Corridor-Based Forecasts of Work-Zone Impacts for Freeways

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16. Abstract

This project developed an analysis methodology and associated software implementation for the evaluation of significant work zone impacts on freeways in North Carolina. The FREEVAL-WZ software tool allows the analyst to predict the operational impacts of work zones, including impacts from capacity reductions, lane closures, reduced speed limits and traffic diversions. The research is based on the 2010 Highway Capacity Manual Freeway Facilities methodology and its companion FREEVAL-2010 computational engine. Through this project, the tool was enhanced to allow for work-zone specific impact assessment, customized to the needs of the NCDOT Traffic Management Unit. The tool includes a new planning-level feature that enables a quick assessment of work zone impacts, while still allowing for a more detailed operational analysis. The tool uses default values for work zone inputs specific for North Carolina conditions. However, all inputs can be adjusted by the user. Further, the methodology allows the analyst to calculate user cost impacts of the work zone. All calculations and algorithms in FREEVAL-WZ are consistent with the methodologies in the 2010 Highway Capacity Manual. The project included a significant field validation and model calibration efforts with operational data collected directly by NCDOT using field sensors. The data was used to compare predicted model performance to field operations and to develop default parameters for typical North Carolina work zone configurations. Project deliverables include a final report, the actual FREEVAL-WZ tool, and a software user manual.

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EXECUTIVE SUMMARY

This project developed an analysis methodology and associated software implementation for the evaluation of significant work zones on freeways and multi-lane highways in North Carolina. The FREEVAL-WZ tool allows the prediction of traffic operational impacts of work zones, including capacity reductions, lane closures, reduced speed limits and traffic diversions. The research is based on the 2010 Highway Capacity Manual Freeway Facilities methodology and its FREEVAL computational engine. Through this project, the tool was enhanced to allow for work-zone specific impact assessment, customized to the needs of the NCDOT Traffic Management Unit. The tool includes a new planning-level feature that allows for a quick assessment of work zone impacts, while still allowing for a more detailed operational analysis. Work zone impacts are coded in the form of default values for North Carolina conditions, but can be adjusted by user input. Further, the methodology allows the analyst to calculate user cost impacts of the work zone. All calculations and algorithms in FREEVAL-WZ are consistent with the methodologies in the 2010 Highway Capacity Manual.

The project found significant variability in the literature about best practices for work zone analysis, and specifically the estimation of the effects of freeway work zones on capacity and speed. The variation of work zone capacity estimates in the literature emphasizes the need for calibration to local and regional conditions. In an effort to achieve such calibration in this project, the team extracted large amounts of work zone sensor data from Traffic.com roadside sensors. The data were used to compare predicted model performance to field operations, and to develop default parameters for typical North Carolina work zone configurations. Work zone contractor diaries were obtained to identify times and locations of construction activity, with an emphasis on lane closures. Sensor data were extracted at days when construction activity was noted. Unfortunately, of the approximately 4,500 extracted fifteen-minute periods, only a little over 500 (roughly 10%) were usable in the research. A lane-by-lane analysis of the remaining time periods showed that the sensor was located outside of the lane closure activity area. For future research it is thus strongly recommended to conduct custom field studies, where equipment can be deployed directly at the beginning of the work zone lane closure, as suggested by the literature review for this study.

With limited field data, the team was not able to reliably estiamte capacity adjustment factors (CAFs) for NC specific work zone operations. The default inputs in the FREEVAL-WZ software tool therefore rely on guidance in the 2010 Highway Capacity Manual. Clearly, these defaults can be updated as more comprehensive NC data become available. When applying these calibrated CAFs to a NC case study, some CAFs needed to be further reduced to produce a better match for field-estimated speed data. In other words, the calibrated CAF underestimated the effect of work zone congestion. It is therefore recommended that in addition to using the NC defaults, the analyst should run a sensitivity analysis in FREEVAL-WZ with a lower CAF for a more conservative estimate of potential work-zone induced delays.

In summary, more experience is needed with the FREEVAL-WZ tool in application to NC work zone analysis, and it is highly recommended that the NCDOT keep a record of analysis results produced from the tool in comparison to field experience. Over time, this will allow the NCDOT to build in-house expertise and best practices for the operational evaluation of freeway work zones in North Carolina.

Through this project, the NCDOT now has a customized software tool that allows for efficient analysis of work zone impacts. Despite the need for further calibration, the FREEVAL-WZ tool represents a significant improvement over the QUEWZ-98 model that was previously used by the Work Zone Traffic Control Unit. With the enhanced user-friendliness, the tool can be applied at high efficiency and at a reduced coding and data collection effort than the former operational-only version of FREEVAL. The FREEVAL-WZ tool and guidance for work zone analysis put forth in this report are expected to facilitate the analysis of significant freeway work zones in North Carolina. The deterministic tool can be readily used by staff within the NCDOT, and can be applied at much reduced cost and coding effort than a simulation-based analysis of work zone impacts for many scenarios. A simulation-based approach remains an important alternative analysis approach, especially for facilities with unusual geometry that does not fit within the deterministic framework of FREEVAL-WZ.

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1. INTRODUCTION

Background

A recent technical assistance report (1) completed by the Institute for Transportation Research and Education (ITRE) for the NCDOT Work Zone and Traffic Control Unit (WZTCU) identified several shortcomings in the way departmental analyses of work-zone impacts have been performed. WZTCU, which has since been re-organized to become the Work Zone Traffic Control Section within the NCDOT Traffic Management Unit (TMU), currently uses the MS-DOS based analysis tool QUEWZ (2), which has not been updated since 1998, is limited to the evaluation of basic freeway segments (no ramps, weaving segments or multi-lane highways) and is not calibrated for use in North Carolina. Additionally, WZTCU experience with the QUEWZ model has shown that it tends to over predict delay and queuing impacts from work zones, and that the tool cannot be customized by the user to reflect present-year user cost or local estimates of work-zone capacity.

The desire to improve work zone analysis is based on the NCDOT *Work Zone Safety and Mobility Policy*, which intends to "support the systematic consideration and management of work zone impacts related to safety, mobility, operations, and training" and emphasizes the importance of "minimizing the effects of work zones/activities on the surrounding transportation network" (3). The North Carolina policy is partially motivated by the *FHWA Rule on Work Zone Safety and Mobility* aiming to "better address the work zone issues of today and the future" (4).

The final report of the technical assistance project (1) identified the potential of one tool in particular that could balance NCDOT requirements for an ability to carry out in-house analyses, while not being overly burdensome in terms of inputs and interpretation as microsimulation models. The FREEVAL (**FRE**eway **EVAL**uation) tool was first developed at ITRE/NCSU as a computational engine for the Highway Capacity (HCM) freeway facilities methodology (5,6) The methodology has since gone through several iterations and is now executed on a Microsoft Excel and Visual Basic programming platform. Since it is designed for the analysis of freeway facilities, its scope is consistent with *significant* work zones as defined in (4). Further, the HCM-based outputs are in agreement with the needs of other units within TMU, including Congestion Management.

While FREEVAL performed well in a preliminary evaluation, it also became clear that in its present form, the model is not suitable for a planning-level application and further lacks calibration parameters for user cost and specific work-zone impacts. Through this research, the methodology and associated software implementation was customized and expanded into the new release FREEVAL-WZ, an assessment tool for work-zone impacts on freeways and multi-lane highways. The enhanced tool will enable the NCDOT Traffic Management Unit to evaluate traffic operational impacts of work zones at both the planning and operational levels.

Research Objectives

The goal of this research is to develop and validate an analysis methodology based on Highway Capacity Manual methodologies that is implementable in software and can be used to predict the traffic operational impacts and user costs of work-zones on freeways and multi-lane highways in North Carolina. This goal is achieved through four specific objectives:

1. Reviewing the literature on the current state of the practice of work zone analysis, including estimates of work zone capacity impacts.
2. Developing a customized software tool, FREEVAL-WZ, that is user-friendly, can be calibrated to reflect NC conditions, and that is applicable to both planning-level and operational analyses.
3. Validating the software tool FREEVAL-WZ using field-operational data from North Carolina work zone case studies and developing capacity estimates for typical NC work zone configurations to serve as model defaults.
4. Building in-house expertise at NCDOT on the use of the software.

Report Organization

This report is organized in nine main sections, with several appendices that provide additional analysis detail and background materials. This section presents background on this project and an overview of problem definition and project objectives.

Section 2 of this report presents a synthesis of the literature, including subsections on a review of work zone analysis software tools, work zone data collection practices, traffic stream models applicable for work zones, and work zone capacity estimation. Section 3 presents the proposed approach for operational analysis of work zones, including details on using roadside sensor stations and contractor diaries to estimate work zone speed-flow relationships.

Section 4 describes the software development of the FREEVAL-WZ analysis tool and how it can be used to evaluate work zone impacts on North Carolina freeway facilities both in a planning application and for more detailed operational analysis. Section 5 presents findings from empirical performance data of North Carolina freeway work zones collected by permanent roadside sensors and combined with detailed contractor diaries of work zone schedules.

Section 6 presents results from validation efforts where FREEVAL-WZ operational analysis results are compared to empirical data gathered from the roadside sensors. The validation results are used to develop guidance for applying the tool for work zone analysis in North Carolina.

Section 7 summarizes the results from this research and offers recommendations for future research. It is followed by Section 8, which presents an implementation and technology transfer plan for assuring that the results of this research find their way into the day-to-day practice at NCDOT. The report concludes with a list of cited references in section 9, and several detailed appendices in section 10.

2. SYNTHESIS OF LITERATURE

Review of Work Zone Analysis Practices

In 2008, NCDOT approved its *Work Zone Safety and Mobility Policy*, which intends to "support the systematic consideration and management of work zone impacts related to safety, mobility, operations, and training" and emphasizes the importance of "minimizing the effects of work zones/activities on the surrounding transportation network" (3). The policy outlines four work zone categories, for the purpose of planning and design. For this research, only the projects falling in the *significant* category (levels I and II) are considered. Level I and II work zones only an estimated 5 and 15% of all projects, respectively,but their expected impacts on day-to-day traffic operations are most severe. They therefore warrant more sophisticated analysis strategies for traffic impacts and construction staging. The criteria used for deciding whether a projects falls into these categories are AADT, truck traffic, anticipated additional travel times, anticipated adverse impacts to the transportation infrastructure, the duration of construction, and the user value and/or user cost of the project. For a full list of threshold values, please refer to the policy implementation guidelines (3).

The North Carolina policy is partially motivated by a requirement in the FHWA *Rule on Work Zone Safety and Mobility* (4) for state agencies (and others receiving federal funding) to develop their own policies consistent with federal guidelines and comply with the provisions set forth in the FHWA rule by October 12, 2007. The FHWA policy is intended to "better address the work zone issues of today and the future" and it "provides a decision-making framework that facilitates comprehensive consideration of the broader safety and mobility impacts of work zones across project development stages" (4). The classification of significant' work zone projects adopted by NCDOT is consistent with requirements put forth in the FHWA rule. These projects are expected to have a relatively high impact on the traveling public and warrant careful analysis of traffic operations during construction.

The FHWA rule emphasizes the importance of program-level and project-level performance assessment. The latter is directly focused on evaluating the actual field performance of work zones and identifying traffic management strategies during construction. The evaluation and prediction of field performance for level I and II work zones is a central component of the rule. The four key measures to assess work zone performance are identified as safety, mobility, construction efficiency and effectiveness, and public perception and satisfaction (4). Because these projects are complex and tend to be located on freeways or busy arterial streets, modern software tools may greatly facilitate their analysis.

FHWA Analysis Guidance

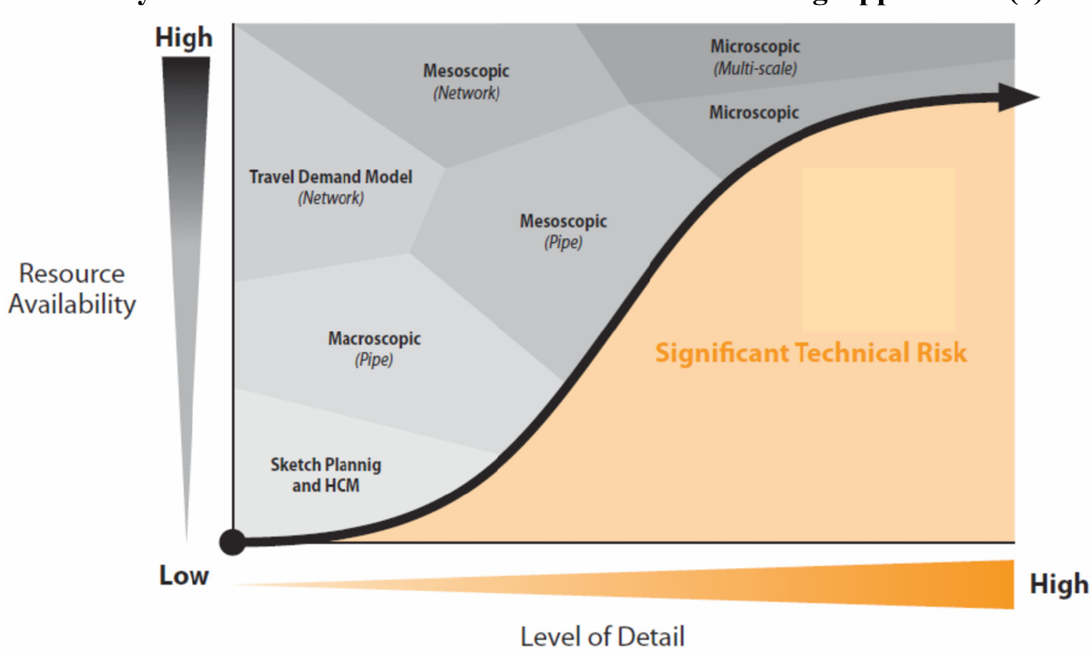
The FHWA *Traffic Analysis Toolbox* provides a national resource with guidance for the use of different traffic analysis tools. Volume II of the FHWA Toolbox (Decision Support Methodology for Selecting Traffic Analysis Tools, (7)) recognizes the increasing sophistication of traffic engineering operational analyses and the variety of analysis methodologies and software tools available today. The documents provide guidance of which category of tool to use for a particular application. In particular, the document distinguishes between seven analysis tool categories:

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

The decision support methodology is supplemented through a Microsoft Excel-based software tool available at http://ops.fhwa.dot.gov/trafficanalysistools/toolbox.htm. The decision support methodology includes a total of 104 performance criteria divided roughly into eight groups: analysis context, geographic scope, facility type, travel mode, management strategy, traveler response, performance measures, and tool/cost effectiveness. The different groups can further be weighted according to relevance to a particular project.

With respect to the analysis of work zones, the FHWA Toolbox has more recently added two volumes that specifically address the challenge of work zone modeling. As their titles suggest, volumes VIII and IX of the Toolbox provide guidance for "*Work Zone Modeling and Simulation*" for decision-makers and analysts (8, 9). The documents discuss analytical/deterministic tools and simulation tools as potential candidates, with some sketch planning tools having limited application for work zones. Travel demand models and traffic optimization tools generally are not applicable for work zone analysis. The document breaks the work zone analysis process into five categories, including work-zone characteristics, data, agency resources, performance measures, and transportation management plan strategies. It then presents a series of case studies that have utilized one or more analysis tool categories. A summary of the FHWA guidance is given in Exhibit 1, adopted from Volume IX of the Toolbox (9).

Exhibit 1: Analytical Work Zone Decision Framework - Modeling Approaches (9)



The exhibit highlights the fact that analysis tools vary along the dimensions of level of analysis detail, but with the trade-off of added resource needs. The HCM methods are on the low end of both dimensions, although the freeway facilities method (and FREEVAL) are more accurately categorized as a "Macroscopic (Pipe)" model. More sophisticated analysis tools include travel demand models and the various simulation models (mesoscopic and microscopic) are on the high end of the spectrum. The exhbit further emphasisze that "significant technical risk" exists as more sophisticated tools are used, including more room for data error, user error, or improper calibration of modeling algorithms.

In Volume 3 of the FHWA Toolbox (Guidelines for Applying Traffic Microsimulation Modeling Software, (10)) additional emphasis is given to the use of microscopic models, including a comparison of different commercially available software at the date of publication. It further includes valuable information about conducting a microsimulation study, model inputs and outputs, and statistical analysis considerations.

Overview of Work Zone Analysis Tools

While the FHWA Traffic Analysis Toolbox provides a useful reference for comparing the relevance of different analysis categories to a particular problem statement, the discussion lacks the necessary work-zone specific detail needed by NCDOT. Through the NCDOT policy specifications, the scope of this research effort is concentrated on *significant* work zones, which are expected to have a high impact on the traveling public and are oftentimes located on freeway facilities. As such, the FREEVAL tool is ideally suited for work zone analysis, since it is fundamentally based on the HCM2010 freeway facilities methodology (6). The tool has been effectively used in national level research to model the effects of recurring freeway bottlenecks (5) and was found to be significantly more efficient when compared to simulation-based analysis tools. FREEVAL has been updated to reflect methodological changes in the HCM2010 (6).

Other existing deterministic tools for work zone evaluation, include QUEWZ-98 (2), which is currently used by NCDOT. QUEWZ evaluates the performance of a freeway segment with and without a lane closure and provides estimates of queues and user cost from the work zone, based primarily on 1998 Texas data. Another spreadsheet-based tool, Quickzone (11), offers greater flexibility than QUEWZ by allowing a network-level analysis. However, it requires significant resources to set up the network, and lacks the operational detail of the effects of weaving segments and ramps. Both tools have been applied in research to model work zone impacts (12). The remaining analysis tools investigated in the technical assistance report (1) all require high levels of data input, user training and are expensive. Alternatively, simulation-based tools are available and include CORSIM, VISSIM, AIMSUN, PARAMICS, and DYNASMART-P.

Work-zone specific software tools are specifically intended for the analysis of work zone impacts. However, many analysis tools, including all simulation packages, are general-purpose traffic engineering tools that can be adopted to represent the effect of work zone. Rather than coding a work zone explicitly, the analyst codes its implicit effect on traffic operations by reducing the number of lanes or lowering the free-flow speed. The authors proposed to conceptually divide the most common work zone strategies into four groups (1):

- **High-Impact Scenarios**: These represent work zone scenarios with significant impacts on traffic operations including full facility closure, a crossover of traffic in the opposing lanes, and permanent and partial/temporary lane closures.

- **Minor Impact Strategies:** Work zones oftentimes feature less severe strategies with lower impacts on traffic operations. These include speed reductions (lower work zone speed limit), shoulder closures, the placement of barriers, narrow lanes, and metering signals.
- **Mitigation Strategies**: Work zones commonly incorporate some form of mitigation strategy by establishing alternate routes or by providing enhanced driver information through deployment of intelligent transportation system (ITS) technology. Through active work zone management, the prevailing traffic demands can be shifted spatially (to a parallel route) or temporally (to an earlier or later time). These effects will be referred to as *traffic diversion*, and *peak reduction*, respectively.
- **Other Effects**: Work zones cause other changes to the traffic operations that go beyond changes to the physical infrastructure or driver behavior. A common example is increased percentage of heavy vehicles due to construction traffic.

These different work zone strategies impact traffic operations by reducing capacity (represented through reduced lanes or a capacity adjustment factor), by causing lower operating speeds (even if not signed) and potentially through a reduction or shift in traffic demand on the facility. The work zone may cause new traffic patterns by re-routing traffic to alternate routes, encouraging people to re-time their trip (temporal diversion), and elevating demand on side streets and parallel routes. Exhibit 2 ties work zone strategies to their impact on traffic operations and traffic demand patterns. The work zone strategies shown were selected because they were believed to be the scenarios most commonly employed by NCDOT.

Exhibit 2: Work Zone Strategies and Operational Impacts (1)

	Traffic Operations Impacts						
Workzone Strategies	Capacity Reduction: # of Lanes	Capacity Reduction: Factor	Speed Reduction	Demand Reduction	Re-Routing	Trip Retiming	Side-St. Demand Increase
High-Impact Strategies							
Full Facility Closure	✓	-	-	✓	✓	-	✓
Crossover	✓	-	✓	✓	✓	-	✓
Permanent Lane Closure	✓	-	✓	✓	✓	-	✓
Partial/Temporary Lane Closure	✓	-	✓	#	#	✓	-
Minor Impact Strategies							
Speed Reductions (Signed)	-	✓	✓	-	-	-	-
Shoulder Closure	-	✓	✓	-	-	-	-
Barrier Placement	-	✓	✓	-	-	-	-
Narrow Lanes	-	✓	✓	-	-	-	-
Metering Signals	-	-	-	✓	-	-	-
Mitigation Strategies							
Alternate Routes	-	-	-	✓	✓	-	✓
Enhanced Driver Information	-	-	-	✓	✓	✓	✓
Other Strategies							
Workzone Traffic (% HV)	-	✓	✓	-	-	-	-
	✓	Yes					
	-	No					
	#	Yes, Under certain circumstances					

While many analysis tools do not explicitly model work zone strategies, their effect on traffic operations can oftentimes be modeled through these implicit impacts. The different rows in Exhibit 2 correspond to work zone strategies that an agency would plan to implement in the field. The different columns represent the impacts of those strategies as they would be entered into an analysis tool.

Exhibit 3 relates the work zone impacts in Exhibit 2 to the ability of various analysis tools to model the impacts. The exhibit includes the deterministic models FREEVAL (6), QUEWZ (2), and QUICKZONE (11) and simulation models CORSIM (13), VISSIM (14), AIMSUN (15), PARAMICS (16), and DYNASMART-P (17). The exhibit further presents facility performance measures that can be obtained from the various tools.

Exhibit 3: Work Zone Impacts and Analysis Tools (1)

Workzone Analysis Inputs	Deterministic			Simulation				
	FREEVAL	QUEWZ-98	QUICKZONE	CORSIM	VISSIM	AIMSUN	PARAMICS	DYNASMART
Freeway Segment Type								
Basic	✓	✓	✓	✓ 1	✓ 1	✓ 1	✓ 1	✓ 1
Ramps and Weaving	✓	-	-	✓ 1	✓ 1	✓ 1	✓ 1	✓ 1
Analysis Details								
Max. Analysis Period	3-Hour	24-Hour	10 years	~52-Hour	~24-Hour	1000 H.	~24-Hour	24-Hour
Analysis Time Units	15 Min.	1 Hour	1 Hour	Flex.	Flex.	Flex.	Flex.	Flex.
Traffic Operations Impacts								
Capacity Reduction - # Lanes	✓	✓	✓	✓	✓	✓	✓	✓
Capacity Reduction - Factor	✓	✓	✓	- 2	- 2	- 2	- 2	✓
Speed Reduction	✓	-	-	✓	✓	✓	✓	✓
Demand Reduction	✓	✓	✓	✓	✓	✓	✓	✓
Re-Routing	✓ 3	✓ 3	✓	✓	✓	✓	✓	✓
Trip Retiming	✓ 3	✓ 3	✓	✓	✓	✓	✓	✓
Side-Street Demand Increase	-	-	✓	✓	✓	✓	✓	✓
Other Factors Impacting WZ Analysis								
High Truck Percentage	✓	✓ 3	-	✓	✓	✓	✓	✓
Off-Ramp Congestion	-	-	-	✓	✓	✓	✓	✓
Commuter vs. Tourist Traffic	-	-	-	-	✓ 4	✓ 4	✓ 4	✓ 4
Auxiliary Lanes (C/D Roads)	-	-	-	✓	✓	✓	✓	✓
Incidents	✓5	-	-	✓	✓	✓	✓	✓
Special Priorities (HOV, BRT)	-	-	-	✓	✓	✓	✓	✓
Facility Performance Measures								
Segment LOS	✓	-	-	PP	PP	PP	PP	PP
Vehicle Delay	✓	-	✓	✓	✓	✓	✓	- 6
Travel Time	✓	-	-	✓	✓	✓	✓	✓
Speeds	✓	✓	-	✓	✓	✓	✓	✓
Average Queue Length	-	-	-	- 7	✓	✓	✓	✓
Longest Queue Length	✓	✓	-	- 7	✓	✓	✓	✓
Queue Duration	✓	-	-	- 7	PP	PP	✓8	✓
User Cost	- 4	✓	✓	- 9	- 9	- 9	- 9	- 9
Emissions	-	✓	-	✓	✓	✓	✓	-
Network Performance Impacts								
Minor Street Queue Spillback	-	✓	✓	✓	✓	✓	✓	✓
Traffic Diversion	-	10		-	✓	✓	✓	✓
Visual Performance Output								
Bird's Eye View Animation	-	-	-	✓	✓	✓	✓	✓
4D Animation	-	-	-	-	✓	✓	✓	-
Network plots	-	-	-	PP	PP	PP	✓	PP
Data Plots by Time	✓	PP	✓	PP	PP	PP	✓	✓
Data Plot by Segment	✓	-	-	PP	PP	PP	✓	✓

LEGEND	
✓	YES
-	NO
PP	Post-Processing necessary

1 Segment types modeled implictly in simulation
2 Micro-Simulation arrives at capacity estimates implicitly through model agorithm (car-following, lane-changing …)
3 Re-Routing and Trip Retiming modeled as modified demand flows
3 Truck Percentage specified for entire facility
4 Modeled implicity through different behavioral parameters by vehicle type
5 FREEVAL can model 15-minute incidents through lane closures or capacity reduction factors
6 DYNAMSART-P doesn't explicitly report delay, but does report travel time and average stopped time
7 CORSIM can only report queue length for arterial streets, not freeways
8 Performance Measure is % Time Queued
9 User cost can be easily obtained by mutliplying simulation total delay output and mutliplying by cost figure
10 Traffic Divesion based on maximum queue or delay assumption - not routing algorithm

The HCM method and associated FREEVAL software implementation are different from other deterministic tools used for work zone analysis, including QUEWZ (2) and QUICKZONE (11). The latter two are limited to the evaluation of basic freeway segments and cannot capture the effects of demand changes at ramps or weaving segments as predicted in the respective HCM chapters. Therefore, while these tools can model a freeway lane drop (for example a four-lane basic segment followed by a three-lane segment), they cannot capture the result of ramp and weaving friction on the operations of the facility. These segment types have lower capacities than a basic segment and further change the demand profiles on the facility. As a result, the location and intensity of queues are expected to change when these segments are considered. They further lack some of the work-zone specific adjustments that can be readily-implemented in FREEVAL. The comparison of maximum analysis periods further shows that FREEVAL is intended as a peak-hour analysis tool, whereas the two others are broad-level work zone analysis tools that model extended time periods. Also FREEVAL also offers more detailed output than the other deterministic tools. It features comprehensive tables of performance measures for each time period, as well as for the aggregated analysis period. Automatically generated contour plots of speed, density, demand-to-capacity ratio, and LOS over the entire analysis domain (all segments and all time periods). This gives the analyst a powerful visual of facility performance.

Simulation tools rely on driver behavioral algorithms to characterize the impacts of congestion. The capacity of different geometric configurations, including freeway ramps, as well as work zone impacts, becomes a function of these algorithms. Ultimately, these algorithms rely on user input. While the models can represent the effect of capacity reduction on overall network delay, it remains up to the analyst to assure that the modeled effects are realistic. Consequently, simulation tools are more challenging to calibrate from field data, since any field measured capacity estimates cannot be input directly into the model, as is the case for a macroscopic tool.

It is recognized in FHWA guidance for users of traffic analysis tools (10) that simulation-based tools are generally more expensive and coding intensive. They have the advantage of coding flexibility, but flexibility brings uncertainty, the need for calibration, and potential error (also see Exhibit 1). For work-zone applications, FHWA (8, 9) generally advises for the use of simpler and less data-intensive approaches if the project scope allows it and acknowledges an increasing level of technical risk with increasing level of detail.

Given the trade-off between simulation detail, coding effort, resource needs, and the degree of coding error risk, deterministic approaches can be favorable for work zone applications. For many public agencies, it is desirable to perform certain types of analysis in-house within a reasonable turnaround time, rather than outsourcing the analysis. Further, it is preferred that the selected analysis tool be user friendly without a steep learning curve that may limit the number of software users within NCDOT. The preferred tool would be one that analysts can become familiar with relatively quickly, one that accurately represents the effect of work zones, one that can be easily calibrated to local conditions, and one that would still allow quick turnaround for in-house analysis. For all these reasons, a deterministic approach can be preferable to a more involved, simulation-based analysis.

The HCM freeway facilities methodology, implemented in the FREEVAL software engine was judged to be a promising candidate in previous work for NCDOT (1). The model allows the analysis of different segment types over multiple time periods and offers quick numerical and graphical results based on nationally calibrated and widely accepted HCM methodologies. The model runs on a Microsoft Excel platform that most analysts are familiar with, thus minimizing the user learning curve. Being a deterministic model, FREEVAL further gives consistent output for a given set of input data and does not require multiple runs as a stochastic simulation tool would. The analyst thus can quickly compare different work zone scenarios and assess their impact on traffic operations.

In summary, the HCM freeway facilities methodology represents an attractive option for work zone analysis, as it can accurately represent most of the traffic operational impacts, while minimizing the cost associated with program acquisition, software training, and coding and analysis resources.

Approaches for Work Zone Data Collection

Dixon, Hummer, and Lorscheider (18) conducted a capacity analysis study for North Carolina freeway work zones. They looked at four closure scenarios on North Carolina freeways. These included the following road types and closure strategies:

- A unidirectional two-lane configuration reduced to a single lane (2-to-1),
- A unidirectional three-lane configuration reduced to a single (3-to-1),
- A unidirectional three-lane configuration reduced to two lane (3-to-2), and
- A divided freeway with two lanes in each direction reduced to a two way, two-lane operation (TWTLO) by use of crossovers.

Additional variables studied in this project were night versus day construction, intensity of work activity (heavy, moderate, or light), proximity of work to active lanes, and proximity of interchanges to the work zone. The data collection team monitored construction sites from summer 1994 through spring 1995 for freeway work zone sites with lane closures. The analysts identified 24 short-term lane closures in freeway work zones and collected data for determining work zone capacity for all sites.

Each of the 24 data collection sites possessed unique features difficult to fully capture with a written description. As a result the team used two methods of data collection for physical conditions. First, a site description checklist was completed for each site. Second, concurrent with data collection, two team members drove through the work zone in a car equipped with a video camera and filmed the conditions. The video camera record included road conditions and odometer readings at critical locations, including sign placement, transition location, and active work location

The project team elected to use Vehicle Magnetic Imaging traffic counters and classifiers developed by Nu-Metrics. The team primarily collected data in 5-min time bins and analyzed space-mean-speeds within these bins in a manner consistent with previous freeway research. Exhibit 4 shows typical placement of data collection devices for a standard 2-to-1 lane closure.

Exhibit 4: Device Configuration for Capacity Analysis (18)

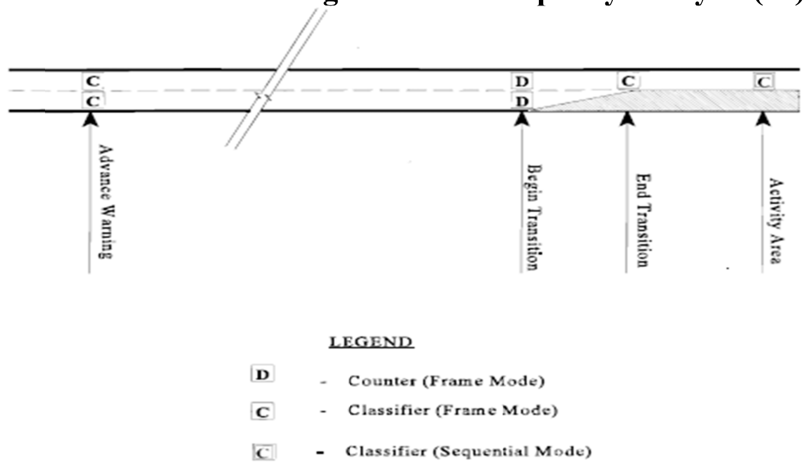


Exhibit 4 illustrates a typical layout of traffic counters at a work zone. The recorded traffic data included free flow traffic (uninterrupted by work zone), merging traffic, and work zone traffic. Eight work zones on interstate highways were randomly selected for traffic data collection. At each of the work zones, traffic data was recorded for two to four days. The available construction sites produced data for seventeen 2-to-1 closures, three 3-to-1 closures, two 3-to-2 closures, and one TWTLO crossover. The traffic data showed that four of the eight work zones experienced traffic congestion during data collection. Queue was observed at 10 sites.

In a comparable research effort in Indiana, Jiang (19) attempted to estimate speed and queue-discharge rate on four-lane freeway work zones. The authors studied two types of work zones:

- Partial Closure (or single lane closure) – when one lane in one direction is closed, resulting in little or disruption to traffic in the opposite direction.
- Crossover (or two-lane two-way traffic operations) – when one roadway is closed and the traffic which normally uses that roadway is crossed over the median, and two-way traffic is maintained on the other roadway.

Traffic data at select work zones on interstate highway sections were collected between October 1995 and April 1997. Traffic counters with road tubes were used for data collection. Traffic volume, vehicle speed and classification were recorded at 5- minute intervals during high traffic volume hours and at 1-hour intervals during low traffic volume hours. The vehicle counters were set up to classify the detected vehicles into three groups: 1). passenger cars, 2) heavy trucks and 3) buses. At each work zone, traffic counters were placed before the work zone transition area, within the transition area, and within the activity area.

Rouphail and Tiwari (20) conducted uncontrolled field studies in an attempt to generate a data base for developing speed-flow models at work zones. Another objective of the research was to estimate the magnitude and direction of work activity impact on observed traffic speed segregated by flow rate, truck occurrences, and work activity levels to study the impact of each parameter on work zone capacity.

Four sites were used for this study located in the Chicago area. Three data elements were collected at each site:

1. Traffic speed and composition upstream of the work zone;
2. Simultaneous 5-min counts of speeds and flow rates at the beginning and end of the lane closure section;
3. Work area activity descriptors for the intervals."

A summary of the site characteristics is provided in Exhibit 5.

Exhibit 5: Summary of Site Characteristics (20)

Site	Lane Closed	Length of Closure (ft.)	Channelizing Device	Average Hourly Volume
I-57	Left	3,000	18-in. Cones	535
I-80	Left	1,035	Type I barricade	1,193
I-290	Right	530	Tubular posts	435[a]
I-55	Left	435	Portable concrete barrier	760

a) Measured in queuing conditions; does not reflect demand.

Traffic speed upstream of the work zone was collected on a random sample of approaching vehicles using a radar gun. Vehicle types were recorded by a time-lapse camera located at a vantage point at each site. The recording interval varied from 1 to 3 sec, depending on the approach speed prevalent at the site. Speed and flow rate counts were collected for a period of approximately 4 hours per site, except for one of the sites where equipment problems limited data collection to 1 hour. Also, an ordinal-level scale to quantify the intensity (in terms of its vehicular impact) of the work activity was presented in this study. The work activity data were collected manually in 5-minute intervals that corresponded to the speed-flow observations obtained by the traffic classifiers.

Benekohal et al. (21) tried to present a new methodology for estimation of operating speed and capacity in work zones. The study was based on extensive data collected in eleven work zones in Illinois. All the data collection sites were located on interstate highways with two lanes per direction. In all sites, one of the lanes was closed due to construction and other lane was open. Three of the data sites were short-term work zone sites and the remaining were long-term work zone sites. Three sites had queues observed at some point during the study. The data collected for this project can be classified into four categories:

- **General Data:** location of the work zone, weather condition, police presence, and flagger presence.
- **Geometric Data:** lane width, total number of lanes in each direction, number of open lanes, presence of ramps, length of the lane closure, position of closed lanes, and length of work activity.

