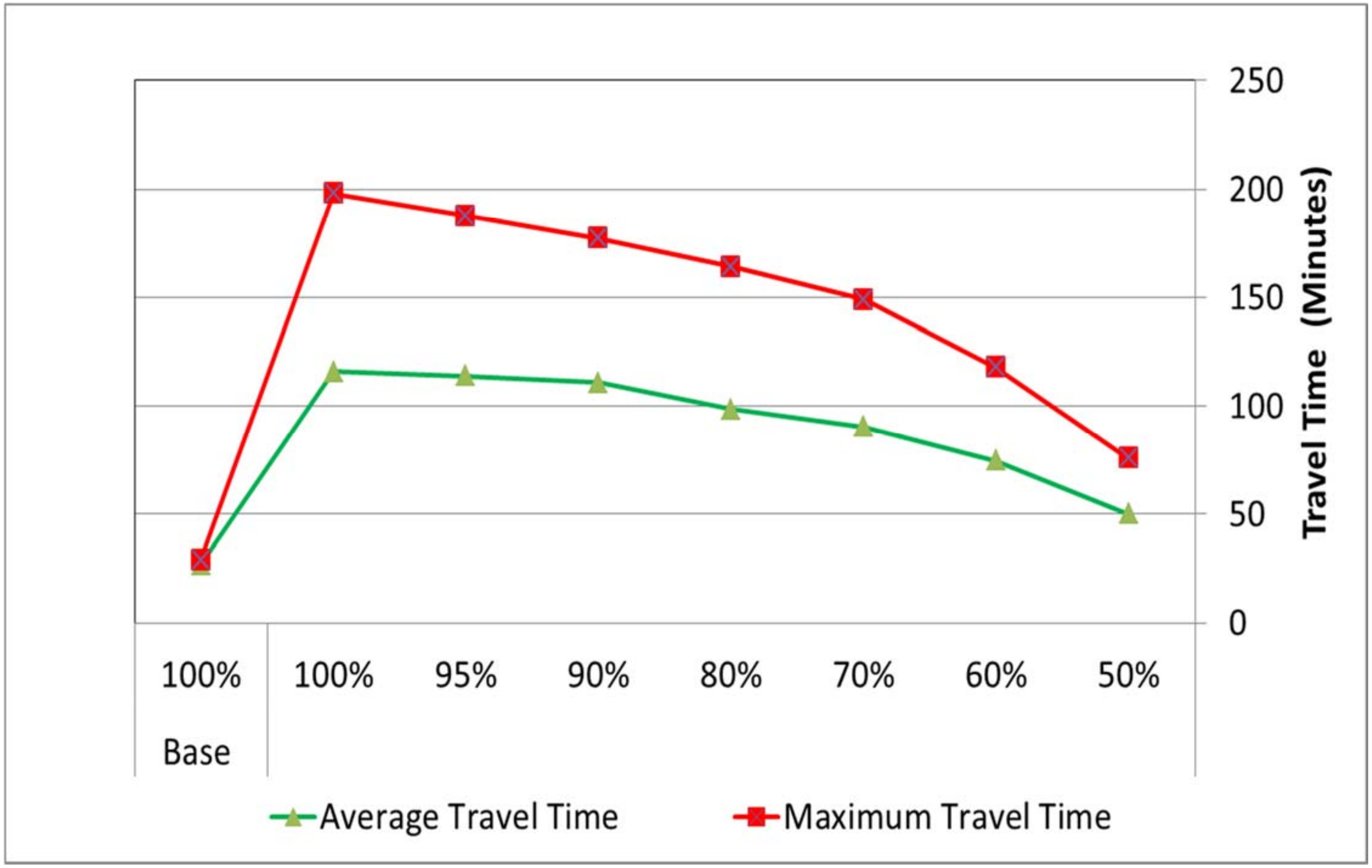


Exhibit 92 Route C WB/AM: WZ-5 (Maintain Three Lanes Open) Average and Maximum Travel Time by % Traffic Remaining on the Freeway

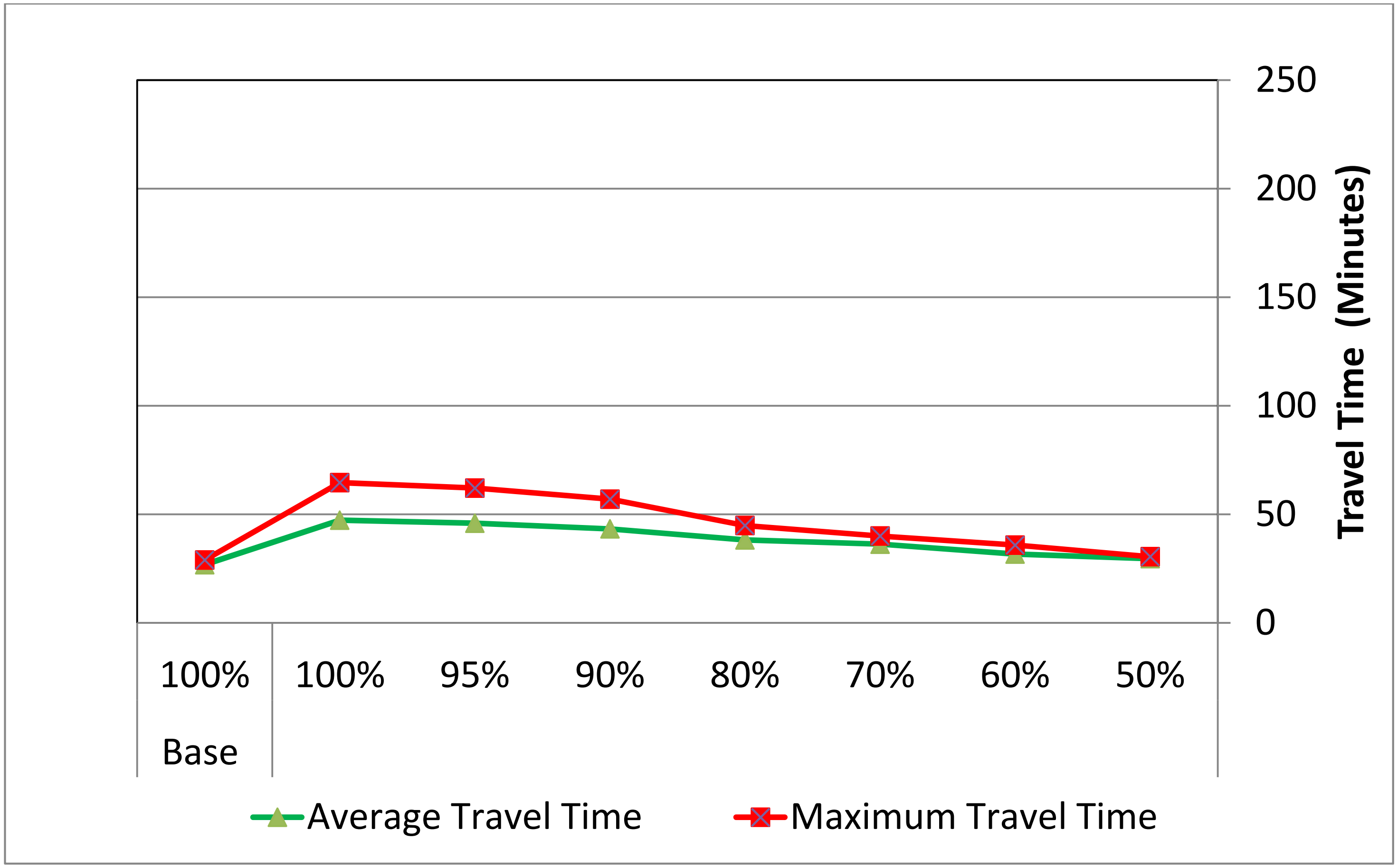


Exhibit 93 Route C WB/AM: WZ-1b (Maintain Two Lanes Open) Denied Entry Queue Length (DEQL) and Mainline Queue Length

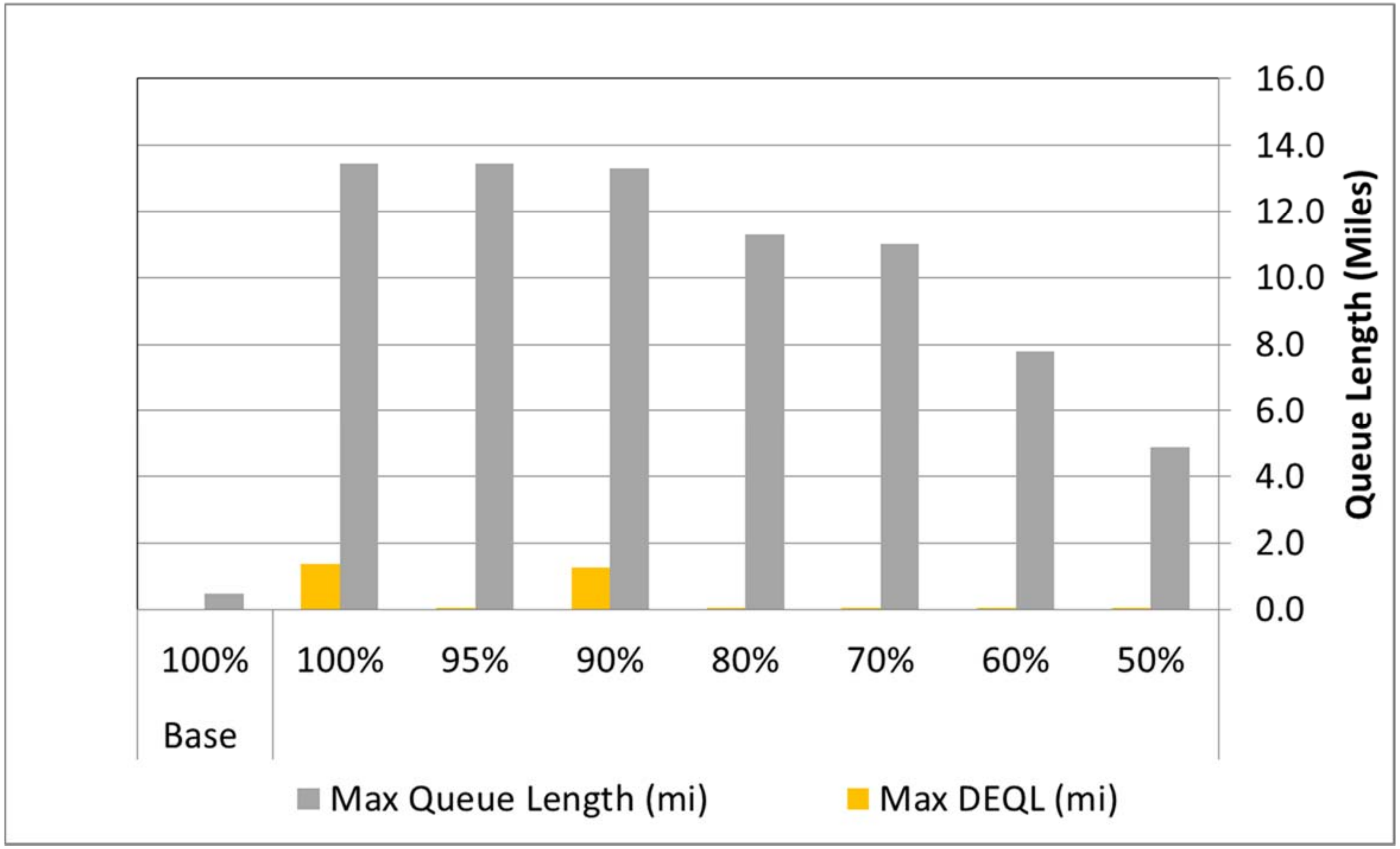


Exhibit 94 Route C WB/AM: WZ-5 (Maintain Three Lanes Open) Denied Entry Queue Length (DEQL) and Mainline Queue Length

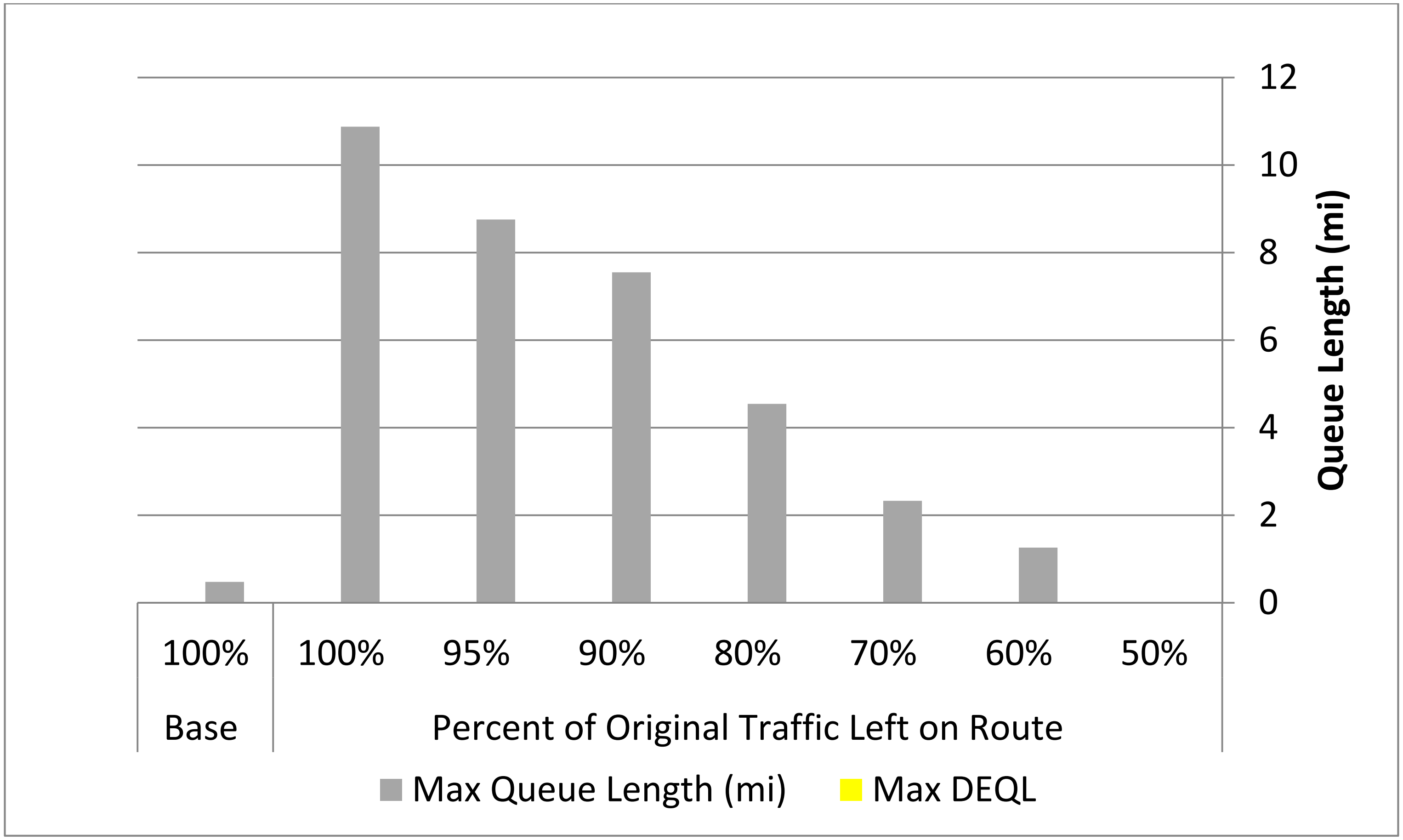
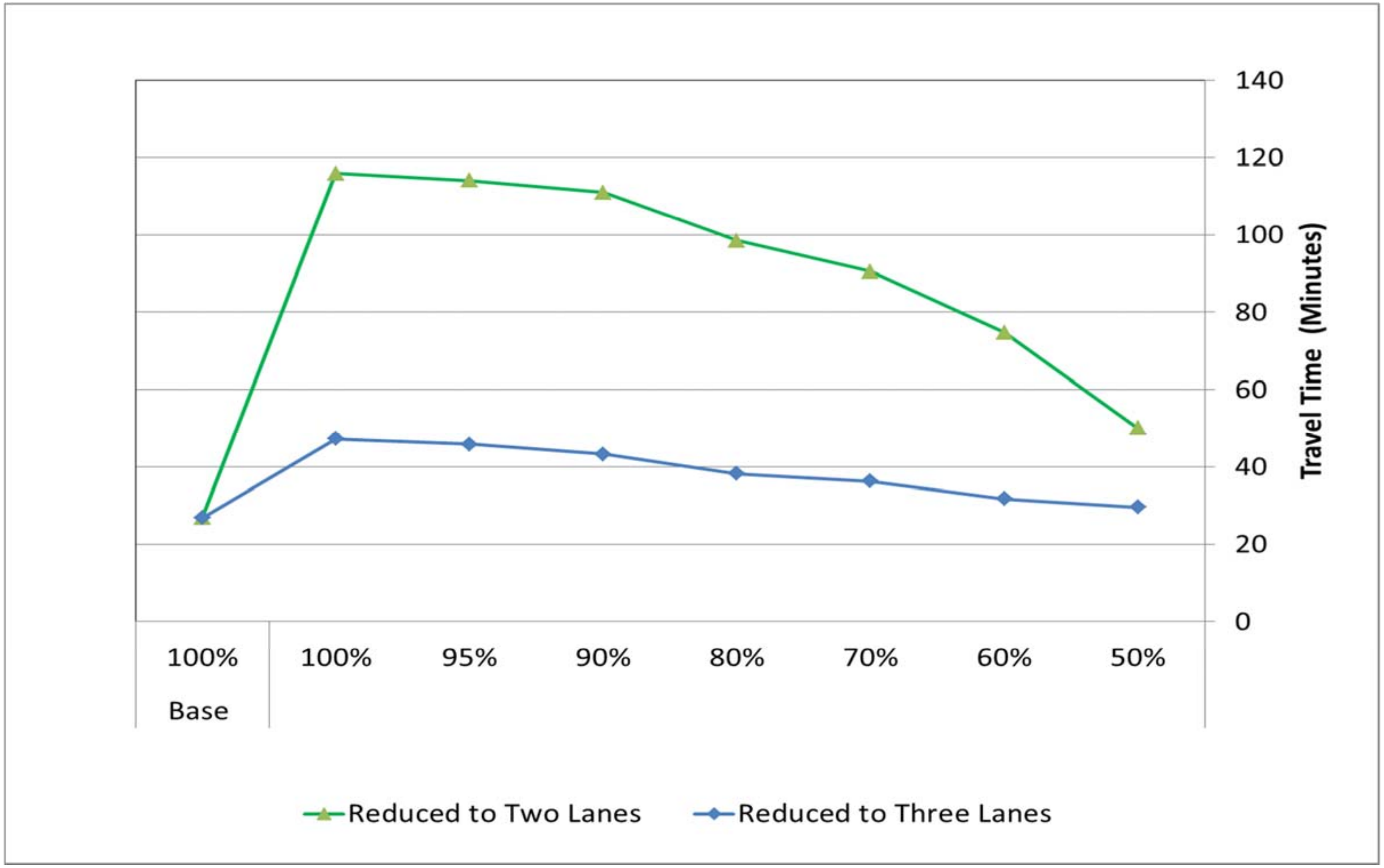


Exhibit 95 Route C WB/AM: WZ-1 (Maintain Two Lanes Open) and WZ-5 (Maintain Three Lanes Open) Average Travel Times Comparison by % Traffic Remaining on the Freeway



FREEVAL Contour Maps

Exhibit 96 - Speed Contours for the Base and Work Zone Scenarios for Route C in (WB/AM)

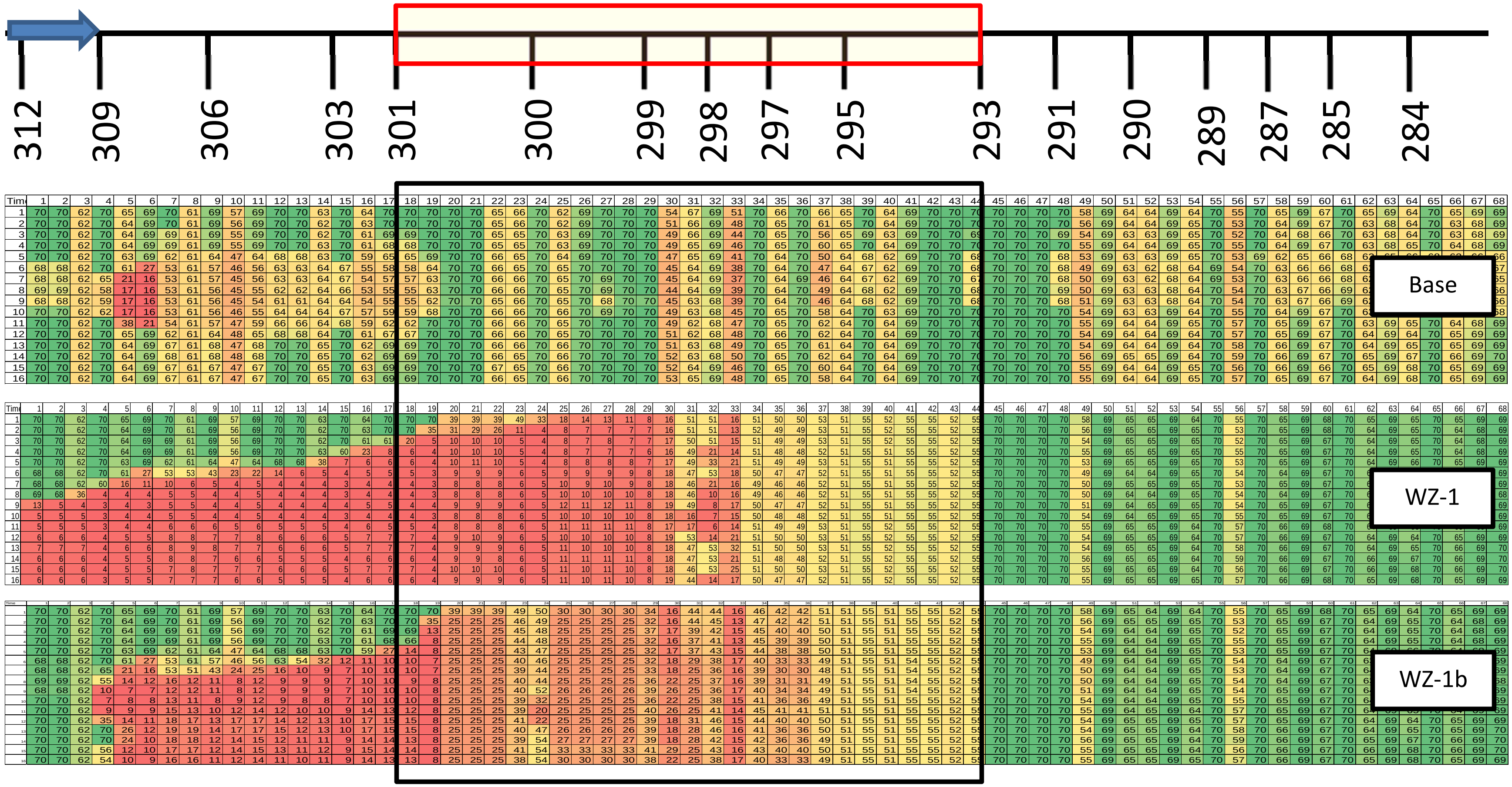


Exhibit 96 (continued)

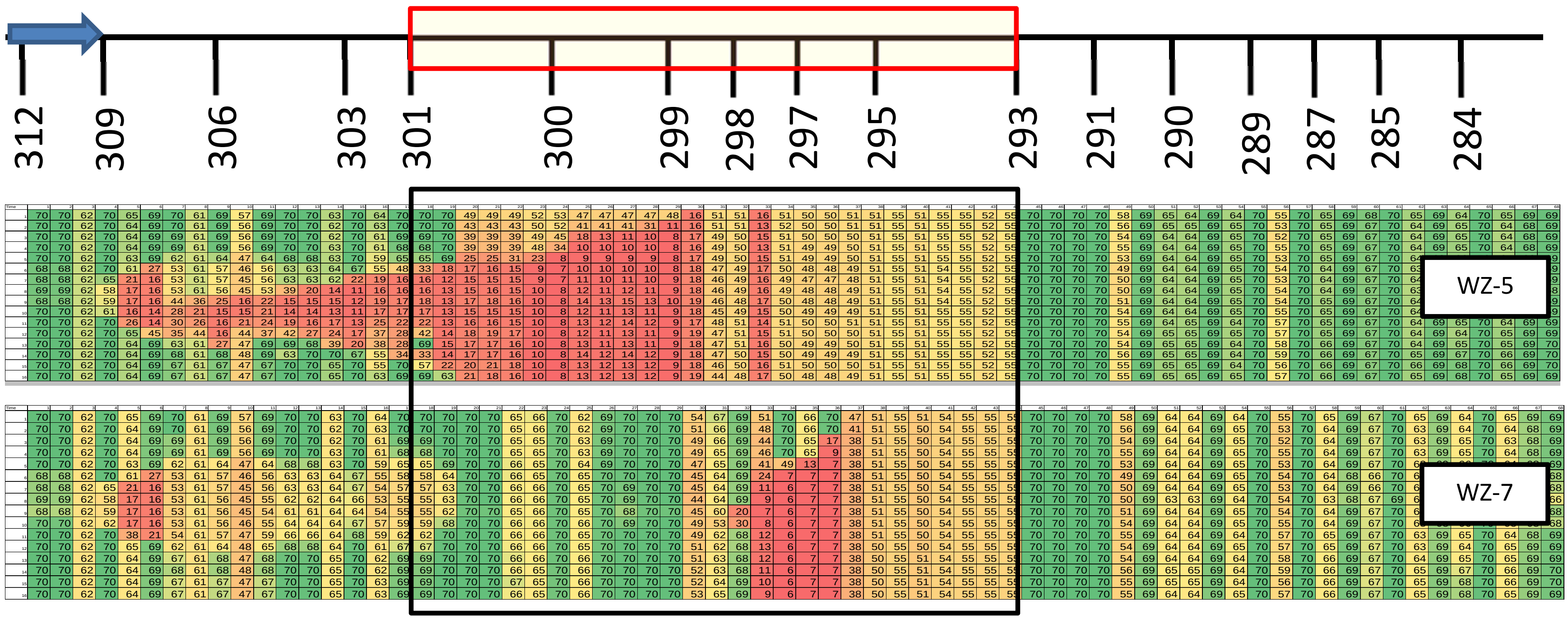


Exhibit 97 - Speed Contours for the Base and Work Zone Scenarios for Route D in (WB/AM)

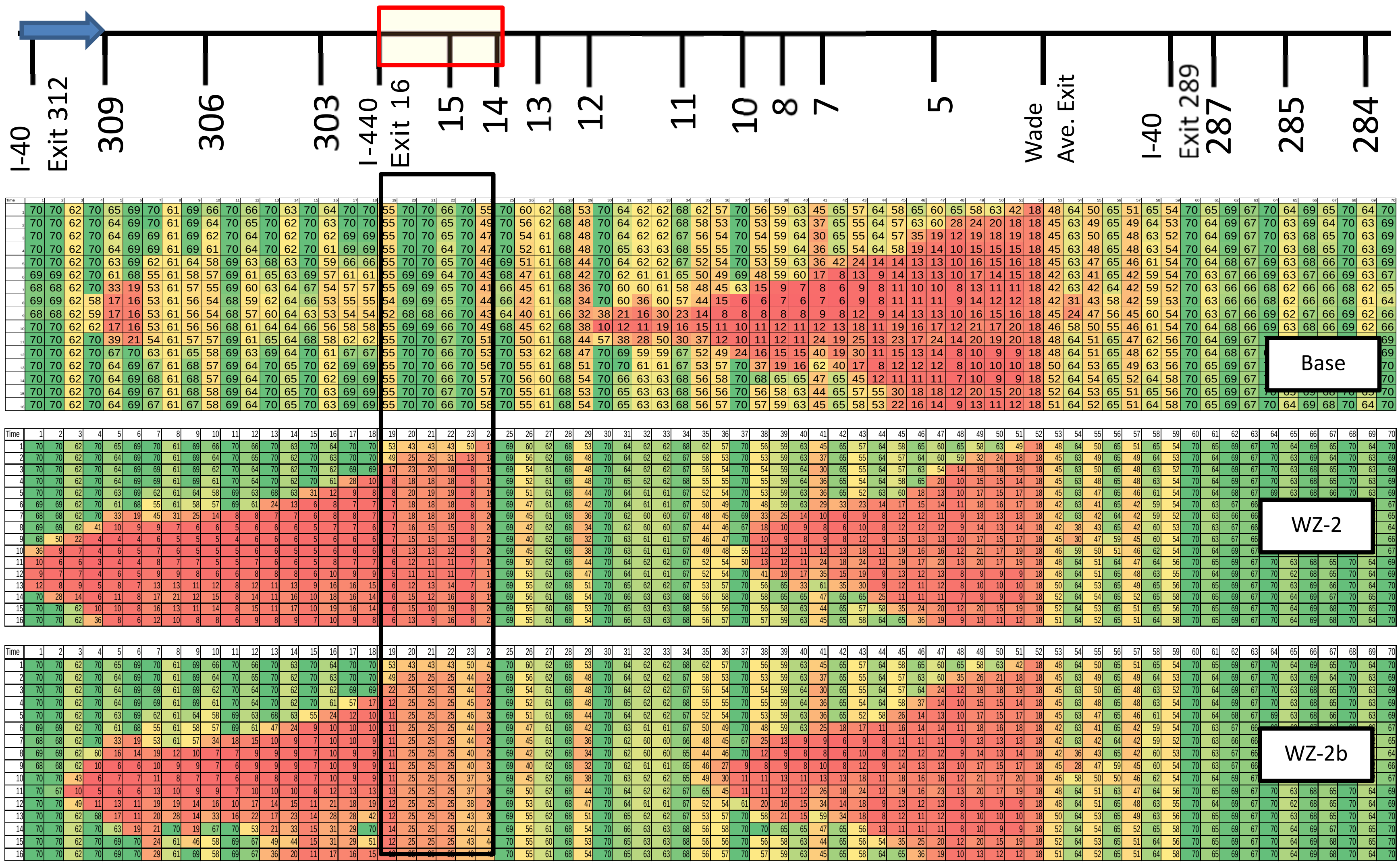
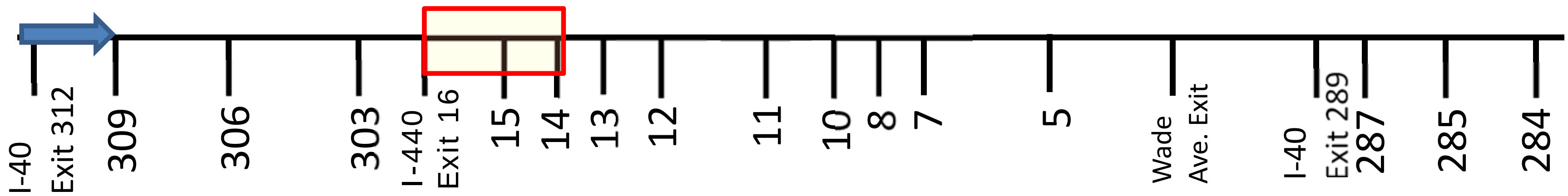


Exhibit 97 (continued)



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
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Time	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
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7	45	67	22	12	8	9	6	9	8	12	11	11	9	13	13	13	18	42	63	42	64	42	59	52	70	63	66	66							65
8	36	33	9	8	7	8	6	10	8	12	12	12	9	14	13	14	18	42	34	43	60	42	60	53	70	63	67	66			WZ-4				64
9	18	9	8	9	8	10	8	12	9	15	13	13	10	17	15	17	18	45	28	47	59	45	60	54	70	63	67	66							66
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Exhibit 98 - Speed Contours for the Base and Work Zone Scenarios for Route D (EB/PM)