- **Data for Work Activity:** type of work activity, number of workers present, number and size of construction equipment, proximity of work activity to the travel lanes in use, and traffic control devices used.
- **Traffic Data:** headways, speed of the vehicle in work zone, volume of traffic, and queue length.

Data regarding the general conditions, geometry and work activity was recorded on paper by an observer. A video camera was used to capture the time at which every vehicle passed specific markers placed at a fixed distance. The distance between the markers was around 250 feet but varied for different sites. An observer noted the presence of any queue and the length of the queue at one minute intervals. Data was collected from 2 hours to 4 hours depending on traffic conditions.

The authors defined "service capacity" as the capacity at which the work zone was operating for the given geometry, work zone and traffic conditions. The number of departures during every minute of the data collection period was computed from the field data. The top one-minute time intervals that had the highest departure volumes were identified. Even under moderate and heavy traffic conditions, the field data showed that there were large headways (greater than 4 seconds) among the platooning vehicles. The reason for this was that a vehicle with a large headway had a spacing less than or equal to 250 feet. These large headways significantly affected the capacity calculation when they were not eliminated. These large headways were removed. For sites without queuing, the top five minutes were used to compute average headway. This was done to ensure that there was continuous demand during those 5 minutes. For sites with queuing, the top fifteen minutes were used to compute average headway. This capacity value is referred as service capacity. The average speed of all vehicles is referred to as the speed corresponding to service capacity for that site.

Sarasua et al. (22) developed a model using data collected from 23 work zone sites in South Carolina. They used video surveillance to collect vehicle count and classification data. Queue length and speed were measured manually in the field, using a system of visible markers placed along the highway shoulders. Speed was measured using a radar gun. Queue length was measured manually from the beginning of taper via visible markers that were placed using a measuring wheel. Video recordings were viewed and tabulated via manual means.

Traffic flow data was collected using video cameras mounted on portable tripods extendable to a height of approximately 30 feet. Two cameras were used and configured to cover taper and lane closure transition immediately upstream of the work zone area. The average speed of the traffic stream was measured using a radar gun. Speed was measured in two different increments. It was recorded in 5-minute interval, unless the speed dropped below 35 miles per hour, at which time speed was then recorded in 1-minute intervals. Vehicle queue length was recorded concurrent with the recording intervals used for speed measurements. Queue length was measured in feet from the beginning of the taper using a marking system established with traffic cones during daytime hours and with internally illuminated markers at night. Markers were placed at varying intervals corresponding with site geometric conditions and camera visibility angles.

Data for this research project was collected at 22 work zone sites extending over an approximate one-year time period. Data collection sites included a variety of short-term lane closure conditions located along four of the six major interstate routes in South Carolina. Truck percentages for work zone locations included in the study ranged from a high of 34 percent to a low of 3 percent, with an average for all sites of approximately 21 percent. Four of the sites experienced vehicle queues extending beyond one mile in length, while ten of the sites did not experience a measurable vehicle queue length.

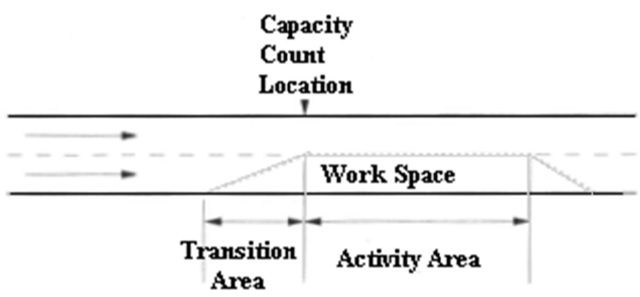
Another work zone capacity analysis research project was completed by Kim, Lovell and Paracha (23) Data was collected at 12 work zone sites with lane closures on four lanes in one direction. Traffic data were collected after the peak hour because the Maryland State Highway Administration (SHA) has a policy against peak hour lane closures to avoid excessive traffic delays, congestion, and motorist aggravation. Traffic volumes were recorded with a video camera at the ends of transition areas when the work zone became a bottleneck, resulting in queue and delays upstream of the work zone. Care was taken to ensure that no queues existed downstream. Speed data were collected at 1-min intervals using a laser speed gun. Additional data such as work zone configuration, geometry, intensity and type of work activity, work duration, weather condition, and work time were also recorded.

At each site, traffic volume was divided into two classes: (a) passenger cars and (b) heavy trucks, and work time also was divided into two types, i.e., day and night. The intensity of work activity was classified into three levels such as low, medium, and heavy based on the types of work activities, the number of workers and the size of the equipment.

A study by Krammas and Lopez (24) on short-term freeway maintenance sites investigated capacity at different lane closure configurations which served as the basis for HCM short-term work zone analysis guidance (6). The data in this project represented more than 45 hour of capacity counts at 33 different freeway work zones with short-term lane closures. Data were collected for four different lane closure configurations: [3,1], [2,1], [4,2], and [4,3].

All sites at which data were collected were short-term lane closures. Most were maintenance work zones, although several were short-term, off-peak lane closures at long-term reconstruction projects. All capacity counts were taken as the vehicle entered the activity area through the transition area of the work zone by using the standard terminology recommended by Lewis (25). The count location is illustrated in Exhibit 6.

Exhibit 6: Work Zone Capacity Count Location (25).



The analysis considered only time periods during which traffic was queued in all lanes upstream of the activity area. Therefore the capacity counts represent the rate at which vehicles discharge from the upstream queue, merge into the reduced number of lanes through the transition area, and enter the activity area. Sites at which ramps were located within the transition area or the upstream end of the activity area were not analyzed.

In previous work zone capacity studies (e.g. 18), some capacity data were collected at points within the activity area (i.e., other than at the downstream end of the transition area and the upstream end of the activity area) where the traffic flow appeared to be the most constrained. At some such sites there were intervening ramps between the upstream end of the activity area and the capacity count location. In these cases, the counts within the work zone would differ from the queue discharge rate entering the activity area by the volume of traffic entering or exiting at the intervening ramps. In the study by Krammes and Lopez (24), it was determined that capacity counts should be taken only at the upstream end of the activity area for the following reasons:

1. To achieve consistency in measurement among work zones,
2. To be consistent with the current general consensus on the definition and measurement of freeway capacity, and
3. To be consistent with the analysis assumptions of demand capacity analysis.

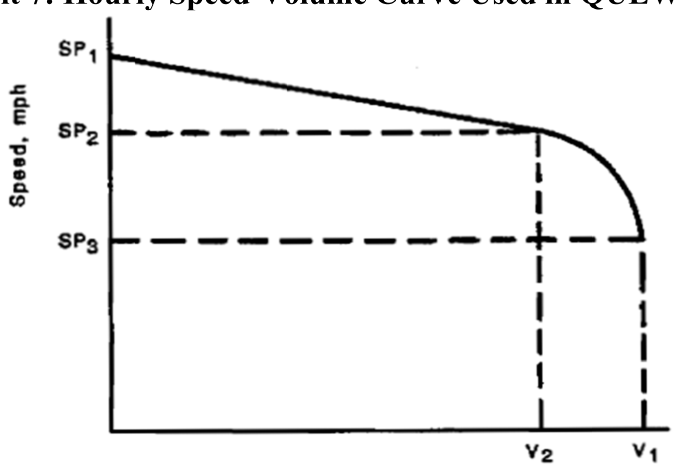
Estimating capacity only at the upstream end of activity area eliminates the variability among sites, because of the effects of ramps on changing demand patterns within the work zone are reduced.

Traffic Stream Models for Work Zones

This section of literature review focuses on the key literature focused on developing and/or analyzing traffic stream models in work zones.

Memmott and Dudek (26) described an early model to estimate capacity and average speed on work zones, which is used in Queue and User Cost Evaluation of Work Zones (QUEWZ) software program. QUEWZ calculates the average speed in a work zone based on the speed-flow curve shown in Exhibit 7.

Exhibit 7: Hourly Speed-Volume Curve Used in QUEWZ (26)



In QUEWZ, Truck speeds are assumed to be 90 percent of car speeds. The three speed parameters (SP_1, SP_2, and SP_3), along with the volume parameters (V_1 and V_2) have preset constant values or default values if the user does not define them. The default values are as follows: SP_1, 60 mph; SP_2, 40 mph, SP_3, 30 mph; V_1, 2,000 vphpl; and V_2, 1,600 vphpl.

The hourly traffic volume specified by the user is converted into a volume-capacity (V/C) ratio, and the approach speed (SP) is calculated using following equations:

If $V_2/V_1 \geq$ V/C,
$SP = SP_1 + [\, V_1(SP_2 - SP_1) / V_2] \,.\, (V/C)$

If $V_2/V_1 <$ V/C $\ll 1$,
$SP = SP_2 + (SP_2 - SP_3)\,(\,1 - \{\,[\,(V/C) - (V_2\,/\,V_1)] \,\div\, [1 - (V_2/V_1)]\}^2)^{1/2}]\,\}$

If $V/C > 1$ or a queue is present,
$SP = SP_3\,[2- (V/C)]$ with the speed constrained to the following range $20 \leq SP \leq SP_3$.

The average speed through the work zone (SP_{wz}) is calculated from the same speed equations given previously using the *V/C* ratio of the work zone area. The same study shows that the minimum speed (SP_{mn}) of vehicles is somewhat lower than the average speed through the work zone and it can be estimated using the *V/C* ratio of the work zone:

$$SP_{mn} = SP_{wz} - 2.3 - 25.7(V/C_{wz})^2 \qquad (1)$$

If there is a queue, $SP_{mn} = 0$.

The result of Rouphail and Tiwari study (20) is presented in three parts: 1-Speed distribution upstream of and at the lane closure area. 2- Speed-flow relationships at each data collection site and comparison with HCM, and 3- Impact of work zone activity on traffic flow parameters.

Speed distributions observed upstream of the work zone were tested for normality. Except for one site which work zone operating was in stop-and-go conditions, speeds followed a normal distribution. However, speeds observed at each end of the lane closures did not follow a normal distribution, except of one site.

Speed-flow patterns were analyzed at each site by aggregating the speed observations in each 5-min interval into a space-mean speed and corresponding mean flow rate. The time interval was selected such that traffic fluctuations associated with short counting intervals were avoided. The general shape formed by the data was similar to the typical HCM speed-flow curve in HCM; that is, nonlinear in the high service volume regime and flow independent speed values at the lower end of service volume.

At first, a second degree polynomial fitted to the data:

$$V = -13.2 + 4.571\,S - 0.055\,S^2 \qquad (2)$$

Where V and S refer to the observed flow rates and corresponding space-mean speed, respectively.

Capacity estimate can be derived from Equation (2) by setting the conditions:

$$\frac{dV}{dS} = 0, \frac{d^2V}{d^2S} < 0 \ at \ V = V_{max} \qquad (3)$$

From Equations (2) and (3) it can be concluded that V_{max} = 975 vph and S_{opt} =41.3 mp. Thus, the regression model in Equation (2) gave unrealistic estimates of optimum speed and capacity, a very poor fit to the observed data (R^2=0.068) and, therefore, would have limited value for capacity estimation purposes. To eliminate inter site variations, individual site models were generated using the linear form:

$$S = a + b\,V \qquad (4)$$

Where a and b are regression coefficients. A total of 146 sample points were included in the analysis.

The models are shown in Exhibit 8.

Exhibit 8: Observed Speed Distribution Upstream of Lane Closure (20)

Site	Range of 5-Minute Flow Rates Observed	Intercept	Slope	Correlation Coefficient Level of Significance
I-57	34-58	49.04	-0.018	0.85
I-80	88-122	72.50	-0.24	<0.01*
I-290	109-147	25.90	+0.04	0.23
I-290 **	26-49	23.16	+0.08	0.11***
I-55	39-88	56.72	-0.087	0.01*

*Significant at the 1 percent level.
** Observations at start of closure under forced-flow conditions.
*** Marginally significant at the 10 percent level.

A statistical test was performed to verify whether drivers in free- and congested-flow conditions react equally to the presence of construction. The original data set was bisected into two groups as low flow rate (less that 100 vph) and high flow rate (remaining records). The sensitivity of traffic speed to work zone activity increase as traffic or truck volumes, or both, increase. It was found that 52 percent of the variation in speed differences is attributed to flow rates and proximity of work to travel lane. A model was formulated as follow:

$$S_t = -14.17 + 2.07\,PL_t + 0.14\,V_t \qquad (5)$$

In equation (5), PL_t is the distance of the work activity to the edge of lane in feet and V_t is the flow rate in vehicle per hour. Equation (5) shows that the impact of flow rates on speed differences is greater when the work activity is within 6 feet of the edge of the lane (PL>2) at approximately 1,000 vph flow rate (V_t).

This study concluded that traffic speed upstream of the work zone follows a normal distribution when no queuing conditions exist. In the closure area, however, the speed distribution shows significant skewness regardless of the quality of flow upstream of the closure. Also, speed-flow models at the observed lane closures are considerably different from HCM curves under similar volumes, truck levels, lane width, and lateral clearance restriction.

In an Illinois study (27), the speed and flow in work zones under continuous discharge flow conditions (considering only platooning vehicles) were computed. The reason to select only platooning vehicles was to focus on the representation of congested traffic conditions.

Different models were tested to express the relationship between speed and flow. A relationship in the form of a power function was found to give a very good representation of these data points. The equation obtained is given as:

$$q = 145.68\, U^{0.6875} \qquad (6)$$

Where,
q = flow in passenger cars per hour per lane (pcphpl)
U = speed in mph (the speed used in equation must be lower than the speed at capacity)

The R^2 for this relation was 0.6891. This indicates that the relationship is strong and the variability of speed and flow is captured by this relationship. It should be noted that this relationship is only for the congested part of the speed-flow curve, and it has to be bound by the upper and lower limit. The upper bound on the flow is the capacity at the corresponding free flow speed. The lower bound is zero.

Equation (6) was used to establish the lower part (congested part) of the speed-flow curve. Thus, it is used in determining capacity values and flow rates when speed is below the optimal speed (speed at maximum flow). The free flow part of the curve is based on information from HCM2000, field data collected in work zones, and the authors' professional experience. A speed range of 65 mph to 40 mph was used to establish the speed-flow curves. The capacity for each speed level was established considering all of the above-mentioned factors. It was also decided that the flow at which the free flow speed begins to drop is 1300 pcphpl. (passenger cars per hour per lane) This value is based on the information in HCM2000 and professional judgment of the authors. The speed drop between 1300 pcphpl and the capacity value is based on the following equation:

$$Speed = FFS - (FFS - U_c)*[\frac{flow-1300}{capacity-1300}]^{2.6} \qquad (7)$$

Where,
FFS = free flow speed (mph)
U_C= Speed at maximum flow (optimal speed) in mph

It should be added that the exponent of 2.6 used in Equation 7 is used in HCM 2000 for comparable equations. Putting the upper and lower parts of the speed-flow curves resulted in a series of speed flow curves as shown in Exhibit 9.

Exhibit 9: Speed-flow curves for work zones (27).

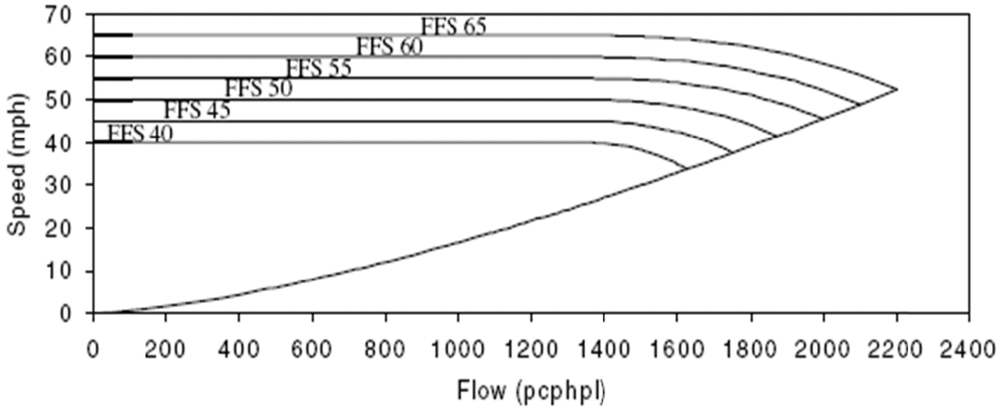
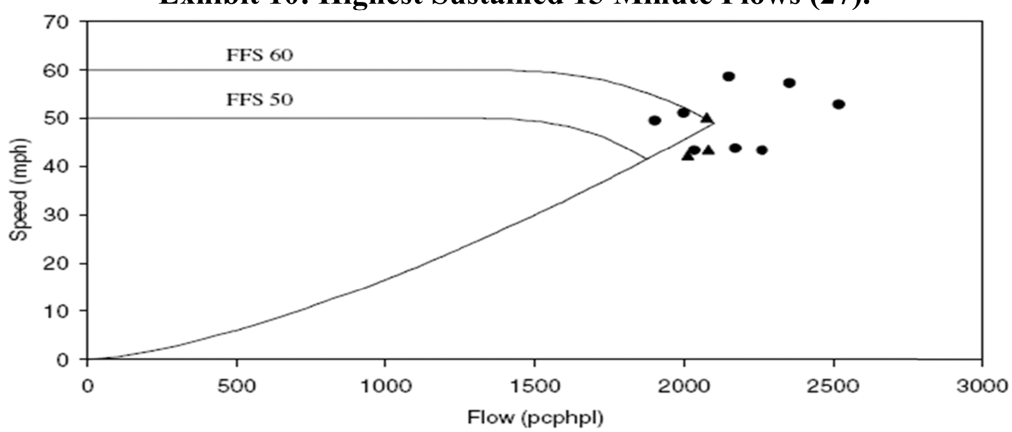


Exhibit 10: Highest Sustained 15 Minute Flows (27).



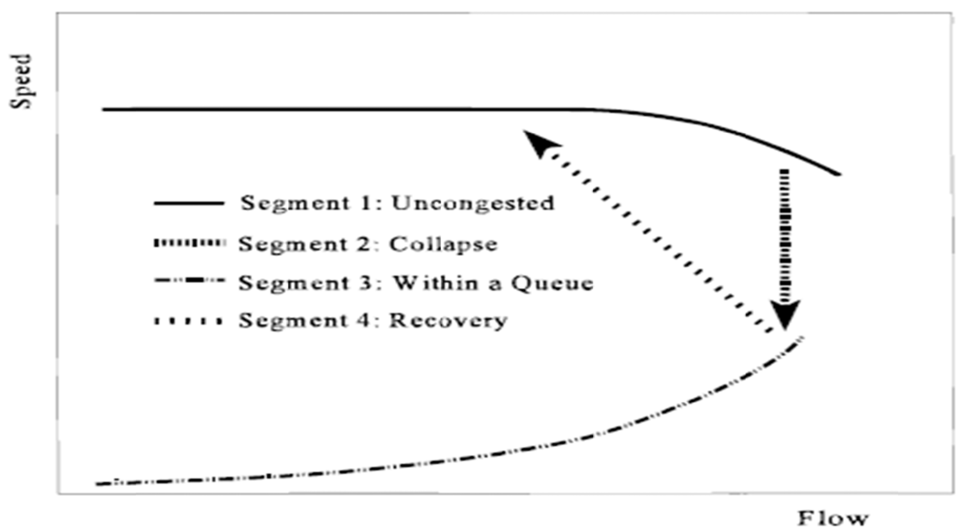
"From the field data the highest sustained 15-minute flows and corresponding speeds were obtained and are shown in Exhibit 10. Out of eleven sites, 8 sites had posted speed limit of 55 mph while the rest had 45 mph. Exhibit 10 also shows the speed flow curves corresponding to FFS of 50 and 60 mph and the field data corresponding to those FFS. From Exhibit 10 it can be seen that the proposed speed-flow curves are conservative because the highest speed-flow values suggested by the curves are mostly lower than the values observed in the field." (27)

Work Zone Capacity Estimation

The North Carolina study by Hummer et al. (18) defined capacity as "the flow rate at which traffic behavior quickly changes from uncongested condition to queued condition". The researchers selected the 95th percentile value of all 5-minute queue observations as end of transition capacity. Duration, closure configuration type (for example, 3-1 lane closure), construction operation, on-ramp and off-ramp proximity, lane narrowing and physical barriers (i.e., barrels, jersey barriers, etc.) are examples of physical site conditions that affect the behavior of the traffic stream in the work zone. They concluded that day versus night capacity difference is not significant while rural/urban sites show significant difference in capacity. The team averaged the capacity counts for each site in particular category and represented that as capacity.

Capacity was presented in a generalized speed-flow curve that suggested a different definition of capacity in congested freeway conditions. Segments 1, 2, and 3 in Exhibit 11 depict a hypothetical configuration of speed versus flow for uncongested conditions, queue discharge (collapse), and queued behavior. The three-segment model described provides two possible capacity values for the freeway. One capacity value occurs during the uncongested condition (located at the high-flow end of the uncongested curve). This value occurs during high volume, steady-state traffic conditions. The second value appears as a vertical line in Exhibit 11 and represents collapse to queued conditions. The collapse flow value is less than the free-flowing capacity and is consistent with behavior generally observed in a work zone. The collapse will typically occur within a range of flow values (not a static flow) and generally conforms to the high-flow volume of the queued condition (Segment 3). Segment 2 in Exhibit 11 represents the flow value at which a queue develops. This value is not necessarily the volume measured at the bottleneck during the presence of a queue. The physical freeway location where critical capacity occurs varies with different construction operations or site characteristics. If a construction activity generates a queue within the activity area, the end of transition may be located in the middle of the queue, and the vehicle count at the end of the transition area could be located anywhere along Segment 3. Measurement of volumes at the end-of-transition location would not provide a consistent value and would be unlikely to represent queue discharge. A given point in the work zone may not exhibit sustained capacity for a measurable duration. The space-mean-speed versus flow relationship should therefore be evaluated to determine work zone capacity (when queue development begins). Capacity can be observed by studying a time sequence of the speed-flow observations to determine when and at what flow rate the shift from the uncongested curve to the curve indicating the presence of a queue occurred. Queue discharge will provide the sustained flow rate after queue development has begun.

Exhibit 11: Hypothesized Relationship of Freeway Speed Flow Relationship (18).



The end of the transition area is identified in much of the literature as the critical location where capacity is observable within a work zone; however several previous research studies also indicated that the actual work zone activity area, and the type of work activity, also restrict freeway work zone capacity. A greater variability in capacity observations occurred adjacent to active work than at the end of transition, likely due to the effects of the dynamic work activity.

Observations t in sites with heavy work activity indicated that the specific location of the activity area is the determining point for work zone capacity. While the transition area functions as an initial bottleneck, the activity area produces the most constrained bottleneck. The presence of two queues (one at the transition and one within the work zone) is likely during the early stages of congestion, whereas later during the construction activity, the work area queue may grow backwards to magnify transition area. Table 3 summarizes general work zone capacities observed on North Carolina freeways. The North Carolina values are compared with Texas values. The Texas volumes appear to conform to values observed in North Carolina moderate construction activity areas. The North Carolina end-of-transition observations exhibited, on average, a volume 10 percent greater than the Texas end-of-transition values.

Exhibit 12: Observations of North Carolina and Texas Work Zone Capacities (18)

Number of Lanes			North Carolina				Texas
Normal	Open	Rural or Urban	End of Transition Capacity [vphpl]	Activity Area Capacity [vphpl]	Intensity of Work Activity	Comparison of Activity Area to End of Transition Capacity [Percent]	End of Transition Queue Discharge [vphpl]
2	1	Rural	1300	1210	Heavy	93	Unknown
2	1	Urban	1690	1560	Moderate	93	1575
				1490	Heavy	88	
3	1	Urban	1640	1440	Moderate	88	1460

Urban and rural sites showed significant differences in capacity. The difference appears to be primarily due to driver type and familiarity. The night versus day observations, though few, indicated that queued vehicles behave similarly during day and night, whereas vehicles in uncongested conditions drive differently at night in work zones.

In the Krammas and G.O. Lopez study (24), freeway capacity was defined and measured as the mean queue discharge rate entering a freeway bottleneck. A work zone lane closure was modeled as a simple bottleneck, with all traffic entering at the upstream end and exiting at the downstream end. The demand would be the traffic flow rates approaching the bottleneck from upstream end of the bottleneck. Therefore, the capacity calculated in the analysis should be the rate at which vehicles can enter the upstream end of the activity area. The capacity data for short-term freeway work zone lane closures are presented in Exhibit 13.

Exhibit 13: Data on Short-Term Freeway Work Zone Lane Closure Capacity (24)

Lane Closure Configuration [Normal, Open]	Number of Studies	Average Capacity (vphpl)	Average Percentage of Heavy Vehicles	Average Capacity (pcphpl)	Average Peak Hour Factor
[3,1]	11	1460	12.6	1588	0.92
[2,1]	11	1575	4.9	1629	0.94
[4,2]	5	1515	9.8	1616	0.92
[5,3]	2	1580	2.0	1601	0.93
[4,3]	4	1552	4.3	1597	0.96
All	33	1536	8.0	1606	0.93

The average capacities for the five lane closure configuration for which new data are available range only from 1,558 to 1,625 pcphpl – a difference of only 41 pcphpl. When the statistical procedure analysis of variance was performed on the data summarized in Exhibit 13, the results indicated no statistically significant differences among the average capacities in pcphpl for the five lane closure configurations (at a .05 significance level).

The overall average capacity (for all lane closure configuration combined) is approximately 1,600 pcphpl. This value compares logically to the HCM-estimated capacities of 2,200 pcphpl for freeways and multilane highways and of 1,900 pcphpl for signalized intersections (saturation flow), which represent the queue discharge rate and saturation flow rate under ideal conditions for the corresponding facility type. The research recommended an equation which combines the base capacity value and the recommended adjustments can be used to estimate work zone capacity:

$$C = (1{,}600 \text{ pcphpl} + I - R) \times H \times N \quad (8)$$

Where,

c = *estimated work zone capacity* (vph)

I = adjustment for type and intensity of work activity (pcphpl)

R = adjustment for presence of ramps (pcphpl)

H =heavy vehicle adjustment factor (vehicles/passenger car) and

N = number of lanes open through work zone.

In summary, the recommended values for the base capacity and the various adjustments are as follow:

- I = range (-160 to +160 pcphpl), depending on type, intensity, and location of work activity;
- R = minimum of average entrance ramp volumes in pcphpl, during lane closure period for ramps located within channelizing taper or within 152 m (500 ft.) downstream of the beginning of full lane closure, or one-half of capacity of one lane open through work zone (i.e., 1,600 pcphpl/2N); and
- H= heavy vehicle adjustment factor

The Indiana study (27) also used the North Carolina study capacity definition as “the flow rate at which traffic behavior quickly changes from uncongested conditions to queue condition” and used speed flow curves to identify capacity values. It was observed that traffic flows in Indiana freeway work zones changed from uncongested to congested conditions with a sharp observed speed drop. Therefore, work zone capacity for this study was defined as “*the traffic flow rate which occurs just before a sharp speed drop followed by a sustained period of low vehicle speed and fluctuated traffic flow rate*”. Data was collected from four different work zones with three different work intensity conditions as medium, non-adjacent, and high (Exhibit 14).

Exhibit 14: Observed Traffic Capacity Values at Freeway Work Zones in Indiana (27)

Work Zone	Mean Capacity (passenger cars/hour)	Standard Deviation
Zone #1	1537	242.21
Zone #2	1688	203.50
Zone #3	1612	28.54
Zone #4	1521	5.66

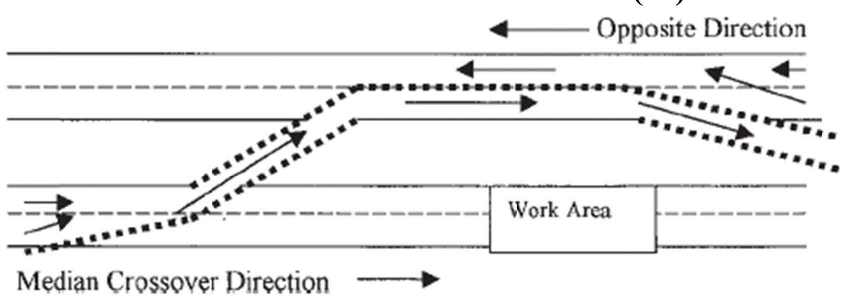
ANOVA tests indicated that the mean capacity values are statistically equal for different work zone types and work intensities. It should be said that there indeed exist some differences in the individual mean values and confidence intervals. Capacity means and confidence intervals are presented in Exhibit 15.

Exhibit 15: Capacity Means and Confidence Intervals (27)

Work Intensity	Mean Capacity (passenger cars/hour)	Standard Deviation
Medium	1537	242.21
Non-Adjacent	1688	203.50
High	1521	5.66

The lower mean value of the partial closure work zones might be attributed to the influences of the work activities in the work area adjacent to the traffic lane. Also, four different work zone scenarios were analyzed in this study as: Crossover (Opposite Direction), Crossover (Crossover Direction), Partial Closure (Right Lane Closed) and Partial Closure (Left Lane Closed). Exhibit 16 displays crossover lane closures. Other types have been explained beforehand.

Exhibit 16: Crossover Work Zone. (27)



As it can be seen in Exhibit 17, among the four types of work zones, the crossover (in crossover direction) has the largest value of mean queue-discharge rate.

Exhibit 17: Work Zone Capacities, Queue-Discharge Rates and Vehicles Speeds (27)

Work Zone Type	Mean Capacity (passenger cars/hour)	Mean Queue-Discharge Rate (Passenger cars/hour)	Mean Speed During Uncongested Condition	Mean Speed During Congestion
Crossover (Opposite Direction)	1745	1393	56 mph (90 km/hour)	25 mph (40 km/hour)
Crossover (Crossover Direction)	1612	1587	57 mph (92 km/hour)	25 mph (40 km/hour)
Partial Closure (Right Lane Closed)	1537	1216	59 mph (95 km/hour)	31 mph (50 km/hour)
Partial Closure (Left Lane Closed)	1521	1374	57 mph (92 km/hour)	39 mph (63 km/hour)

A study by Al-Kaisy and Hall (28) suggested a base capacity value of 2000 pcphpl for reconstruction sites under favorable conditions. Heavy vehicles and driver population were found to have the most significant effect on capacity. Work zones on freeways were classified into short-term maintenance sites and long term reconstruction sites. Capacity in long term construction work zones was typically higher than that of short term maintenance zone. According to the research, two factors were believed to contribute to this difference in capacity. First, the use of portable concrete barriers at reconstruction sites provides a better physical separation between the work activity area and the traveled lanes when compared to plastic barrels and cones commonly used at maintenance sites. The second factor is that regular drivers gain familiarity over time with long-term reconstruction sites, a matter that is quite unlikely at short term maintenance sites.

The study (28) included a total of six long-term freeway reconstruction sites and one normal freeway site with a recurrent bottleneck. Exhibit 18 shows the mean capacity for each of the sites during periods when these conditions were met, as well as the type of lane/shoulder closure and the amount of data used at each site to calculate the mean.

Exhibit 18: Mean Capacity Observations at Six Study Sites in Canada during Weekdays, Peak Period, Daylight, and Clear Weather Conditions (28)

Site	Type of Closure	Mean Capacity	Data Period (hours)
Gardiner Expressway-WB	3→2	2102 vphpl	2.3
Gardiner Expressway – EB	3→2	1950 vphpl	2.3
HWY 403 – WB	Right Shoulder	2252 pcphpl	10.5
QEW at Burlington – WB	Left & Right Shoulders	1853 pcphpl	6.7
QEW at BBS-Toronto-bound	4→2	1989 pcphpl	33
QEW at BBS-Niagara-bound	4→2	1985 pcphpl	18

A number of factors were suggested as being important for estimating work zone capacity as follows:

- Heavy Vehicles
- Driver Population
- Light Condition (day versus night)
- Inclement weather
- Work activity on site
- Lane closure configuration, and
- Rain

Based on the variables listed above, a multiplicative capacity model was presented:

$$C = C_b \times f_{HV} \times f_d \times f_w \times f_s \times f_r \times f_l \times f_i \quad (9)$$

Where,
C = Work zone capacity (vphpl)
C_b =Base work zone capacity (pcphpl)
f_{HV} = Adjustment factor for heavy vehicles
f_d = Adjustment factor for driver population
f_w = Adjustment factor for work activity
f_s = Adjustment factor for side of lane closure
f_r = Adjustment factor for rain
f_l = Adjustment factor for light condition
f_i = Adjustment factor for non-additive interactive effects

As discussed before, a base capacity of 2000 pcphpl would be an appropriate estimate for use in this generic capacity model. Conservative study results suggest that freeway capacity at reconstruction sites significantly decreases in the nighttime, and that it would be appropriate to expect roughly a 5% reduction in capacity during nighttime hours, for a facility with good illumination. The adjustment factors recommended for use with the proposed model are included in Exhibit 19. The values shown were developed based on the results of the individual capacity investigations and the site-specific models at the work zone sites.