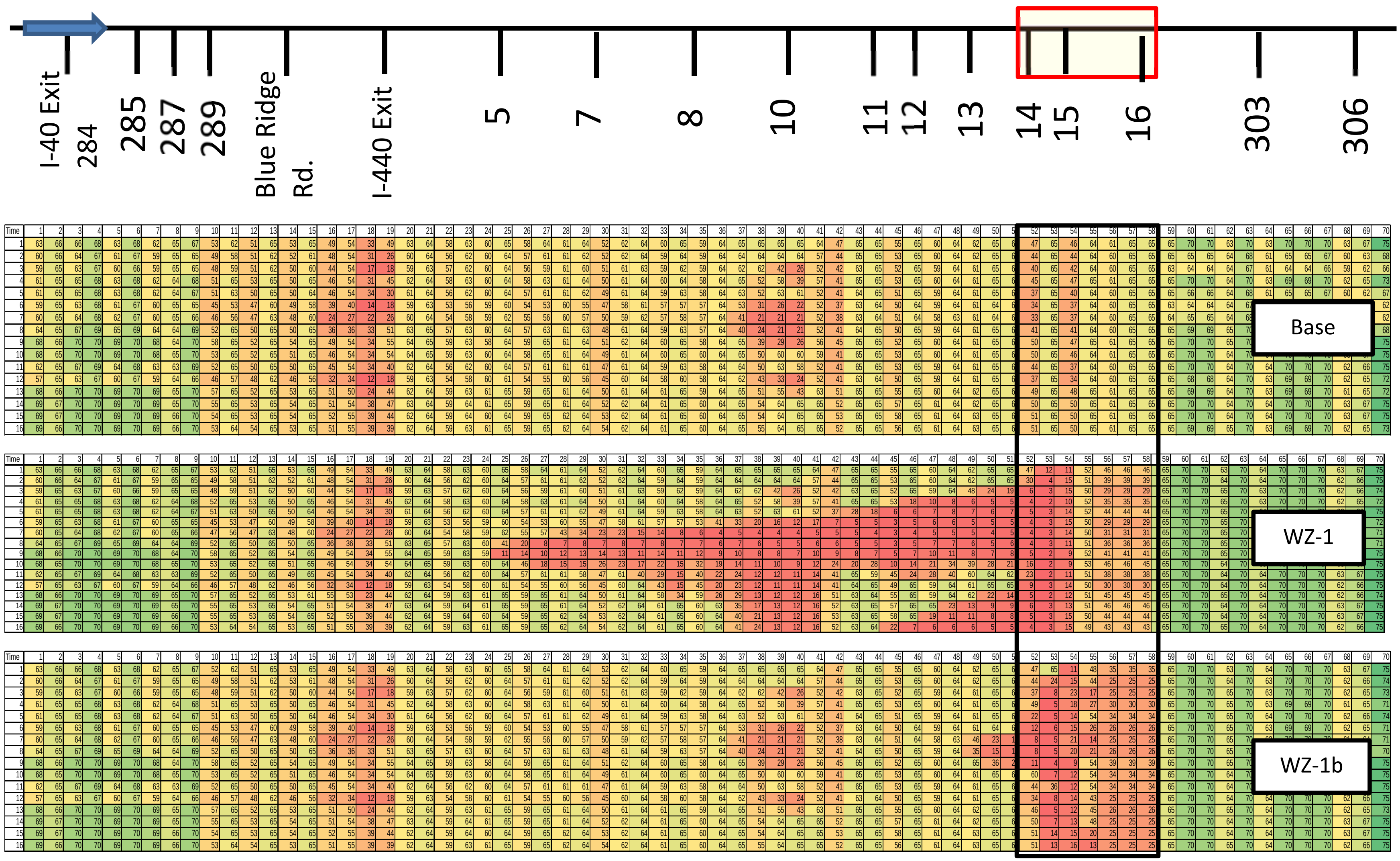
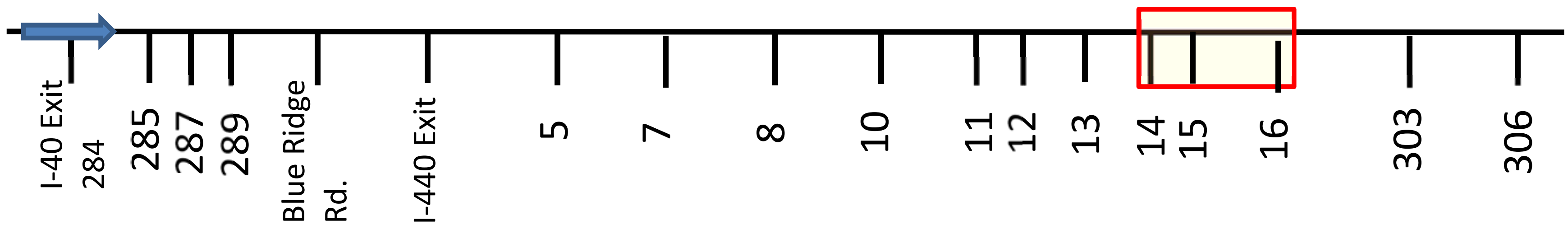


Exhibit 98 (continued)



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6	64	53	31	26	22	52	37	63	64	50	64	59	64	61	64	63	12	6	15	50	39	39	39	65	69	69	65	70	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	70
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9	64	65	39	29	26	56	45	65	65	52	65	60	64	61	33	24	11	4	9	52	47	47	47	65	70	70	65	70	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	75
10	64	65	50	60	60	59	41	65	65	53	65	60	64	61	65	62	60	7	12	53	50	50	49	65	70	70	64	70	65	70	70	70	63	67	75
11	64	64	50	63	58	52	41	65	65	53	65	59	64	61	65	65	44	36	12	51	44	44	45	65	70	70	64	70	64	70	70	70	63	67	75
12	64	62	43	33	24	52	41	63	64	50	65	59	64	61	65	65	34	8	14	50	40	40	40	65	70	70	64	70	64	70	70	70	62	66	74
13	64	65	51	55	43	63	51	65	65	55	65	60	64	62	65	65	46	5	12	51	47	47	47	65	70	70	65	70	64	70	70	70	62	65	73
14	64	65	54	64	65	65	52	65	65	57	65	61	64	62	65	65	50	7	13	51	48	48	48	65	70	70	64	70	64	70	70	70	63	67	75
15	64	65	54	64	65	65	53	65	65	58	65	61	64	63	65	65	51	14	15	50	46	46	46	65	70	70	64	70	64	70	70	70	63	67	75
16	64	65	55	64	65	65	52	65	65	56	65	61	64	63	65	65	51	12	15	49	45	45	45	65	70	70	65	70	64	70	70	70	62	66	74

WZ-3

Appendix D: Detailed DynusT Results

Introduction

This section presents the work zone impact results from the DynusT mesoscopic simulation analysis. For all the work zone scenarios, the analysis distinguishes between a *no-diversion* and a *with-diversion* scenario. The no-diversion case corresponds to a "one-shot" assignment, where all vehicles remain on their baseline paths despite the presence of the work zone. Conceptually, this corresponds to a worst-case analysis of that work zone scenario where drivers are not aware of the presence of the work zone. The with-diversion results were obtained from running DynusT's DTA modules to (near) user-equilibrium, by repeating the network assignment twenty times. After each assignment, each simulated vehicle in the network reconsiders its routes based on its experience in the previous run. After 20 iterations, the model therefore results in a modified traffic assignment, where each vehicle minimizes its origin-to-destination travel time, under the constraints imposed by the work zone. Conceptually, this corresponds to a user equilibrium solution, under the assumption of fixed demand.

Results

The results are demonstrated in terms of network-wide impacts of the work zone, the impacts of the work zone on the key routes, and on other diversion routes throughout the network.

Network-Wide Impacts

Exhibit E-1 shows four network-wide performance measures (average travel time, average travel distance, and average stop time) for the Baseline and different work zone scenarios in the AM peak period. In addition, the percent difference for each performance measure from the Baseline scenario is presented. As expected, the Baseline scenario has the lowest average travel time, highest average travel distance, and lowest average stop. This indicates that all tested work zone scenarios have resulted in a deteriorated network performance in the AM peak period, which was anticipated.
All no-diversion work zone scenarios, as expected, resulted in longer average travel time, shorter average travel distance, and longer average stop time when compared to the with-diversion work zone scenarios in the AM peak period. This was expected since in the no-diversion work zone scenarios, vehicles were not allowed to change their routes in response to the congestion resulting from the work zone. On the other hand, in work zone scenarios with diversion, vehicles may switch their routes to those with lower travel time and consequently improve overall network performance.

The labeling of work zone scenarios was presented in an earlier section, but is repeated here for quick reference:

- WZ 1 – Westbound lane closure, two lanes open throughout
- WZ 2 – Eastbound lane closure, two lanes open throughout
- WZ 3 – Westbound lane closures, maintain three lanes for sections with 4 or 5 base lanes
- WZ 4 – Eastbound lane closures, maintain three lanes for sections with 4 or 5 base lanes
- WZ 5 – Westbound lane closures, maintain three lanes throughout

- WZ 6 – Eastbound lane closures, maintain three lanes throughout
- WZ 7 – Eastbound two-lane cross-over scenario in three lane section, with three lanes open throughout rest of the facility.

Exhibit D-1 Network Performance for AM Peak

Scenario		Average TT		Average Travel Distance		Average Stop Time	
		Min.	% Diff	Min.	% Diff	Min.	% Diff
Baseline		23.7	n/a	15.2	n/a	6.1	n/a
WZ 1	One-shot	25.5	**7.7%**	16.1	**6.1%**	9.1	**49.1%**
	UE	24.0	**1.1%**	15.0	**-1.2%**	6.7	**9.3%**
WZ 2	One-shot	23.8	**0.4%**	16.2	**6.5%**	7.4	**20.4%**
	UE	23.7	**0.0%**	15.0	**-1.1%**	6.6	**7.2%**
WZ 3	One-shot	24.7	**4.1%**	16.2	**6.6%**	7.4	**19.9%**
	UE	23.8	**0.3%**	15.0	**-1.1%**	6.6	**8.2%**
WZ 7	One-shot	23.9	**0.7%**	16.2	**6.6%**	7.2	**17.9%**
	UE	24.4	**2.8%**	13.8	**-9.1%**	7.8	**27.4%**

For the no-diversion work zone scenarios, the average network travel time increased from 0.7% to 7.7%. The one-shot results suggest reasonable results with congestion due to work zone; however, it should be noted that no-diversion scenarios represent worst-case scenarios that are highly unlikely to occur in real-world conditions. Scenarios with fewer open lanes (scenarios WZ-1) yielded longer average delay than those with more open lanes (scenarios WZ-3 and WZ-5).

The average travel time increased from 0% to 3.3% for the work zone scenarios with diversion (compared to the base line). As mention before, the WB direction carries heavier traffic in the AM peak period than the EB direction. Therefore, scenario WZ-1 (with WB lane closure) resulted in slightly higher network-wide average travel times than scenario WZ-2 and WZ-3. Scenarios WZ resulted in the highest network-wide average travel time due to the full closure. It should be emphasized that the user-equilibrium results appear to be very optimistic in having drivers find alternate routes. It may be true that there are spare capacities on arterial network. However, it is not likely that the drivers can fully utilize the spare capacities in the real-world.

In the PM peak period, as expected, WZ-2 yielded longer average travel time and longer average stop time. However, other work zone scenarios yielded similar performance compared with AM peak period, as shown in Exhibit D-2. It should be emphasized that PM peak results were expected to be more severe than AM Peak because the traffic demand in PM peak is significantly higher than that in AM peak. Similar to the AM peak period, the work zone scenarios with diversion resulted in more efficient network performance compared to the ones without diversion. However, the user-equilibrium results still appear to be very optimistic. In addition, scenarios with more open lanes (WZ-4 and WZ-7) yielded shorter average travel time and average stop time than scenarios with fewer open lanes (WZ-1 and WZ-2).

Exhibit D-2 Network Performance for PM Peak

Scenario		Average TT		Average Travel Distance		Average Stop Time	
		Min.	**% Diff**	**Min.**	**% Diff**	**Min.**	**% Diff**
Baseline		24.2	n/a	14.0	n/a	7.2	n/a
WZ 1	**One-shot**	25.7	**6.2%**	14.9	**6.4%**	9.9	**39.0%**
	UE	24.4	**1.0%**	13.8	**-1.2%**	7.9	**9.9%**
WZ 2	**One-shot**	25.0	**3.3%**	14.9	**6.7%**	9.2	**29.0%**
	UE	24.3	**0.5%**	13.8	**-1.2%**	7.8	**8.5%**
WZ 4	**One-shot**	24.7	**2.2%**	14.9	**6.7%**	8.5	**19.4%**
	UE	24.3	**0.6%**	13.8	**-1.2%**	7.8	**9.2%**
WZ 7	**One-shot**	24.9	**2.9%**	14.9	**6.7%**	9.2	**29.1%**
	UE	24.4	**0.7%**	13.8	**-1.2%**	7.8	**9.2%**

Route Performance

Based on the results of DynusT user equilibrium, speed profiles and volume profiles were generated for routes C and D in both directions in AM and PM peak. The profiles are obtained for the Base case where no work zone is activated in area, and all defined work zone scenarios (i.e. WZ1, WZ2, WZ3, WZ4, and WZ7). Exhibit 99 through Exhibit 102 show different speed profiles and Exhibit 103 through Exhibit 106 show different speed profiles. In addition, using the speed and volumes obtained from DynusT, several maps are generated using ARCGIS software to better illustrate the network-wide impacts of different work zone scenarios. These maps are shown in Exhibit 107 through Exhibit 114.

It should be noted that for speed profiles, each data points corresponds to the average of DynusT 15-minute average speed of the segment. In addition, a moving average (3 point) trend line is drawn.

Each data point of the volume profiles corresponds to the sum of DynusT 15-minute volume observed on each segment. In addition, a moving average (3 point) trend line is added.

Exhibit 99: Detailed Route Speed Profiles - Route C Westbound

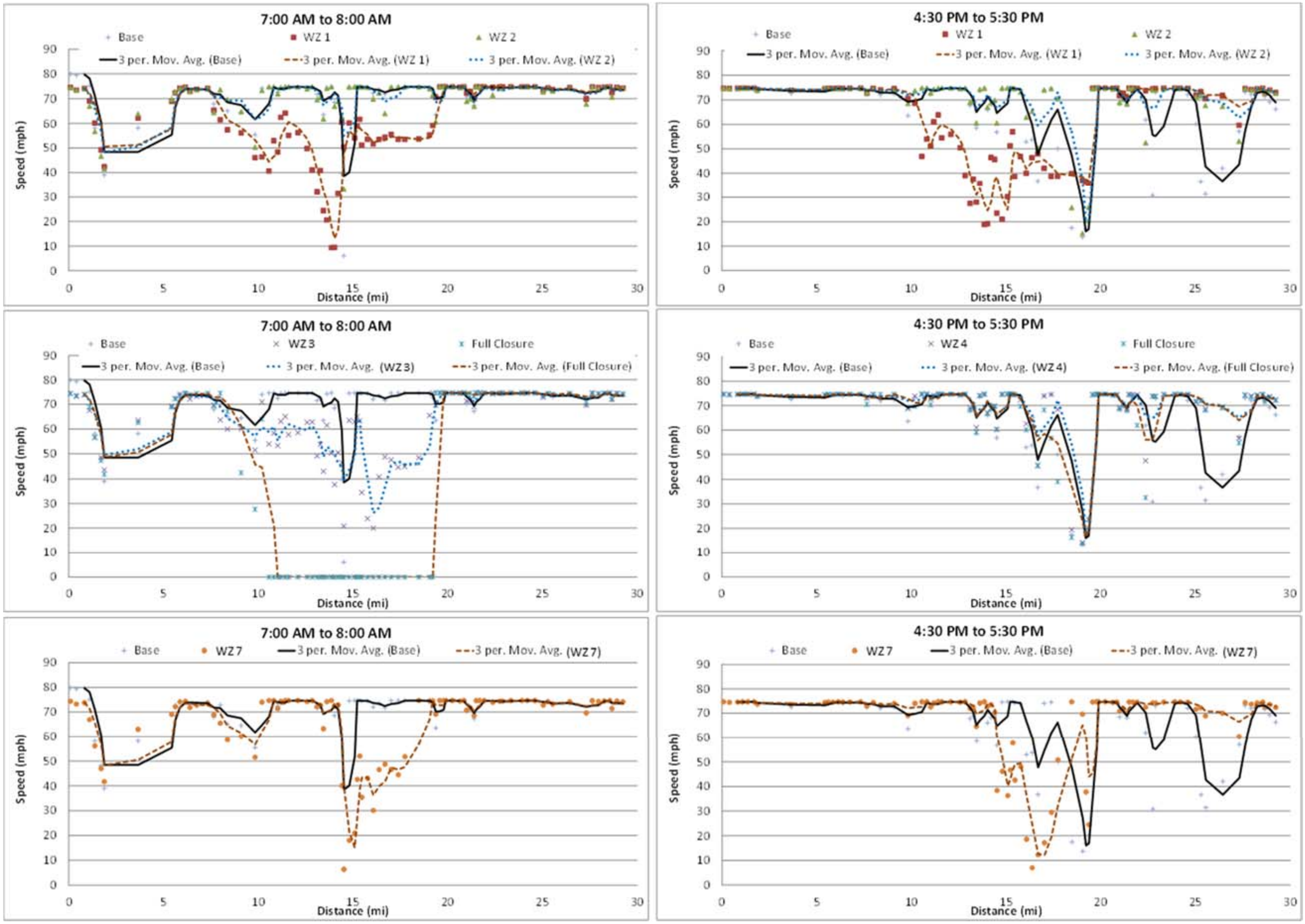


Exhibit 100: Detailed Route Speed Profiles - Route C Eastbound

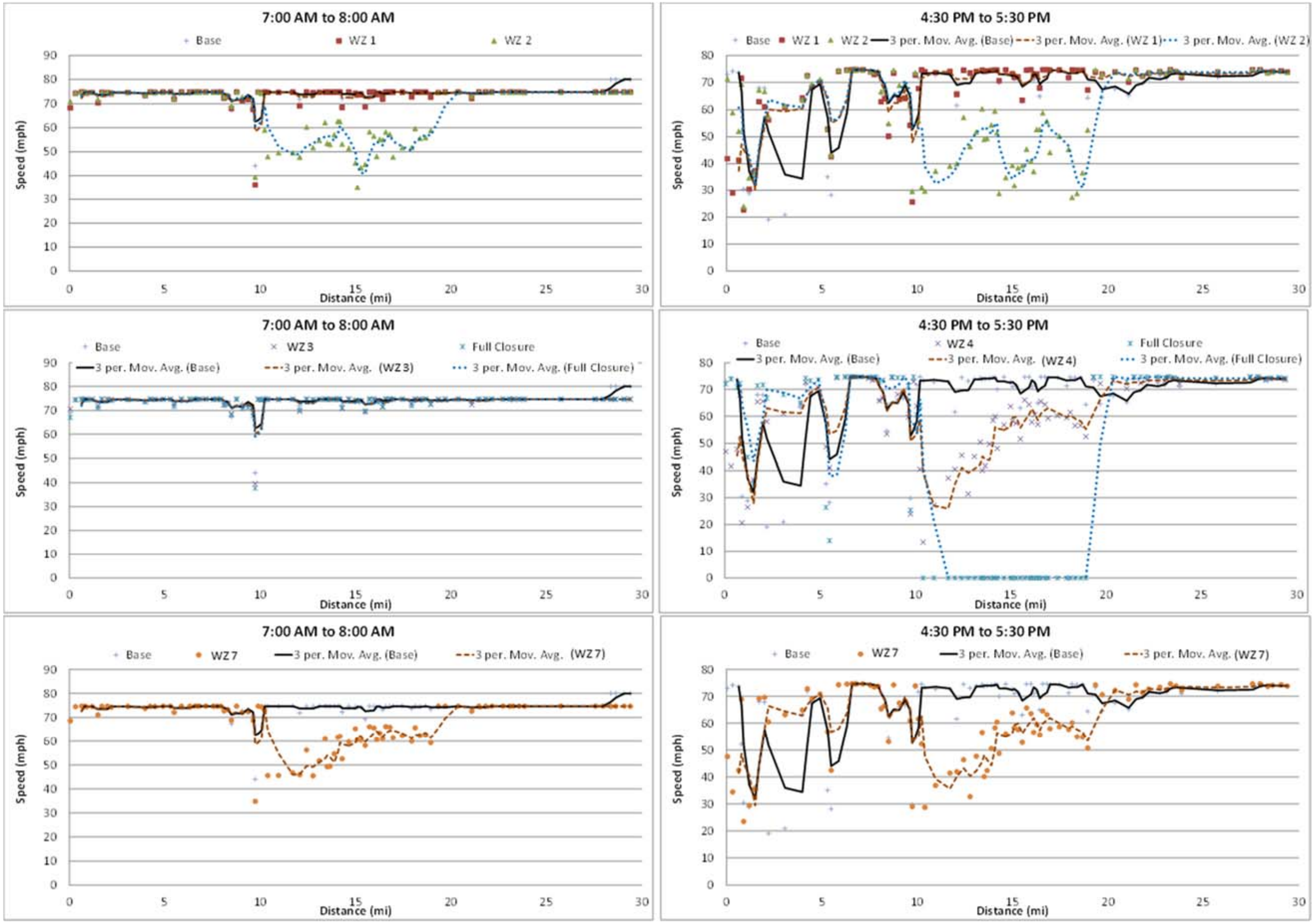


Exhibit 101: Detailed Route Speed Profiles - Route D Westbound

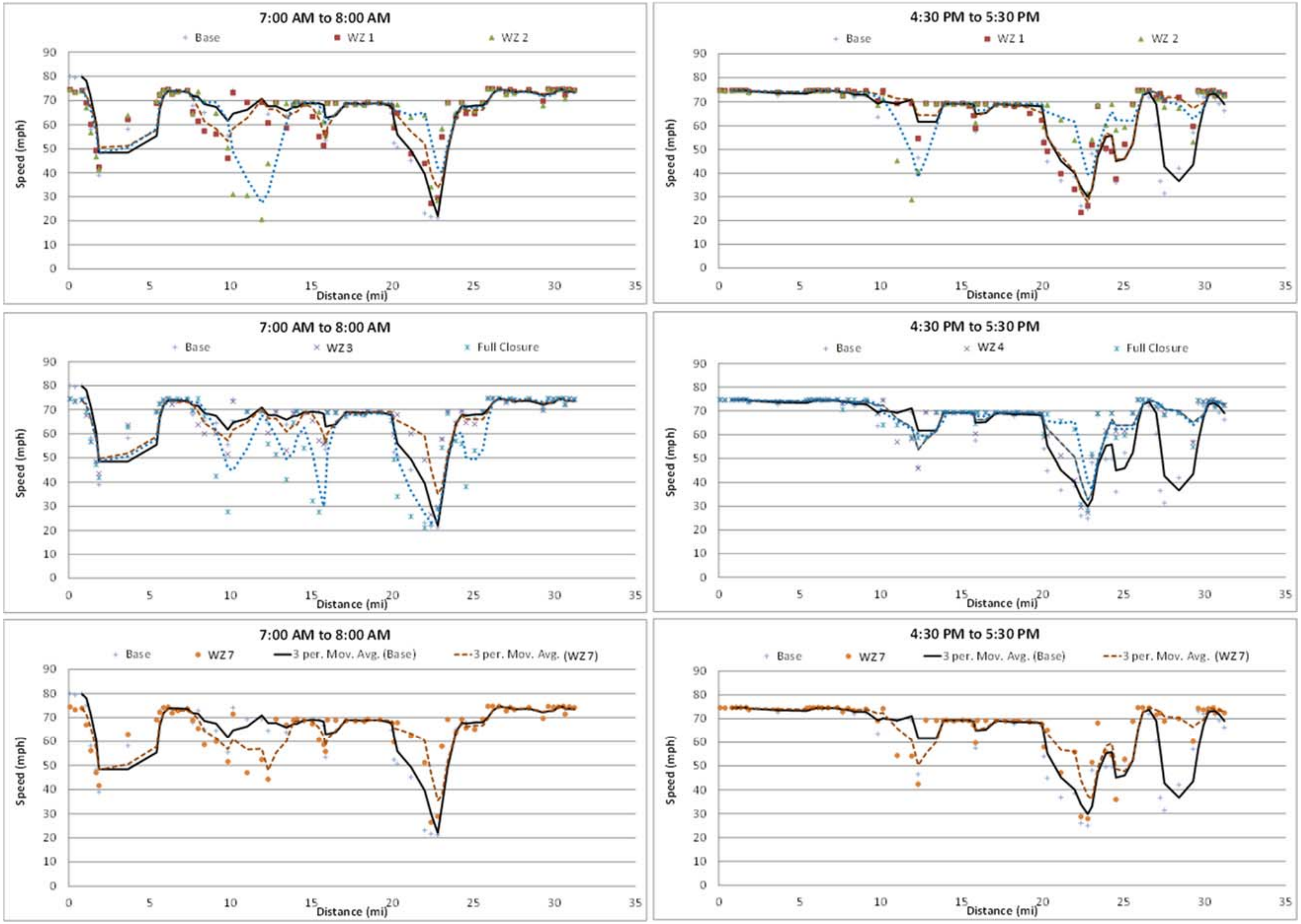
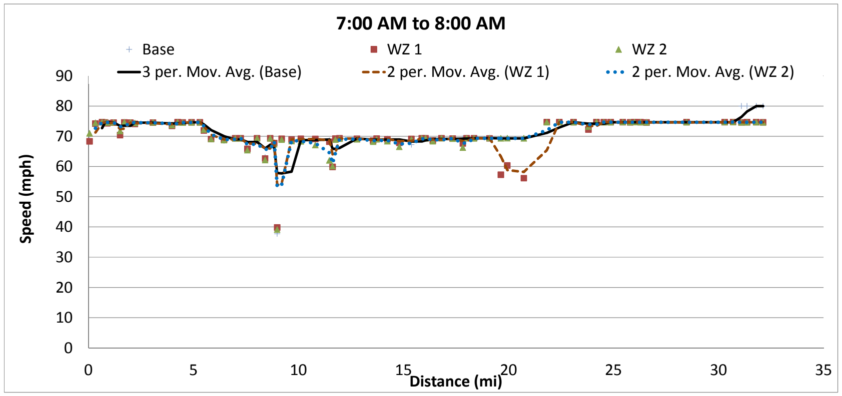
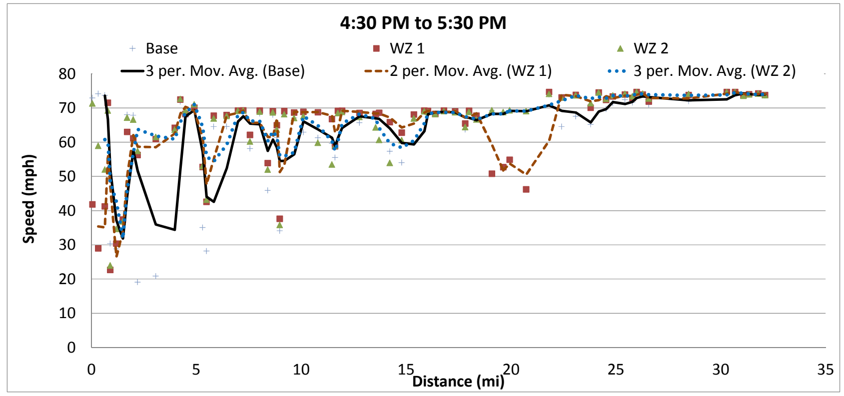
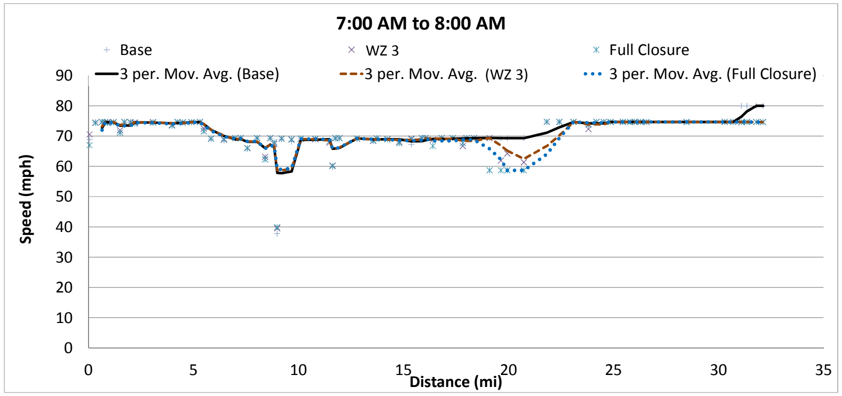
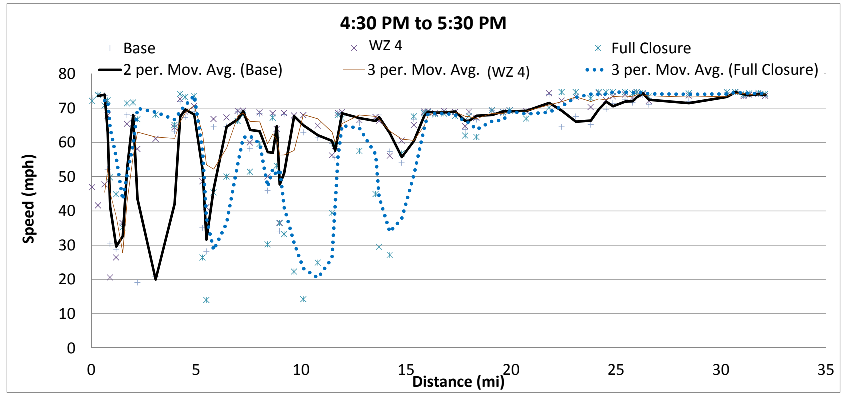


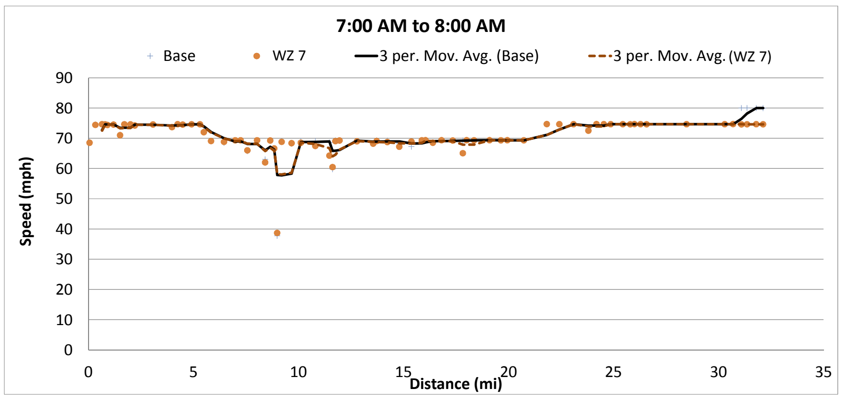
Exhibit 102: Detailed Route Speed Profiles - Route D Eastbound











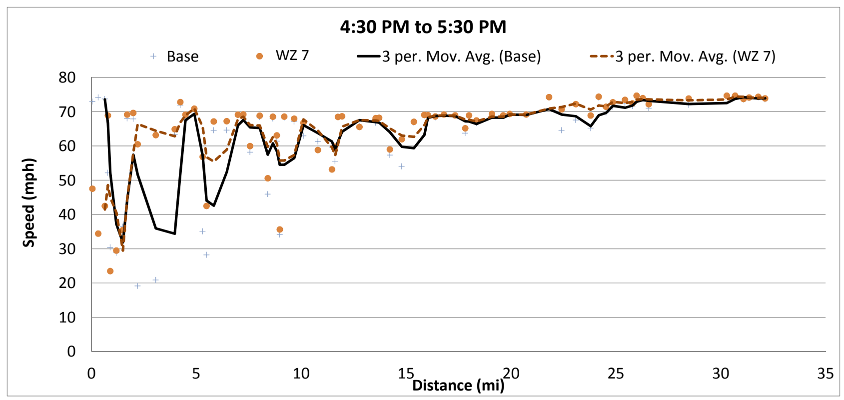
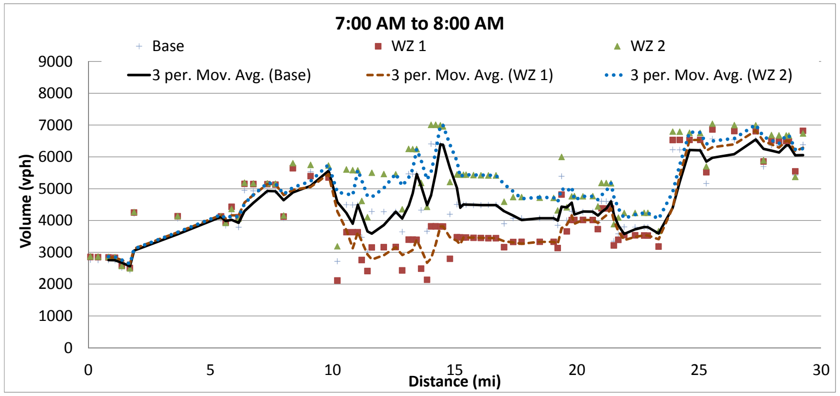
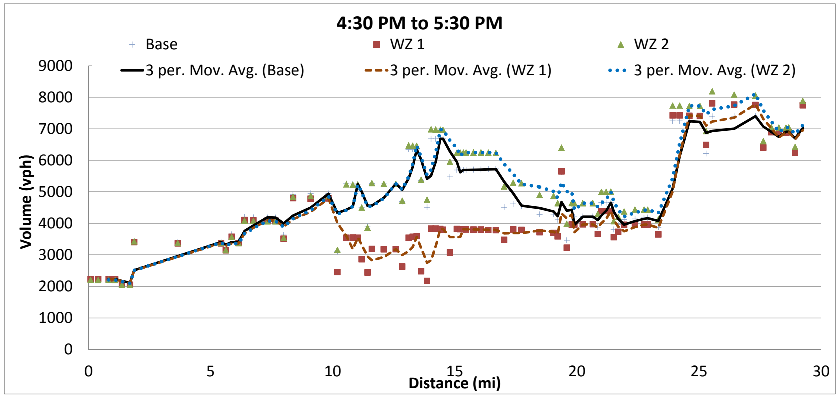
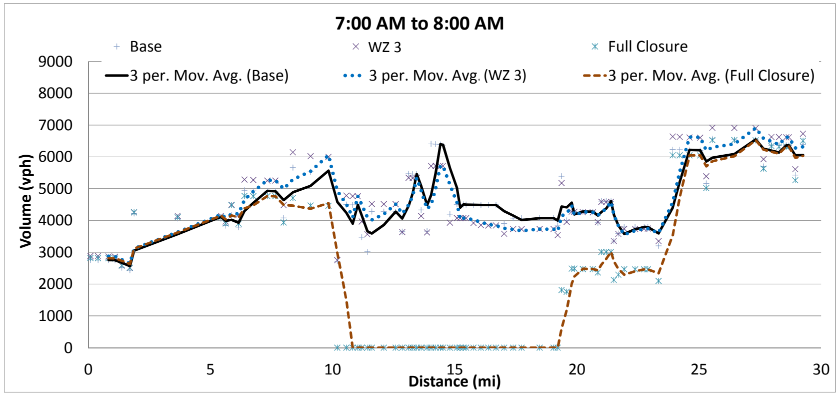
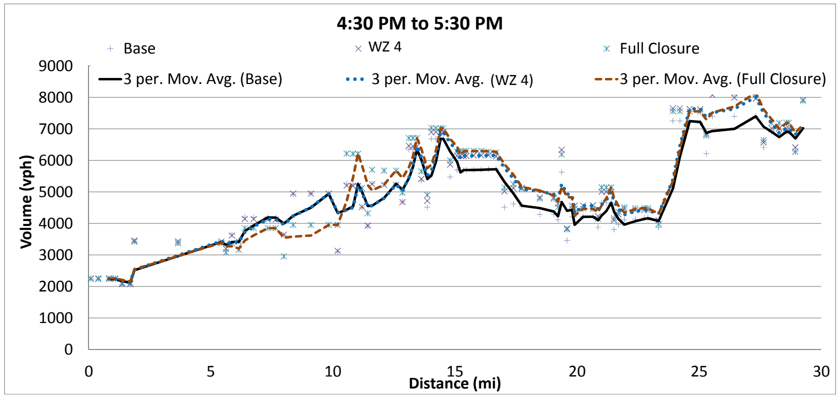