Exhibit 19: Recommended Adjustment Factors for the Proposed Capacity Model (28)

Adjustment Factor	**Recommended Values for Proposed Capacity Model**
Heavy Vehicles (f_{HV})	Model utilizes the same HCM formula for heavy vehicles adjustment factor. However, the recommended equivalency factors for trucks and buses at freeway reconstruction sites are: *EHV = 2.4 level terrain* *EHV = 3.0 for 3% 1-km upgrade* *For other grades with similar length (around 1-km), linear interpolation may provide a reasonable approximation. For specific grades with different lengths, the values for 1-km length may be adjusted in the same proportions calculated using the HCM 2000 equivalency factors for trucks and buses*
Driver Population (*fd*)	*fd = 1.00 peak hours – weekdays* *fd = 0.93 off-peak - weekdays* *fd = 0.84 weekends*
Work Activity (*fw*)	*fw = 1.00 no work activity at site* *fw = 0.93 work activity at site*
Side of Lane Closure (*fs*)	*fs = 1.00 closure of right lanes* *fs = 0.94 closure of left lanes*
Rain (*fr*)	*fr = 1.00 no rain* *fr = 0.95 light to moderate rain* *fr = 0.90 heavy rain*
Light Condition (*fl*)	*fl = 1.00 daytime* *fl = 0.96 nighttime with illumination*
Non-Additive Interactive Effect (*fi*)	*fi = 1.03 for left-lane closures during weekdays-off peak* *fi = 1.08 for weekends when work activity is present* *fi = 1.02 for left-lane closures during weekends* *fi = 1.05 for rain during weekends* *fi = 1.00 for all other conditions*

3. OPERATIONAL ANALYSIS

Methodology

One key component of this research was to develop traffic stream models and capacity estimates for work zone operations, specific to North Carolina. These operational data were used to develop defaults for the FREEVAL-WZ software that largely match expected performance across the state. The study team relied heavily on the availability of roadside sensors. The sensor data were analyzed for several key pieces of information, including estimates of:

1. Free-flow speed under various work zone scenarios for default development
2. Capacity under various work zone scenarios for default development
3. Speed-flow relationship for various work zone scenarios for default development
4. Segment speed and density across multiple time periods for model validation
5. Travel time along the freeway containing work zone activity for model validation

This chapter discusses the sources of data, approaches for data "cleaning" and verification, and how the data were used to arrive at the measures described above. The basic analysis steps are as follows:

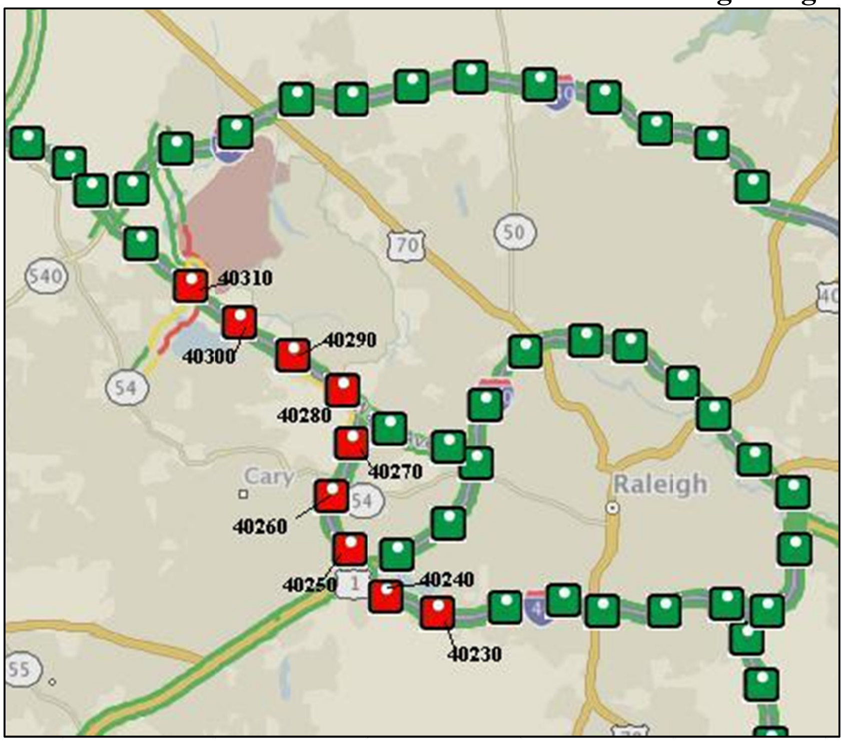
1. Obtain and review work zone diaries to identify candidate dates and locations;
2. Extract one-minute lane-by-lane data from NCDOT roadside sensors for the appropriate time periods;
3. Evaluate one-minute lane-by-lane data graphically to confirm that a lane closure was in effect and at what time it was implemented;
4. Obtain 15-minute roadside sensor data from NCDOT for the confirmed lane closures;
5. Categorize work zone data into scenarios (4→3 lane closure, 4→2 lane closure, etc.);
6. Extract 15-minute data points consistent with Highway Capacity Manual (HCM) theory and plot temporal distributions and speed-flow relationships;
7. Combine data, based on lane closure scenario, and estimate free flow speed and capacity
8. Estimate appropriate capacity adjustment factors for each of these scenarios to use in HCM analysis method;
9. Assign segment length between each sensor to determine field data travel time
10. Compare the field data travel time findings to those produced by FREEVAL-WZ

Overview of Sensor Data

The research team was fortunate to have access to detailed side-fire radar sensor data in North Carolina's Research Triangle Region. The data were accessed through the Traffic.com web interface and provide lane-by-lane speed, flow, density, and classification data aggregated in as high as one-minute resolution.

The team obtained work zone diaries from the construction contractors through coordination with the North Carolina Department of Transportation (NCDOT). The diaries provided detail to two projects in Raleigh, North Carolina along I-40: State Transportation Improvement (STIP) project I-4744 (I-40 Widening from Jones Franklin Road to Harrison Avenue) and STIP I-5112 (I-40 Rehab from Wade Avenue to I-540). The work zone diaries reported construction activities at a mile posting range and date. This information was used to guide what data to download from Traffic.com, which stores the mobility data collected by side-fire radar units in a central database. The location of these sensors is provided in Exhibit 20. A detailed listing of extracted data is given in the Appendix.

Exhibit 20: TRAFFIC.com Sensor Locations in Triangle Region



Data Preparation

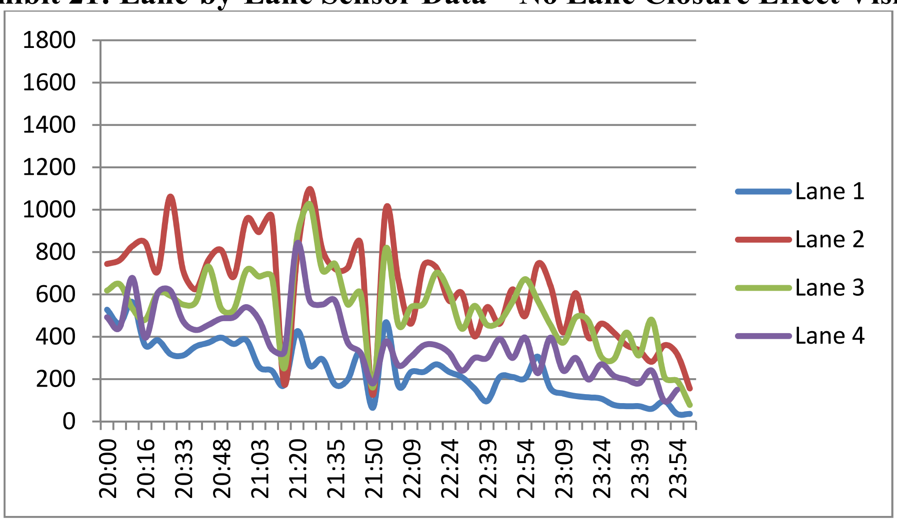
The work zone contractor diaries provided a starting point for data extraction, but additional verification was necessary before data could be used for this project. In general, the contractor diaries provided a rough estimate of location (usually closest milepost) and starting time (usually closest full hour). For the purpose of this research, however, precision was critical to assure that a particular sensor actually captured the lane closure condition and that the temporal analysis period was reflective of work zone activity. To confirm work zone activity, a lane-by-lane analysis was conducted, which required a download of detailed one-minute data. Only after verifying the lane closure location and time from the lane-by-lane data, was a site included in the 15-minute HCM analysis pool for the particular lane closure condition.

Lane-by-Lane Work Zone Verification

The work zones analysis was typically conducted for a time period from 9:00 PM to 12:00 AM. NCDOT generally doesn't allow lane closures to begin before 9:00 PM to minimize congestion impacts. Time periods after midnight were not considered, since traffic volumes were generally far below capacity and therefore not applicable for this project. To verify the specific times that work zones became active, one-minute lane-by-lane data were extracted from Traffic.com for a two-hour period spanning from 8:00 PM to 10:00 PM. This time period was also chosen to allow for a better comparison of operations before and after the lane closure was put in place. One hour of data before the work zone becomes active, allows enough time to establish a comparative average speed and volume count to be used for confirmation. This also allows identification of the time of the work zone implementation up to the closest 15-minute interval. An example of the method used for the lane-by-lane analysis of two particular work zone days occurring on July 7th, 2009 and July 8th, 2009 is presented below.

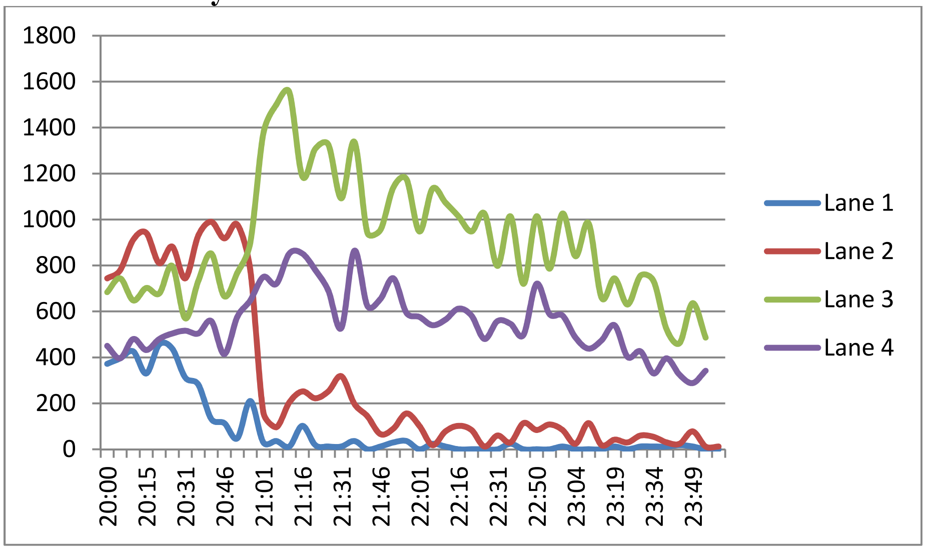
The work zone diary provided by NCDOT stated that the work zone configuration occurring on July 7th, 2009 was a 4→2 lane closure (two left lanes), and occurred along a segment passing through sensor 40280 (Milepost 288.5). After extracting and analyzing the lane-by-lane data, it was determined that the listed work zone activity must have been performed away from the sensor location. Although there seems to be a consistent drop of volumes in all four lanes at 9:00 PM, the two rightmost lanes are never closed (Exhibit 21). In fact, lane 2 (second lane from outside shoulder) carries a majority of the traffic through this segment, which is not unusual. For this particular date, the sensor information is therefore not useful for estimating work zone performance.

Exhibit 21: Lane-by-Lane Sensor Data – No Lane Closure Effect Visible



For a sample taken on July 8th, 2009, the lane distribution diagram confirms the lane closure scenario (4-to-2) as shown in Exhibit 22. The rightmost lane (lane 1) experiences a drop in volume at 9:00 PM, followed soon thereafter by a drop in lane 2. Some volume appears to remain in both lanes after the lane closure, and some measured flow is evident throughout the remainder of the work zone. The volume drop in lanes 1 and 2 is also accompanied by an increase in traffic in lanes 3 and 4. Some volume appears to remain in lanes 1 and 2 even after the lane closure, which is attributable to a "bleed-over" effect. This effect can occur with side-fire radar devices if vehicles travel close to the lane line. For work zones, an added issue may be temporary lane shifts without recalibration of the radar device. For purpose of analysis, it was assumed that the total throughput at the sensor location was equal to the sum of all observed lane-volumes. In other words, the measured vehicles in lanes 1 and 2 (attributed to the "bleed-over" effect) were added to the flows of lanes 3 and 4 in this case, to get the total estimated throughput for this 4-to-2 lane closure.

Exhibit 22: Lane-by-Lane Sensor Data – 4-to-2 Lane Closure Effect Visible



Fifteen-Minute Mobility Data Analysis

After it was confirmed that there was a lane closure in place at the sensor location, sets of 15-minute data for applicable dates were extracted from Traffic.com for analysis. The time that the work zone began was noted and coincided with the first time period for the datasets. Data sets were then categorized by lane closure scenario and combined for analysis. Volumes were adjusted, based on the number of open lanes and a heavy vehicle adjustment factor, to convert volume data from vehicles per hour to passenger cars per hour per lane (pcphpln). The adjusted volume, along with the average speed recorded for each 15-minute time period, were then used to create a speed-flow diagram and compared to free flow speed curves for various speeds, based on HCM calculations.

The heavy vehicle adjustment factor (f_{HV}) was calculated using Equation 2 adopted from the HCM (6). All sensors are located in level terrain ($E_T = 1.5$).

$$f_{HV} = \frac{1}{1 + P_T(E_T - 1)} \qquad (2)$$

Where,

E_T = passenger-car equivalents for trucks and recreational vehicles (RVs) in the traffic stream.

P_T = proportion of trucks/buses and RVs in the traffic stream.

After converting to pcphpln, the verified 15-minute data were used to estimate free-flow speed and capacity for each work zone scenario.

Free-Flow Speed Estimation

The free-flow speed (FFS) is defined as the space mean speed of vehicles under low flow conditions, where the interaction amongst vehicles is limited, and where the speed is thus primarily impacted by the geometry of the facility. For the purpose of this research, free-flow speeds were estimated by calculating the average speed of observation periods with a flow rate of 500 pcphpl or less. Before estimating FFS, the data were cleaned to assure that all observations are in the uncongested free-flow regime, as severe congestion can also cause low flows but at much lower speeds. These outlier events considered to be outside of one standard deviation from the observed mean. After removing the outliers, a FFS was calculated and rounded to the nearest five mph, consistent with HCM2010 guidance. The FFS is also related to the non-work zone base capacity in the HCM, which is needed for the next step in the analysis.

Capacity Adjustment Factor Calculation

Work zone and maintenance activities will cause a reduction in freeway capacity that can be described by applying Capacity Adjustment Factors (CAF), following the HCM freeway facilities methodology. The use of a CAF will result in a shifted speed-flow curve that extends from the estimated work-zone free-flow speed to a field-measured work zone capacity at a density equal to 45 passenger cars per mile per lane. A CAF is applied as shown in Equation 1: (*HCM: Equation A22-1*)

$$S = FFS + \left[1 - e^{\ln\left(FFS+1-\frac{C*CAF}{45}\right)\frac{V_p}{C*CAF}}\right] \quad (1)$$

Where,

S = segment speed (mi/h),
FFS = segment free-flow speed (mi/h),
C = original segment capacity (pcphpl),
CAF = capacity adjustment factor (≤ 1), and
v_p = segment flow rate (pcphpl).

The estimation of a CAF relies on accurate measurements of the free-flow speed and work zone capacity. While the first is readily estimated from field data (night-time work zones usually result in sufficient low-volume free-flow periods), the second requires observations near or at capacity. This was one of the most challenging aspects for field-data analysis in this project, as most work zones were designed to occur in time periods that would minimize the impacts on congestion for the traveling public. Specifically, all of the observed work zones generally did not allow any lane closures to be put in place prior to a 9:00 PM start time. Consequently, the team had limited observations of near-capacity flow conditions for several of the work zone scenarios.

In an effort to overcome this limitation, the team used a regression-based approach to guide the estimation of appropriate work zone CAF estimations. The iterative approach explored various CAF factors (and the resulting speed-flow curves), with the goal of arriving at a CAF estimate that maximizes the regression R-Square statistic, and thus minimizes the regression error relative to field data. A spreadsheet tool was developed to aid with this analysis step. However, in some cases, even this approach didn't result in reasonable results, usually because all of the observed field data was clustered in very low flow periods. In those cases, the team had to rely on previous estimates of work zone capacity in the literature. Thus, the approach to estimating work-zone capacity and the corresponding CAF use three methods, summarized here in order of preference:

1. Estimating capacity directly from field data that is at or near capacity.
2. Inferring capacity using regression techniques based on best-fit of speed-flow curve to field data for various CAFs

3. Assuming capacity for a specific lane closure scenario based on a synthesis of the related literature for the lane closure configuration.

The results of this analysis approach are presented in section 5. The next section provides a discussion of the software development portion of this research.

4. SOFTWARE DEVELOPMENT

Introduction

Only a limited number of software tools are specifically intended for the analysis of work zone impacts. However, many analysis tools, including all simulation packages, are general-purpose traffic engineering tools that can be adopted to represent the effect of a work zone on traffic flow. Rather than coding a work zone explicitly, the analyst codes its implicit effect on traffic operations by reducing the number of lanes or lowering the free-flow speed. The literature review in section 2 provided a detailed overview of many of these tools.

The software development effort in this research is based on the computational engine for the Highway Capacity Manual's freeway facility methodology, called FREEVAL. The method is ideally suited for evaluating work zone impacts on extended freeway facilities, as it already incorporates many of the building blocks needed to model work zone impacts on operations, including lane closures, capacity-adjustment factors, and reduced speed limits. The core tool was significantly enhanced in this research to add a planning-level user interface, and to incorporate NC specific work zone defaults based on this research. The modified tool will be referred to as FREEVAL-WZ (work zone) in this document.

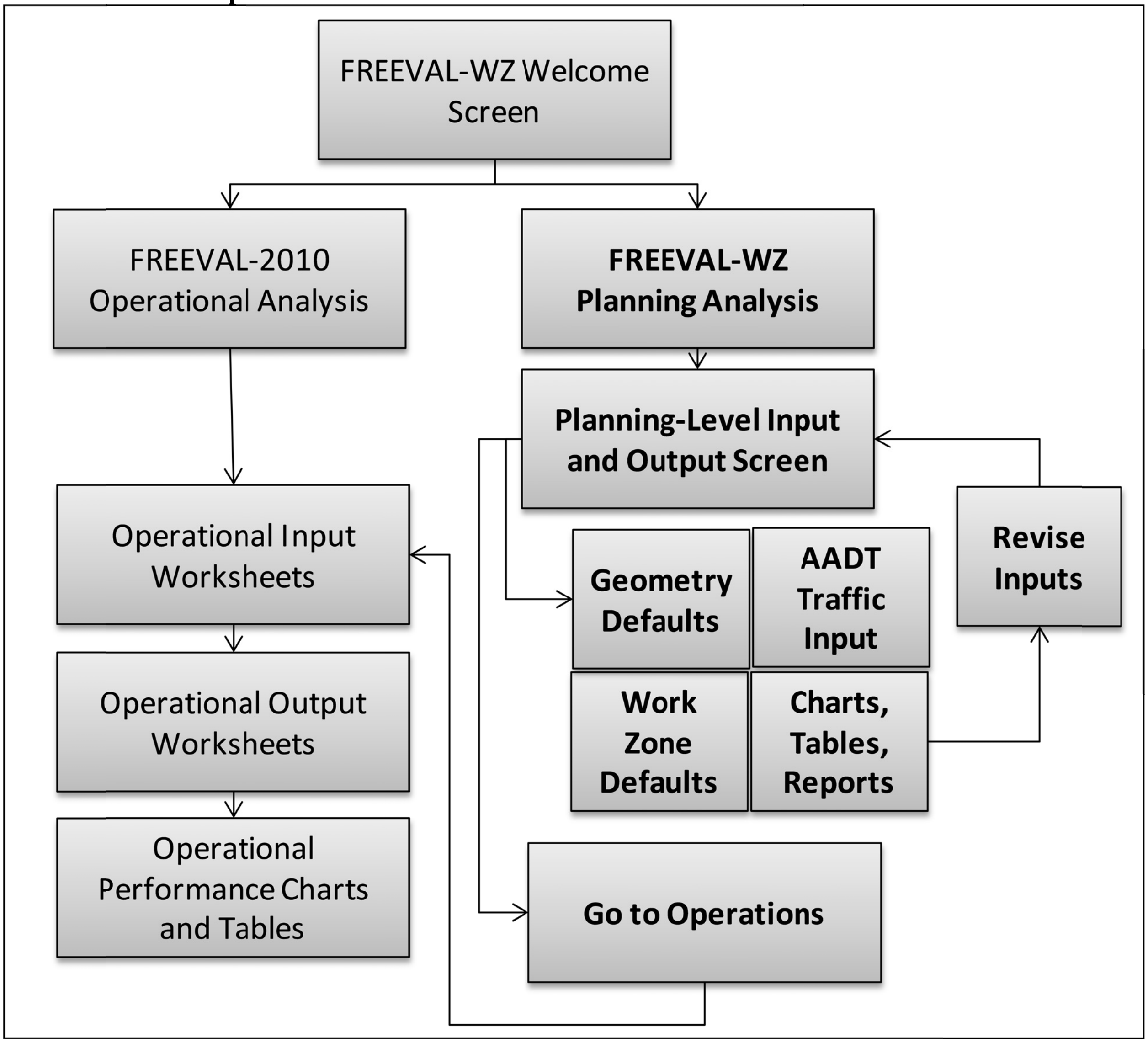
Planning Level Interface

While all the above work zone impacts can be modeled in the original FREEVAL program, there was a need to facilitate data entry and customize the tool to the needs of the NCDOT. Specifically, the original FREEVAL requires 15-minute traffic demand flows to be entered for each segment and each time period. In addition to being coding intensive, the required demand data are usually not available in planning-level analyses that rely principally on estimates of average annual daily traffic (AADT). An important component of the new planning-level interface is the ability to use AADT volume inputs. Specific goals of the development of the FREEVAL-WZ tool are as follows:

- Facilitate user input by accepting many input cells as (customizable) default values;
- Enable user to enter single AADT number for all time periods across all segments instead of entering individual demand value in all time periods for all segments;
- Integrate work zone analysis and NC-specific defaults in a user-friendly interface;
- Allow quick and efficient analysis of multiple scenarios from the same facility template;
- Incorporate estimation of user cost in software output;
- Generate printable summary reports that capture essential information about facility operations;
- Maintain seamless transfer to operational analysis mode for more detailed analysis.

Exhibit 23 shows the revised program architecture.

Exhibit 23: Conceptual Architecture for FREEVAL-WZ Software Tool



Conceptually, the new planning level interface is implemented through a "wrapper" around the computational operational core of FREEVAL. The interface facilitates user input, automatically populates operational worksheets, and extracts key performance measures for display in the planning-level interface. At any time, the user can select to go to operational mode for more detailed analysis. Given the software architecture, it is not possible to return to planning mode from operations. The following sections provide further details on the new features in FREEVAL-WZ.

New Demand Volume Input as AADT

In the HCM version of FREEVAL, the user has to enter demand at the starting segment of each fifteen-minute time period. Also, ramps and weaving segments have their own demand input boxes at each time period. Since the nature of planning analysis requires straightforward input accompanied by easy-to-use output, it was decided to use hourly demand volume profile for all analyzed time periods.

Two major hourly volume profiles were generated, based on a previous NCDOT research project (29) as Urban Hourly Volume Profile and Rural Hourly Volume Profile. These profiles were generated by averaging over 30 different volume profiles collected across North Carolina. Exhibit 24 and Exhibit 25 demonstrate different hourly volume profiles across North Carolina for urban and rural freeway sites. The bold lines in the exhibits show the average profile, which was used as the default in FREEVAL-WZ. Additionally, the user can define a custom profile, by entering hourly volumes or percentage manually.

Exhibit 24: Rural Hourly Traffic Volume Profile (29)

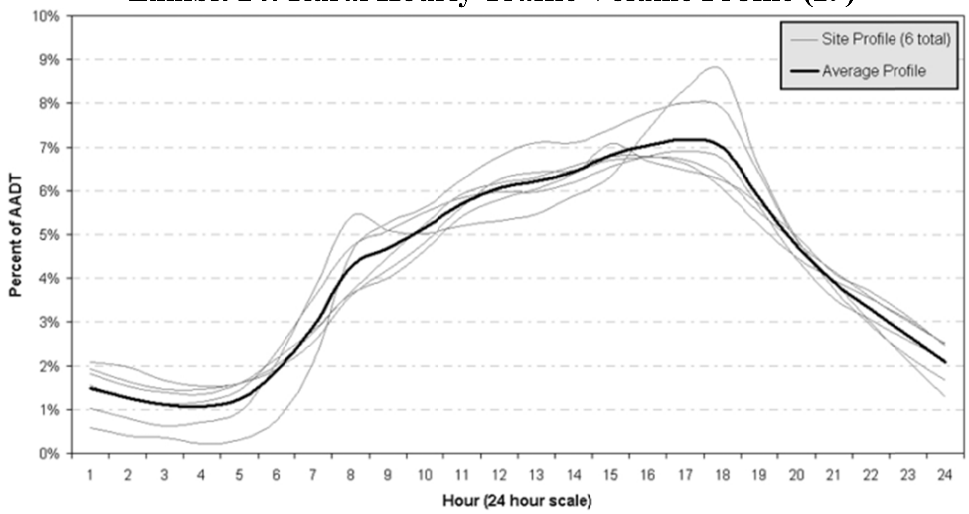
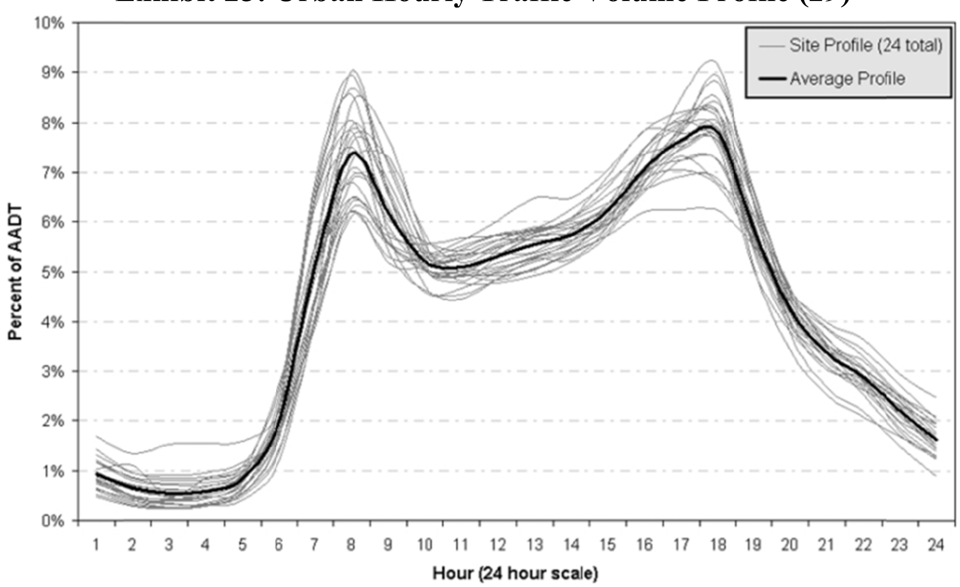


Exhibit 25: Urban Hourly Traffic Volume Profile (29)



These hourly volume profiles were converted into 15-mins bins using linear interpolation. The demand at each time period is calculated by multiplying the AADT with the respective time period volume percentage and an interpolation factor. It should be noted that other adjustment factors such as the peak-hour directional factor (d-Factor) and facility-wide growth factor are also considered in the demand calculation for each time period.

Default Values

In an effort to increase the efficiency of data entry in FREEVAL-WZ, several default values were developed for variables that are not likely to vary in a planning level analysis. These variables are listed as follow:

1- Capacity Adjustment Factor: Default value set at 1.0. However, it is possible to change it applying different work zone scenarios.
2- Origin/Destination Adjustment Factor: A single input value will be used for all time periods across different segments.
3- Percent Trucks Adjustment Factor: A single input value will be used for all time periods across different segments.
4- Percent RV's: Default value set at 0.0%.
5- Percent Ramp Trucks: A single input value will be used for all time periods across different segments.
6- Acceleration/Deceleration Lane Length: Default value 500 feet is used for all ramps.
7- Ramp on Left or Right (L/R): Default set as right-side for all ramps.
8- Ramp FFS: Default set to 40 mph for all time periods and segments.

User Cost Calculation

A key consideration in the evaluation of work zone impacts is the user cost for the traveling public, who may be delayed by the work zone activities. The economic impacts of traffic congestion are directly related to the vehicle-hours of delay (VHD) on the freeway facility, which is already an output in FREEVAL. The VHD is estimated for each time period and is largely calculated by multiplying the difference of free-flow and congested travel time by the number of vehicles in a given segment.

Based on a review of literature on user-cost estimation, such as the "Red Book" (30), work zone analysis guidance used in the state of Texas (31), and benefit-cost analyses completed for the NCDOT (32), the team derived an approach for user cost estimation that is compatible with FREEVAL-WZ and correlates with the literature. Specifically, user cost is modeled as the summation of two independent values: (1) the Total User Delay Cost (UDC_{total}) and (2) Total Vehicle Operating Cost (VOC_{total}). The UDC is based primarily on the economic impacts from lost wages for the drivers (and passengers) delayed by the work zone. UDC further distinguishes between wages (hourly salary) of standard passenger cars and commercial vehicles. The second component, VOC is determined by estimating the economic impacts of the transported (truck) goods being delayed in traffic. It estimated from assumptions of the monetary value of the average truck load and the economic amortization cost of those goods while delayed in traffic. The VOC concept assumes that the operating agency of the truck has to take on a loan (at an average interest rate) to cover the value of the loaded goods for each hour that the truck is delayed in traffic. The detailed calculations are beyond the scope of this report, but can be referenced in the "Red Book" (30) or guidance for benefit-cost analysis in NC (32).

In the implementation in FREEVAL-WZ, UDC and VOC are calculated by multiplying the default UDC and VOC rates (per hour) by the vehicle-hours of delay for each time period, and summing over the entire analysis period. The formulas for user cost modeling in FREEVAL-WZ are given below:

$$UDC_{time\ period\#} = VHD_{time\ period\ \#} \times (P_c \times UDC_{cars} + P_t \times UDC_{trucks})$$

$$VOC_{time\ period\#} = VHD_{time\ period\ \#} \times (P_c \times VOC_{cars} + P_t \times VOC_{trucks})$$

$$UC_{time\ period\ \#} = UDC_{time\ period\#} + VOC_{time\ period\#}$$

$$UDC_{total} = \sum_{i=1}^{Number\ of\ Time\ Periods} UDC_i$$

$$VOC_{total} = \sum_{i=1}^{Number\ of\ Time\ Periods} VOC_i$$

$$UC_{total} = UDC_{total} + VOC_{total}$$

Where,

$UDC_{time\ period\#}$ = User Delay Cost at Specific Time Period
$VOC_{time\ period\#}$ = Vehicle Operating Cost at Specific Time Period
$TVHD_{time\ period\ \#}$ = Travel Vehicle Hours of Delay at Specific Time Period
P_c = Percent Cars
P_t = Percent Trucks
UDC_{cars} = User Delay Cost for Cars
UDC_{trucks} = User Delay Cost for Trucks
VOC_{cars} = Vehicle Operating Cost for Cars
VOC_{trucks} = Vehicle Operating Cost for Trucks
$UC_{time\ period\ \#}$ = User Cost at Specific Time Period
UDC_{total}= Total User Delay Cost over All Time Periods
VOC_{total} = Total Vehicle Operating Cost over All Time Periods
UC_{total}= Total User Cost over All Time Periods

To facilitate user input, NC defaults have been developed for UDC and VOC rates per hour for cars and trucks, which are as follows.

UDC_{cars} = \$21.07 per hour
UDC_{trucks} = \$26.08 per hour
VOC_{cars} = \$22.85 per hour (for FFS=65mph)
VOC_{trucks} = \$154.73 per hour (for FFS=65mph)

The default values for User Delay Cost (UDC) for passenger cars and User Delay Cost for trucks are based on the recently completed *US 401 User Benefits Analysis* (32), which was assumed as an adequate example for NC.

The default values for Vehicle Operation Costs (VOC) are based on estimates from the AASHTO "Red Book" (30) and a recent NCDOT Benefit Cost Report (32). They take into account the average fuel consumption of vehicles per minute of delay. If multiplied by the price of gas, this gives an estimate of the dollar cost of being delayed in traffic. The AASHTO "Red Book" then expresses the cost of fuel as a percentage of VOC. In other words, VOC can be estimated by dividing the cost of fuel by the percentage fuel cost of VOC.

Exhibit 26 gives guidance for how the VOC default values for a free-flow speed of 65mph were estimated, and how the analyst can estimate parameters for other facilities. The table uses an estimate of fuel consumption per minute of delay from the literature (30), which is multiplied by 60 to get fuel consumption (in gallons) per hour of delay. That estimate is then multiplied by the assumed cost of fuel, and divided by the parameter for fuel cost as percent of VOC from (36). The resulting estimates in Exhibit 26 should be treated with care, as several assumptions tend to change quickly, due to changing economic conditions.

Exhibit 26: VOC Estimation Guidance (adapted from (30) and (31))

Free-Flow Speed	Fuel Consumption per Minute of Delay (34)		Fuel Consumption per Hour of Delay (gal)		Estimated VOC per Hour of Delay ($)	
	Car	Truck	Car	Truck	Car	Truck
20	0.022	0.102	1.32	6.12	$ 7.62	$ 35.31
25	0.026	0.133	1.56	7.98	$ 9.00	$ 46.04
30	0.03	0.167	1.8	10.02	$ 10.38	$ 57.81
35	0.034	0.203	2.04	12.18	$ 11.77	$ 70.27
40	0.038	0.241	2.28	14.46	$ 13.15	$ 83.42
45	0.043	0.28	2.58	16.8	$ 14.88	$ 96.92
50	0.048	0.321	2.88	19.26	$ 16.62	$ 111.12
55	0.054	0.362	3.24	21.72	$ 18.69	$ 125.31
60	0.06	0.404	3.6	24.24	$ 20.77	$ 139.85
65	**0.066**	**0.447**	**3.96**	**26.82**	**$ 22.85**	**$ 154.73**
70	0.073	0.49	4.38	29.4	$ 25.27	$ 169.62
75	0.08	0.534	4.8	32.04	$ 27.69	$ 184.85

Assumed Cost of Fuel ($/gal)	
Gas	$ 3.00
Diesel	$ 3.00

Fuel Cost as % of VOC
52%

FREEVAL-WZ uses the VOC for a free-flow speed of 65mph as a default input value, but other factors can readily be entered in the software. All inputs can be customized as necessary and should be changed in the future, as hourly wages, gas prices, and the value of goods increase.

5. EMPIRICAL PERFORMANCE DATA

Using a combination of work zone diaries, one-minute lane-by-lane data, and 15-minute data, the team developed a process for obtaining and reducing work zone data from the sensors, which was described in detail in the Operational Analysis portion of this report (Section 3). Several analysis examples and supporting tables for this process are also provided in Appendices C and D. This section presents the results of this empirical performance analysis, which aimed at developing estimates of work-zone free-flow speed and capacity specific to NC conditions.

Sample Size

The work zone projects analyzed were within an area of I-40 that had extensive side-fire radar sensor coverage, which was accessed through the Traffic.com website (33). The team was able to obtain a large amount of data, which is summarized in Exhibit 27. Overall, the team has extracted and examined over 4,500 fifteen-minute data points that cover various work-zone lane closure configurations.

Exhibit 27: Sample Size for Work Zone Scenarios

WZ Lane Closure Scenario	Number of Sensor Days	Number of 15-Min Data Points
4-3	80	572
4-2	8	60
4-1	8	60
3-2	261	3892
3-1	7	72
2-1	15	314
Total	**379**	**4548**

The sensor days column provides the total count of all sensors analyzed for all dates and for all locations that fit a given work zone lane closure scenario. Note that in some cases, multiple sensors provided data for the same lane-closure event. Typically the period of analysis for each work zone was from 9:00 PM to 12:00AM. NCDOT generally did not allow lane closures to take place prior to 9:00 PM, and volumes were generally too low after midnight to be useful for this research. Due to occasional malfunctions with the side-fire radar, some 15-minute periods are missing in some of the datasets, resulting in non-contiguous data. In some instances the work zone was deployed for longer than a three hour period, which would lead to more than twelve 15-minute data points per sensor date. Appendix C and D contain a more detailed listing of the data points obtained.

The speed-flow data were obtained from TRAFFIC.com roadside sensors. Exhibit 28 summarizes the number of data points for each scenario that were obtained for each sensor. A map of these sensors was provided earlier in Exhibit 20.