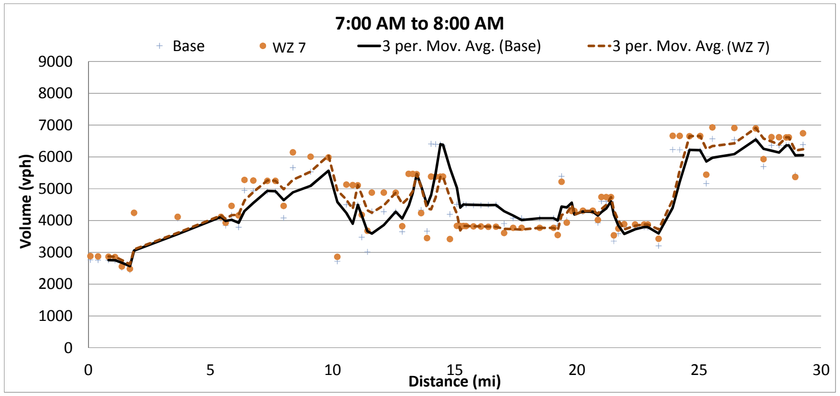
Exhibit 103: Detailed Route Volume Profiles - Route C Westbound











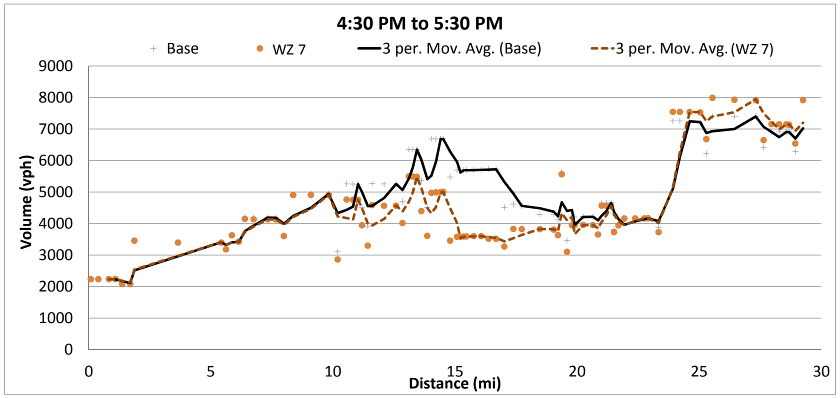


Exhibit 104: Detailed Route Volume Profiles - Route C Eastbound

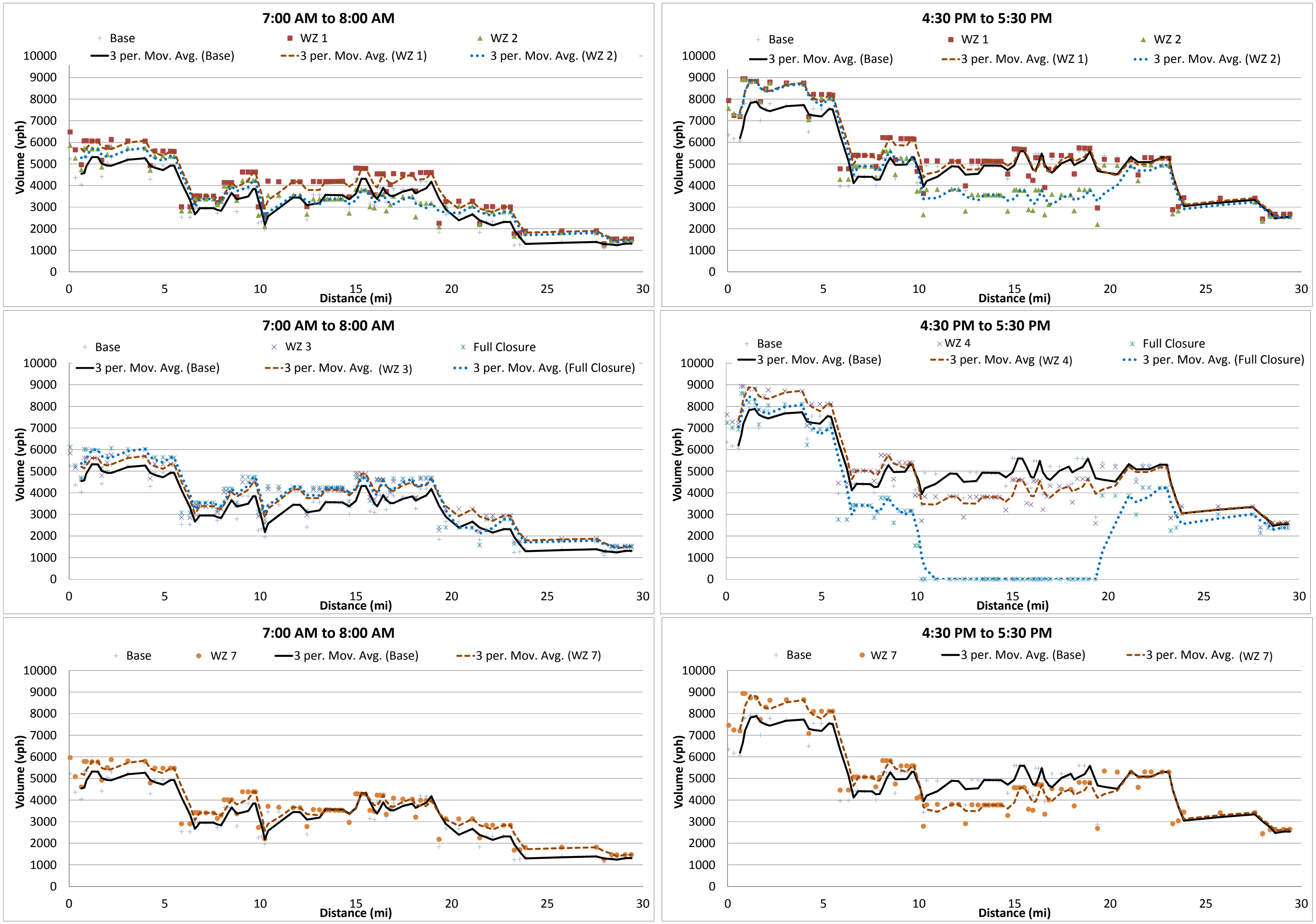
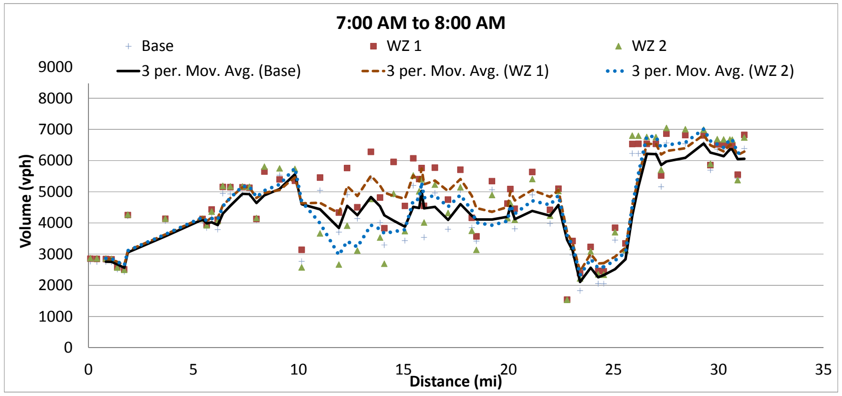
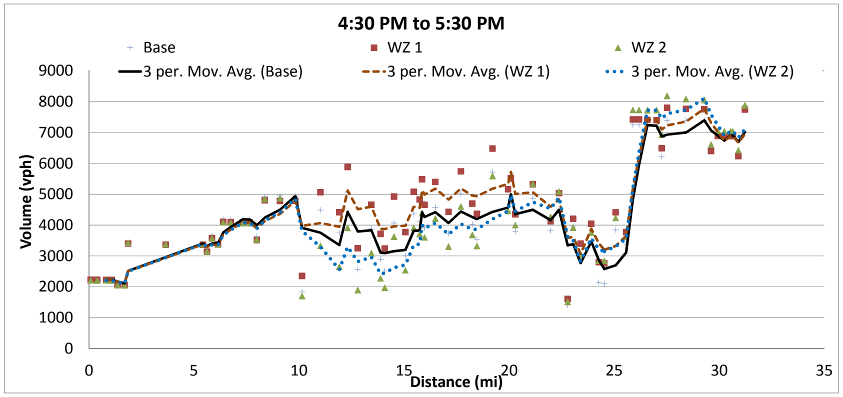
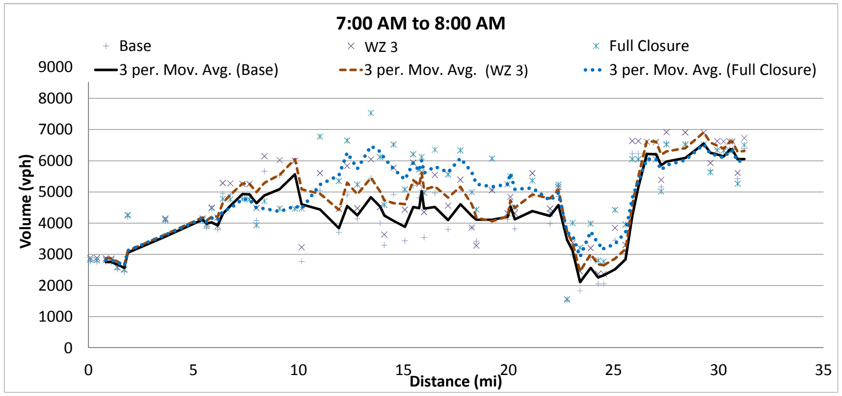
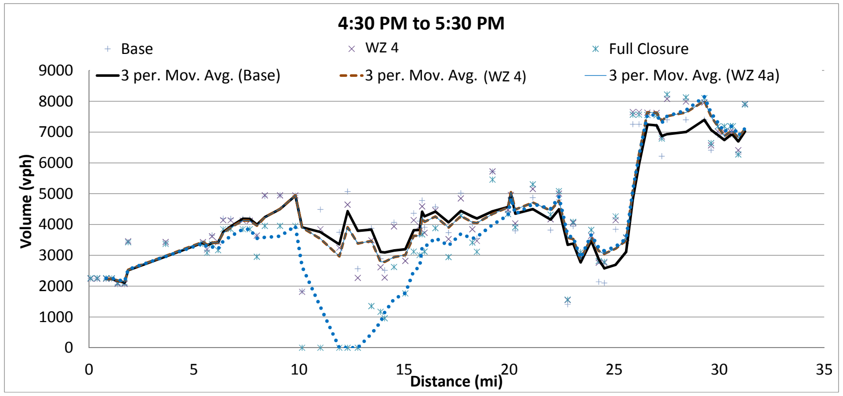


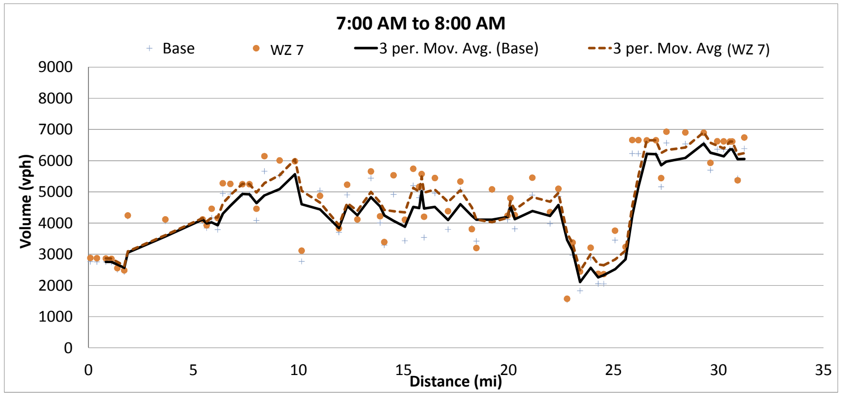
Exhibit 105: Detailed Route Volume Profiles - Route D Westbound











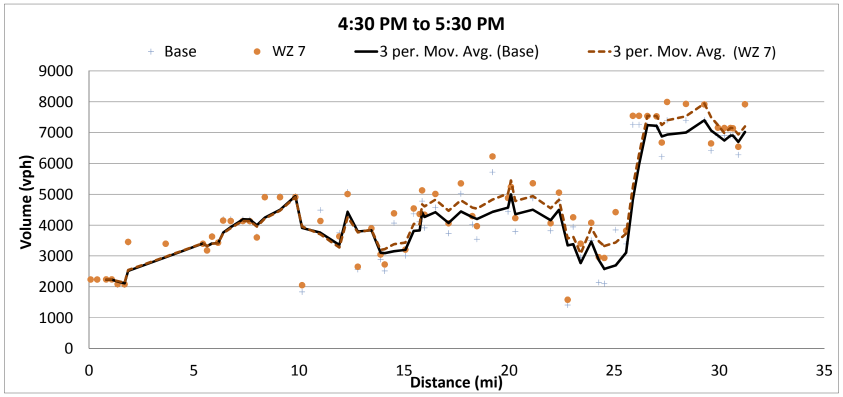
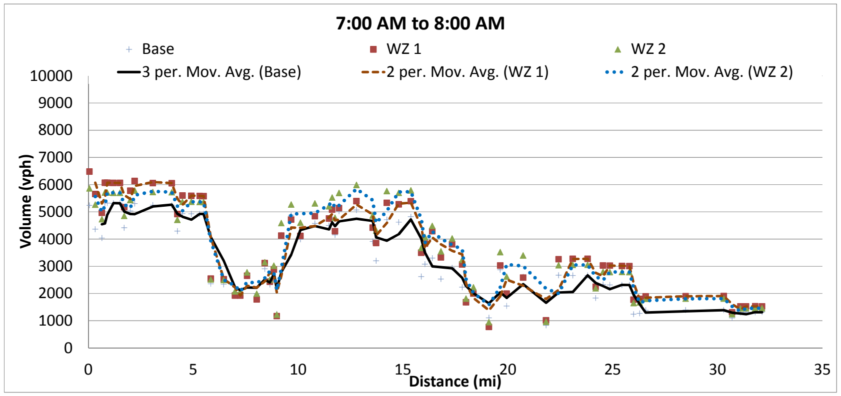
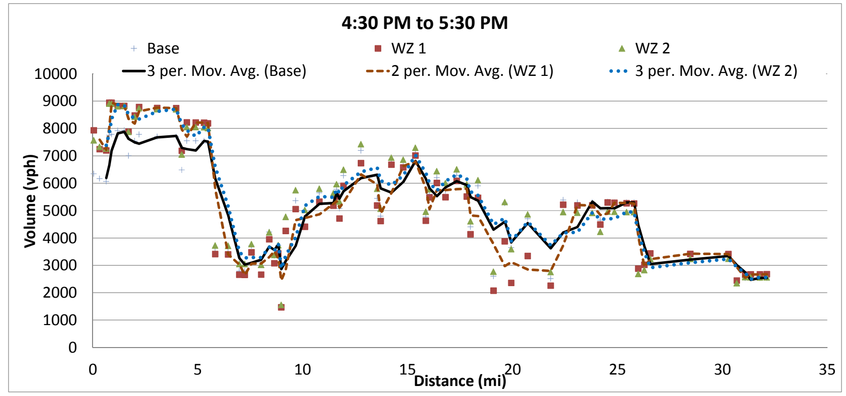
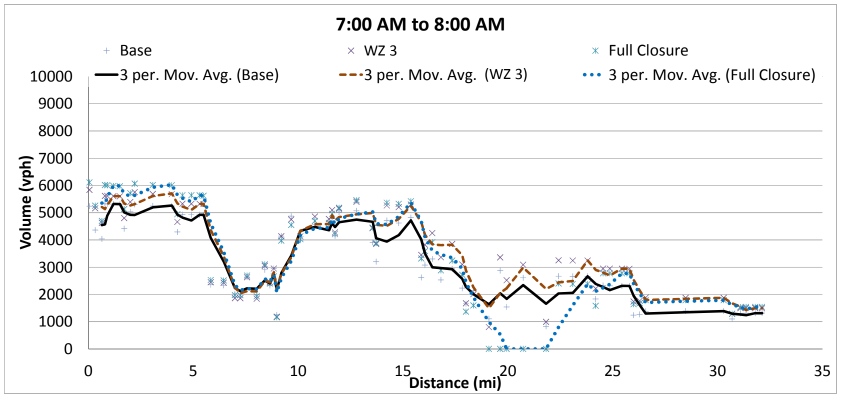
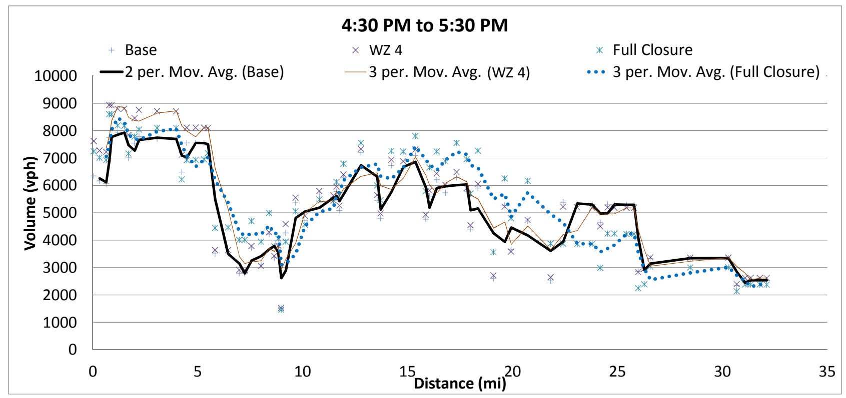