Exhibit 28: Work Zone Lane Closure Sample Size by Sensor

TRAFFIC.com Sensor ID	Number of Sensor Days	EB Lanes	WB Lanes	15-Min Data Points
40220	4	3	3	48
40230	60	3	4	720
40240	93	3	3	1116
40250	51	3	3	612
40260	53	3	3	636
40270	22	3	2	264
40280	68	4	4	816
40290	16	4	4	192
40300	12	4	4	144

Lane-by-Lane Confirmation

Before including the data in the analysis, the team went through a data verification step using lane-by-lane (LBL) analysis to confirm work-zone activities, as well as the exact starting time.. At the time of the study, the 2009 candidate sites were unable to be confirmed by lane-by-lane analysis, due to a restriction of storage space that limited the amount of time this data was stored in the database. Also, issues with some of the sensors led to an inability to confirm a large amount of the latter 2010 collection dates. For the remaining available sites, a lane-by-lane analysis was conducted. Exhibit 29 summarizes the data verification results.

Exhibit 29: Lane-by-lane Confirmation Statistics

WZ Lane Closure Scenario	Number of Sensor Dates	15-Min Bins	Confirmed by LBL	Unconfirmed Due to Sensor Down	Unconfirmed by LBL
4-3	80	960	216	0	744
4-2	8	96	78	0	18
4-1	8	96	45	0	51
3-2	261	3132	245	468	2419
3-1	7	84	72	0	12
2-1	15	180	48	0	132
All	379	4548	516	468	3564

The results in Exhibit 29 makes it evident that the majority of data could not be confirmed by lane-by-lane analysis, which reduced the available data set to only a little over 10% of the full sample. Specifically, 468 data points could not be confirmed due to sensor malfunction. The remaining 3,564 data points did not show any lane closure activity in the specified period. Rather than suggesting errors in the contractor diary, the likely reason here was that the sensor did not cover the actual work zone. For example, if the sensor was located just downstream of the actual lane closure, it was not useful for estimating operational parameters of the lane closure scenario.

Without being able to confirm when and where (exactly) the lane closure was active, too many sources of error would have compromised data (including changes in volumes from ramps and changes in speed from accelerating downstream of the work zone).

Unfortunately, this project was limited by the availability of permanent sensor stations. For future work, a mobile data collection approach should be considered, where the researchers can control the exact location of the sensor and match them up with the work zone, as was done in prior research for NCDOT (18).

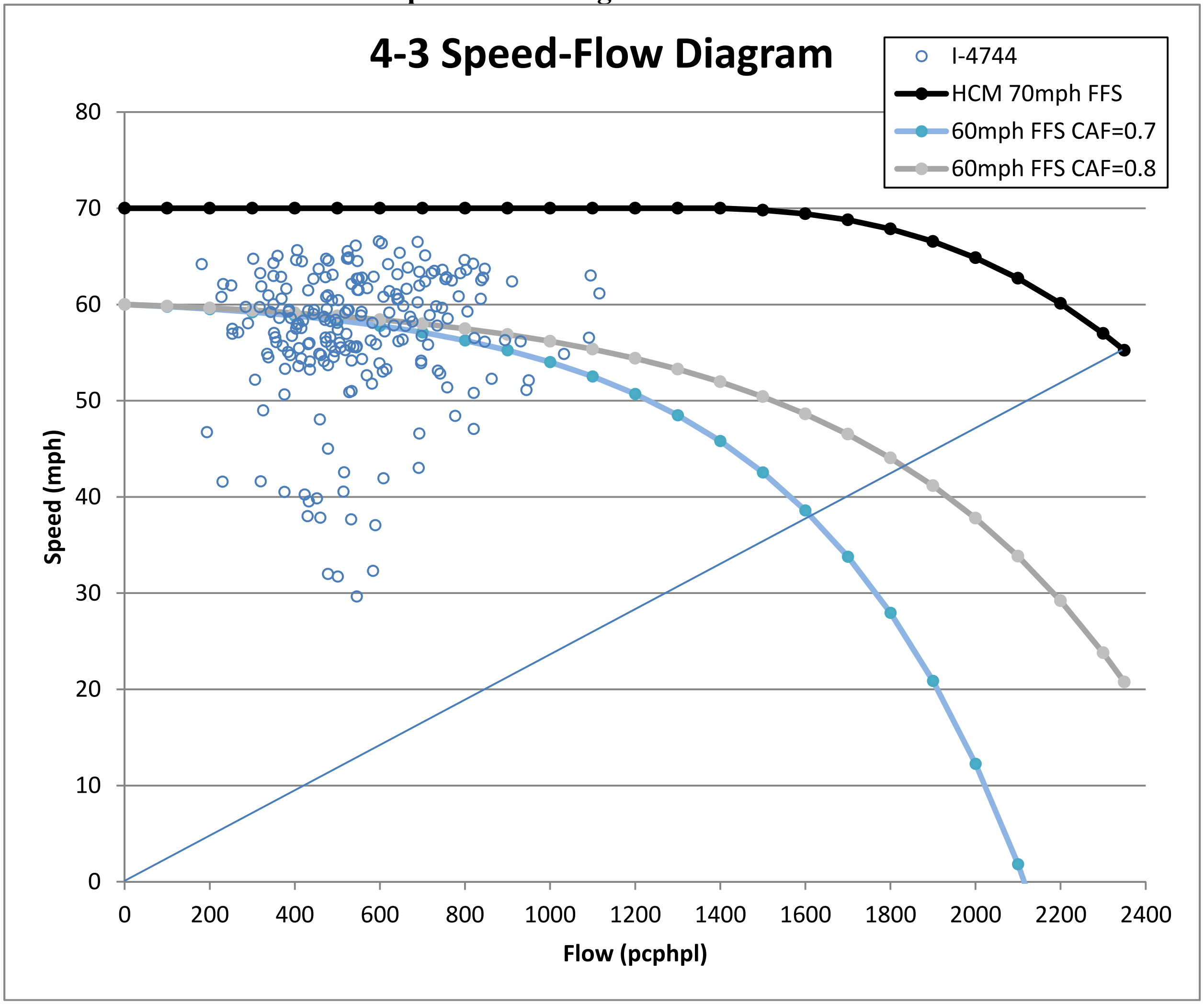
Speed and Capacity Estimations

As mentioned previously, FFS and capacities for each scenario were estimated with the goal of determining the scenario specific CAF to use in FREEVAL-WZ. The speed-flow diagrams for each scenario, as well as the results from the CAF calculations, are shown in the following sections.

Lane Closure 4-3 Scenario Speed and Capacity Estimations

A 4-3 lane closure is expected to be only marginally impacted by the work zone deployment, compared to the other five designated work zone scenarios in this study, because three travel lanes remain open. Exhibit 30 presents the speed-flow data for the 84 usable fifteen-minute periods in the 4-3 scenario.

Exhibit 30: Lane Closure 4-3 Speed-Flow Diagram

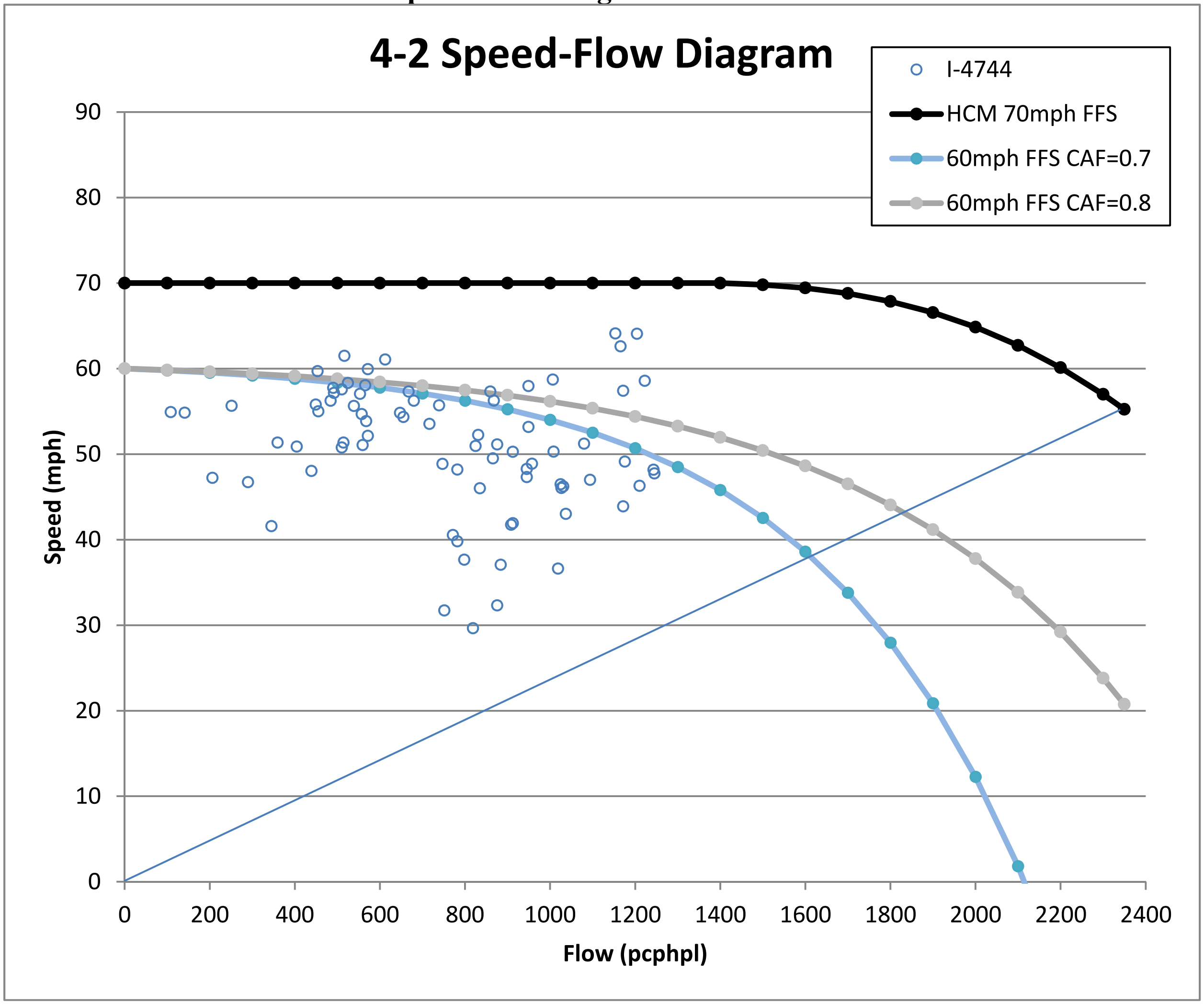


The exhibit shows the sensor data, along with the speed-flow curve for the 70mph free-flow speed is shown as a solid black line, which represents the base condition of this facility without work zone. A comparison of the data and the HCM speed-flow line, makes evident that some adjustments are needed to accurately represent this scenario in FREEVAL-WZ. From the graph, it is evident that FFS is closer to 60 mph, which was confirmed by calculation of the average speed of volume levels below 500 pcphpln (for details see Section 3). For a 60 mph free-flow speed, the HCM predicts a capacity of 2300 pcphpl. Based on the limited data available, the team calculated a CAF of 0.89 for this particular scenario, but curves corresponding to CAF of 0.7 and 0.8 are shown for visual reference. With very limited data in the high flow regions, the team does not have a lot of confidence in the predicted CAF, and suggests referring to literature for more robust estimates.

Lane Closure 4-2 Scenario Speed and Capacity Estimations

The 4-2 scenario data consisted of a relatively small sample of 48 fifteen-minute periods, and is shown in the speed-flow diagram provided in Exhibit 31.

Exhibit 31: Lane Closure 4-2 Speed-Flow Diagram

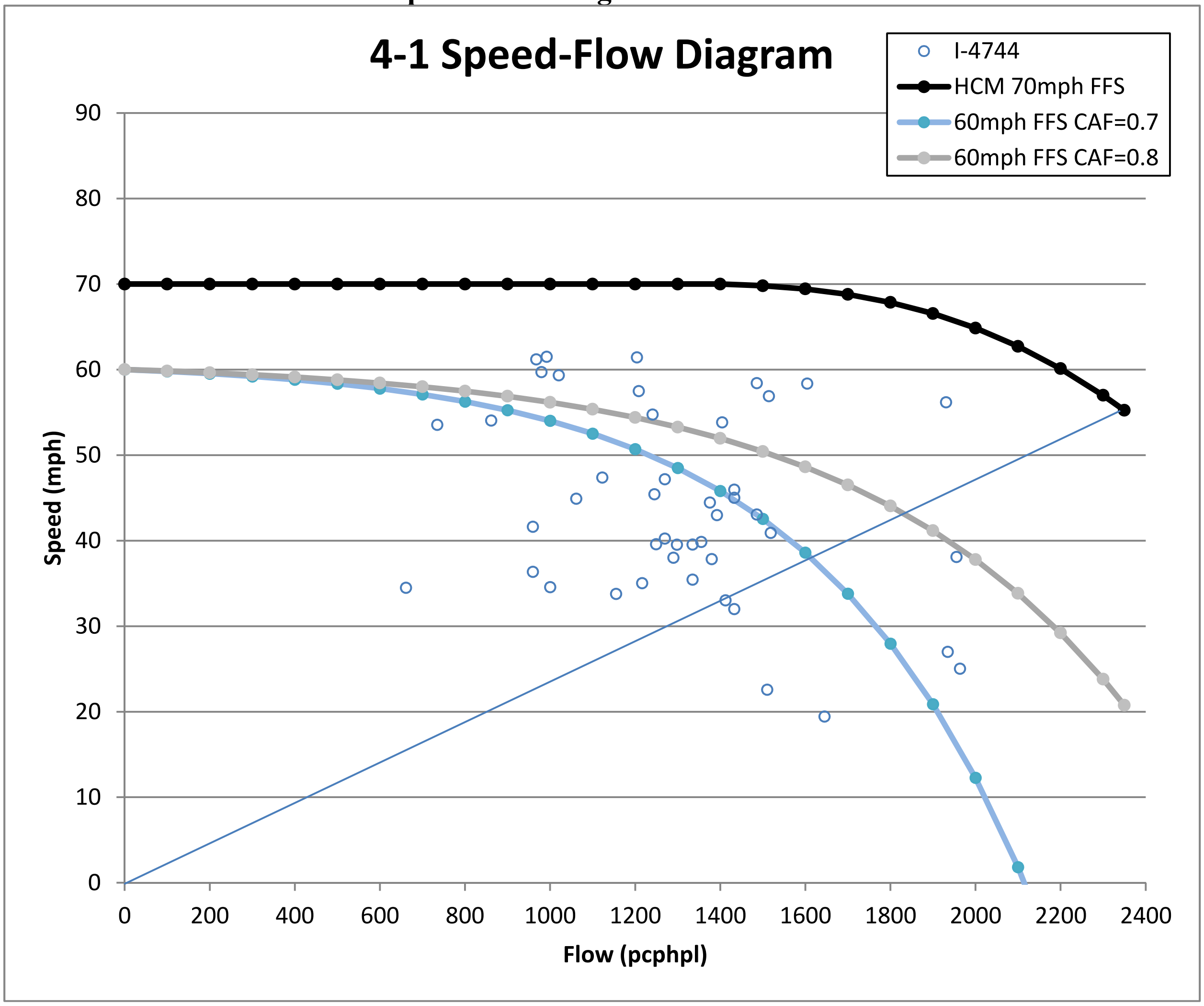


The FFS was calculated at 53 mph for volumes below 500 pcphpl, which was rounded to 55 mph. The data appear to show some higher-speed observations at higher volumes, which would suggest a free-flow speed closer to 60. The 55 mph FFS correlates to a base capacity of 2,250 pcphpl according to the HCM. After applying the regression-based approach to the data, the estimated work zone capacity for the 4-2 scenario was 1,850 pcphpln, which corresponds to a CAF of 0.82 for the 2,250 base capacity at a 55 mph FFS.

Lane Closure 4-1 Scenario Speed and Capacity Estimations

The 4-1 scenario data was similar to the 4-2 in that it consisted of a relatively small sample size of 24 fifteen-minute time periods. It did experience some even larger volumes, on average, than both the 4-2 and 4-3 scenarios, as shown in Exhibit 32.

Exhibit 32: Lane Closure 4-1 Speed-Flow Diagram

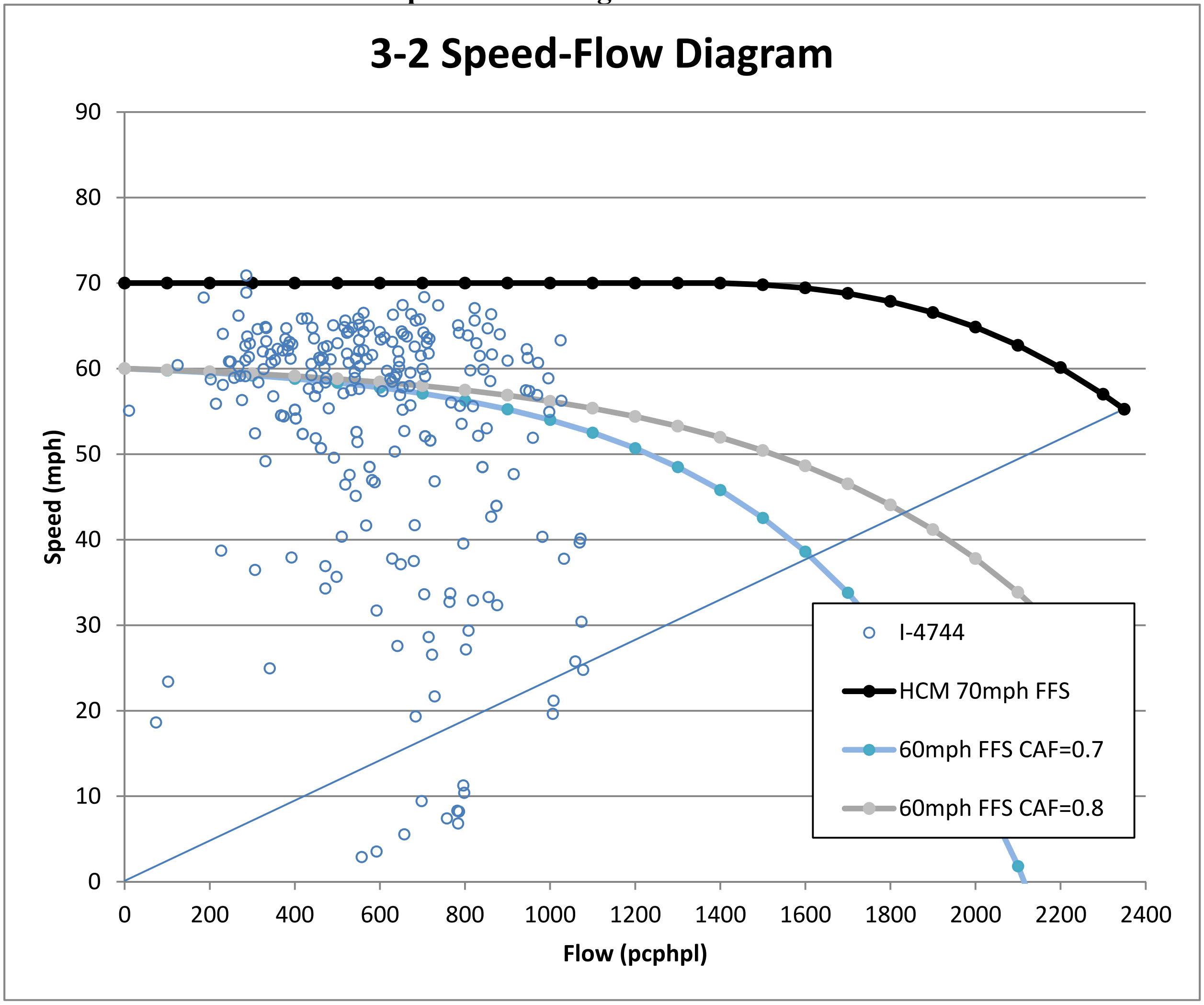


Only limited data for this scenario were available at low-flow periods, and the FFS for this scenario was therefore estimated visually to be approximately 55 mph. This correlates to a base capacity of 2250 pcphpl according to the HCM. Due to the relatively small and scattered sample size, an accurate estimation of the CAF was not possible. However, a visual comparison of the data to the speed-flow curve for CAF of 0.7 and 0.8 generally seem to be in the reasonable range.

Lane Closure 3-2 Scenario Speed and Capacity Estimations

The 3-2 scenario comprised the largest sample size at 252 fifteen-minute periods. However, the bulk of the data was observed at lower volume levels relative to the theoretical capacity, as evident in Exhibit 33.

Exhibit 33: Lane Closure 3-2 Speed-Flow Diagram

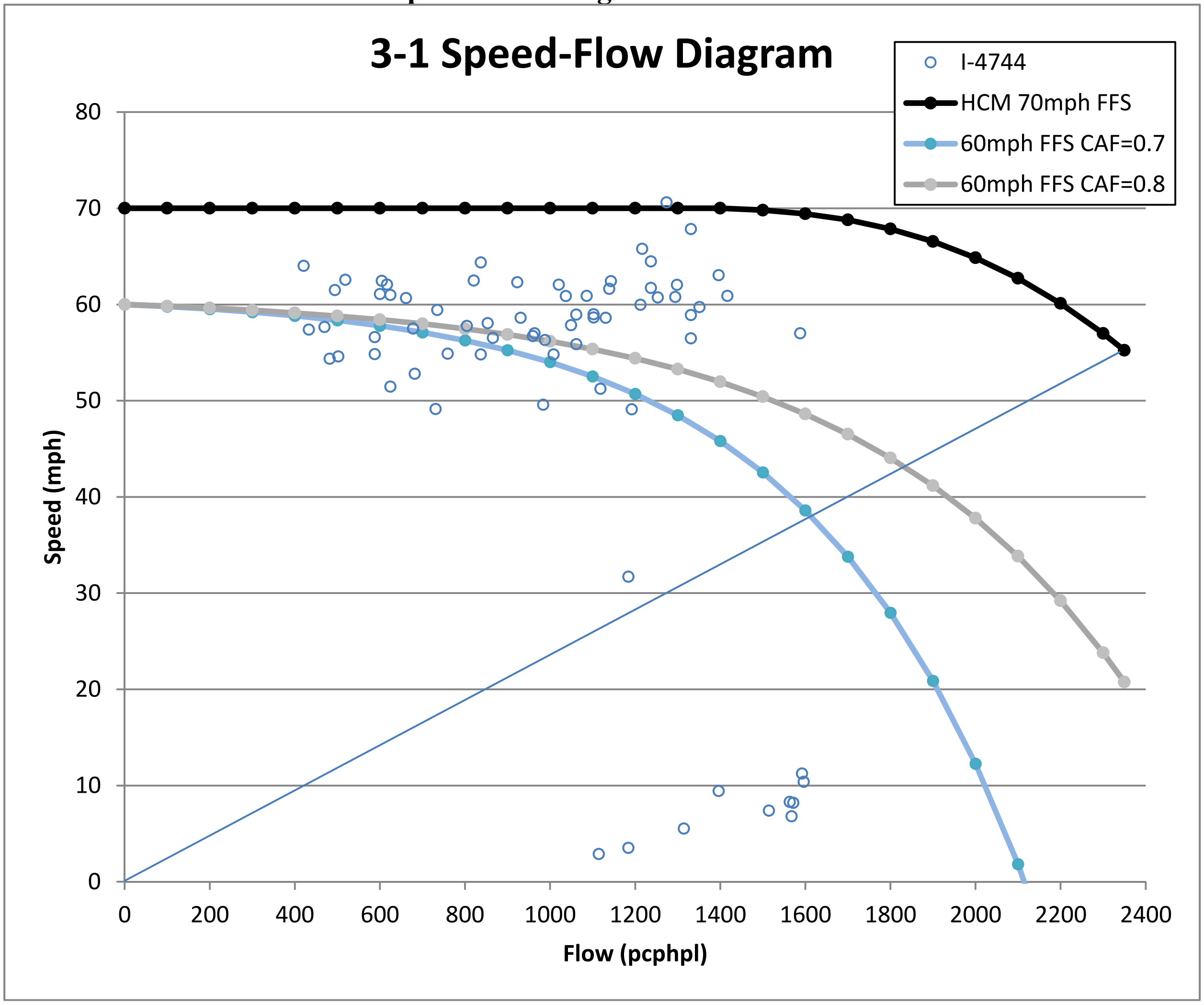


The scenario FFS was estimated at 60mph, which correlates to a base capacity of 2300 pcphpl according to the HCM. Several data points were observed below the 45 pcphpln density line, which correspond to densities in queues formed from downstream bottlenecks. Accordingly, these were excluded from the CAF estimation. From the remaining valid data set, a CAF of 0.80 is estimated, corresponding to a scenario capacity of 1,850 pcphpln.

Lane Closure 3-1 Scenario Speed and Capacity Estimations

The sample size for the 3-1 scenario dataset was relatively small , with 84 fifteen -minute periods analyzed. The resulting speed-flow data are shown in Exhibit 34.

Exhibit 34: Lane Closure 3-1 Speed-Flow Diagram

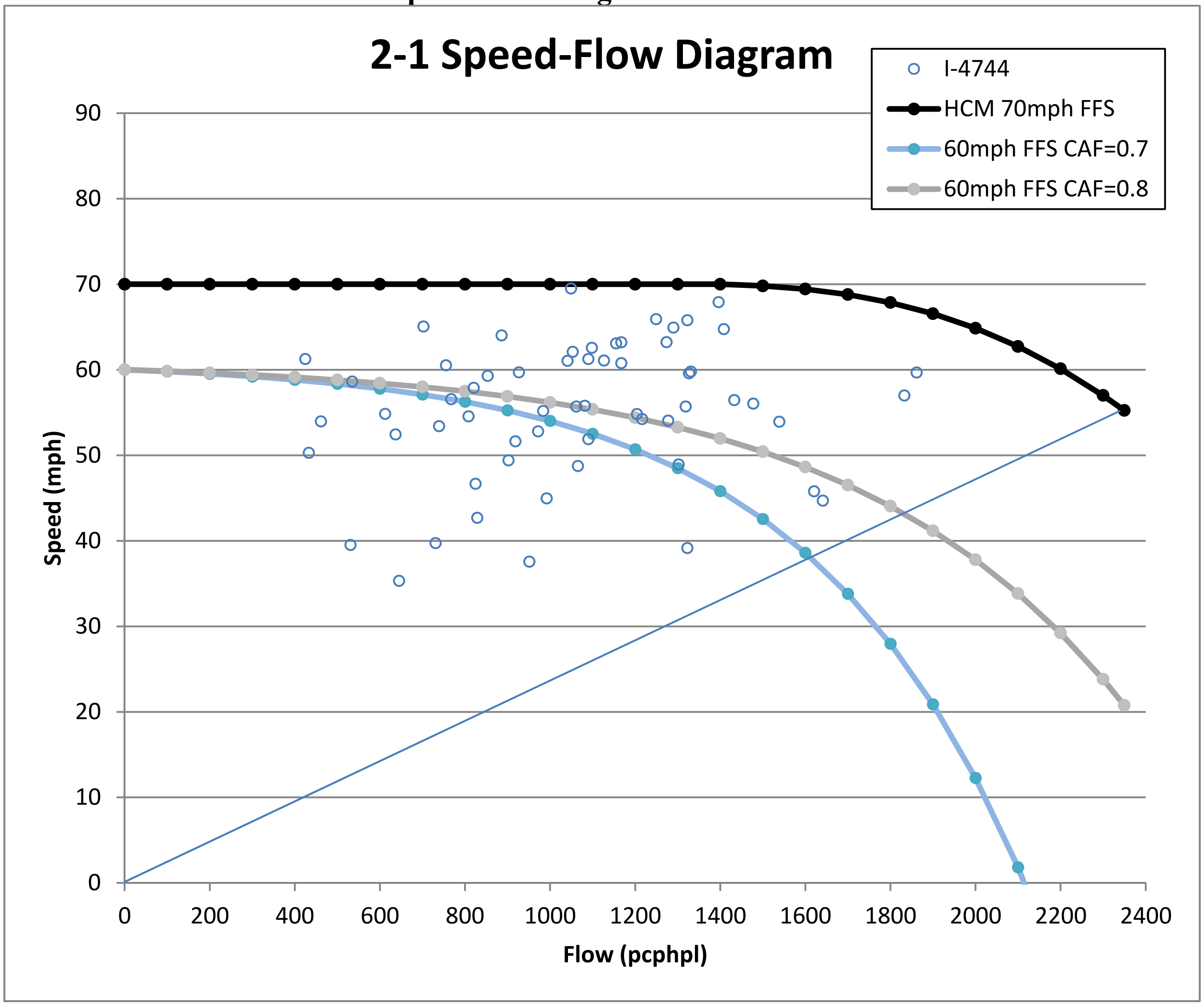


For this particular scenario, a FFS of 60 mph was calculated, which correlates to a base capacity of 2300 pcphpl, according to the HCM. Due to the relatively small and scattered sample size, an accurate CAF could not be calculated. From a visual inspection of the CAF 0.7 and 0.8 curves, it appears that the higher CAF=0.8 provides a better fit to the data, although a CAF of 0.9 (not shown) may work even better. Similar to the previous scenario, observations below the 45 density line were not included in the CAF estimation.

Lane Closure 2-1 Scenario Speed and Capacity Estimations

The 2-1 scenario produced an acceptable sample size with relatively high observed volumes, close to the theoretical capacity. The resulting speed-flow relationship is shown in Exhibit 35.

Exhibit 35: Lane Closure 2-1 Speed-Flow Diagram



For this scenario, a FFS of 60 mph was calculated, which correlates to a base capacity of 2300 pcphpl according to the HCM. Due to the relatively scattered sample size, an accurate CAF was unable to be calculated. Again, a visual comparison of the CAF 0.7 and 0.8 curves suggests a reasonable fit to the data.

Speed and Capacity Estimate Summary

Due to the relatively small sample sizes in most lane closure scenarios, a reliable and robust estimation of the CAF was not possible in most cases. In some cases, the regression-based approach gave the team an estimate for the CAF, although sparse data still raises questions about the validity of the results. In other cases, the team had to rely on a visual approximation of an appropriate CAF based on limited data. Exhibit 36 summarizes the speed and capacity estimates for each of the scenarios observed in this research.

Exhibit 36: NC-Proposed Lane Closure Speed and Capacity Estimations Summary

WZ Lane Closure Scenario	Free Flow Speed, FFS (mph)	Capacity Adjustment Factor, CAF	Approximate WZ Capacity (pcphpl)
4-3	60	0.89	2,050
4-2	55	0.82	1,850
4-1	55*	0.70-0.80*	1,580-1,800
3-2	60	0.80	1,840
3-1	60	0.80*	1,840
2-1	55	0.70-0.80*	1,580-1,800

*) Estimated by visual inspection

Most of the work zone scenarios were consistent in resulting in a free-flow speed of 60mph or 55mph. Both number are likely appropriate for most work zones. The team recommends that the lower FFS of 55mph be considered when the lane closure scenario involves more than one lane closure. The 60pm FFS may be more appropriate for single lane closures for facilities with three or more base lanes. A two-lane facility with a single-lane closure would likely call for a 55mph free-flow speed. It is emphasized here that all work zones in this study were signed at a speed limit of 55 mph. It can be assumed that a lower posted speed limit of 50 mph or even 45 mph, would result in even lower free-flow speeds. However, current analysis practice in the HCM2010 does not consider facilities with FFS less than 55mph.

The estimation of CAFs proved even more challenging, due to limited data. For most scenarios, the resulting CAF was around 0.8, which means that the work zone only provides 80% of the per-lane base capacity. A higher CAF of 0.89 was estimated for the 4-3 lane closure scenario, which makes intuitive sense, as that particular scenario is less severe in terms of restricting vehicular movement. A lower CAF of 0.7-0.8 was estimated for lane closure scenarios 4-1 and 2-1, which is also intuitive, as they represent a more severe narrowing of the facility. These estimates should be treated with caution, however, because the available data were limited.

Finally, Exhibit 36 converts the CAF to a per-lane capacity for the work zone scenario by multiplying the CAF by the base capacity for free-flow speed of 55 or 60 mph (2,250 and 2,300 pcphpln, respectively).

Work Zone Capacity Recommendations as NC Defaults

Based on the field data results, the team did not arrive at a satisfactory sample size for most work zone lane closure scenarios. In the absence of robust and recent North Carolina data, it is recommended to use the HCM2010 default work zone capacities as applicable (6). However, the HCM2010 only covers work zones up to four normal lanes. Additionally, an estimate for a 5-to-2 lane closure capacity was available based on research by Krammas and Lopez (24). Since the FREEVAL-WZ computational engine should be flexible for a range of facility types, the following defaults are recommended to us in the software (Exhibit 37). It is emphasized that the gray shaded cells are the authors' assumptions and are not supported by empirical data. It is highly recommended that additional data collection be performend for all lane closure scenarios, specific to North Carolina conditions.

Exhibit 37: Recommended WZ Capacity by lane closure scenario (pcphpln)

Closed Lanes \ Normal Lanes	2	3	4	5	6	7	8
1	1400 (1)	1450 (1)	1500 (1)	1700	2000	2100	2200
2		1450 (1)	1450 (1)	1580 (2)	1800	1900	2000
3			1350 (1)	1400	1600	1700	1800
4				1300	1300	1300	1300
5					1300	1300	1300
6						1300	1300
7							1300

(1) Source: HCM2010 Exhibit 10-14 (Reference 6)

(2) Source: Krammas and Lopez Study (Reference 24)

Default inputs in gray cells are assumptions and not supported by data!

In order to estimate the capacity adjustment factor (CAF) for work zones, a free-flow speed (FFS) needs to be estimated. The following FFS defaults are recommended and are used in the FREEVAL-WZ software (Exhibit 38).

Exhibit 38: Suggest FFS Based on Lane Closure Scenarios

Closed Lanes \ Normal Lanes	2	3	4	5	6	7	8
1	55	55	55	55	55	55	55
2		60	55	55	55	55	55
3			60	60	60	60	60
4				60	60	60	60
5					60	60	60
6						60	60
7							60

The FFS default recommendation is 55 mph for any lane closures that only leave one or two lanes open, except for a 3-2 lane closure. For all remaining scenarios, a FFS of 60 mph is recommended. Again, no facilities with five or more base lanes were included in this research, and the estimates in Exhibit 38 are assumptions (gray shaded cells). It should further be emphasized that, where possible, local data should be used to estimate the FFS directly, especially if the work zone is signed at a speed limit less than 55 mph!

In HCM2010 theory (6) the FFS is linked to a base capacity per lane, in the absence of lane closures. Specifically, a FFS of 55 mph corresponds to a base capacity of 2,250 pcphpl, while a FFS of 60 mph corresponds to a base capacity of 2,350 pcphpl. By dividing the work zone capacity (Exhibit 37) by the corresponding base capacity associated with the FFS in Exhibit 38, a set of default CAFs is obtained. The CAFs are presented in Exhibit 39.

Exhibit 39: Estimated WZ Capacity by lane closure scenario (pcphpln)

Closed Lanes \ Normal Lanes	2	3	4	5	6	7	8
1	0.62	0.64	0.67	0.76	0.89	0.93	0.98
2		0.63	0.64	0.70	0.80	0.84	0.89
3			0.59	0.61	0.70	0.74	0.78
4				0.57	0.57	0.57	0.57
5					0.57	0.57	0.57
6						0.57	0.57
7							0.57

The FREEVAL-WZ software tool uses the work zone capacity defaults from Exhibit 37 and the FFS defaults from Exhibit 38 in estimating the CAF for a specific work zone lane closure scenario. The user is able to override these defaults for any scenario as necessary. In other words, the CAFs in Exhbit 39 are what FREEVAL-WZ would use without user inputs, but the CAFs are not hard-coded in the software.