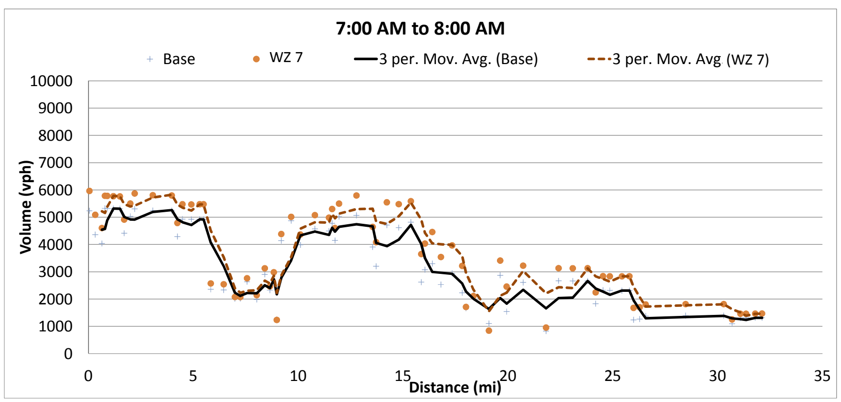
Exhibit 106: Detailed Route Volume Profiles - Route D Eastbound











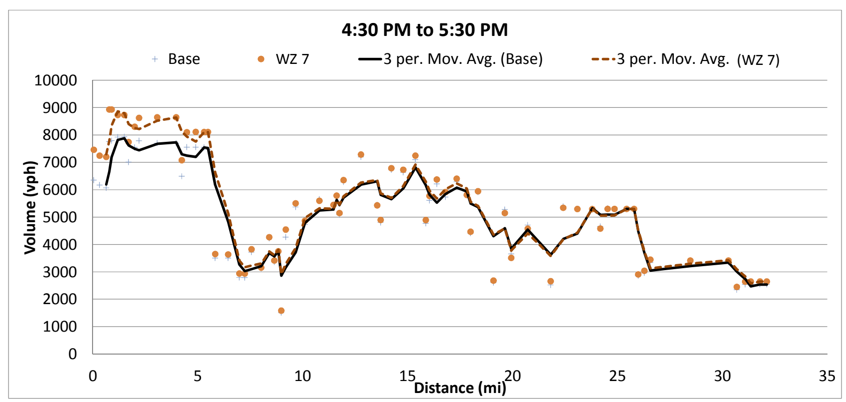


Exhibit 107 Network Wide Speed, Base Case AM Peak

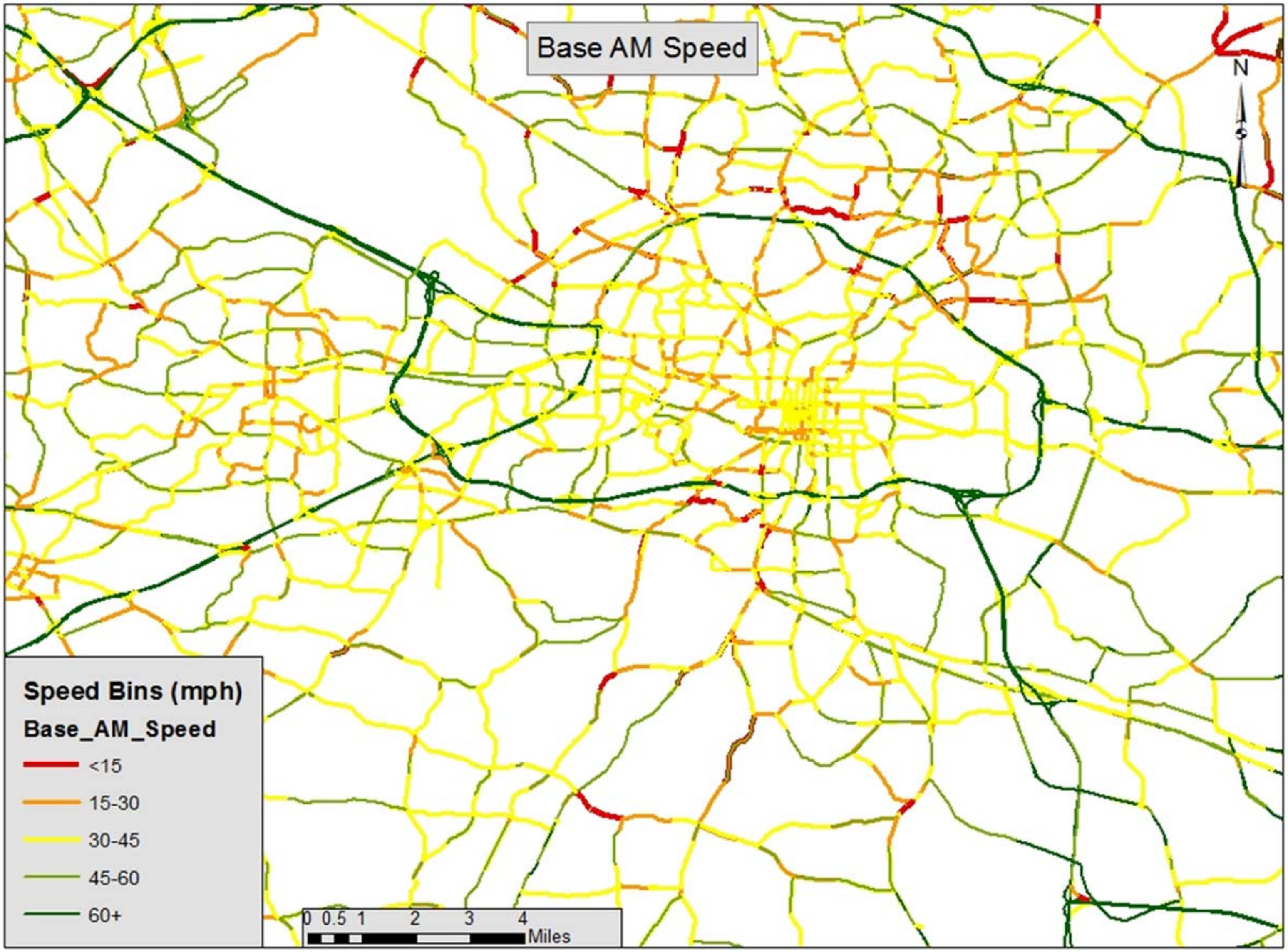


Exhibit 108 Network Wide Speed, Work Zone 1, AM Peak, No Diversion

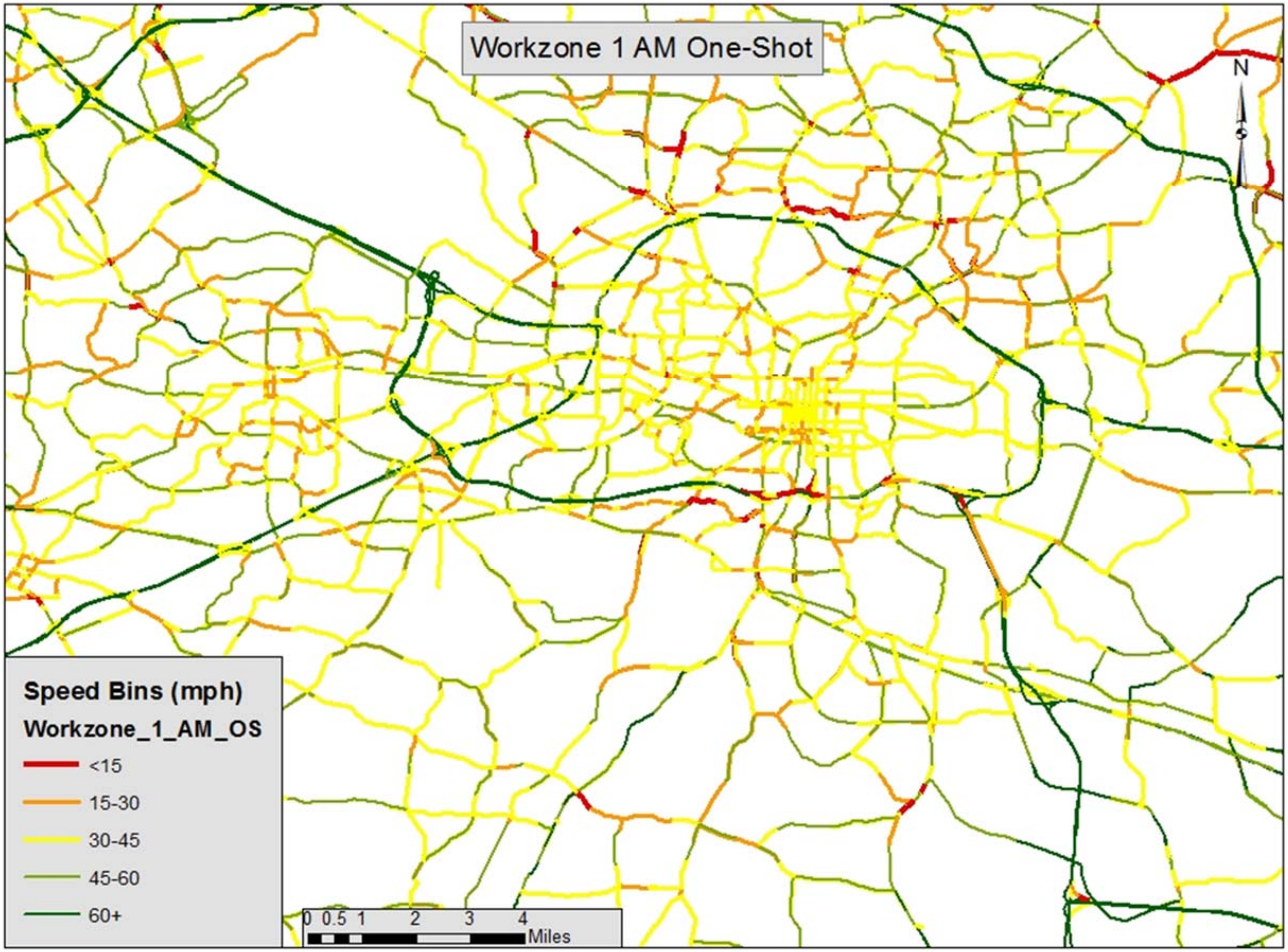


Exhibit 109 Network Wide Speed, Work Zone 1, AM Peak, User Equilibrium

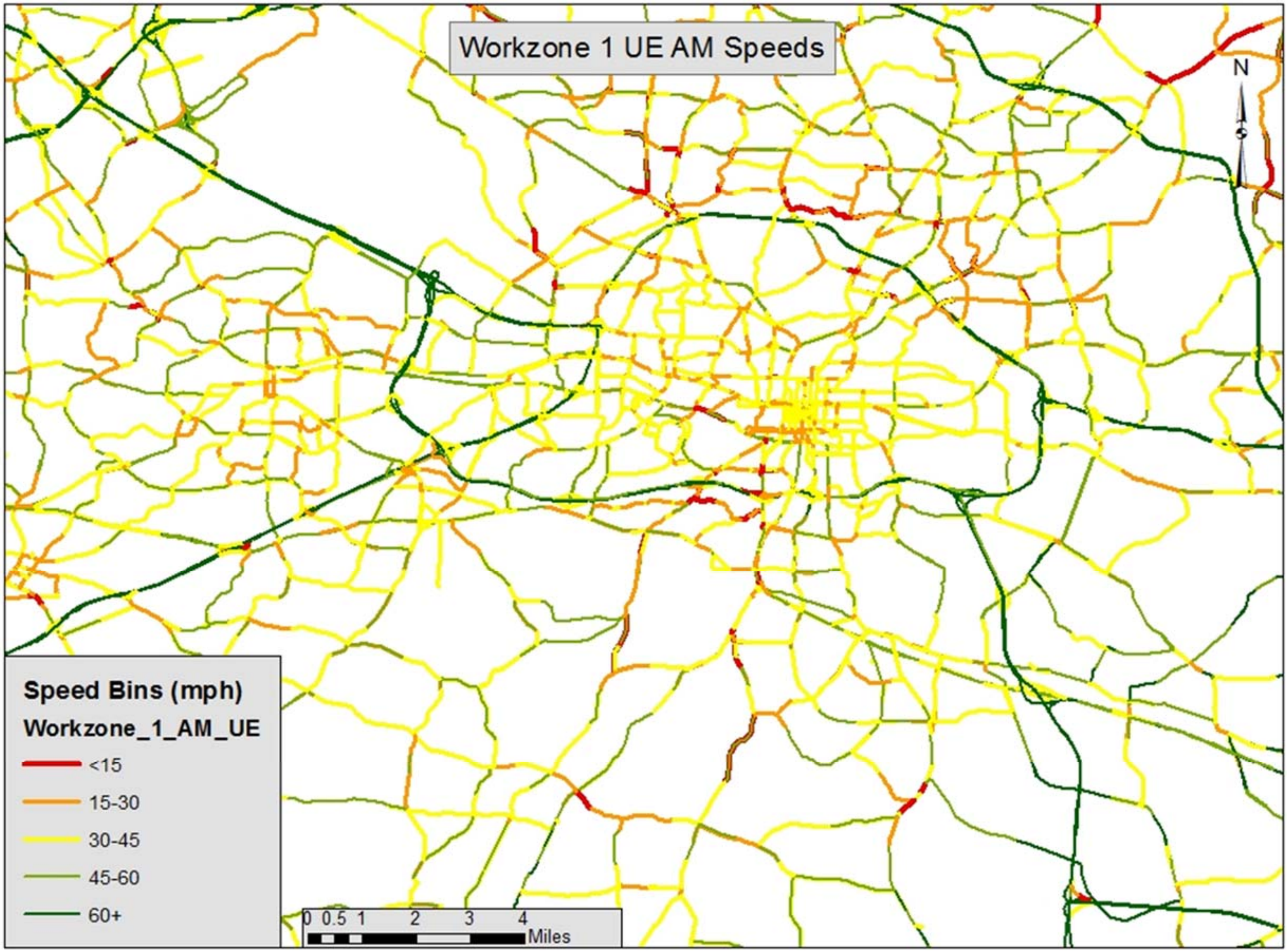


Exhibit 110 Network Wide Volume Difference (vs. Base Case), Work Zone 1, AM Peak, User Equilibrium