6. VALIDATION

This section describes an effort to validate the FREEVAL-WZ operational methodology to a series of work zones in North Carolina from available sensor data. The data sources and work zone scenarios were largely consistent with those extracted for the development of default capacity values in Chapter 5. However, in this section the focus is on the operational performance and the congestion impacts of the work zone over time and space.

Study and Data Preparation Approach

In the initial stages of the study, work zone diaries completed by the work zone contractor were obtained through communications with the North Carolina Department of Transportation (NCDOT). The diaries pertained primarily to two projects in Raleigh, North Carolina along interstate I-40, which were labeled I-4744 (I-40 Widening from Jones Franklin Road to Harrison Avenue) and I-5112 (I-40 Rehab from Wade Avenue to I-540). The work zone diaries included an affected mile posting range, which could be used to determine the correct sensor data to extract, as well as the proposed number of lanes to be closed along with the time period in which the work zone occurred. The sensor site used for data extraction was Traffic.com (37). Archival data at 15 minute time resolution and lane-by-lane speeds and volumes were downloaded for analysis, after categorizing the temporal and spatial ranges.

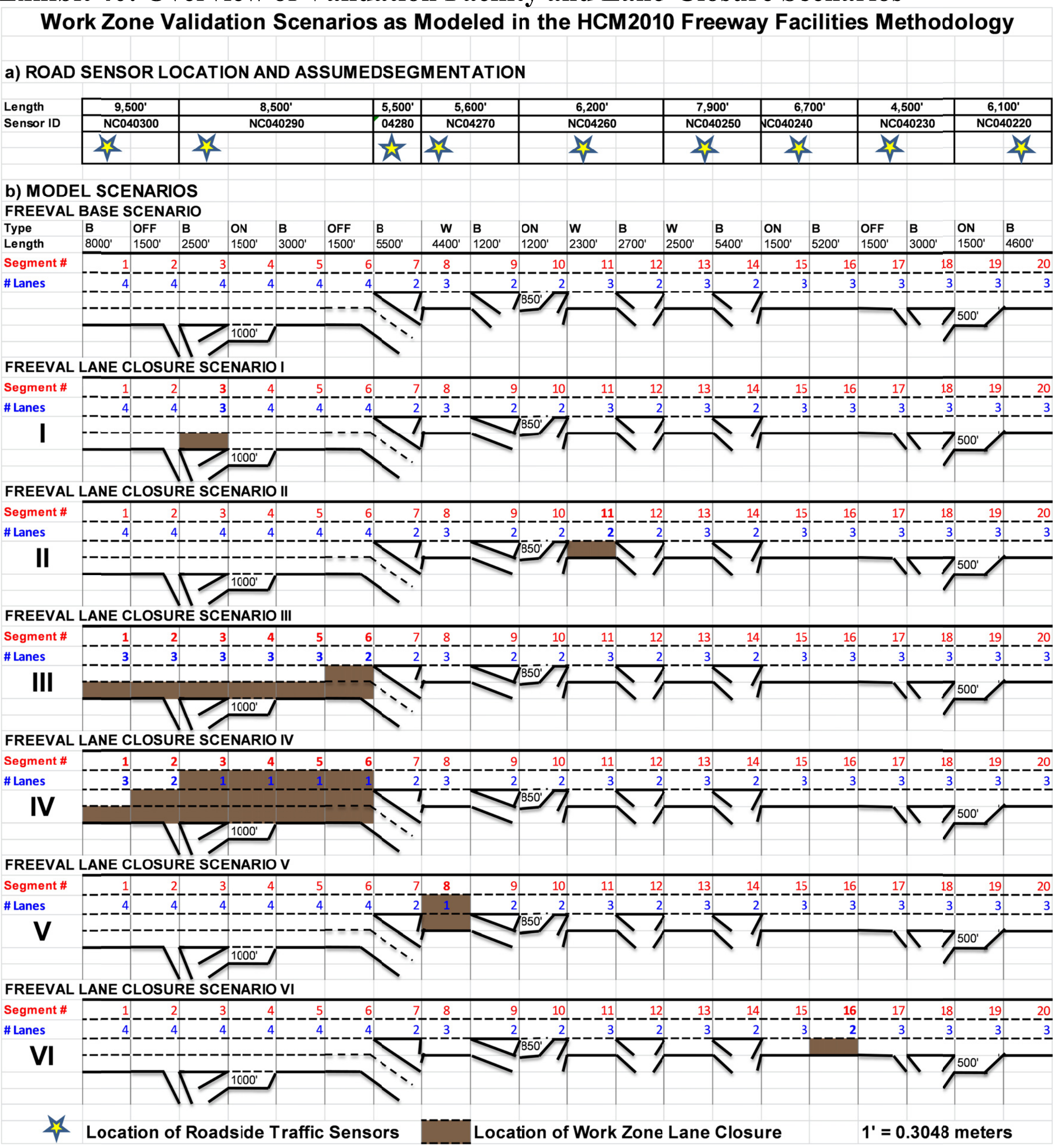
After extraction, the datasets were first graphed on a lane-by-lane basis to confirm that the particular work zone took place, to ensure that the specified lane closure scenario was accurate, and to assess at what time lanes were physically closed. Three-dimensional surface charts were developed to more accurately understand the 15 minute flow and speed data. These charts allowed for coordination between defining the FREEVAL segments and locating the Traffic.com sensors.

All of the analyzed work zones were compiled and organized based on the specified date of the lane closures. These dates were then analyzed according to possible lane closure configurations at each of the nine Traffic.com sensors used earlier in the study. Candidate dates were then selected based on the accuracy and completeness of the data. The selected dates covered multiple lane closure configurations (e.g. 4-3, 4-2, 3-2, etc.), as well as multiple work zone scenarios (barrier and non-barrier) and work encompassing multiple directions (eastbound and westbound). Speed and volume contour maps were subsequently produced for both the Traffic.com and FREEVAL datasets for each of the selected candidate dates to compare model results to field data.

Validation Scenarios

The validation scenarios were selected to represent a variety of work zone configurations, and the STIP I-4744 long-term construction zone on a section of Interstate 40 in North Carolina. The work zone involved an 18-month widening project that added a travel lane in both directions between mileposts 289 and 293 in Raleigh, NC. Due to heavy daytime traffic demands, all lane closures were restricted to nighttime and weekend work and all daytime work was performed behind barrier. The approximately 11.5-mile test location (18.4 kilometers) encompasses a range of different cross-sections (two to four lanes per direction) and includes basic freeway segments, merge and diverge sections, and several freeway weaving segments. It therefore represents an ideal test location to demonstrate both the applicability of the FREEVAL-WZ method to a complex facility, and to illustrate the viability of the work zone scenario modeling. The facility is shown in Exhibit 40.

Exhibit 40: Overview of Validation Facility and Lane-Closure Scenarios



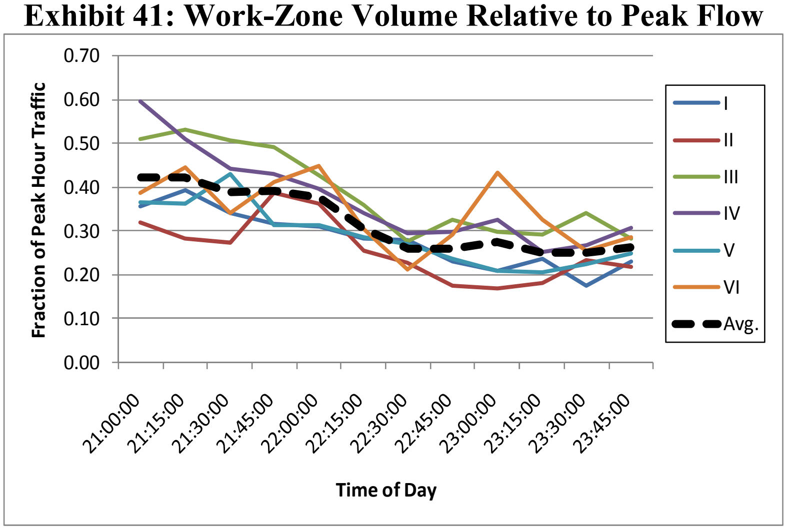
The exhibit shows that the facility includes a total of 20 HCM segments, but only 9 roadside traffic sensors. In order to allow for a direct comparison of the two, the Traffic.com and FREEVAL segments were both subdivided into 500' sections, which brought the two data sets to a common denominator of 120 segments. This allows for a direct comparison of model and empirical data set over the analyzed time-space domain.

The analysis initially focused on the base scenario, which was modeled for the 2010 PM Peak Hour. The base scenario was then compared to conditions in August 2009 (PM Peak Hour), prior to the onset of any construction at the work zone. That baseline scenario is also compared initially to a set of *barrier* scenarios, which represent conditions during the construction activities, but without any lane closures. The PM peak barrier scenarios are used to explore impacts of added friction on the facility due to construction activities and reduced shoulder width.

Besides exploring the effect of work zone barriers on daytime peak hour conditions, the analysis also included night time and weekend lane closure scenarios. The range of tested lane closure scenarios is also shown in Exhibit 40. All lane closures were implemented during nighttime traffic conditions. All nighttime lane closures were scheduled to start at 9:00 PM, but the actual start of the lane closure was oftentimes closer to 10:00 PM. The exact start time of the lane closure (rounded to the nearest 15 minutes for compatibility with HCM theory) was estimated from lane-by-lane sensor data. An example lane-by-lane data plot was shown in Chapter 3.

One of the most critical inputs into a freeway facilities analysis besides lane geometry, are traffic demand flows at all entry and exit points in 15-minute intervals. The team obtained detailed base year hourly data for the peak period. From this information, volume profiles for a three-hour analysis period were developed using a peak hour factor of 0.90 and assuming a lead-in and lead-out period that equals 80% and 70% of peak hour demand, respectively. These demand pattern assumptions were later confirmed from sensor data. Detailed demand data for the off-peak lane closure scenarios were not available. The authors therefore had to rely on the assumption of a decreased demand pattern that is proportional to the available peak-hour distribution. The percentage of peak hour traffic that was modeled in each off-peak time period was estimated, based on sensor data. Exhibit 41 shows a plot of the entering traffic demands for the six work zone scenarios expressed as a proportion of peak hour demand.

Exhibit 41: Work-Zone Volume Relative to Peak Flow



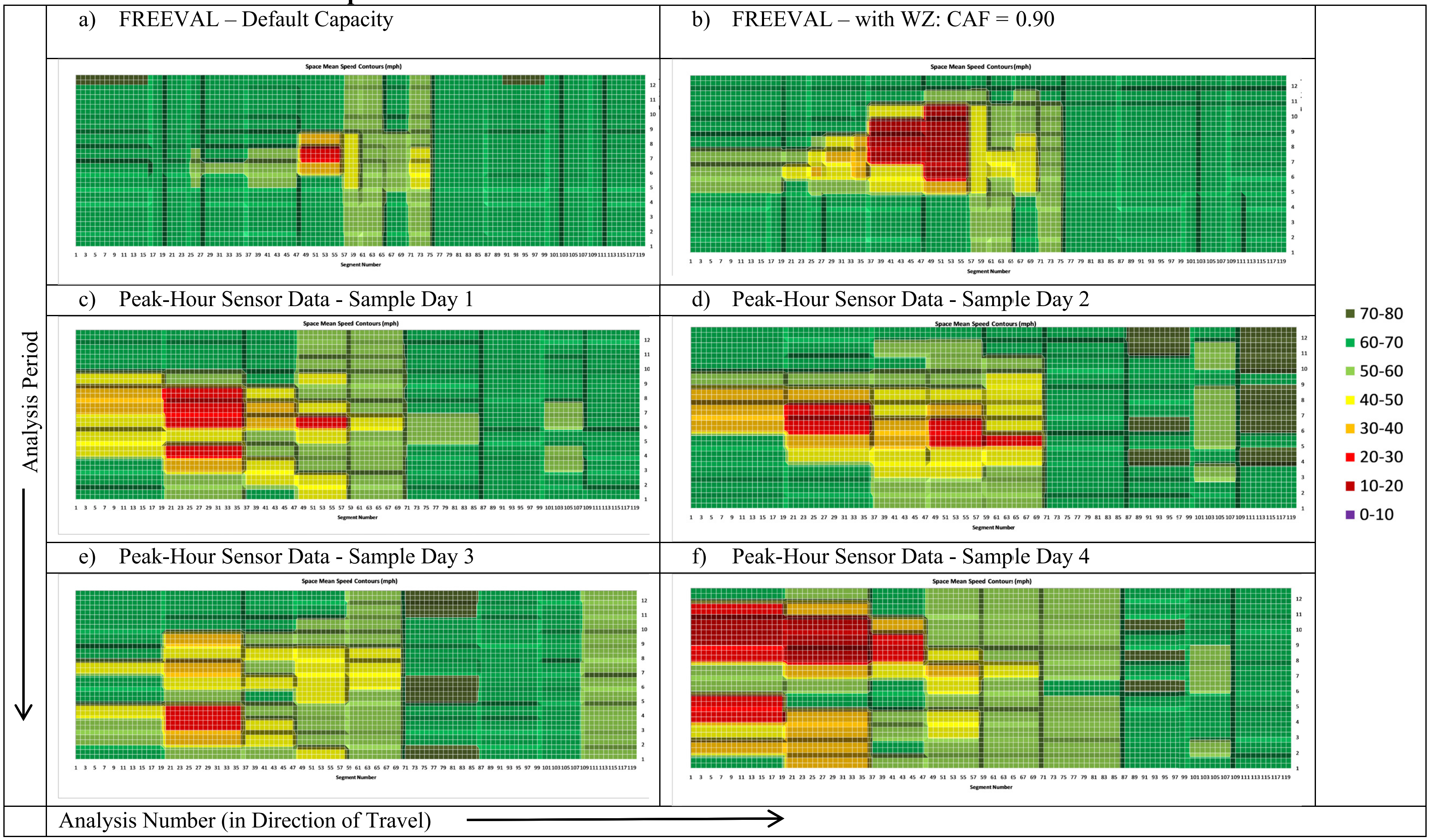
In the evaluation of these scenarios it was assumed that the average proportion curve (black dashed line) applies to all scenarios. This assumption seems incorrect in the assessment of scenario VI, which experiences an unexplained peak in demand around 11:00 PM.

Results

The key objective of this section is to compare the field-estimated performance of the freeway facility, with and without work zones, to the predicted performance using the FREEVAL-WZ. All computations were performed using the operational analysis function of the FREEVAL-WZ tool. The key performance measures are the average facility travel time over the three-hour analysis period, as well as the maximum 15-minute travel time across the facility. While most freeway traffic flow theory is based on the concepts of speed-flow-density relationships, travel time is arguably the most meaningful measure in a facility context, and is further directly perceived by drivers. FREEVAL estimates travel time by dividing each segment length by the calculated space mean speed for the segment. Facility travel time is obtained through simple summation. For the empirical sensor data, the travel time is estimated accordingly and by assuming a corresponding segment length for each sensor, where the sum of all lengths equals the overall modeled facility. Assumptions for the length associated with each segment were shown in Exhibit 40.

In addition to travel time comparison, the analysis used a visual comparison of speed over the modeled time space domain. In FREEVAL, a matrix of speeds by segment and time period is automatically generated, which can be plotted on a contour plot for visual assessment. By plotting the corresponding speed contours from the sensor data on the same scale, a direct comparison becomes possible. Exhibit 42 shows the FREEVAL predicted time-space speed distribution, as well as the peak hour observations for the four weekday work zone scenarios.

Exhibit 42: PM Peak-Hour Speed Contour Plots



The exhibit shows that the default estimates in FREEVAL from the base year (a) underestimate the operations on the facility under daytime work zone conditions with barrier installed (c through f). With a globally applied capacity adjustment factor of 0.90 (b), the estimated performance is closer to the empirical data. The plots for the work zone scenarios (c through f) correspond to peak hour conditions with construction work ongoing behind barrier, but without lane closures. As mentioned above, all lane closures on this facility were restricted to nights and weekends. The peak hour conditions show some variability across day-to-day observations as is expected on a real-world facility with slight demand fluctuations. However, all observations show a similar pattern of PM peak congestion in the first half of the facility. Referring back to Figure 1, significant turbulence is created by the major diverge and 4-to-2 lane transition in segment 7. However, it appears that the more severe congestion point is represented by a combination of segments 10 and 11, where heavy demands from two closely-spaced ramps cause ultimately cause the weaving segment 11 to be over capacity. The created queues spill back into upstream segments to a total modeled queue length of over 17,000 feet (3.2 miles or 5.2 kilometers) and reach all the way into segment 3 of the facility. By evaluating the congestion and queuing patterns in both the modeled facility and sensor data, it is evident that the ongoing construction should help improve operations, as a full lane will be added between segments 7 and 14.

After a visual calibration of the peak hour conditions, the analysis was expanded to the off-peak lane closure scenarios described in Exhibit 40. The location of each lane closure and the number of lanes closed was based on the field diaries of the work zone contractor, and were confirmed by evaluating the lane-by-lane sensor data. One of the most challenging tasks proved to be correlating the contractor description to one of the 20 segments on the freeway facility. The specified construction length in the diaries often times spanned several miles, and the lane-by-lane sensors were therefore critical to reliably determine where the lane closures took place. Even with the availability of sensor data, some assumptions for exact placement had to be made.

Exhibit 43 summarizes the work zone scenarios, including the contractor description and the actual FREEVAL segments that were closed in the evaluation. The lane closures were scheduled to go in effect at 9:00 PM, but lane-by-lane sensors showed that the actual lane closures didn’t start until 10:00PM, with the exception of scenario V, which started at 9:15 PM. All FREEVAL models were evaluated for a three-hour period from 9:00PM to 12:00 AM, with the work zone taking effect sometime within that analysis period. The end time of 12:00AM was justified, because traffic volumes at midnight had been reduced to the point where most congestion had cleared.

Exhibit 43: Summary of Scenarios and CAF Inputs

Scenario	Date	Lane Closure Milepost (Per Contractor)	Scenario Description	FREEVAL Segments Closed	HCM Default Capacity (pcphpln)	HCM Default CAF	CAF after Calibration
Base	8/30/2009	----	Base Case, PM Peak 2009	----	2400	1.00	0.95
Barrier	6/22/2010	----	Barrier Work, PM Peak 2010	----	2400	1.00	0.90
I	4/13/2010	289 to 291	4 to 3 LC, Off Peak	4	1500	0.63	0.55
II	9/15/2009	289 to 291	3 to 2 LC, Off Peak	11	1450	0.60	0.40
III	3/7/2010	288 to 289	4 to 2 LC, Weekend Off Peak	1 to 6	1450	0.60	0.60/0.70
IV	3/14/2010	285 TO 289	4 to 1 LC, Weekend Off Peak	1 TO 6	1350	0.56	0.75
V	3/18/2010	289 to 291	3 to 1 LC, Off Peak	8	1450	0.60	0.55
VI	6/22/2010	291 to 294	3 to 1 LC, Off Peak	16	1450	0.60	0.35

Exhibit 43 also shows the HCM2010 default work zone capacity for each scenario, as well as the corresponding capacity adjustment factor (CAF). Following HCM guidance, the work zone was modeled by first reducing the number of lanes in the appropriate segment, and then by applying the CAF to each of the remaining open lanes. Based on further calibration, a lower CAF ended up being used for most of the scenarios, which is also shown in the table. As discussed above, the primary calibration target was the facility travel time for the three-hour average, as well as for the worst 15-minute period during the analysis. Exhibit 44 shows the field-estimated travel time and the FREEVAL predictions before and after calibration. The table also shows the percent difference for the FREEVAL runs relative to the empirical data.

Exhibit 44: Travel Time Comparisons by Work Zone Scenario (Minutes/Vehicle)

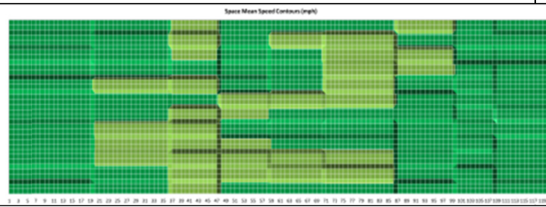
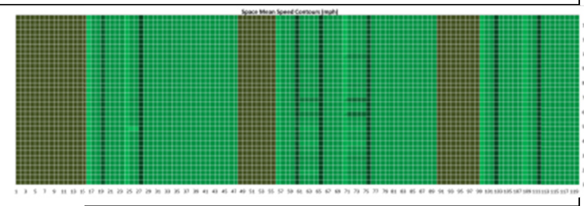
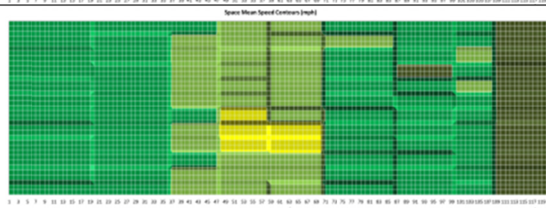
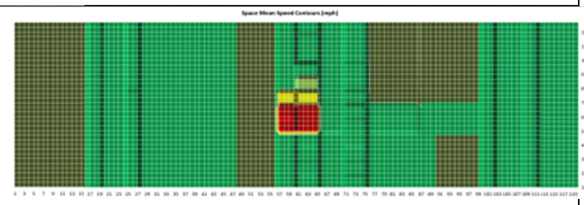
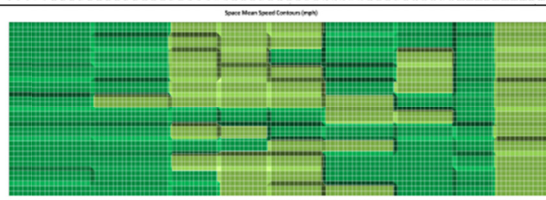
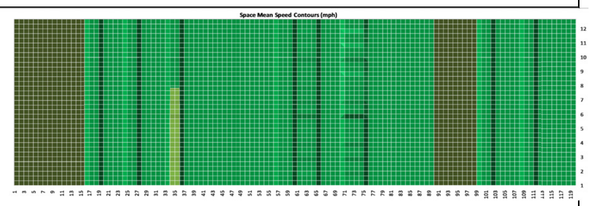
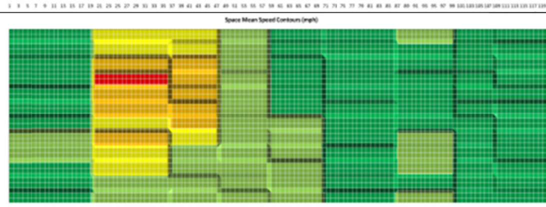
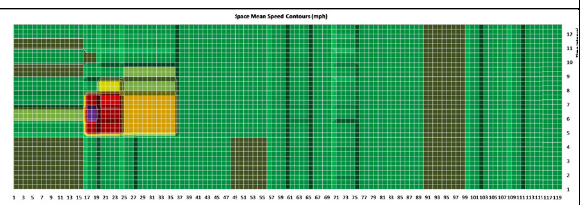
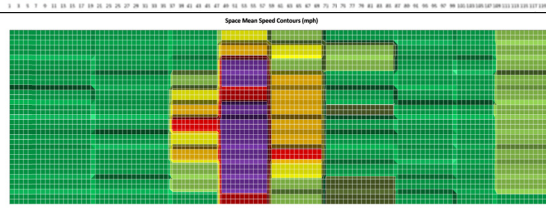
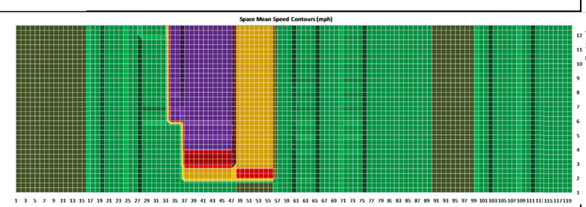
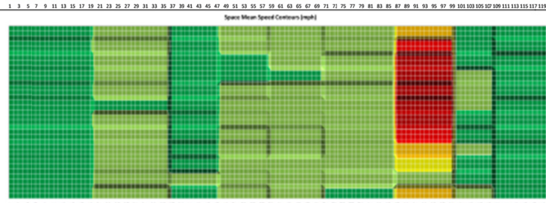
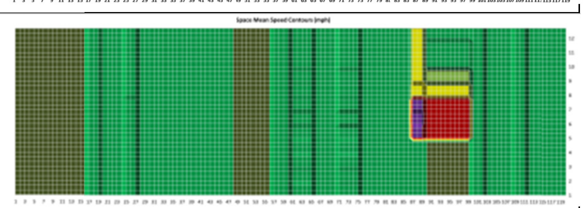
	Field Sensors		FREEVAL before Calibration)		FREEVAL (after Calibration)		% Difference (before Calib.)		% Difference (after Calib.)	
Scenario	Avg. TT	Max TT	Avg. TT	Max TT	Avg. TT	Max TT	Avg. TT	Max TT	Avg. TT	Max TT
Base	12.4	16.4	10.9	12.56	11.9	14.9	-12.1%	-23.4%	-4.0%	-9.1%
Barrier	14.1	20	10.9	12.56	13.4	18.2	-22.7%	-37.2%	-5.0%	-9.0%
I	11.1	11.2	10.0	10.0	10.7	10.8	-9.9%	-10.7%	-3.6%	-3.6%
II	11.1	11.7	10.0	10.0	10.3	11.7	-9.9%	-14.5%	-7.2%	0.0%
III	11.3	11.5	10.0	10.1	10.2	10.8	-11.5%	-12.2%	-9.7%	-6.1%
IV	12	12.8	19.1	29.9	11.0	14.3	59.2%	133.6%	-8.3%	11.7%
V	22.7	41.4	18.8	27	26.3	37.1	-17.2%	-34.8%	15.9%	-10.4%
VI	12.9	15.7	10	10	11.4	15.5	-22.5%	-36.3%	-11.6%	-1.3%

The results in Exhibit 44 suggest that the default HCM2010 work zone capacity estimates appeared to under-predict the resulting travel time on the facility in most cases, as evident by negative values in the percent error column. The error was most pronounced for the 15-minute maximum travel time, which is more volatile than the average. Before calibration, several scenarios exhibited a percent difference in excess of -30% for the 15-minute maximum, and around -20% for the average 15-minute travel time over the three-hour analysis. Interestingly, scenario IV was the only one where the default HCM lane closure setting overestimated the level of congestion on the facility. As a result, the default HCM CAF was increased from 0.56 to 0.75 after calibration. That scenario represents a four to one nighttime lane closure on a weekend, corresponding to traffic that is lower than the average weeknight demands. While further volume adjustments were made to reflect these lower demands, a difference in demand volumes during the night in question may contribute to the difference.

For the remaining scenarios, the CAF had to be decreased further to calibrate the facility travel time. Accordingly, the per-lane capacities of the open lanes in the work zone were lower than the HCM defaults. A number of factors may have contributed to that effect, including the fact that these work zones occurred at night, which may cause added friction due bright construction lights. A more thorough assessment of nighttime speed-flow data on the modeled network is necessary to explore this hypothesis, which is planned for future research. However, with the additional (marginal) calibration, the percent error in most cases was reduced to less than 10%. Given the stochastic nature of freeway operations, these results are quite promising for the deterministic HCM freeway facilities methodology.

With the travel time data showing reasonable results, the analysis also included to the visual inspection of the space-mean- speed contours. Exhibit 45 shows a side-by-side comparison for the time-space domain of twelve 15-minute analysis periods over 20 FREEVAL segments and nine traffic sensors.

Exhibit 45: Speed Contours of Lane Closure Scenarios

	SENSOR DATA	FREEVAL RESULTS
I		
II		
III		
IV		
V		
VI		

As before, results were divided into 500-foot analysis segments to allow for a direct comparison. The contours are color-coded to correspond to different speed bins, ranging from free-flow conditions (green) to congested flow (orange and red) to stopped conditions (purple). Obtaining an exact match between empirical and modeled data is clearly very difficult, but the two data sets should largely coincide in their identification of active bottlenecks, as well as the temporal and spatial extent of the resulting congestion. For the evaluation of freeway facilities, the evaluation of an extended time-space domain is critical, as bottlenecks tend to be active for several time periods. The HCM methodology and its FREEVAL implementation are ideally suited for this level of analysis.

In a review of the speed contours in Exhibit 45, it is evident that scenario I is not associated with any congestion in either the empirical data or the FREEVAL results. Evidently, a 4-to-3 lane closure in basic segment 3 at nighttime conditions keeps the facility well below capacity. From the contractor and agency perspective, this scenario represented a well-timed low-impact construction activity that didn't cause significant impact to the traveling public. The FREEVAL analysis in this case appears to predict accurate results.

Regarding scenario II, the 3-to-2 lane closure in weaving segment 11 results in a speed drop in the field data over a distance of approximately 10,000 feet (3 kilometers) for a duration of about 45 minutes. In the calibrated FREEVAL, the intensity of the speed drop is slightly more severe, but approximately matches the 45-minute duration. However, the spatial extent of the congestion appears too small in two aspects. First, FREEVAL places the location of the lane closure bottleneck at the beginning of segment 11, with a resulting drop in speeds in upstream segments 10 and 9. However, the field data appears to suggest a lower speed in segment 11 itself, which is not reflected in the modeled data. The bottleneck section itself in HCM theory is modeled to operate at capacity, which corresponds to LOS E with non-breakdown speeds. This example may suggest a closer look at the speed-flow relationships immediately downstream of an active bottleneck, or revisiting the assumption of the bottleneck being placed at the beginning of the segment. A secondary observation is that the slow-speed regime in FREEVAL doesn't seem to extend as far back as suggested by the sensor data.

Scenario III models a 4-to-2 lane closure in segment 6, which is preceded by a 4-to-3 in upstream segments to gradually transition drivers to the lane closure segment. With low weekend volumes recorded in this scenario, the sensor data does not show a drop in speed, which is also reflected in the calibrated FREEVAL. The second weekend scenario (IV) corresponds to a 4-to-1 lane closure in segment 6, again with a gradual transition from the full four-lane segment. In this case, the sensor data does show congestion caused by the lane closure, spanning a distance of nearly 15,000 feet (4.6 kilometers) and extending for over 2 hours from time of closure. In FREEVAL, a similar spatial extent of congestion is visible; however, the temporal extent appears too low at only about 45 minutes. Interestingly, the default HCM scenario (not shown) resulted in an extended period of congestion, however at a too high intensity as was shown by too-high travel times in Exhibit 44. It appears then, that the FREEVAL evaluation captures the onset of the congestion accurately (with the start of the lane closure), but then appears to dissipate the queued traffic too quickly over subsequent analysis periods. Of course, reduced traffic demands (field data relative to FREEVAL) could be an explanation, but the trends for this scenario actually follow the modeled average quite well. It is therefore suggested that the queue release portion of the oversaturated flow regime in the HCM2010 may need further research to match these observed field traffic conditions.

Scenario V represents a 3-to-1 lane closure in segment 8. It appears to provide the best match between FREEVAL and field data. In both cases congestion is severe, and extends over a time-space region of 2.5-3.0 miles and most of the modeled three-hour period. However, one important difference between the two contour plots is the speed in the bottleneck itself. Similar to the discussion above, FREEVAL assumes the bottleneck location to be at the upstream end of the segment, leaving the bottleneck itself at LOS E and relatively high speeds. A look at the sensor data suggests, however, that speeds within the bottleneck section itself are quite low as a result of the work zone friction. With two scenarios showing this pattern, this analysis suggests a need for future research to revisit the assumed location of the bottleneck and the assumed speed prediction algorithm in that segment.

The final scenario (VI) corresponds to a 3-to-2 lane closure in basic segment 16. The sensor data show a congested region of approximately 3 kilometers in length that lasts over most of the three-hour analysis period. Similar to other scenarios, the FREEVAL modeled spatial extent of the queues seems to match field observations quite well. But as before, the temporal extent of congestion is too low, with most queues clearing within about 60 minutes, while field-estimated speeds staying low beyond the modeled time period (midnight).

Summary

For validation purposes, the research team applied the HCM2010 freeway facilities methodology to a variety of work zone scenarios on a busy urban interstate facility. The evaluation included modeling of peak hour operations and off-peak lane closure scenarios covering a range of geometric work zone configurations. The evaluation performed in the FREEVAL computational engine was compared to detailed automated sensor data that was available for all scenarios. Those field data were previously used to calibrate methodology input parameters, and in particular settings for the evaluation of freeway work zone lane closures.

The analysis focused on calibration of the HCM capacity adjustment factor (CAF) to represent the proportion of available per-lane capacity that is available under various work zone configurations. The calibration utilized both facility travel time, as well as space-mean-speed contour maps across the entire modeled time-space domain. The analysis showed that the HCM freeway facility methodology has merit for the application to freeway work zone and allows sufficient ability for calibration to match field-observed performance. The analysis suggests that the default work zone lane capacity values were a little too high for the modeled facility, which may be explained by the fact that all studied lane closures corresponded to night-time conditions. With relatively minor adjustments, most facility travel time estimates were calibrated to within a 10 percent difference from collected data.

A closer look at the speed contour plots identified several areas within the HCM methodology that warrant future research. First, there is evidence that while the HCM assumes the bottleneck to be placed at the upstream end of the segment, the field data suggests some degree of speed drop within that segment itself. Current HCM theory assumes that the bottleneck segment itself operates at acceptable speeds and a LOS of E. Future research should investigate the speed performance within the bottleneck itself with the goal of developing an improved speed prediction algorithm. Second, several tested scenarios suggest that the HCM methodology underestimates the temporal extent of congestion resulting from the bottleneck. The HCM results accurately matched the spatial extent and travel time through the bottleneck, but tended to clear the queues too quickly relative to field data. Future research should therefore re-evaluate the portion of the oversaturated flow regime algorithms that deals with recovery from breakdown condition.

Finally, future research should explore differences in segment types when applying the CAF. In current theory, the CAF and associated speed prediction algorithm is applied consistently to all freeway segment types, including basic segments, merge/diverge segments, and weaving segments. These segments operate quite differently in undersaturated conditions, which is why three different computational methodologies exist (in three different HCM chapters). There is concern related to a discrepancy in results when the CAF is applied, which essentially overrides the HCM chapter methodologies when estimating capacity and segment speed prediction. But even with these limitations, the results in this research report make a strong case for the validity of the HCM2010 freeway facilities methodology and its applicability to the evaluation of freeway work zones with high impact to the traveling public. Given the efficiency and deterministic consistency of HCM results, the method should remain to be a strong contender against microsimulation analysis tools.

7. FINDINGS, CONCLUSIONS, AND RECOMMENDATIONS

This project developed an analysis methodology and associated software implementation for the evaluation of significant work zones on freeways and multi-lane highways in North Carolina. The FREEVAL-WZ tool allows the prediction of traffic operational impacts of work zones, including capacity reductions, lane closures, reduced speed limits and traffic diversions. The research is based on the 2010 Highway Capacity Manual Freeway Facilities methodology and its FREEVAL computational engine. Through this project, the tool was enhanced to allow for work-zone specific impact assessment, customized to the needs of the NCDOT Traffic Management Unit. The tool includes a new planning-level feature that allows for a quick assessment of work zone impacts, while still allowing for a more detailed operational analysis. Work zone impacts are coded in the form of default values for North Carolina conditions, but can be adjusted by user input. Further, the methodology allows the analyst to calculate user cost impacts of the work zone. All calculations and algorithms in FREEVAL-WZ are consistent with the methodologies in the 2010 Highway Capacity Manual.

The project found significant variability in the literature about best practices for work zone analysis, and specifically the estimation of the effects of freeway work zones on capacity and speed. The variation of work zone capacity estimates in the literature emphasizes the need for calibration to local and regional conditions. In an effort to achieve such calibration in this project, the team extracted large amounts of work zone sensor data from Traffic.com roadside sensors. The data were used to compare predicted model performance to field operations, and to develop default parameters for typical North Carolina work zone configurations. Work zone contractor diaries were obtained to identify times and locations of construction activity, with an emphasis on lane closures. Sensor data were extracted at days when construction activity was noted. Unfortunately, of the approximately 4,500 extracted fifteen-minute periods, only a little over 500 (roughly 10%) were usable in the research. A lane-by-lane analysis of the remaining time periods showed that the sensor was located outside of the lane closure activity area. For future research it is thus strongly recommended to conduct custom field studies, where equipment can be deployed directly at the beginning of the work zone lane closure, as suggested by the literature review for this study.

With limited field data, the team was not able to reliably estiamte capacity adjustment factors (CAFs) for NC specific work zone operations. The default inputs in the FREEVAL-WZ software tool therefore rely on guidance in the 2010 Highway Capacity Manual. Clearly, these defaults can be updated as more comprehensive NC data become available. When applying these calibrated CAFs to a NC case study, some CAFs needed to be further reduced to produce a better match for field-estimated speed data. In other words, the calibrated CAF underestimated the effect of work zone congestion. It is therefore recommended that in addition to using the NC defaults, the analyst should run a sensitivity analysis in FREEVAL-WZ with a lower CAF for a more conservative estimate of potential work-zone induced delays.

In summary, more experience is needed with the FREEVAL-WZ tool in application to NC work zone analysis, and it is highly recommended that the NCDOT keep a record of analysis results produced from the tool in comparison to field experience. Over time, this will allow the NCDOT to build in-house expertise and best practices for the operational evaluation of freeway work zones in North Carolina.

Through this project, the NCDOT now has a customized software tool that allows for efficient analysis of work zone impacts. Despite the need for further calibration, the FREEVAL-WZ tool represents a significant improvement over the QUEWZ-98 model that was previously used by the Work Zone Traffic Control Unit. With the enhanced user-friendliness, the tool can be applied at high efficiency and at a reduced coding and data collection effort than the former operational-only version of FREEVAL. The FREEVAL-WZ tool and guidance for work zone analysis put forth in this report are expected to facilitate the analysis of significant freeway work zones in North Carolina. The deterministic tool can be readily used by staff within the NCDOT, and can be applied at much reduced cost and coding effort than a simulation-based analysis of work zone impacts for many scenarios. A simulation-based approach remains an important alternative analysis approach, especially for facilities with unusual geometry that does not fit within the deterministic framework of FREEVAL-WZ.

8. IMPLEMENTATION AND TECHNOLOGY TRANSFER PLAN

Research Products

The product of this research is a systematic procedure for analyzing the impacts of significant work zones on traffic operations on freeways and multi-lane highways and a companion software tool implementing the methodology. The Microsoft Excel and Visual Basic based software tool FREEVAL-WZ is customized for the needs and requirements of the NCDOT Traffic Management Unit. The product is adaptable for planning-level and operational analyses and can be calibrated to reflect present-day user cost and local estimates of work zone capacity in calculation algorithms consistent with HCM2010 procedures.

The research team also provided technical training for personnel in the NCDOT Traffic Management Unit on the use of the software through a full-day training class at ITRE in March 2011 . This final report further summarizes the overall research findings. The report includes a detailed case study application of the software to a significant North Carolina work zone application that demonstrates the abilities and limitations of the software.

With the completion of this research, FREEVAL-WZ is intended to be used by the Work Zone Traffic Control Section to evaluate traffic operational impacts of work zones on freeways and multi-lane highways in-house. The tool is shown to have greater accuracy than current state-of-the-practice tools and allows for more time-efficient analysis than is possible by contracting private entities for simulation analysis. The need for a more detailed simulation analysis remains for some more complex work zone scenarios, especially as the modeled geometry exceeds the limitations of the HCM2010 analysis framework. Since it is based on the methods of the Highway Capacity Manual, the software further has application for other units within NCDOT, including Congestion Management.

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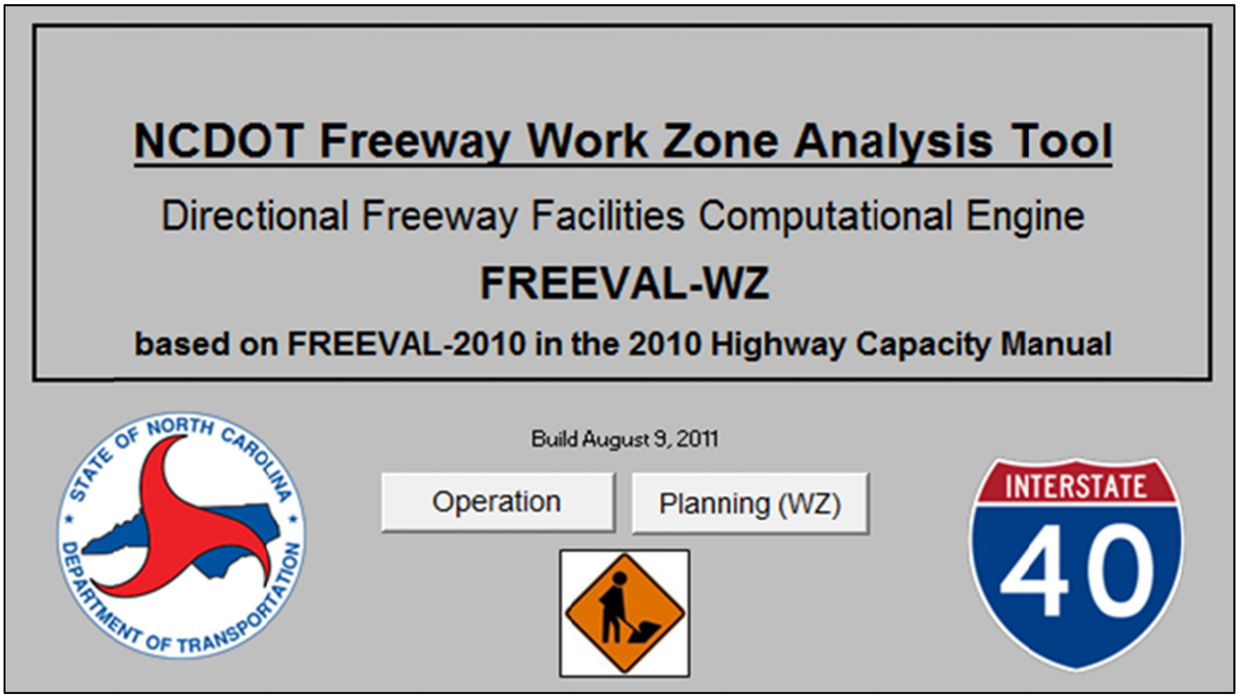
10. APPENDIX

Appendix A: FREEVAL-WZ User Guide - Planning

FREEVAL-WZ User Guide
Planning-Level Interface



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Based on NCDOT Research Project 2010-08

August 9, 2011

Introduction

This appendix presents a user guide of the FREEVAL-WZ Software Tool. It focuses on how to use the new planning-level input and output utility that was added to the software as part of this research. Guidance for using the operational analysis features of FREEVAL is provided through a user guide that is part of HCM2010 Volume IV. That user guide is also appended to this report as Appendix B. No changes to the operational side of FREEVAL were performed through this project.

The main flow-chart for a FREEVAL-WZ analysis is shown in Exhibit 46. The user initial has the ability to chose between performing an operational analysis (see Appendix) or a (new) planning-level analysis. For the planning-level analysis, the user first goes to a series of steps to generate a **Facility Template** file. This template contains all geometric and volume information for the freeway facility analysis, but has not yet been processed. It is of critical importance that the user saves this template *prior to commiting to the number of time periods and analysis segments*. After the facility has been processed, changes can no longer be made to the extend of the analysis time-space-domain. More importantly, only a non-processed file in *template mode* can be re-opened in the planning-level interface. Once a file has been processed, it can still be saved, but after closing it will automatically re-open in the operational analysis mode.

After processing the template, the user enters the **Scenario-Specific Mode**, where various outputs are presented through charts, tables, and printable reports. The user can "go to operations" at any point in the analysis, but will not be able to return to planning mode.

A proposed work-flow of a FREEVAL-WZ analysis is as follows:

1. Gather All Input Data
2. Develop **Facility Template** in Planning-Level mode
3. Save Template PRIOR TO going processing facility and going to output!
4. Use Template to develop scenarios (do not change inputs from completed scenario)
5. Process base-year facility in **Scenario-Specific Mode**, calibrate if necessary, copy putput, save results file (*will only be able to re-open as operational FREEVAL*)
6. Re-open template to develop other scenario files, calibrate, copy output, save results file
7. Perform comparison of scenarios

The remaining material in this appendix is presented through a series of screenshots that guide the reader through the various menus of the FREEVAL-WZ planning-level analysis tool. When FREEVAL-WZ is first started, the user may be prompted to "enable macros". This is critical to assure the functionality of the tool. In Office 2010, all FREEVAL-WZ files should always be saved as a macro-enabled file (.xlsm).

Exhibit 47 shows the opening screen of the tool. The user has the choice between selecting "Operation" or "Planning" analysis, where the latter includes the direct work zone functionality. This appendix only addresses "Planning"; for details on "Operation" the reader is referred to Appendix B.

Exhibit 46: FREEVAL-WZ Work Flow Diagram

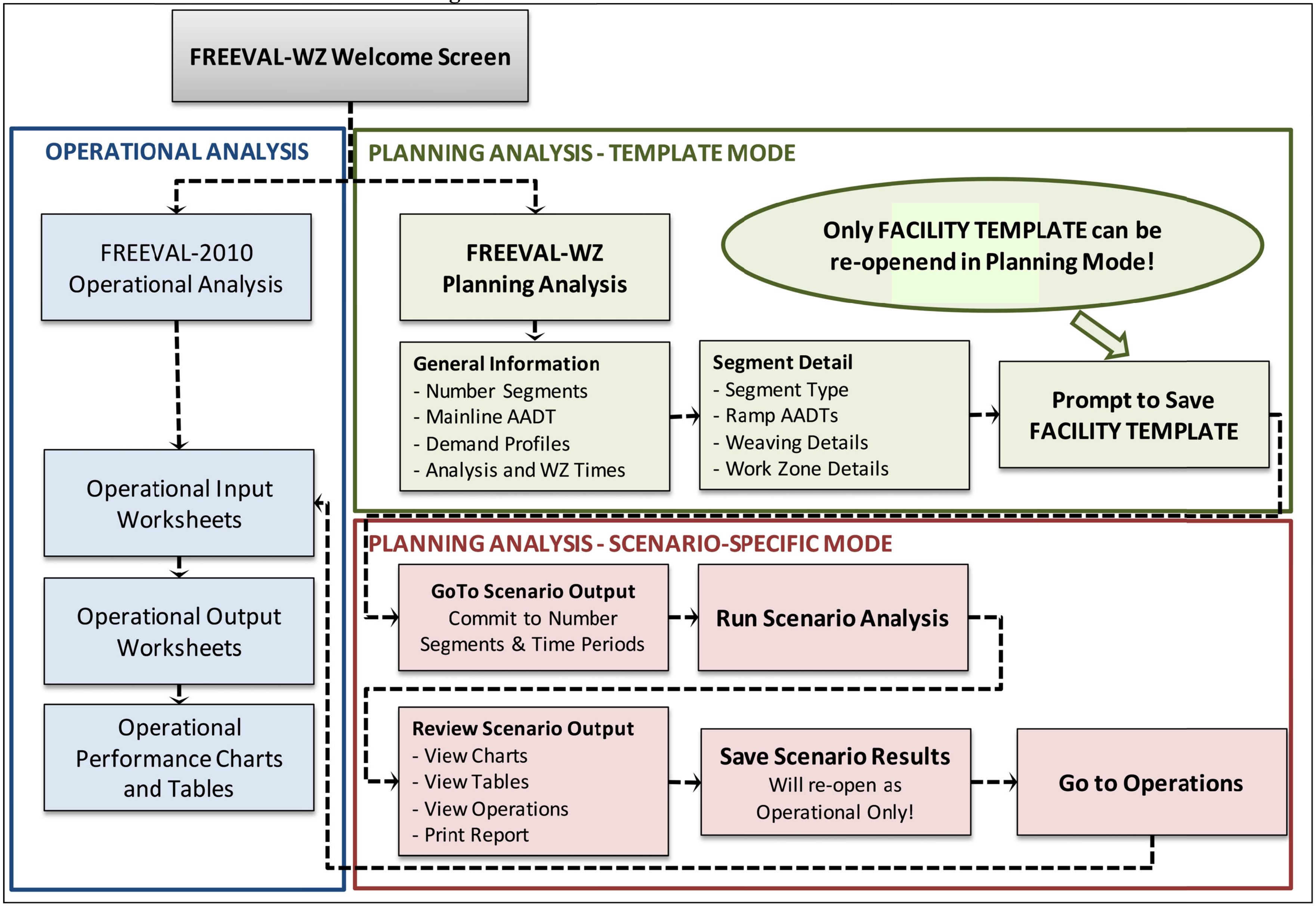
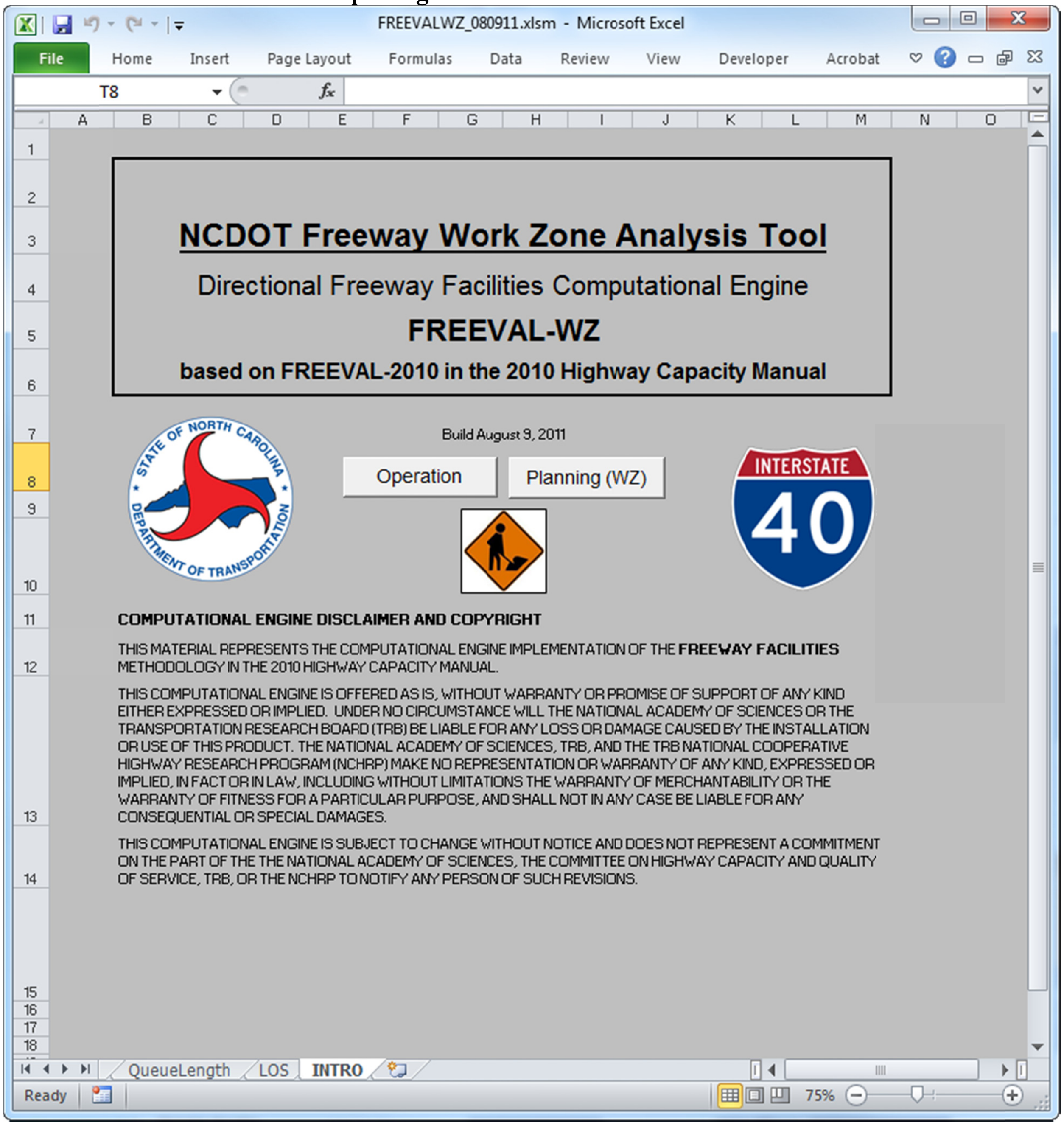
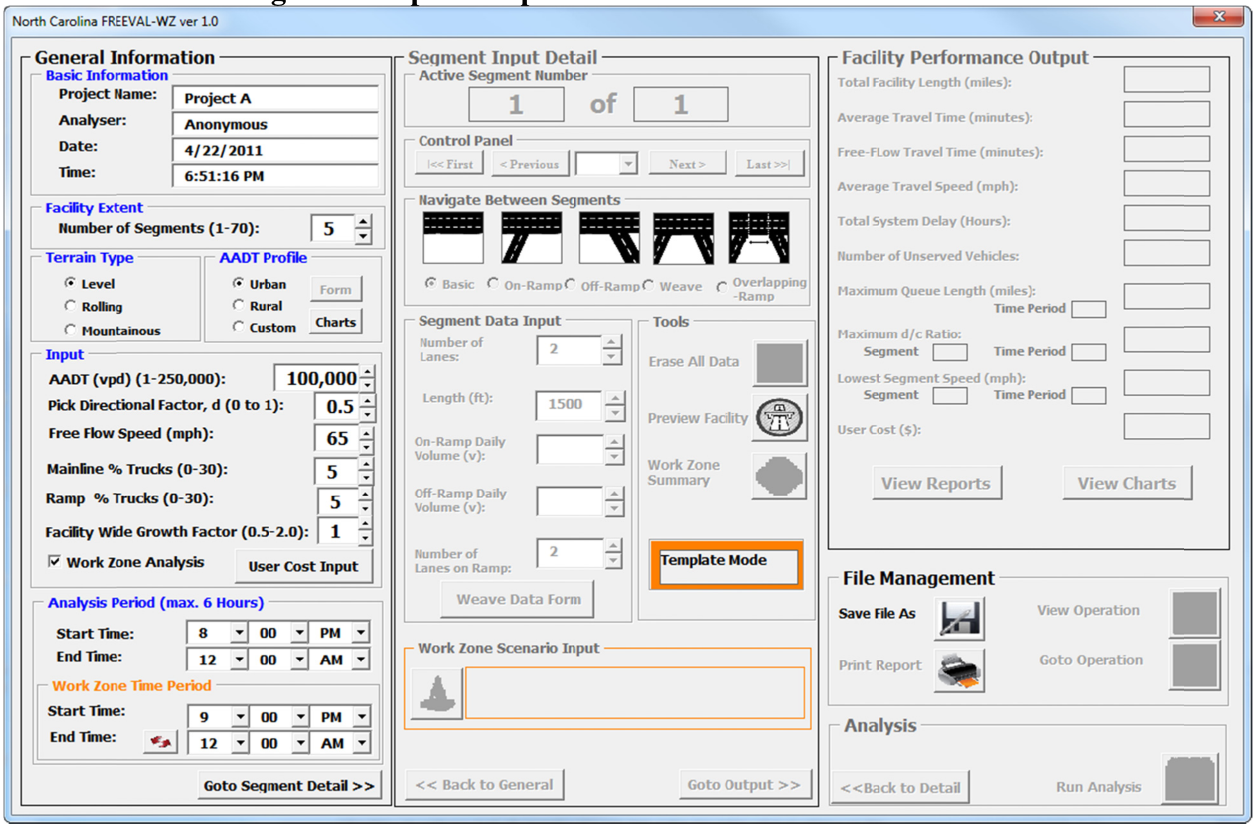


Exhibit 47: FREEVAL-WZ Opening Screen



The FREEVAL-WZ planning interface is built around a one-screen input and output utility. Exhibit 48 shows that screen for a new facility. The screen is organized in three columns: (1) General Information, (2) Segment Input Detail, and (3) Facility Performance Output. The user navigates between these columns using the navigational aids at the bottom of the screen. This user guide provides a step-by-step procedure for how to execute the tool and run an analysis. Notice that the middle colum currently shows "Template Mode" for this non-processed facility.

Exhibit 48: Planning-Level Input-Output Screen



First, the user enters general project information, which will be printed in the output reports. The user then selects the number of segments to analyze. The user then selects the terrain type (for truck adjustment factors) and the AADT profile to use for distributing AADT traffic input across the analysis period. The build-in profiles are shown in Exhibit 49 for urban, rural, and custom facilities. The custom profile can be edited to reflect any desired k-factor distribution across 24 hours.

Several other adjustments are available to the analyst, include directional factor, free flow speed, percentage trucks on mainline and ramps, and a facility-wide growth factor for easy sensitivity analyses. The User cost input button opens the dialog shown in Exhibit 50, where UDC and VOC defaults can be adjusted.

Exhibit 49: Daily Volume Profiles

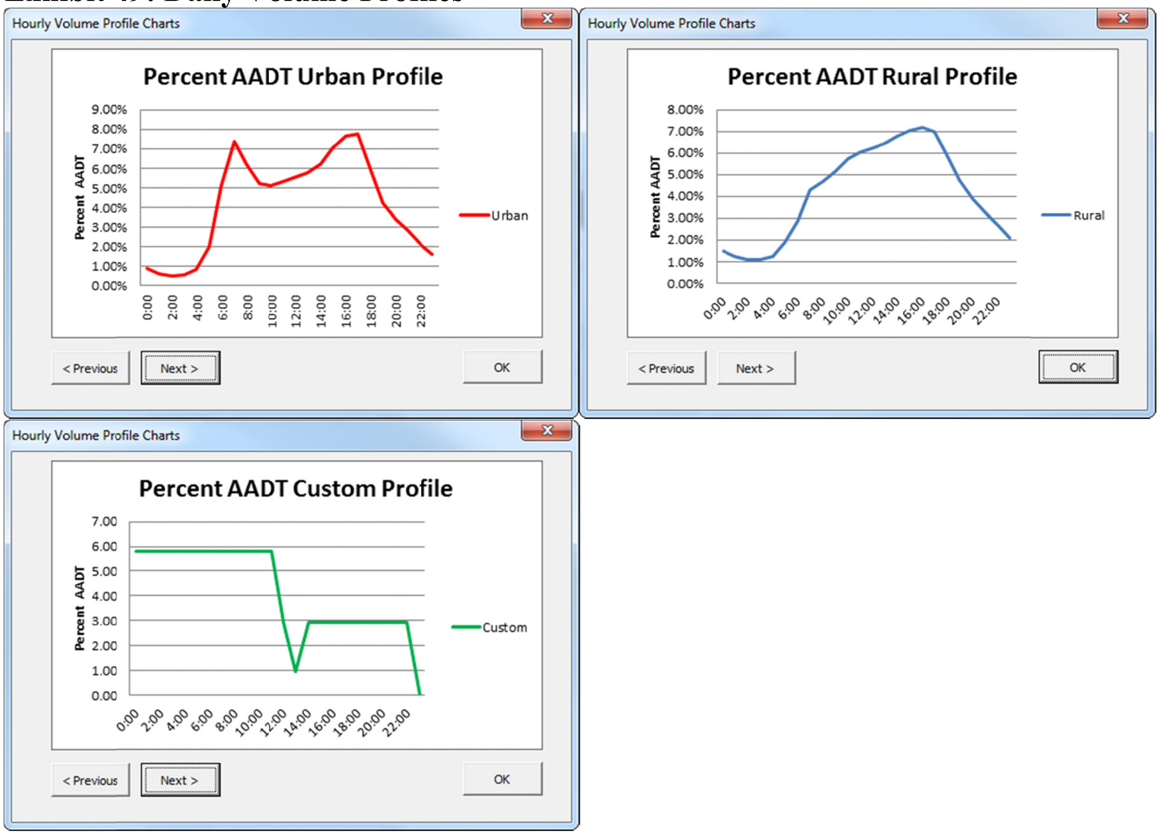
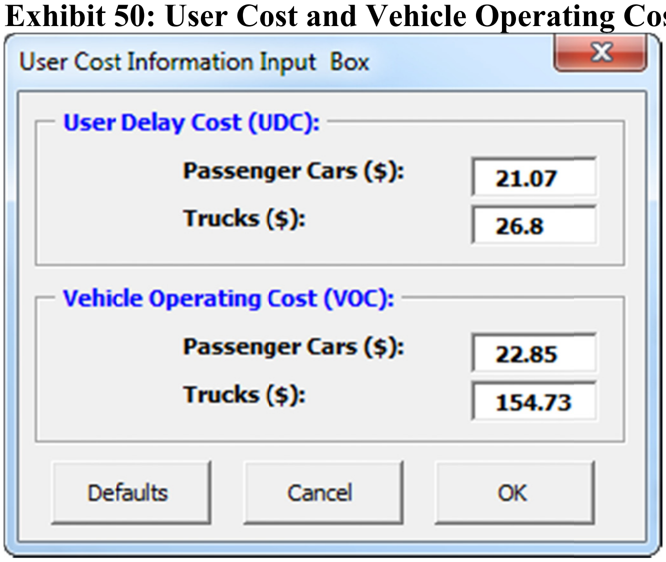


Exhibit 50: User Cost and Vehicle Operating Cost Inputs



After completing the general input, the user selects "Go to Segment Detail" at the bottom of the window (Exhibit 51). For each segment, the user can select the segment type as basic, on-ramp, off-ramp, weave, or overlapping ramp segment, consistent with HCM2010 theory. Each segment detail further includes the number of lanes, segment length, and AADT for any on- or off-ramps. For weaving segments, additional detail can be entered (Exhibit 52) if desired, although the method defaults to a standard one-sided weave with a single auxiliary lane (old "Type A" weave from HCM2000). When clicking “Preview Facility” the analyst gets a visual representation of the facility (Exhibit 53). This feature only works if the folder “FREEVAL Pics” is stored in the same directory as the current FREEVAL file.

Exhibit 51: Segment Entry Details

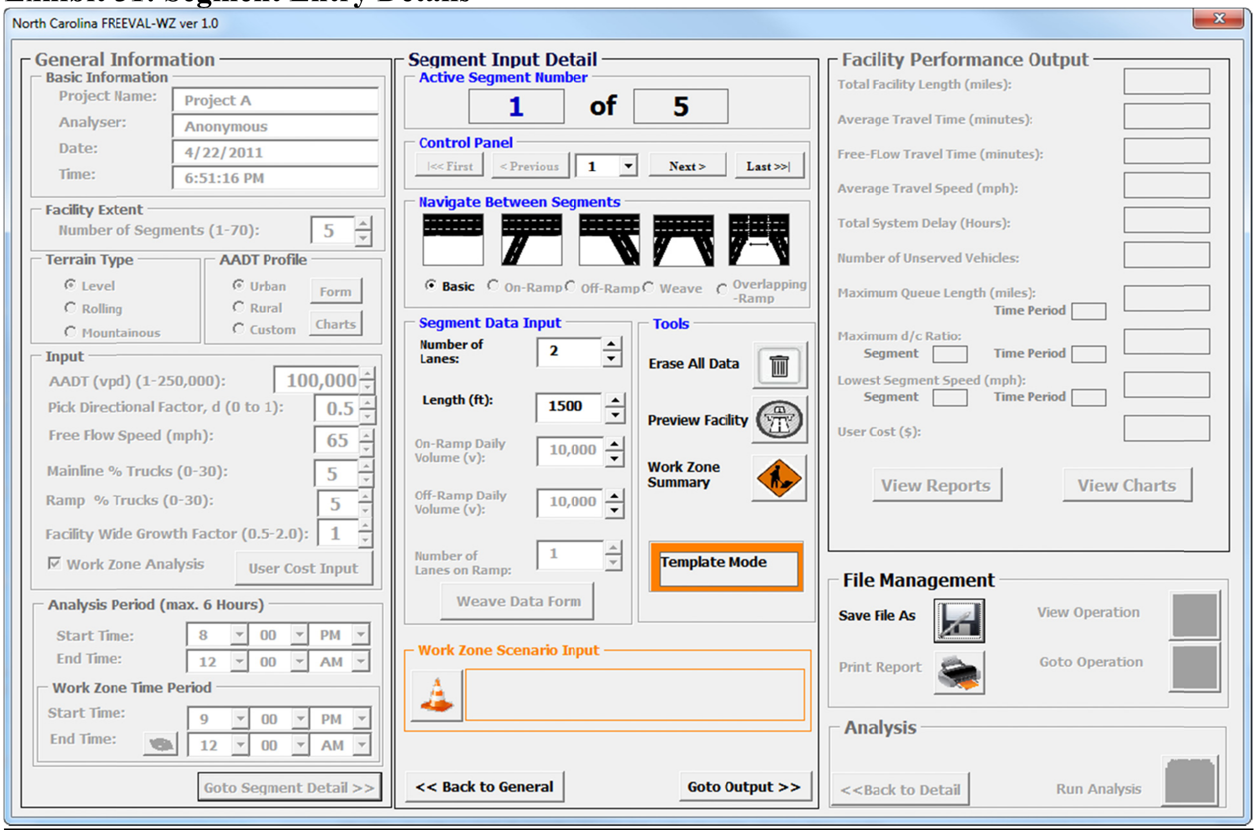


Exhibit 52: Supplemental Weave Data Entry

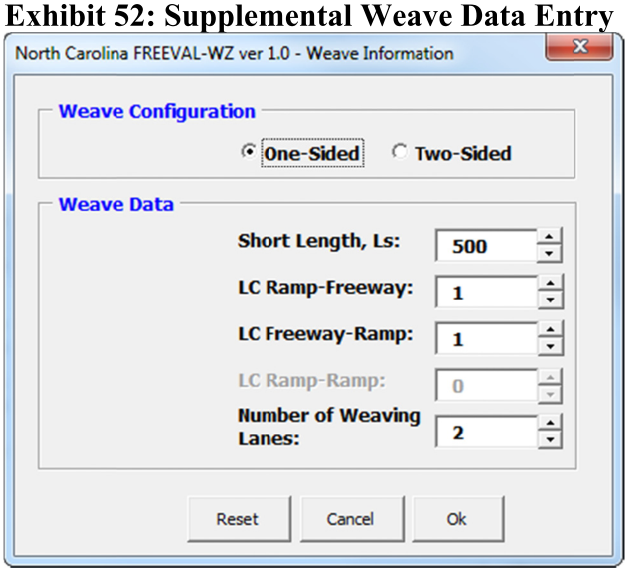
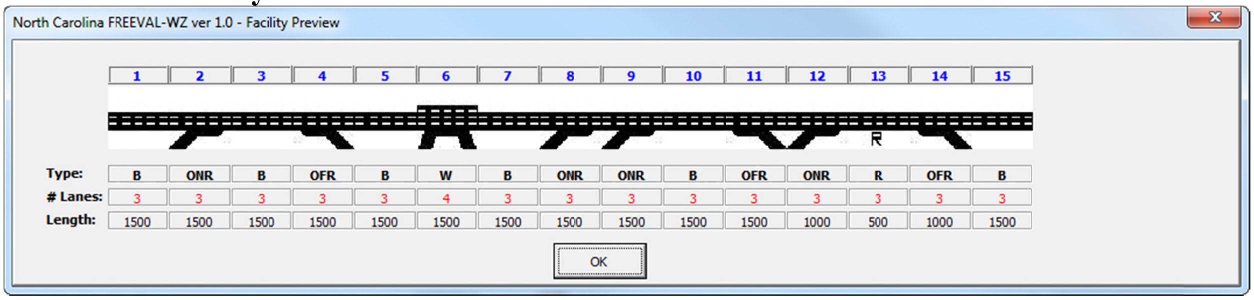


Exhibit 53: Facility Preview

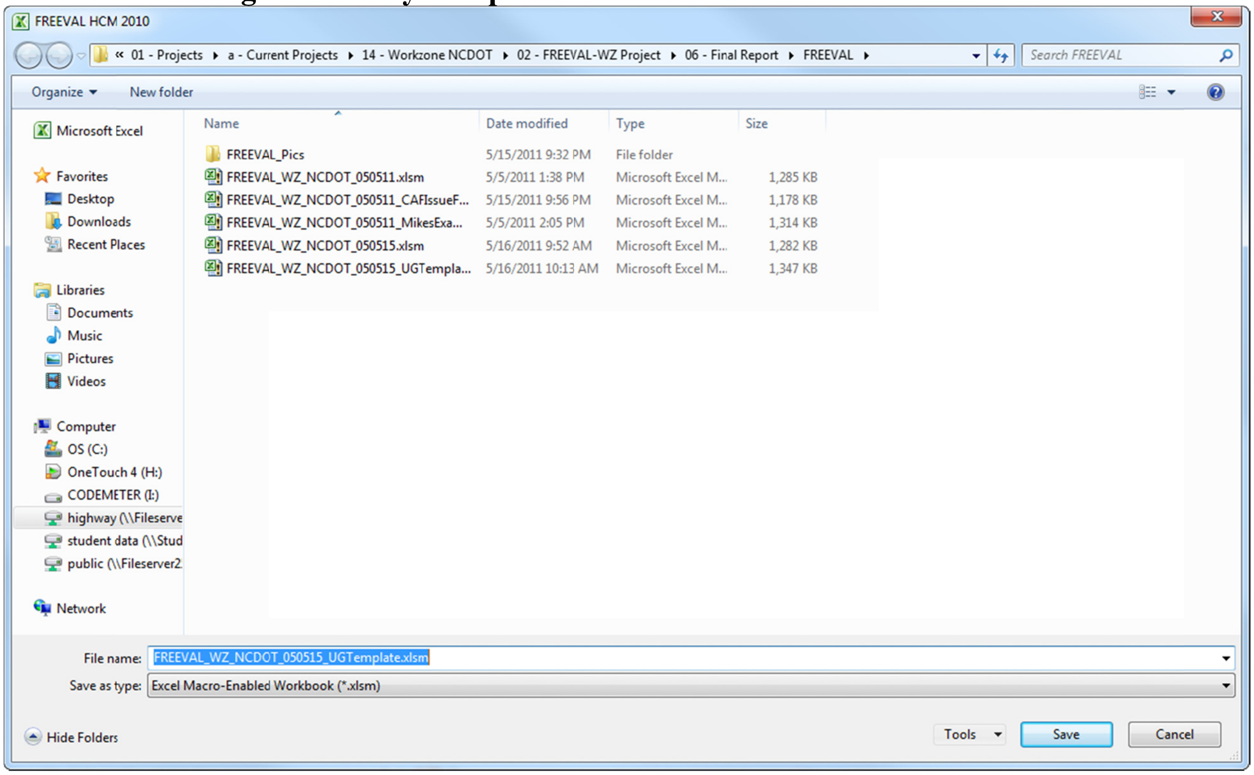


After segment details for all segments have been entered, the analyst is ready to get some results for the base facility (without work zones). At this point in the analysis, it is recommended to save the facility template. To do this, the analyst should click on "Go to Output" (see Exhibit 51), at which point the user is prompted to save the file. Two very important things need to be considered here:

1. The analyst should navigate to the current working directory to assure that the folder "FREEVAL Pics" is in the correct location. Without this folder, the program will not execute directly.
2. The analyst has to change the filename to a macro-enabled file format (.xlsm). This file extension is new in Office 2010, but is critical to correctly run FREEVAL-WZ

The screenshot in Exhibit 54 shows a potential working directory for a FREEVAL-WZ Project, where several version of the software are saved to represent different analysis scenarios. Also note that file name is changed to .xlsm.