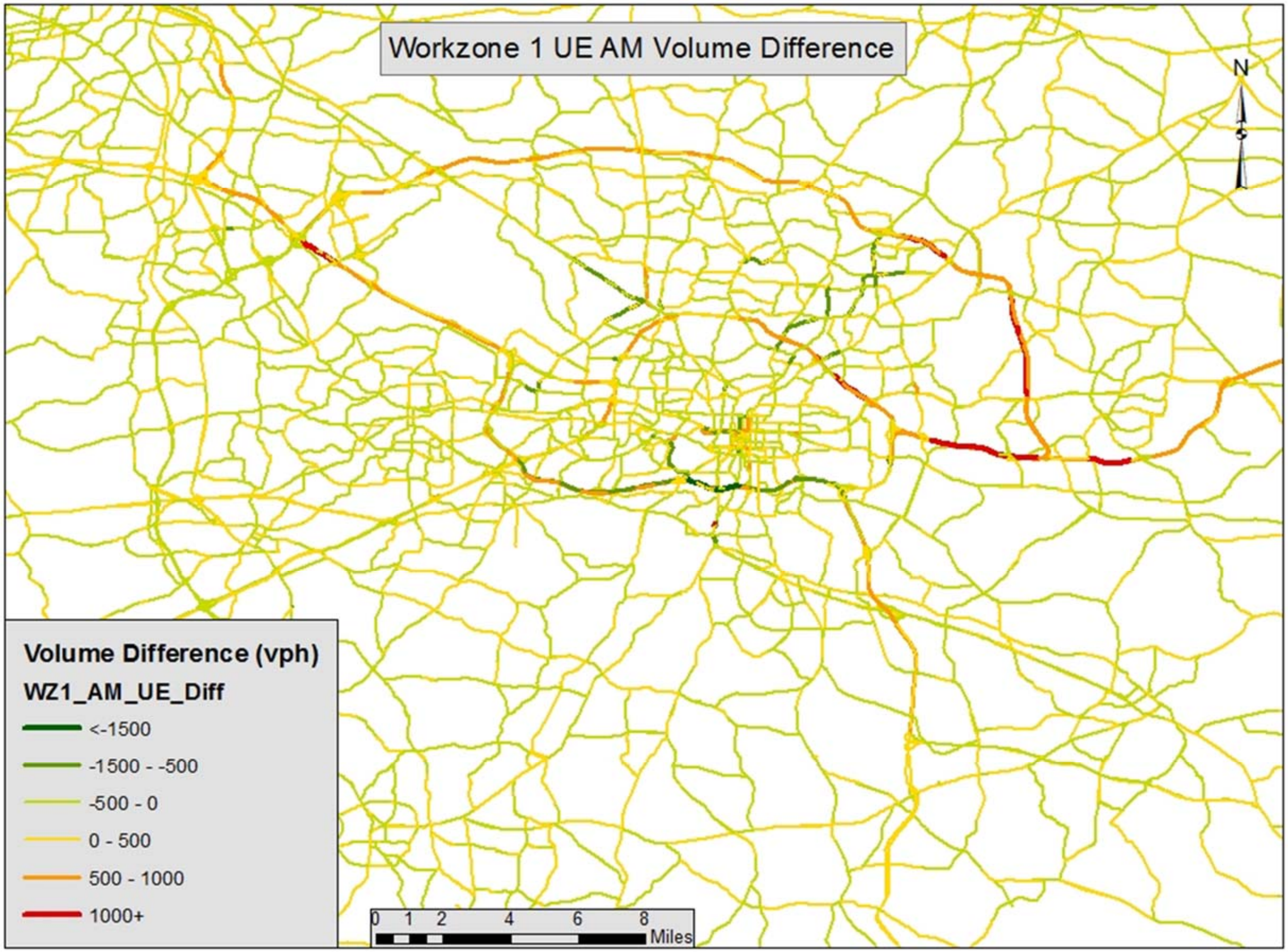


Exhibit 111 Network Wide Volume Difference (vs. Base Case), Work Zone 2, AM Peak, User Equilibrium

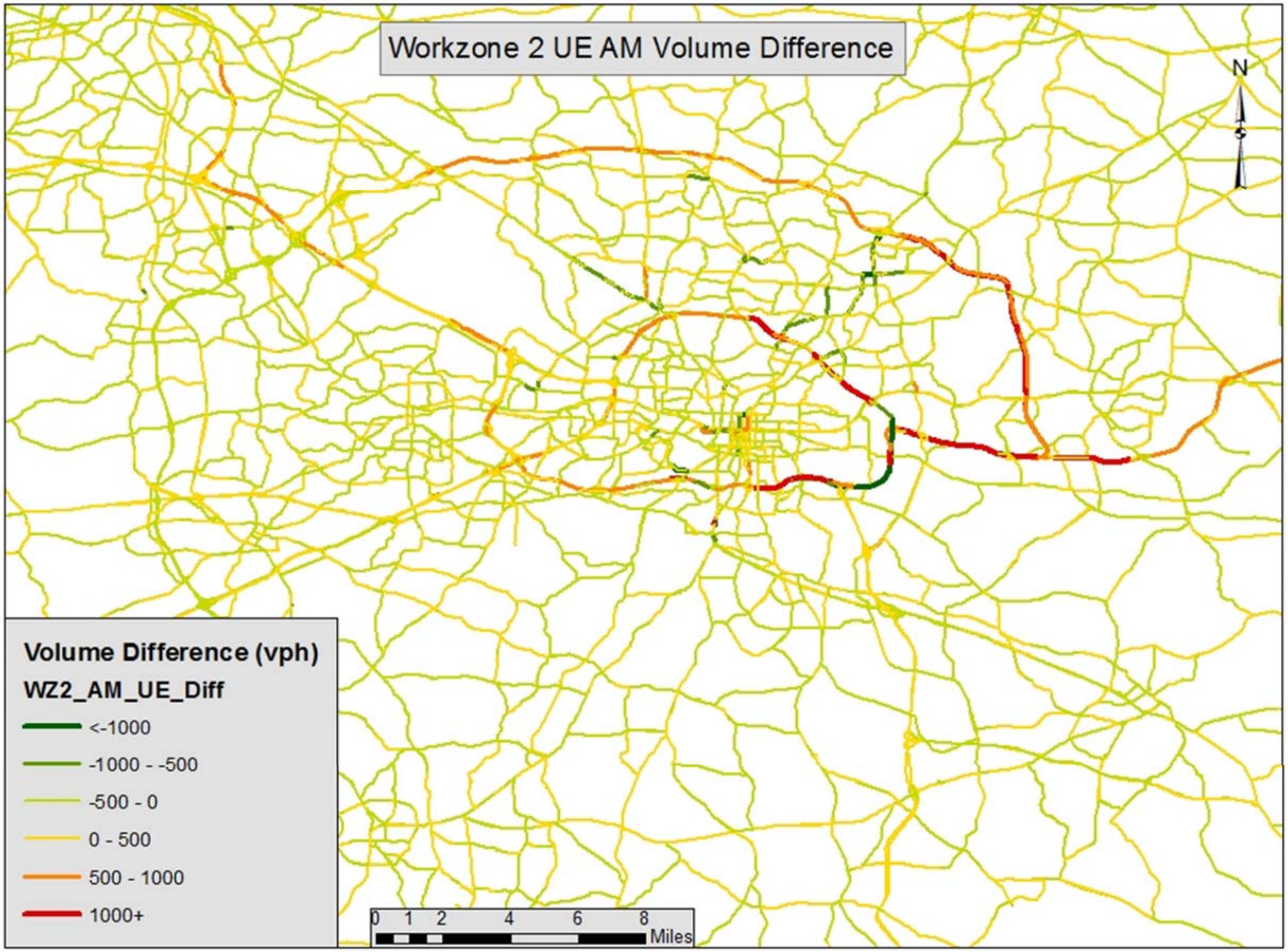


Exhibit 112 Network Wide Speed, Base Case PM Peak

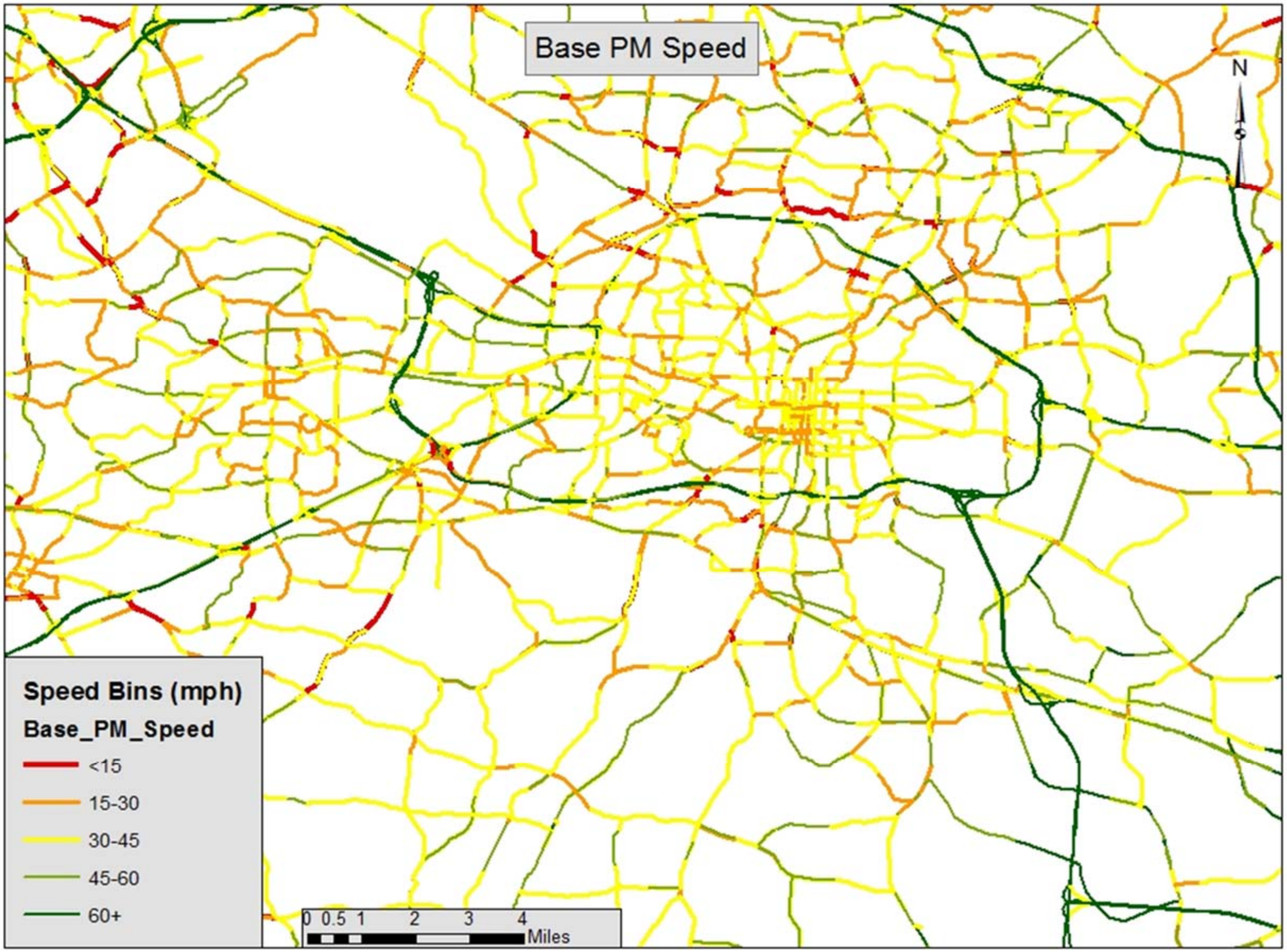


Exhibit 113 Network Wide Speed, Work Zone 2, PM Peak, No Diversion

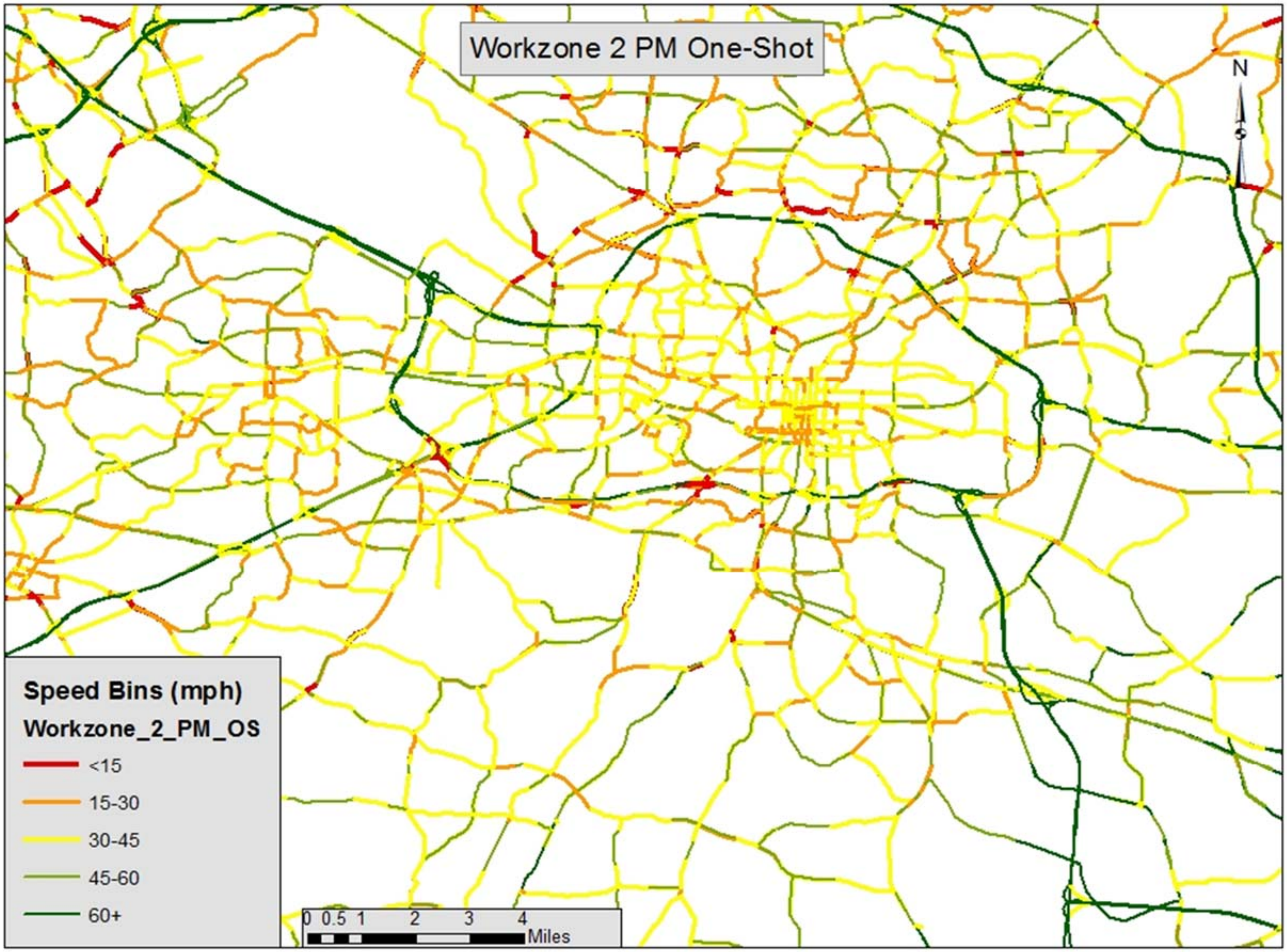
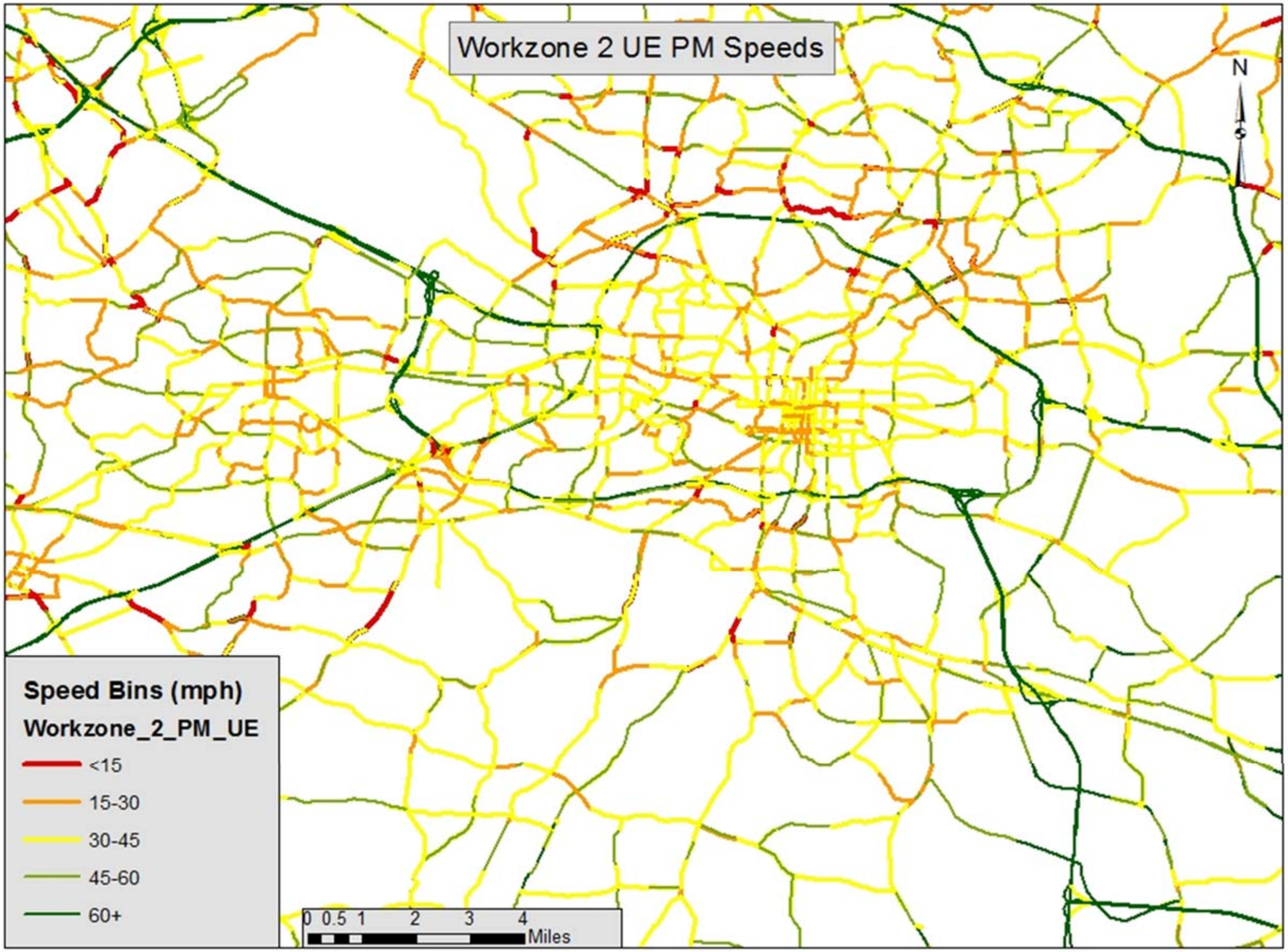


Exhibit 114 Network Wide Speed, Work Zone 2, PM Peak, User Equilibrium



Appendix E: Detailed DTALite Results

Introduction

In this appendix, the impacts of different work zone scenarios on the average travel time and average volume of certain key routes of the network are presented. The analysis is carried out for both AM and PM peak hours. AM peak hour is from 7:00 AM to 8:00 AM and PM peak starts at 4:30 PM and ends at 5:30 PM.