Exhibit 54: Saving the Facility Template



After saving the analysis template, output can be generated by clicking on "Run Analysis" as shown in the bottom right corner of Exhibit 55. At this point the software will actually execute the operational version of FREEVAL in the background and the user may see some of these computations being performed. When the analysis is completed, the input/output screen will be populated with summary statistics as shown on Exhibit 56. Notice that the label "Template Mode" has now changed to "Scenario-Specific Mode".

Output is provided in several forms:

- Facility-wide summary statistics are provided in the main input/output screen (Exhibit 56) including average travel time, total system delay, maximum queue length, and detail on the worst-performing segments.
- When clicking "View Report" (Exhibit 57), the user has access to four on-screen reports including a facility-summary, segment detailed summary (can navigate between segments), LOS overview, and user cost overview. The screen can be captured using "print screen" if desired or may just serve as a quick overview.
- When clicking "View Charts" (Exhibit 58), the user can review four contour plots for key performance measures over the analysis time-space domain including demand-to-capacity ration (d/c), volume-to-capacity ratio (v/c), space mean speed (SMS), and density. Again, screenshots can be taken to capture these graphs.
- When clicking "Print Report" the user can generate a two-page summary report (Exhibit 59). This report can either be sent directly to a printer, or can be used to create a .pdf file.

The "Print Preview" feature should not be used due to a bug in Office 2010 that will cause the program to crash!

- Finally, the user has the option to "View Operations", which provides on-screen viewing capability of the detailed operational output of FREEVAL (described further in Appendix B). Exhibit 60 shows what the view operations feature looks like, including an enlarged view of the navigational tool that can be used to scroll up and down or jump to different worksheets. Closing this navigational tool (click "x") will return the user to the planning-level input/output screen.

The analyst also has the option to click "Go to Operation", which returns the user to the detailed operational portion of FREEVAL-WZ. This step cannot be undone.

Exhibit 55: Running the Analysis

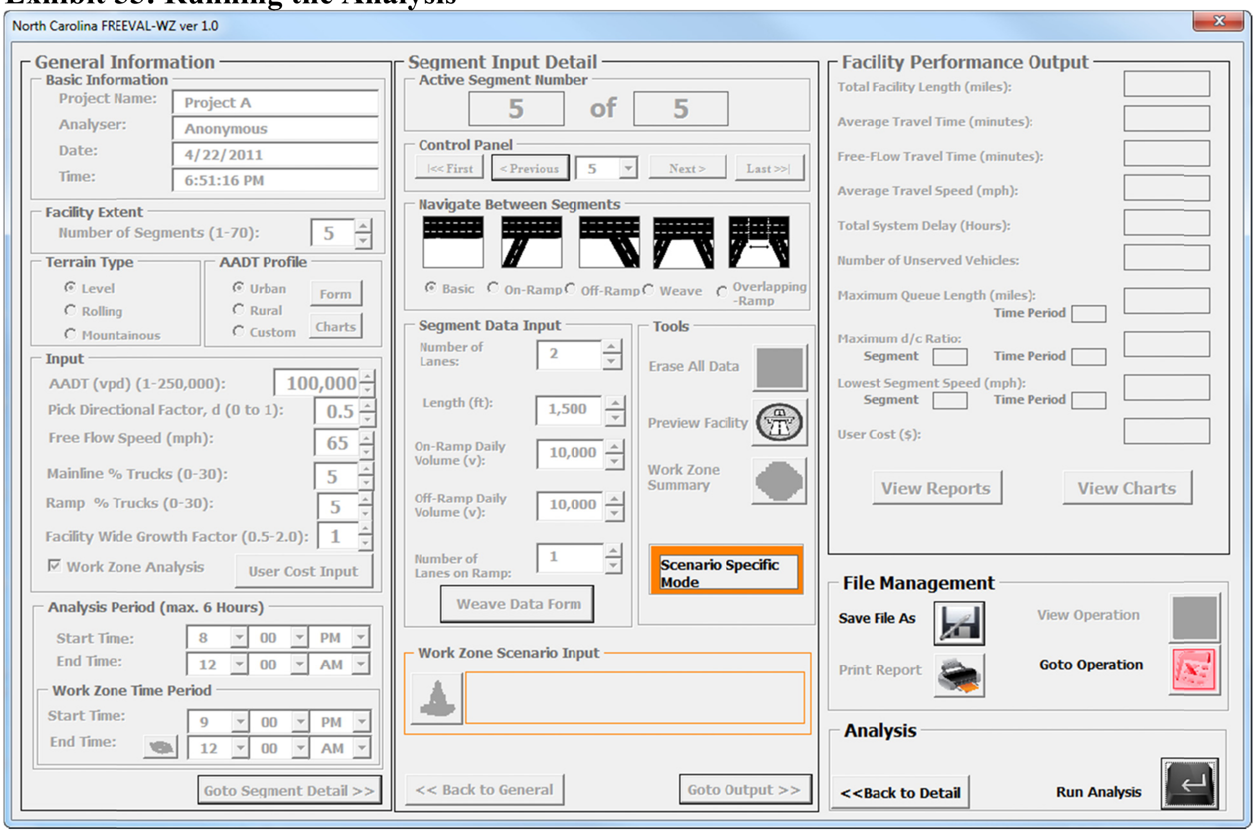


Exhibit 56: Planning-Level Outputs

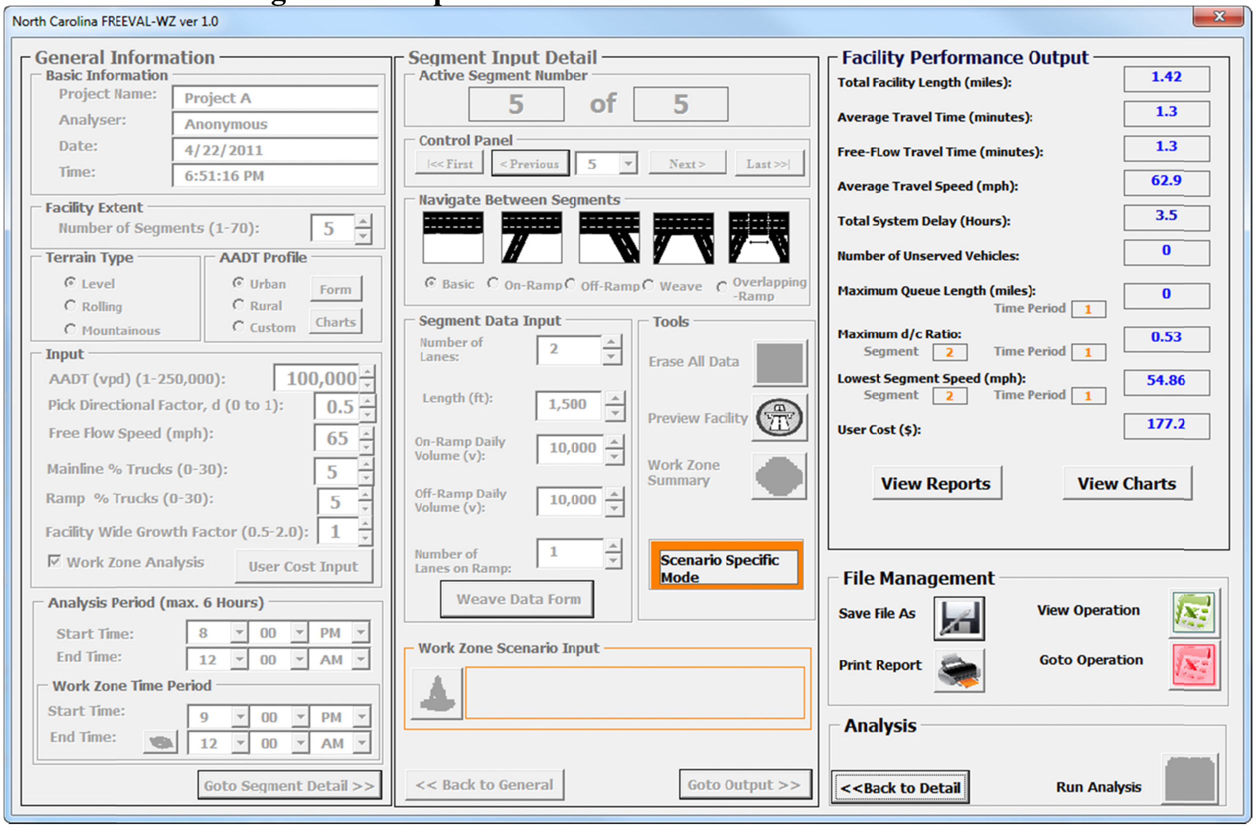
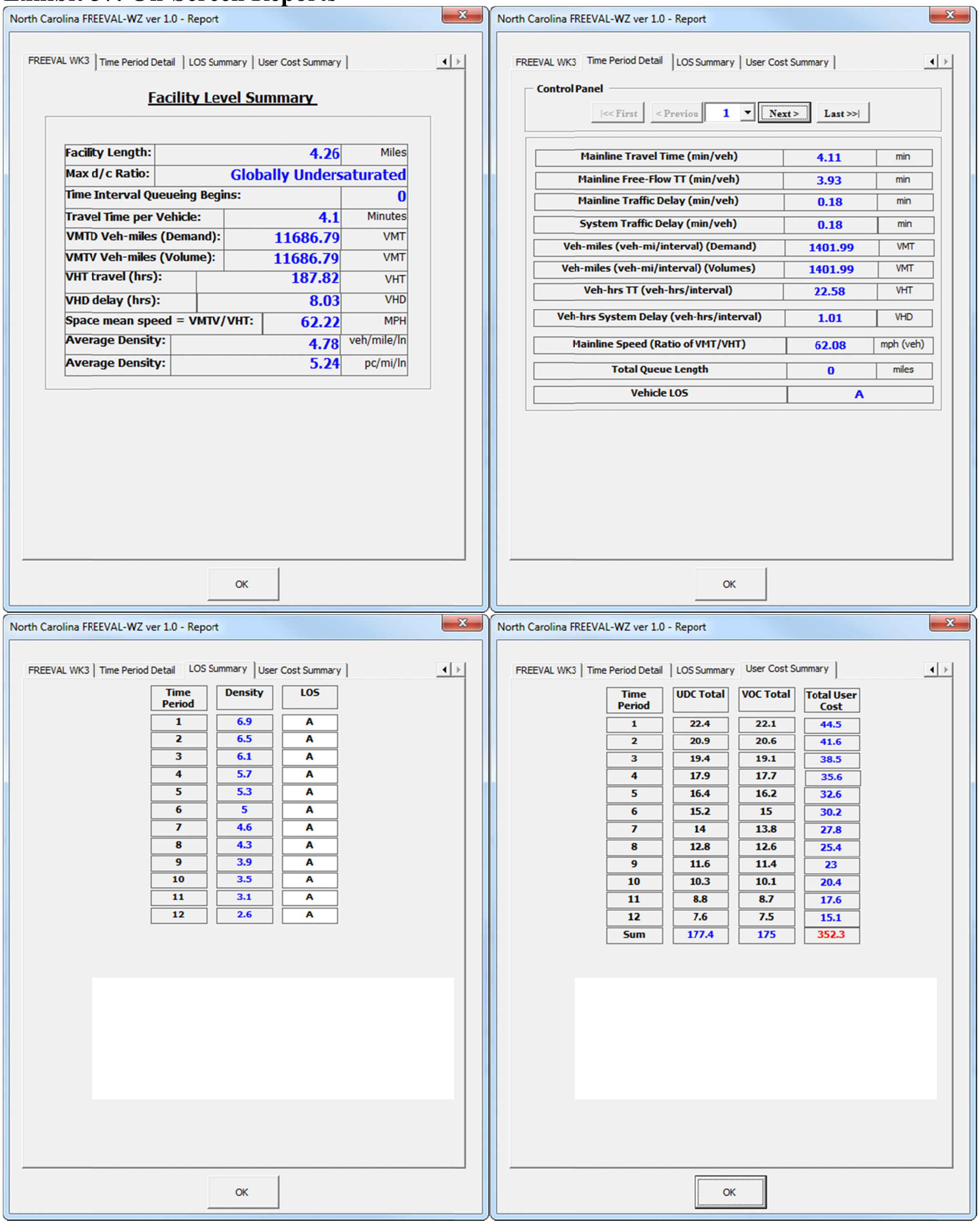


Exhibit 57: On-Screen Reports



Facility Length:	4.26	Miles
Max d/c Ratio:	Globally Undersaturated	
Time Interval Queueing Begins:	0	
Travel Time per Vehicle:	4.1	Minutes
VMTD Veh-miles (Demand):	11686.79	VMT
VMTV Veh-miles (Volume):	11686.79	VMT
VHT travel (hrs):	187.82	VHT
VHD delay (hrs):	8.03	VHD
Space mean speed = VMTV/VHT:	62.22	MPH
Average Density:	4.78	veh/mile/ln
Average Density:	5.24	pc/mi/ln

Mainline Travel Time (min/veh)	4.11	min
Mainline Free-Flow TT (min/veh)	3.93	min
Mainline Traffic Delay (min/veh)	0.18	min
System Traffic Delay (min/veh)	0.18	min
Veh-miles (veh-mi/interval) (Demand)	1401.99	VMT
Veh-miles (veh-mi/interval) (Volumes)	1401.99	VMT
Veh-hrs TT (veh-hrs/interval)	22.58	VHT
Veh-hrs System Delay (veh-hrs/interval)	1.01	VHD
Mainline Speed (Ratio of VMT/VHT)	62.08	mph (veh)
Total Queue Length	0	miles
Vehicle LOS	A	

Time Period	Density	LOS
1	6.9	A
2	6.5	A
3	6.1	A
4	5.7	A
5	5.3	A
6	5	A
7	4.6	A
8	4.3	A
9	3.9	A
10	3.5	A
11	3.1	A
12	2.6	A

Time Period	UDC Total	VOC Total	Total User Cost
1	22.4	22.1	44.5
2	20.9	20.6	41.6
3	19.4	19.1	38.5
4	17.9	17.7	35.6
5	16.4	16.2	32.6
6	15.2	15	30.2
7	14	13.8	27.8
8	12.8	12.6	25.4
9	11.6	11.4	23
10	10.3	10.1	20.4
11	8.8	8.7	17.6
12	7.6	7.5	15.1
Sum	177.4	175	352.3

Exhibit 58: On-Screen Charts

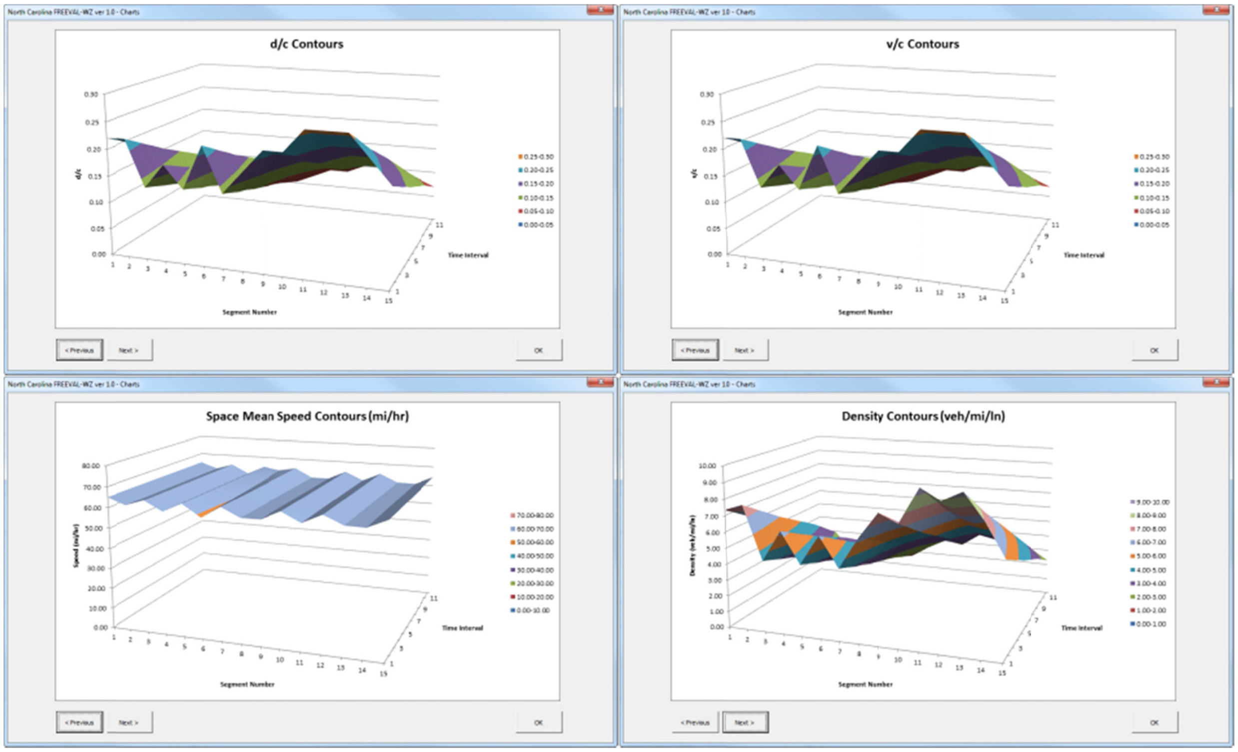


Exhibit 59: Printing Summary Report

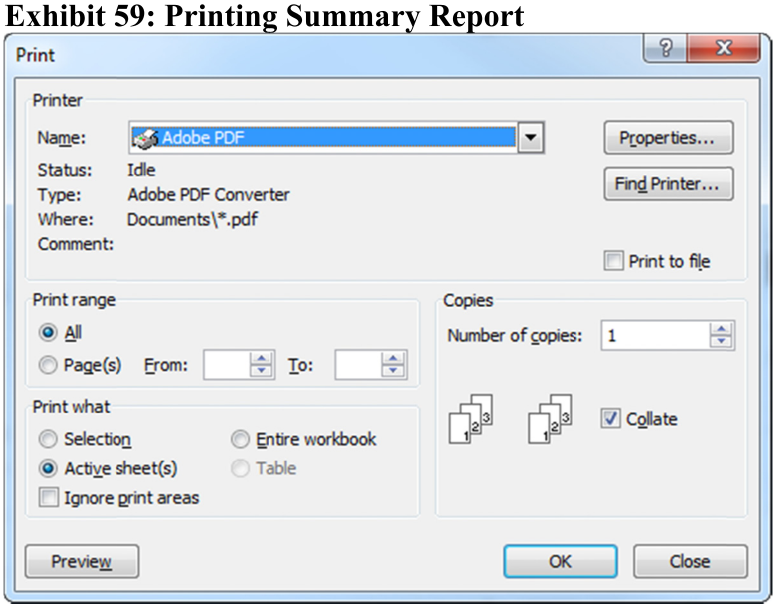
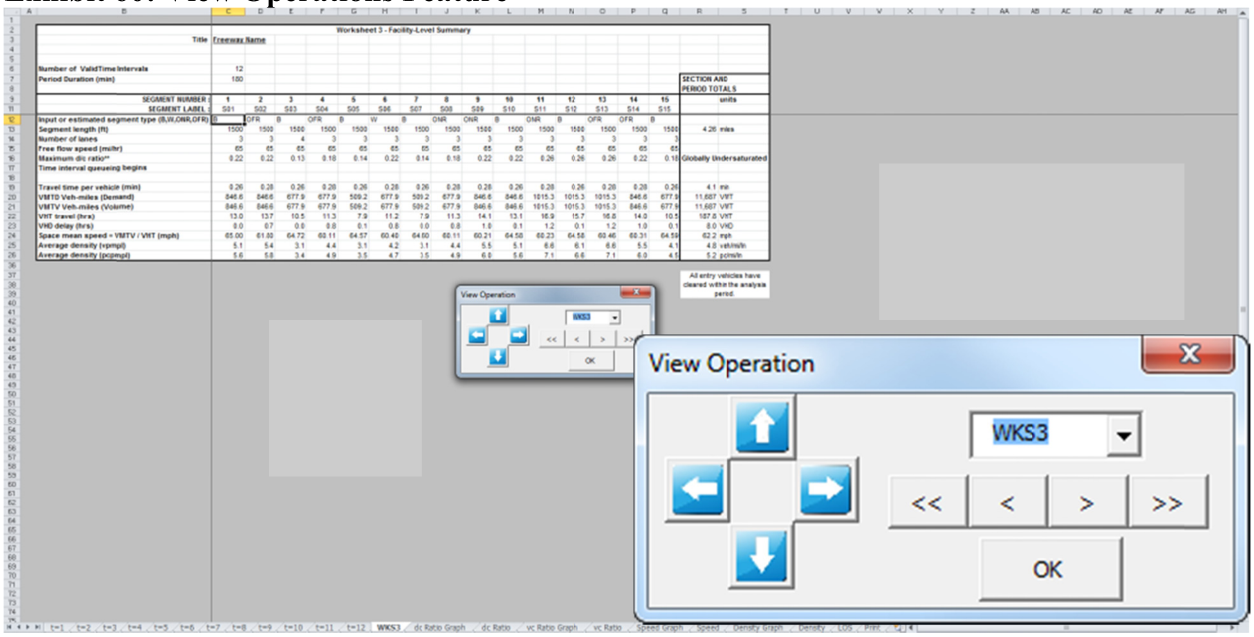


Exhibit 60: View Operations Feature

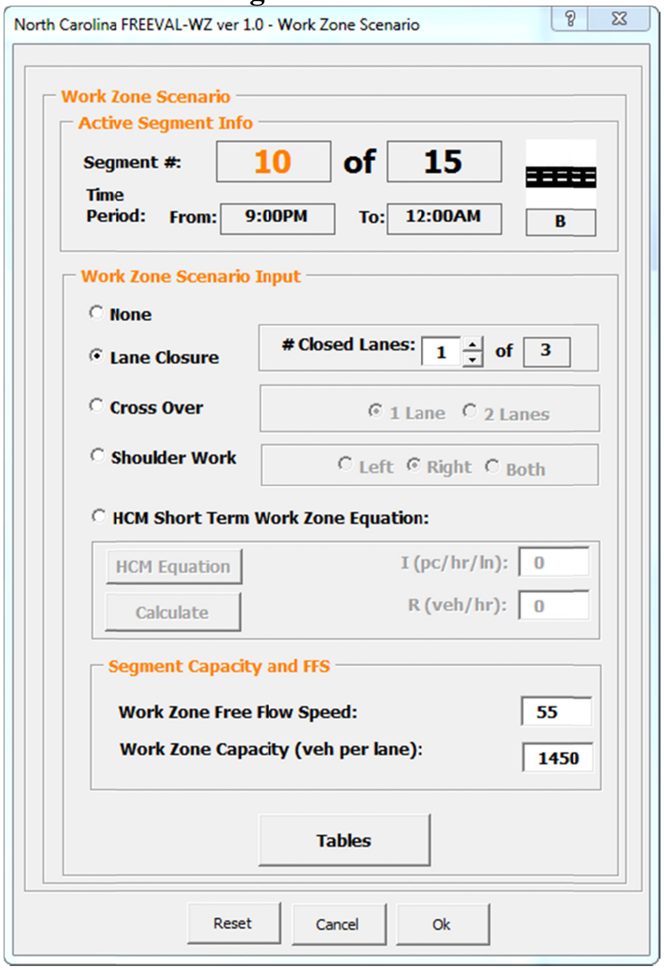


At this point, the analyst can save the base scenario file (recommended) before evaluating further scenarios. If a file saved at this point (really any time after hitting "Go to Output") is re-opened in FREEVAL, it will automatically go to the "Operations" portion of the analysis. It is therefore recommended to perform all further analyses (for work zone scenarios etc.) by re-opening the originally-saved facility template. As a reminder, the proposed work-flow of a FREEVAL-WZ analysis is as follows:

1. Gather All Input Data
2. Develop **Facility Template** in Planning-Level mode
3. Save Template PRIOR TO going processing facility and going to output!
4. Use Template to develop scenarios (do not change inputs from completed scenario)
5. Process base-year facility in **Scenario-Specific Mode**, calibrate if necessary, copy putput, save results file (*will only be able to re-open as* *<u>operational</u>* *FREEVAL*)
6. Re-open template to develop other scenario files, calibrate, copy output, save results file
7. Perform comparison of scenarios

If the facility template is re-opened, the user has the option of returning to the planning-level interface. At this point, the analyst may explore a work-zone scenario. This is done in the Segment Detail entry step (Exhibit 51), by clicking on the work zone icon in the desired segment. The work zone will be applied over the time interval specified in the "General Information" column (Exhibit 48). After clicking the work zone icon, the input dialog in Exhibit 61 opens. Several defaults are provided for North Carolina based on this research effort, but the analyst has the ability to customize any entries.

Exhibit 61: Adding Work Zone Detail



When clicking “tables”, the analyst is provided with several tables that give convenient guidance for work zone capacity estimation (Exhibit 62), including defaults developed in this research (Exhibit 63) and resources from the HCM2010 Chapter on freeway facilities (Exhibit 64). The latter includes lane closure capacities, capacity reduction due to weather, capacities under day and nighttime conditions, and estimated impacts of freeway incidents.

After returning to the input/output screen (Exhibit 51), the user can request a summary of work zone inputs we shows Exhibit 65. The facility preview has been updated to show any segments impacted by work zones in orange highlights (Exhibit 66).

From this point, the analyst can repeat the analysis steps described above, by first selecting “Go To Output”, saving the revised scenario file (as .xlsm in the working directory!), and then running the analysis. Examples of revised outputs reports are given in Exhibit 67 (Levels of Service), Exhibit 68 (Congested Segment Detail), and Exhibit 69 (Contour Plots). In this example of severe congestion, a look at “View Operations” is particularly useful. For example, the sheet “LOS” provides a graphical representation of all segments LOS over all time periods, which gives a good overview of the facility (Exhibit 70). After reviewing outputs on-screen and taking screen shots as necessary, the analysis can print a revised report for this work zone scenario as shown in Exhibit 71. The scenario analysis is then repeated for other work zone cases, changes in volume inputs, or geometric improvements to the facility.

Exhibit 62: Work Zone Capacity Guidance Tables

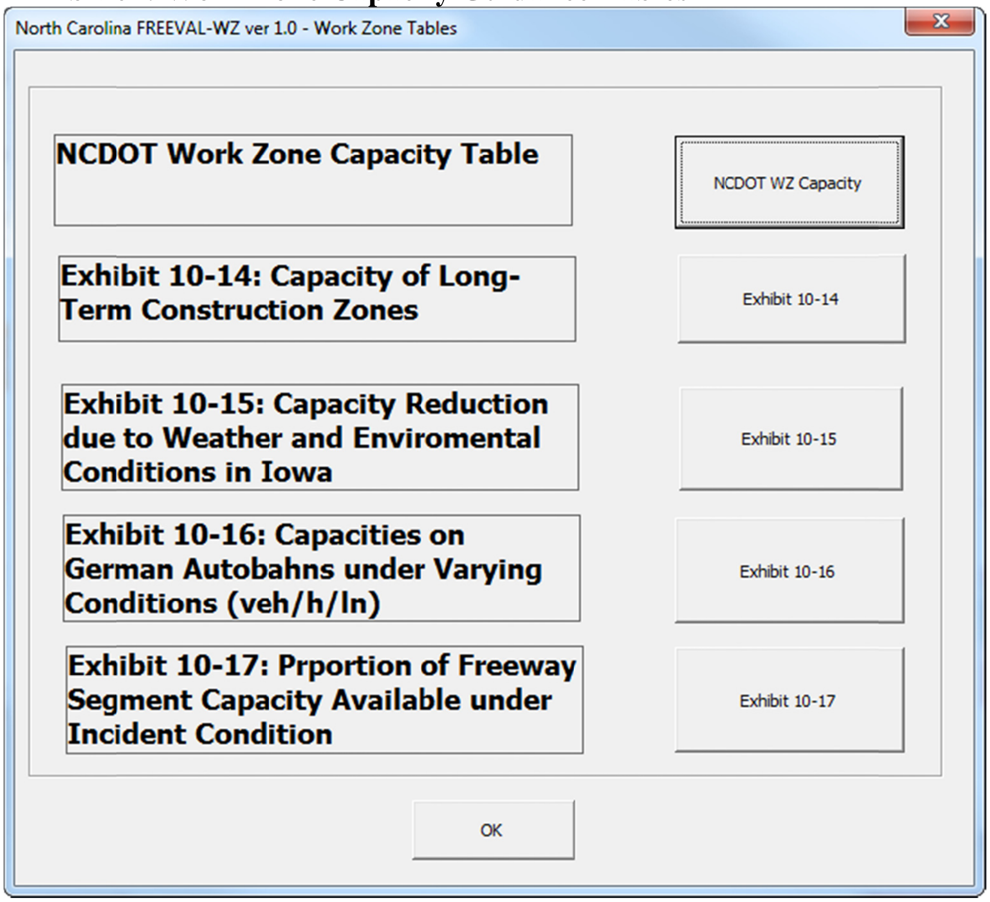


Exhibit 63: NC Work Zone Capacity Defaults

North Carolina Work Zone Capacities

FREEVAL-WZ Default Values

CL \ NL	2	3	4	5	6	7	8
1	1400	1450	1500	1700	2000	2100	2200
2		1450	1450	1580	1800	1900	2000
3			1350	1400	1600	1700	1800
4				1300	1300	1300	1300
5					1300	1300	1300
6						1300	1300
7							1300

CL: Number of Closed Lanes
NL: Number of Normal Lanes

OK

Exhibit 64: Supplemental Capacity Guidance Tables

Long Term Construction Work Zones

Exhibit 10-14 Capacity of Long-Term Construction Zones

State	Normal Lanes to Reduced Lanes 2-1	3-2	3-1	4-3	4-2	4-1
TX	1,340		1,170			
NC	1,690		1,640			
CT	1,500–1,800		1,500–1,800			
MO	1,240	1,430	960	1,480	1,420	
NV	1,375–1,400		1,375–1,400			
OR	1,400–1,600		1,400–1,600			
SC	950		950			
WA	1,350		1,450			
WI	1,560–1,900		1,600–2,000		1,800–2,100	
FL	1,800		1,800			
VA	1,300	1,300	1,300	1,300	1,300	1,300
IA	1,400–1,600	1,400–1,600	1,400–1,600	1,400–1,600	1,400–1,600	1,400–1,600
MA	1,340	1,490	1,170	1,520	1,480	1,170
Default	**1,400**	**1,450**	**1,450**	**1,500**	**1,450**	**1,350**

Ok

Weather and Enviromental Effect on Capacity

Exhibit 10-15 Capacity Reductions Due to Weather and Environmental Conditions in Iowa

Type of Condition	Intensity of Condition	Percent Reduction in Capacity Average	Range
Rain	>0 ≤ 0.10 in/h	2.01	1.17 – 3.43
	>0.10 ≤ 0.25 in/h	7.24	5.67 – 10.10
	>0.25 in/h	14.13	10.72 – 17.67
Snow	>0 ≤ 0.05 in/h	4.29	3.44 – 5.51
	>0.05 ≤ 0.10 in/h	8.66	5.48 – 11.53
	>0.10 ≤ 0.50 in/h	11.04	7.45 – 13.35
	>0.50 in/h	22.43	19.53 – 27.82
Temperature	<10° C ≥ 1° C	1.07	1.06 – 1.08
	<1° C ≥ -20° C	1.50	1.48 – 1.52
	<-20° C	8.45	6.62 – 10.27
Wind	>16 ≤ 32 km/h	1.07	0.73 – 1.41
	>32 km/h	1.47	0.74 – 2.19
Visibility	<1 ≥ 0.50 mi	9.67	One site
	<0.50 ≤ 0.25 mi	11.67	One site
	<0.25 mi	10.49	One site

OK

Capacity Under Varying Conditions

Exhibit 10-16 Capacities on German Autobahns Under Varying Conditions (veh/h/ln)

Freeway Lanes	Weekday or Weekend	Daylight Dry	Dark Dry	Daylight Wet	Dark Wet
6	Weekday (% Change*)	1,489	1,299 (13%)	1,310 (12%)	923 (38%)
6	Weekend (% Change*)	1,380	1,084 (21%)	1,014 (27%)	-- --
4	Weekday (% Change*)	1,739	1,415 (19%)	1,421 (18%)	913 (47%)
4	Weekend (% Change*)	1,551	1,158 (25%)	1,104 (29%)	-- --

OK

Capacity Under Incident Condition

Exhibit 10-17 Proportion of Freeway Segment Capacity Available Under Incident Conditions

Number of Lanes (1 Direction)	Shoulder Disablement	Shoulder Accident	One Lane Blocked	Two Lanes Blocked	Three Lanes Blocked
2	0.95	0.81	0.35	0.00	N/A
3	0.99	0.83	0.49	0.17	0.00
4	0.99	0.85	0.58	0.25	0.13
5	0.99	0.87	0.65	0.40	0.20
6	0.99	0.89	0.71	0.50	0.26
7	0.99	0.91	0.75	0.57	0.36
8	0.99	0.93	0.78	0.63	0.41