The results correspond to the with-diversion strategy where drivers are allowed to change their individual routes to reduce their travel time. For a route, the average travel time is found by summing up the average travel time of all links of the route. Average volume is simply the average of volume of all links of the route.

Peak Hour Travel Time for Other Routes

AM Peak Period

Exhibit 115 and Exhibit 116present the average travel time for other key routes of the network. The first three columns correspond to the name of the route, its start point, and its end point, respectively. The next two column show the travel time in the base case and the work zone scenario with two and three lanes open on the peak direction (WZ 1 and WZ 5) for both eastbound/northbound and westbound/southbound directions

Exhibit 115: Average Travel Time Change on Other Routes of the Network, Two Lanes Open - AM Peak

Route	From	To	Approx. Route Length (miles)	Route Travel Time EB/NB	Route Travel Time WB/SB
I-440	40/440 Split	Wade Ave.	12.7	13.5 -> 17.8 min.	24.7 -> 18.6 min.
I-540	I-40	US64	26.0	23.7 -> 23.8 min.	28.2 -> 30.4 min.
Wade Avenue	I-440	I-40	2.7	2.7 -> 2.9 min.	2.7 -> 2.6 min.
US70	White Oak	I-40	6.1	10.4 -> 20 min.	7.8 -> 7.5 min.
US64	NC55	US1	4.6	7.1 -> 4.7 min.	4.8 -> 4.9 min.
US1	US64	Wade Ave.	7.4	17.4 -> 10.4 min.	7.9 -> 7.8 min.
NC50	NC210	US70	13.9	25.5 -> 24.2 min.	14.9 -> 14.8 min.
NC55	I-40	US64	11.4	12.1 -> 13.2 min.	13.6 -> 13.7 min.
Hammond Road	US70	MLK Blvd.	3.7	9.1 -> 19.6 min.	4.6 -> 4.4 min.
Tryon Road	US70	US1	9.2	18.6 -> 16.9 min.	15.9 -> 16.2 min.
Rock Quarry	Jones Sausage	MLK Blvd.	4.0	5.8 -> 6.1 min.	7.2 -> 10.3 min.
Ten-Ten Road	US401	US1	8.4	16.7 -> 11.4 min.	25.2 -> 27.1 min.
Timber Drive	NC50	US70	4.0	6.1 -> 6 min.	4.9 -> 5 min.
Davis Drive	I-40	US64	11.3	24.5 -> 15.5 min.	16.3 -> 14.2 min.

Exhibit 116: Average Travel Time Change on Other Routes of the Network, Three Lanes Open - AM Peak

Route	From	To	Approx. Route Length (miles)	Route Travel Time EB/NB	Route Travel Time WB/SB
I-440	40/440 Split	Wade Ave.	12.7	13.5 -> 14.8 min.	24.7 -> 18.7 min.
I-540	I-40	US64	26.0	23.7 -> 23.8 min.	28.2 -> 30.3 min.
Wade Avenue	I-440	I-40	2.7	2.7 -> 2.9 min.	2.7 -> 2.7 min.
US70	White Oak	I-40	6.1	10.4 -> 15 min.	7.8 -> 8 min.
US64	NC55	US1	4.6	7.1 -> 4.7 min.	4.8 -> 5.1 min.
US1	US64	Wade Ave.	7.4	17.4 -> 10.2 min.	7.9 -> 8.4 min.
NC50	NC210	US70	13.9	25.5 -> 21.2 min.	14.9 -> 15.1 min.
NC55	I-40	US64	11.4	12.1 -> 14.1 min.	13.6 -> 13.5 min.
Hammond Road	US70	MLK Blvd.	3.7	9.1 -> 14 min.	4.6 -> 5.6 min.
Tryon Road	US70	US1	9.2	18.6 -> 16.6 min.	15.9 -> 17.3 min.
Rock Quarry	Jones Sausage	MLK Blvd.	4.0	5.8 -> 5.9 min.	7.2 -> 9.5 min.
Ten-Ten Road	US401	US1	8.4	16.7 -> 10.8 min.	25.2 -> 21.8 min.
Timber Drive	NC50	US70	4.0	6.1 -> 6.1 min.	4.9 -> 4.7 min.
Davis Drive	I-40	US64	11.3	24.5 -> 14.9 min.	16.3 -> 14.1 min.

PM Peak Period

Exhibit 117 and Exhibit 118 show average travel time for the key routes of the network for work zone scenarios with two and three lanes open on the peak direction in the PM peak, respectively (WZ2 and WZ 6).

Exhibit 117: Average Travel Time Change on Other Routes of the Network, Two Lanes Open - PM Peak

Route	From	To	Approx. Route Length (miles)	Route Travel Time EB/NB	Route Travel Time WB/SB
I-440	40/440 Split	Wade Ave.	12.7	13.8 -> 16.5 min.	18.8 -> 18.4 min.
I-540	I-40	US64	26.0	32.6 -> 39 min.	28.2 -> 25 min.
Wade Avenue	I-440	I-40	2.7	3.9 -> 6.2 min.	2.7 -> 2.9 min.
US70	White Oak	I-40	6.1	16.7 -> 16 min.	14.6 -> 11 min.
US64	NC55	US1	4.6	4.6 -> 4.6 min.	4.7 -> 6.1 min.
US1	US64	Wade Ave.	7.4	18.9 -> 9.8 min.	8.5 -> 8.3 min.
NC50	NC210	US70	13.9	20.1 -> 17.8 min.	19.2 -> 17.2 min.
NC55	I-40	US64	11.4	12.6 -> 13.8 min.	18 -> 16.2 min.
Hammond Road	US70	MLK Blvd.	3.7	8.2 -> 5.6 min.	12.5 -> 8.1 min.
Tryon Road	US70	US1	9.2	65.8 -> 25.8 min.	40 -> 16.5 min.
Rock Quarry	Jones Sausage	MLK Blvd.	4.0	6.7 -> 7.3 min.	7.4 -> 6.4 min.
Ten-Ten Road	US401	US1	8.4	41.6 -> 24.5 min.	17.9 -> 14.8 min.
Timber Drive	NC50	US70	4.0	6.2 -> 5.7 min.	5 -> 5 min.
Davis Drive	I-40	US64	11.3	18.5 -> 16.2 min.	17 -> 22.6 min.

Exhibit 118: Average Travel Time Change on Other Routes of the Network, Three Lanes Open - PM Peak

Route	From	To	Approx. Route Length (miles)	Route Travel Time EB/NB	Route Travel Time WB/SB
I-440	40/440 Split	Wade Ave.	12.7	13.8 -> 16.2 min.	18.8 -> 17.3 min.
I-540	I-40	US64	26.0	32.6 -> 35.6 min.	28.2 -> 25 min.
Wade Avenue	I-440	I-40	2.7	3.9 -> 4.7 min.	2.7 -> 3.3 min.
US70	White Oak	I-40	6.1	16.7 -> 10.8 min.	14.6 -> 10.6 min.
US64	NC55	US1	4.6	4.6 -> 4.8 min.	4.7 -> 6.2 min.
US1	US64	Wade Ave.	7.4	18.9 -> 10.7 min.	8.5 -> 9.2 min.
NC50	NC210	US70	13.9	20.1 -> 17.6 min.	19.2 -> 17 min.
NC55	I-40	US64	11.4	12.6 -> 14.4 min.	18 -> 17.6 min.
Hammond Road	US70	MLK Blvd.	3.7	8.2 -> 7 min.	12.5 -> 7.3 min.
Tryon Road	US70	US1	9.2	65.8 -> 32 min.	40 -> 25.4 min.
Rock Quarry	Jones Sausage	MLK Blvd.	4.0	6.7 -> 7.2 min.	7.4 -> 6.4 min.
Ten-Ten Road	US401	US1	8.4	41.6 -> 28.1 min.	17.9 -> 13.5 min.
Timber Drive	NC50	US70	4.0	6.2 -> 5.8 min.	5 -> 5 min.
Davis Drive	I-40	US64	11.3	18.5 -> 16 min.	17 -> 18.7 min.

Peak Hour Traffic Volume for Other Routes

AM Peak Period

Exhibit 119 and Exhibit 120 show average traffic volume on the key routes of the network for work zone scenarios with two and three lanes open on the peak direction in the AM Peak, respectively (WZ1 and WZ 5).

Exhibit 119: Average Volume Change on Other Routes of the Network, Two Lanes Open - AM Peak

Route	From	To	Route Volume EB/NB	Route Volume WB/SB
I-440	40/440 Split	Wade Ave.	3514 -> 3261 Veh.	3664 -> 3777 Veh.
I-540	I-40	US64	2668 -> 2663 Veh.	4753 -> 4753 Veh.
Wade Avenue	I-440	I-40	3192 -> 2935 Veh.	2222 -> 2961 Veh.
US70	White Oak	I-40	1907 -> 1788 Veh.	1859 -> 1946 Veh.
US64	NC55	US1	1553 -> 1708 Veh.	1041 -> 1666 Veh.
US1	US64	Wade Ave.	3453 -> 3372 Veh.	2041 -> 2748 Veh.
NC50	NC210	US70	784 -> 845 Veh.	227 -> 236 Veh.
NC55	I-40	US64	286 -> 1243 Veh.	394 -> 896 Veh.
Hammond Road	US70	MLK Blvd.	1339 -> 1103 Veh.	257 -> 282 Veh.
Tryon Road	US70	US1	686 -> 703 Veh.	460 -> 419 Veh.
Rock Quarry Road	Jones Sausage	MLK Blvd.	300 -> 378 Veh.	977 -> 1254 Veh.
Ten-Ten Road	US401	US1	386 -> 265 Veh.	542 -> 647 Veh.
Timber Drive	NC50	US70	602 -> 534 Veh.	738 -> 639 Veh.
Davis Drive	I-40	US64	367 -> 376 Veh.	264 -> 191 Veh.

Exhibit 120: Average Volume Change on Other Routes of the Network, Three Lanes Open - AM Peak

Route	From	To	Route Volume EB/NB	Route Volume WB/SB
I-440	40/440 Split	Wade Ave.	3514 -> 3319 Veh.	3664 -> 3775 Veh.
I-540	I-40	US64	2668 -> 2661 Veh.	4753 -> 4635 Veh.
Wade Avenue	I-440	I-40	3192 -> 3136 Veh.	2222 -> 2823 Veh.
US70	White Oak	I-40	1907 -> 2114 Veh.	1859 -> 2144 Veh.
US64	NC55	US1	1553 -> 1718 Veh.	1041 -> 1722 Veh.
US1	US64	Wade Ave.	3453 -> 3466 Veh.	2041 -> 2689 Veh.
NC50	NC210	US70	784 -> 845 Veh.	227 -> 222 Veh.
NC55	I-40	US64	286 -> 1254 Veh.	394 -> 877 Veh.
Hammond Road	US70	MLK Blvd.	1339 -> 1372 Veh.	257 -> 274 Veh.
Tryon Road	US70	US1	686 -> 657 Veh.	460 -> 450 Veh.
Rock Quarry Road	Jones Sausage	MLK Blvd.	300 -> 381 Veh.	977 -> 1276 Veh.
Ten-Ten Road	US401	US1	386 -> 278 Veh.	542 -> 647 Veh.
Timber Drive	NC50	US70	602 -> 494 Veh.	738 -> 606 Veh.
Davis Drive	I-40	US64	367 -> 366 Veh.	264 -> 195 Veh.

PM Peak Period

Exhibit 121 and Exhibit 122 how average traffic volume on the key routes of the network for work zone scenarios with two and three lanes open on the peak direction in the PM peak , respectively (WZ2 and WZ 6).

Exhibit 121: Average Volume Change on Other Routes of the Network, Two Lanes Open – PM Peak

Route	From	To	Route Volume EB/NB	Route Volume WB/SB
I-440	40/440 Split	Wade Ave.	4895 -> 5284 Veh.	4191 -> 3675 Veh.
I-540	I-40	US64	3822 -> 3893 Veh.	3905 -> 2984 Veh.
Wade Avenue	I-440	I-40	2729 -> 3224 Veh.	2909 -> 3253 Veh.
US70	White Oak	I-40	1107 -> 1905 Veh.	2547 -> 2758 Veh.
US64	NC55	US1	1287 -> 1811 Veh.	1146 -> 2167 Veh.
US1	US64	Wade Ave.	2549 -> 3778 Veh.	2953 -> 3840 Veh.
NC50	NC210	US70	749 -> 682 Veh.	675 -> 670 Veh.
NC55	I-40	US64	495 -> 1628 Veh.	487 -> 2033 Veh.
Hammond Road	US70	MLK Blvd.	1115 -> 813 Veh.	1329 -> 1424 Veh.
Tryon Road	US70	US1	652 -> 793 Veh.	499 -> 583 Veh.
Rock Quarry Road	Jones Sausage	MLK Blvd.	859 -> 858 Veh.	568 -> 501 Veh.
Ten-Ten Road	US401	US1	663 -> 634 Veh.	554 -> 556 Veh.
Timber Drive	NC50	US70	436 -> 449 Veh.	449 -> 493 Veh.
Davis Drive	I-40	US64	565 -> 419 Veh.	500 -> 532 Veh.

Exhibit 122: Average Volume Change on Other Routes of the Network, Three Lanes Open - AM Peak

Route	From	To	Route Volume EB/NB	Route Volume WB/SB
I-440	40/440 Split	Wade Ave.	4895 -> 5061 Veh.	4191 -> 3733 Veh.
I-540	I-40	US64	3822 -> 3718 Veh.	3905 -> 2932 Veh.
Wade Avenue	I-440	I-40	2729 -> 3002 Veh.	2909 -> 2970 Veh.
US70	White Oak	I-40	1107 -> 1891 Veh.	2547 -> 2648 Veh.
US64	NC55	US1	1287 -> 1644 Veh.	1146 -> 2178 Veh.
US1	US64	Wade Ave.	2549 -> 3806 Veh.	2953 -> 3965 Veh.
NC50	NC210	US70	749 -> 683 Veh.	675 -> 649 Veh.
NC55	I-40	US64	495 -> 1660 Veh.	487 -> 1960 Veh.
Hammond Road	US70	MLK Blvd.	1115 -> 712 Veh.	1329 -> 1400 Veh.
Tryon Road	US70	US1	652 -> 772 Veh.	499 -> 616 Veh.
Rock Quarry Road	Jones Sausage	MLK Blvd.	859 -> 864 Veh.	568 -> 546 Veh.
Ten-Ten Road	US401	US1	663 -> 619 Veh.	554 -> 582 Veh.
Timber Drive	NC50	US70	436 -> 450 Veh.	449 -> 495 Veh.
Davis Drive	I-40	US64	565 -> 422 Veh.	500 -> 536 Veh.