OK

Exhibit 65: Work Zone Scenario Summary

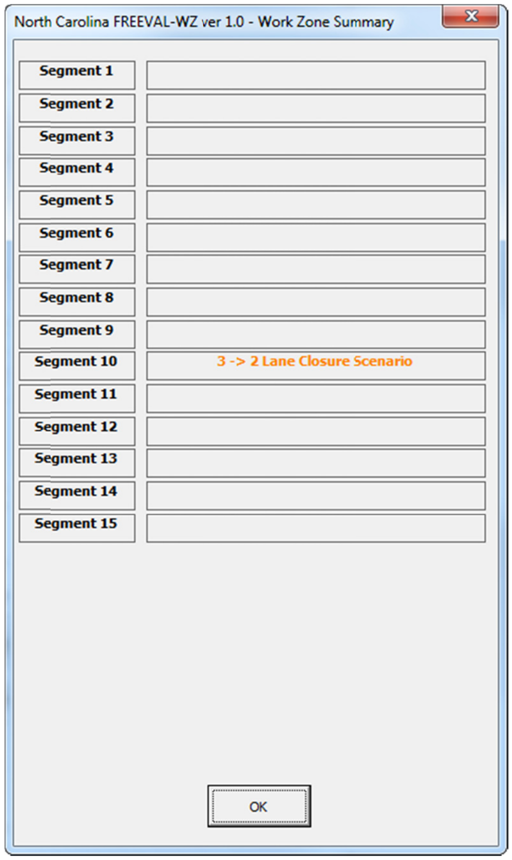


Exhibit 66: Facility Preview with Work Zone

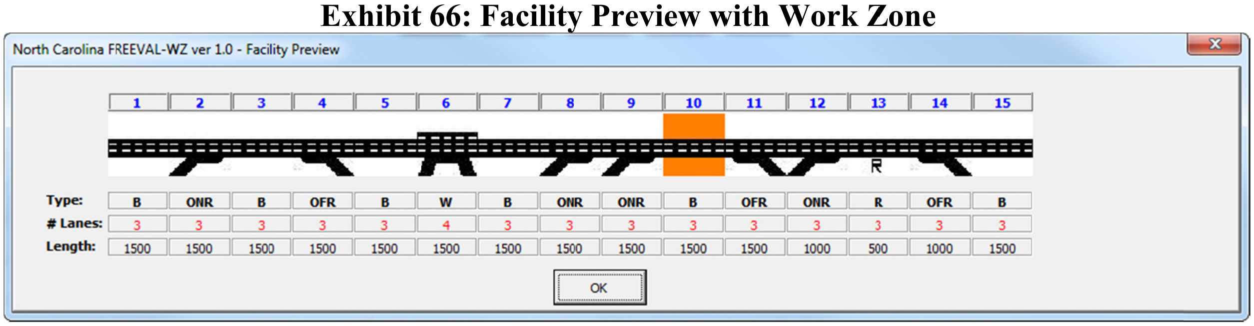
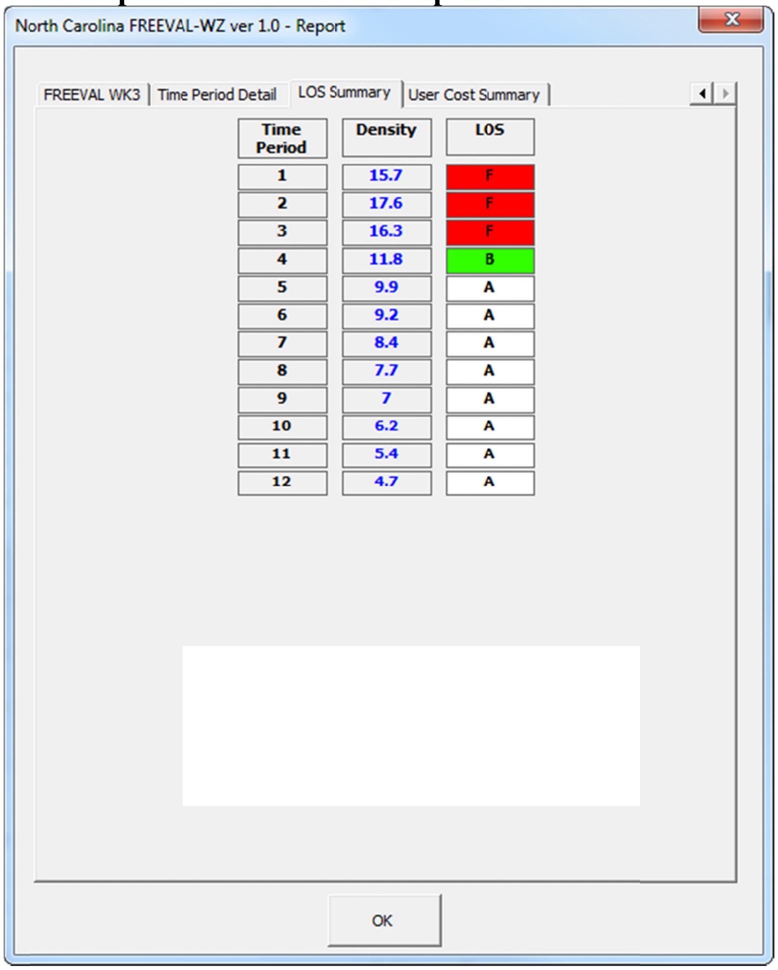


Exhibit 67: Updated LOS Exhibit 67performance with Work Zone



Time Period	Density	LOS
1	15.7	F
2	17.6	F
3	16.3	F
4	11.8	B
5	9.9	A
6	9.2	A
7	8.4	A
8	7.7	A
9	7	A
10	6.2	A
11	5.4	A
12	4.7	A

Exhibit 68: On-Screen Performance Summary with Work Zone

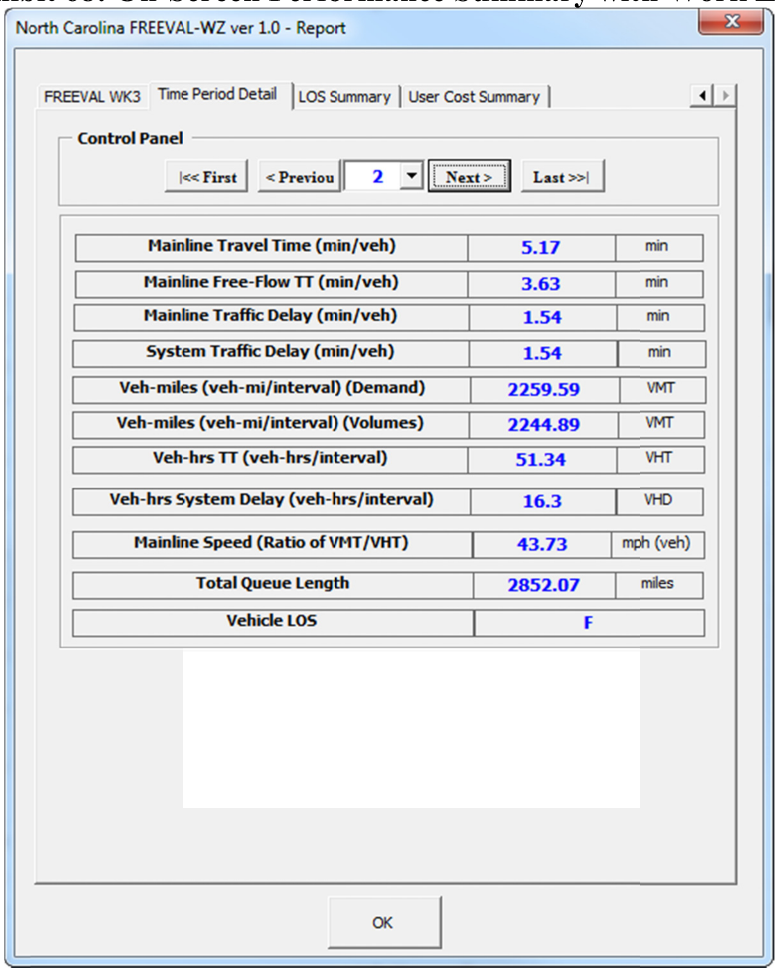


Exhibit 69: On-Screen Charts with Congestion

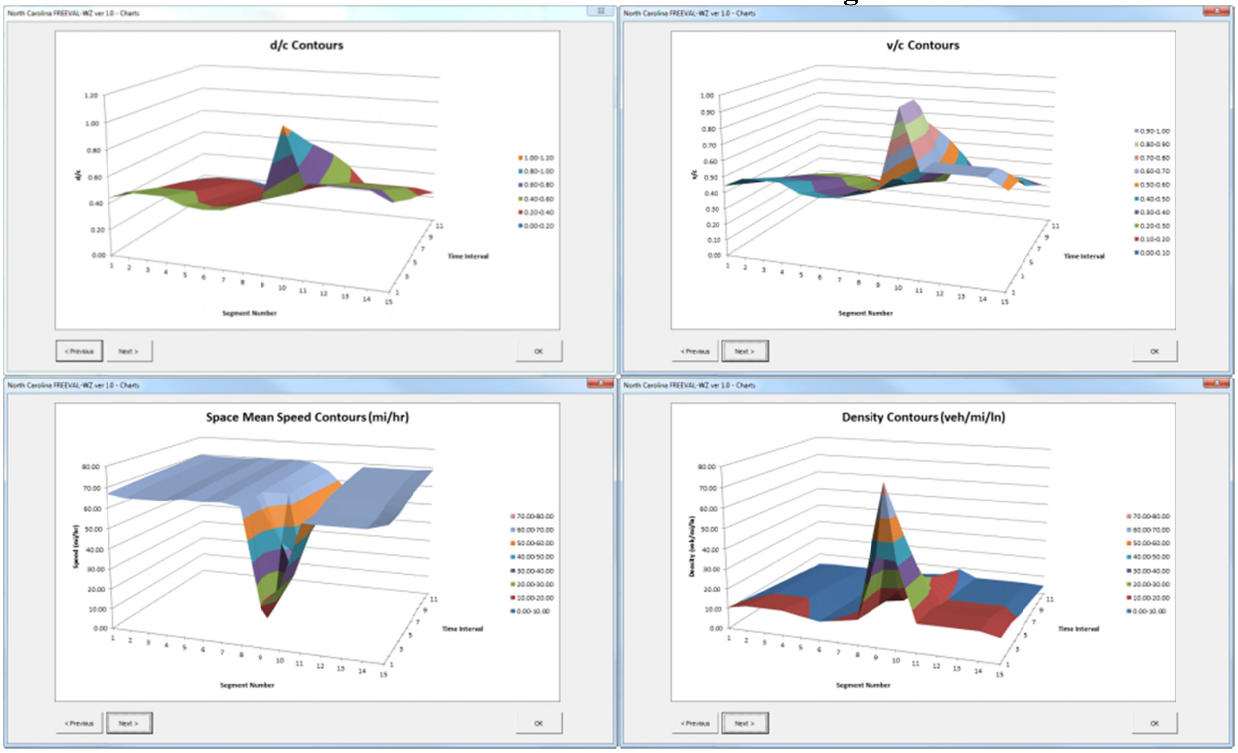
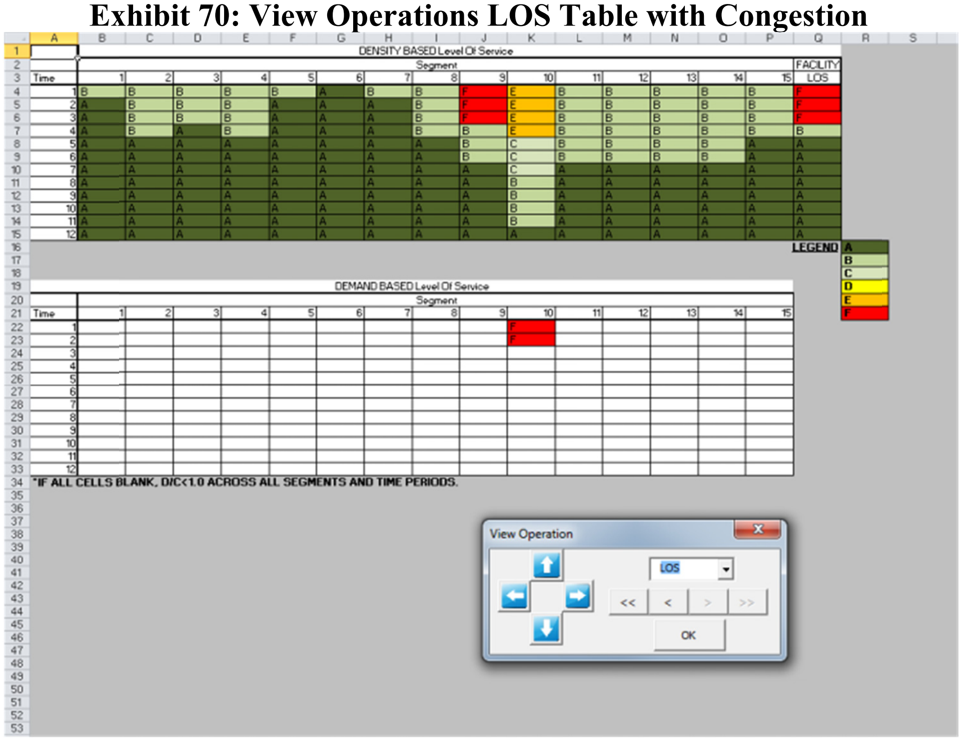


Exhibit 70: View Operations LOS Table with Congestion



DENSITY BASED Level Of Service

Time	Segment 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	FACILITY LOS
1	B	B	B	B	B	A	B	B	F	E	B	B	B	B	B	F
2	A	B	B	B	A	A	A	B	F	E	B	B	B	B	B	F
3	A	B	B	B	A	A	A	B	F	E	B	B	B	B	B	F
4	A	B	A	B	A	A	A	B	B	E	B	B	B	B	B	B
5	A	A	A	A	A	A	A	A	B	C	B	B	B	B	A	A
6	A	A	A	A	A	A	A	A	B	C	B	B	B	B	A	A
7	A	A	A	A	A	A	A	A	A	C	A	A	A	A	A	A
8	A	A	A	A	A	A	A	A	A	B	A	A	A	A	A	A
9	A	A	A	A	A	A	A	A	A	B	A	A	A	A	A	A
10	A	A	A	A	A	A	A	A	A	B	A	A	A	A	A	A
11	A	A	A	A	A	A	A	A	A	B	A	A	A	A	A	A
12	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A	A

LEGEND: A, B, C, D, E, F

DEMAND BASED Level Of Service

Time	Segment 1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1										F					
2										F					
3															
4															
5															
6															
7															
8															
9															
10															
11															
12															

*IF ALL CELLS BLANK, D/C<1.0 ACROSS ALL SEGMENTS AND TIME PERIODS.

Exhibit 71: Standard Report with Work Zone

NCDOT FREEVAL-WZ Report

Basic Information	
Project Name	Project A
Analyser	Anonymous
Date	4/22/2011
Time	6:51:16 PM

General Information					
Total Segments	15		Free Flow Speed	65	mph
Terrain Type	Level		Mainline % Trucks	18	
Volume Profile	Urban		Ramp % Trucks	5	
AADT	150,000	vpd	Growth Factor %	1	
Pick Directional Factor	0.5				

Time Schedule			
Project Start Time	9:00PM	Work Zone Start Time	9:00PM
Project End Time	12:00AM	Work Zone End Time	12:00AM

Facility Performance Output					
Total Facility Length	3.88	miles	Max Queue Length	0.19	miles
Average Travel Time	4	minutes	*Time Period #*	2	
Free Flow Travel Time	3.6	minutes	Max d/c Ratio	1.08	
Average Travel Speed	57.2	mph	*Segment #*	1	
Total System Delay	37.8	hours	*Time Period #*	10	
# Unserved Vehicles	0		Min Segment Speed	11.08	mph
Total User Cost	1,661	$	*Segment #*	2	
			Time Period #	9	

Facility Level Summary					
Time Period Queueing Begin	0		VHT travel (hrs)	349.2	VHT
Travel Time per Vehicle	4.02	minutes	VHD delay (hrs)	37.84	VHD
VMTD Veh-Miles (Demand)	19946	VMT	Average Density	9.99	veh/mile/ln
VMTV Veh-Miles (Volume)	19946	VMT	Average Density	10.8	pc/mi/ln
Space Mean Speed = VMTV/VHT	57.1	mph			

Page 1

NCDOT FREEVAL-WZ Report

TimePeriod Detail						
Time Period	Time	Travel Time (min)	Queue Length (miles)	VMT-Demand	VMT-Volume	Status
1	21:00	4.52	843.55	2397	2324	Queue Forming
2	21:15	5.17	1004.26	2260	2245	Queue Forming
3	21:30	4.90	501.23	2122	2165	Queue Dissepating
4	21:45	3.89	2.28	1979	2023	Queue Dissepating
5	22:00	3.64	3.06	1841	1841	Queue Forming
6	22:15	3.59	3.48	1723	1723	Queue Forming
7	22:30	3.56	3.71	1600	1600	Queue Forming
8	22:45	3.53	3.78	1477	1477	Queue Forming
9	23:00	3.50	3.72	1354	1354	Queue Forming
10	23:15	3.48	3.54	1211	1211	Queue Dissepating
11	23:30	3.46	3.25	1063	1063	Queue Dissepating
12	0:00	3.44	2.90	921	921	Queue Dissepating
13						
14						
15						
16						
17						
18						
19						
20						
21						
22						
23						
24						

Page 2

Appendix B: FREEVAL User Guide for Operational Analysis

This appendix contains the user guide for the operational portion of FREEVAL-WZ. This document is based on the user guide for FREEVAL-2010, which is available in Volume IV of the 2010 Highway Capacity Manual. FREEVAL-2010 represents the computational core of FREEVAL-WZ, which added a new planning-level interface that was described in Appendix A.

1. INTRODUCTION

Overview

This document is intended to provide general guidance on the use of the computational engine for Chapter 10 of the 2010 Highway Capacity Manual: Freeway Facilities. This document is practitioner-friendly, not developer oriented. The focus is on how to use and interpret the results of the computational engine. Detailed discussion on the procedure itself along with engine documentation guidance for software developers is provided in HCM2010 Chapter 25.

The computational engine, FREEVAL (FREeway EVALuation) 2010 is a computerized, worksheet-based environment designed to faithfully implement the operational analysis computations for Undersaturated and Oversaturated Directional Freeway Facilities. Thus, FREEVAL-2010 is a faithful implementation of HCM Chapter 10, which necessarily incorporates all freeway segment procedures outlined in HCM2010 Chapters 11, 12, and 13.

FREEVAL-2010 is executed in Microsoft Excel with most computations embedded in Visual Basic modules. The environment allows the user to analyze a freeway facility of up to 70 analysis segments (to be defined) and for up to 24 fifteen-minute time intervals (6 hours). The engine can generally handle any facility that falls within these temporal and spatial constraints. However, it is highly recommended that the total facility length not exceed 10-15 miles in length to ensure consistency between demand variability and facility travel time. Further, the analysis boundaries (in time and space) should be uncongested and should allow all queues to form and clear within the facility to assure that performance measures fully encompass the predicted extent of congestion and delay. These aspects are discussed in detail in Chapter 10. In conformance with the HCM2010, all analyses are carried out using US units.

FREEVAL--2010 is organized as a sequence of linked Excel worksheets, and can be used autonomously to analyze individual freeway elements (i.e. basic, ramp, and weaving sections) or an entire directional facility. The user defines the different freeway segments and enters all necessary input data that would also be required in the individual segment chapters. These include segment length, number of lanes, length of acceleration and deceleration lanes, heavy and recreational vehicle percentages, and the free-flow speed, which can also be calculated from the segment or facility geometric attributes.

Consistent with Chapter 10, FREEVAL covers undersaturated and oversaturated conditions. For oversaturated time periods, traffic demands and queues are tracked over time and space as discussed in more detail in Chapter 25. In addition to characterizing oversaturated conditions, the most significant difference from the segment-based chapters is that FREEVAL carries out all calculations using 15-minute flow rates (expressed in vehicles per hour). It therefore does not use a peak-hour-factor (PHF). To replicate the example problem results found in the segment chapters, PHF-adjusted flow rates must be entered in FREEVAL directly. Heavy vehicle adjustments (using general terrain factors or directly input for specific grade segments) are automatically handled by the methodology.

The computational engine is further designed to allow the user to revise input data following an analysis. This feature is intended to perform quick sensitivity or "what if" analyses of different demand scenarios or geometric changes to the facility. However, the user is cautioned to ensure that all prior inputs are maintained when using FREEVAL for extensive scenario evaluation. FREEVAL-2010 is not a commercial software product, and as such relies on the voluntary commitment by the TRB Committee on Highway Capacity and Quality of Service to address software bugs and update methodological changes.

Chapter Organization

The next section gives a brief description of the FREEVAL2010 structure and organization. The document then presents a series of screenshots from the computational engine, in a step-by-step outline of input and output requirements. The document concludes with a discussion on interpreting the output for an oversaturated case, which is one of the major strengths and unique attributes of the methodology.

The software user guidance in sections 3 and 4 is based on example problems 1 and 2 of Chapter 10 and the user is encouraged to reference that discussion for further information on the interpretation of results.

2. ENGINE STRUCTURE AND ORGANIZATION

The FREEVAL2010 Computational Engine is organized as a sequence of computational worksheets; one for each fifteen-minute time period. These worksheets are used both for data input and data output, with portions of the worksheets that are irrelevant to a particular segment type automatically hidden by the procedure. Additional worksheets are used for interim calculations and to present facility summary statistics. Worksheets are hidden and write-protected automatically as needed. A total of 24 time periods can be included and up to 70 user-defined segments can be coded for one directional facility.

Inputs

Data input in FREEVAL2010 takes place in three locations.

- First, a global input screen appears when first executing the methodology. It contains basic settings for the number of time periods and segments, as well as global settings for free-flow speed and other facility-wide parameters.
- Second, most inputs on individual segment geometry and volumes appear in the individual time-period worksheets. Some variables are pre-coded with default values, but can be overridden by user input. Also, many inputs entered in time-period 1 are automatically copied to later time periods. The user always needs to enter the demand flows for each mainline segment and each ramp in every time period. These cells are highlighted in the engine to assist with user entry.
- The third and final set of inputs is related to the new HCM2010 weaving segment methodology. Due to the special data requirements for this methodology, inputs are handled through a separate input dialog box that automatically appears when a user codes a weaving segment and executes the analysis.

Outputs

Data output in FREEVAL also appears in three places.

- First, every time-period worksheet contains a summary of the measures of effectiveness (MOEs) for each segment in that time period. The worksheet also contains facility average estimates of MOEs such as overall travel-time and facility-average density, which is needed to estimate facility levels of service.
- Second, a summary worksheet (labeled WKS3) gives average segment performance over all time periods and all segments.
- The third type of output is given in the form of 3-D contour plots and summary tables showing a select number of MOEs by segment and time-period such as volume-to-capacity ratio (v/c), demand-to-capacity ratio (d/c), segment speed in mph, segment density in vehicles/mile/lane and Level of Service (table only). All outputs are used to evaluate the operational performance of a facility as will be described in section 4.

The next section provides a step-by-step outline of the coding procedure.

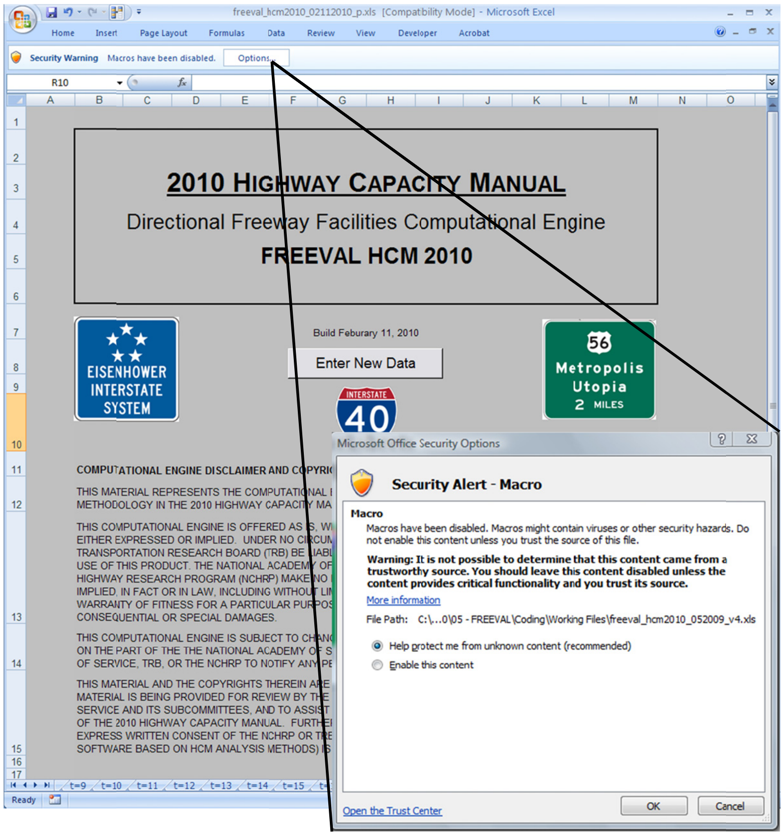
3.STEP-BY-STEP CODING PROCEDURE

This section presents a detailed overview of the data input process in FREEVAL2010 through a series of screenshots. The engine is saved as an .xlsm file (macro-enabled file), but can also be opened and executed in earlier versions of Excel. The computations are performed using Visual Basic Macros and macros must be enabled in order to execute the spreadsheet.

STEP A: WELCOME SCREEN

After opening the program, a welcome screen appears (Exhibit 72). To begin coding, the user clicks on the “Enter New Data” button in the center of the screen. If macros are disabled, a security warning will appear at the top of the screen (shown in Exhibit 125-1 for Office 2007). Click and select “enable this content” in the appearing dialog box.

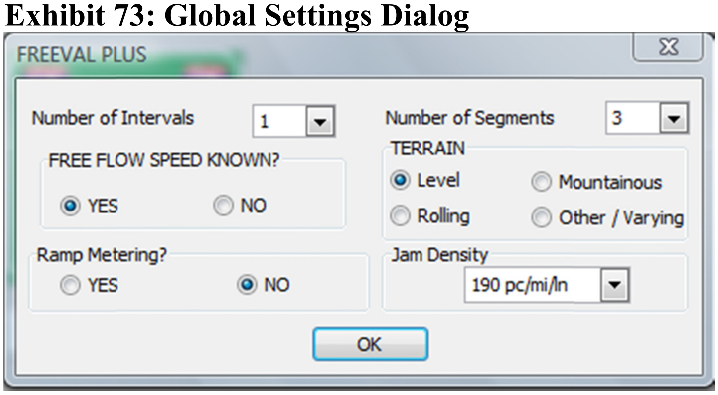
Exhibit 72: FREEVAL2010 Welcome Screen



STEP B: GLOBAL INPUT PARAMETERS

After selecting "Enter New Data" the global input dialog will appear (Exhibit 73). Here the user selects the number of intervals and number of segments to be analyzed. Other settings include whether the facility free-flow speed is known or should be calculated, whether ramp metering is used, the type of terrain, and the jam density of the facility (used for oversaturated calculations). After completing all global settings, select "OK". After selecting "OK" the macro will automatically delete all extra worksheets for time intervals and unused columns for segments. Output charts and tables are also updated. Depending on the computer used, this may take a few minutes.

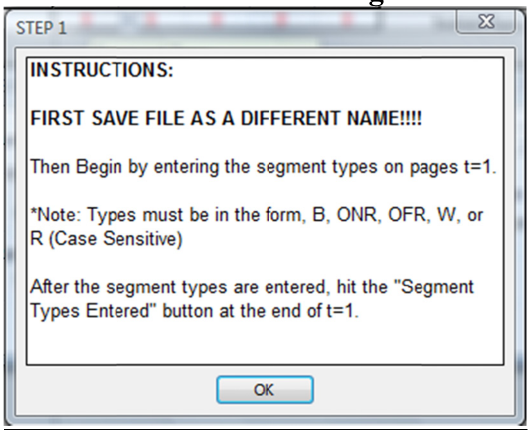
Exhibit 73: Global Settings Dialog



STEP C: SAVE FILE AS A DIFFERENT NAME

A dialog box will prompt the user to save the file under a different name (Exhibit 74). This step is of critical importance, since saving using the same name will override the original macro and the code will be lost!

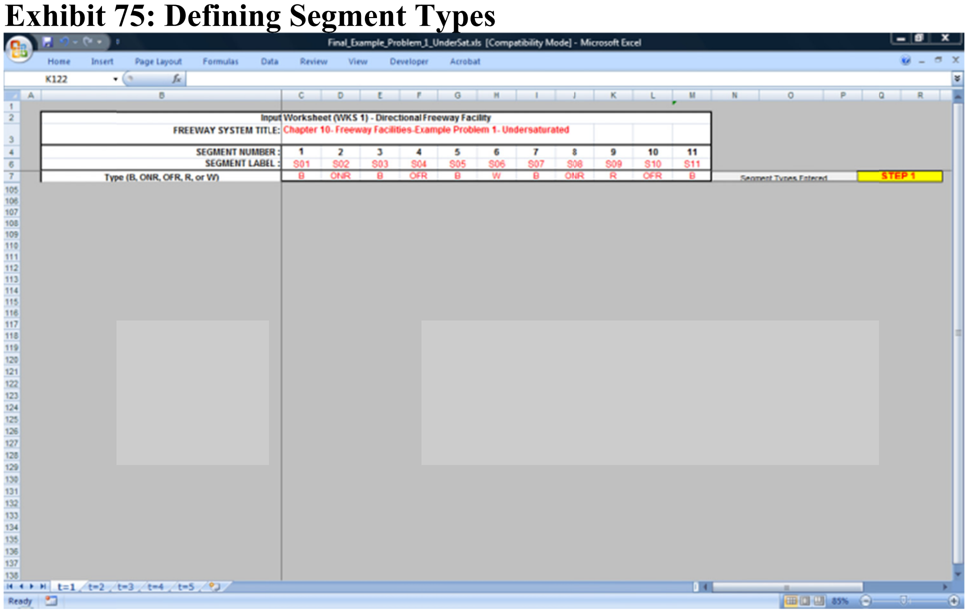
Exhibit 74: Save File Dialog



STEP D: CODE SEGMENT TYPES

Next, the user enters the type of each segment (Exhibit 75). Note that the number of columns has been reduced to match the number of segments defined by the user. The proper way to define the appropriate number of segment is explained in Chapter 10, including the requirement that the first and last segments of the facility should be basic segments. Also, the number of input worksheets matches the number of (15 min) time periods selected in the global dialog box. Using drop-down menus, the user defines each segment as a basic, on-ramp, off-ramp, weaving, or overlapping ramp segment following HCM2010 conventions (see Chapter 10). After identifying all segments, click on the "Segment Types Entered" button. After that action, the macro will automatically 'black-out' all unneeded data entry cells. This process may take a few minutes.

Exhibit 75: Defining Segment Types



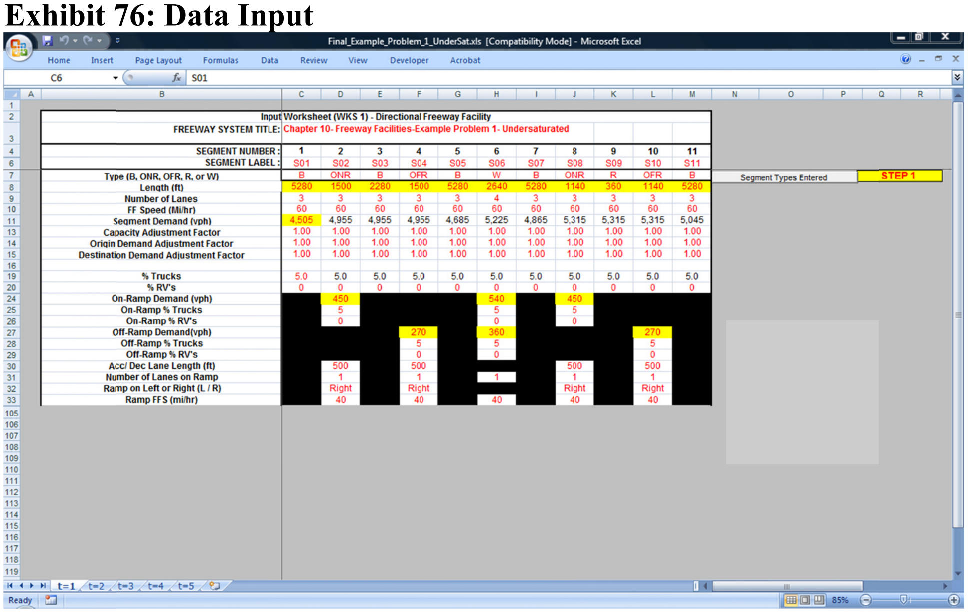
All traffic data input need to be entered in the form of demand flow rates. The method internally tracks whether these demands are processed and distinguishes in the output between demand volumes (input) and the actual volume served (output).

STEP E: SEGMENT DATA ENTRY

Next, the user enters all segment data for each time period in sequence (Exhibit 76). The common inputs needed for all segments are: Length (feet), Number of Lanes, Free-Flow Speed (mph), Segment Demand (vph), %Trucks, and %RVs. Additionally, the user can utilize several adjustment factors that may affect the operations of the facility. These will be discussed in a later section.

For all ramp and weaving segments, the user further needs to enter the ramp demand flows and can adjust the heavy vehicle percentages as desired. Note that a time interval corresponds to a 15-minute period and as a result all volume inputs should take the form of 15-minute demand flow rates (in vehicles per hour). No peak-hour-factor adjustment is necessary.
After completing all input for one time period, the user opens the tab for the worksheet in the next time period. For all subsequent time periods, some inputs are automatically copied from the t=1 worksheet. However, the engine generally allows the user to override automatically generated input. Demand volumes always need to be entered for all time periods. After completing all inputs for all time periods and checking for correctness, click “Run Entire Analysis” button shown on the worksheet in the last time interval.

Exhibit 76: Data Input



For weaving segments, the segment length is the length over which performance measures are applied. The performance measures are calculated using the short length, which is commonly shorter than the segment length.

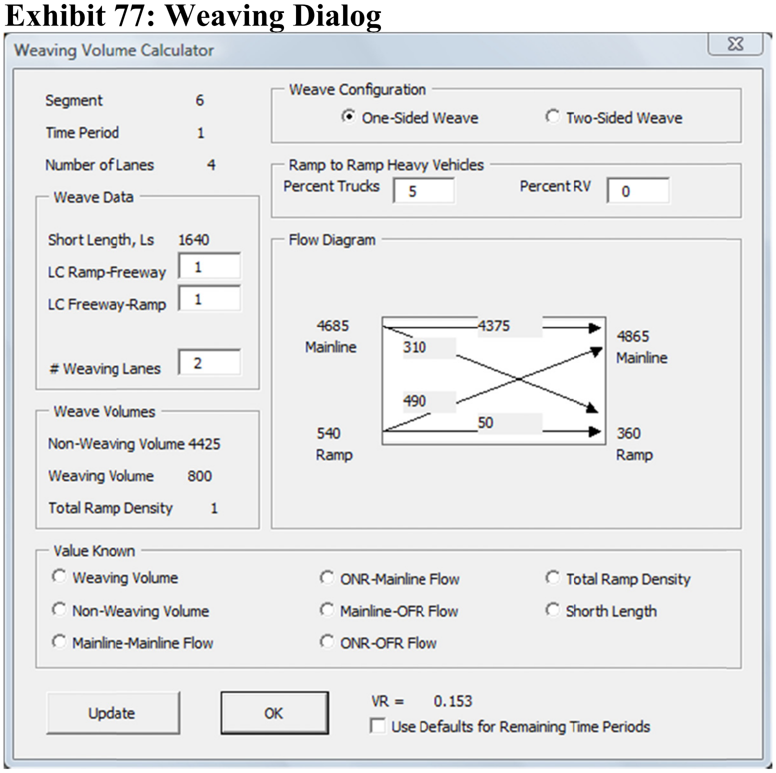
STEP F: WEAVING DATA

If the analyst coded at least one weaving segment in the facility, a weaving dialog box will appear after clicking “Run Entire Analysis” (Exhibit 77). The dialog contains all needed input variables for the new HCM2010 weaving methodology. Some variables are automatically passed through from the main input worksheets, but can be edited by selecting any of the radio buttons in the "Value Known" group. After editing a value, it is important to click "Update" first to assure that the new data have been saved, then click "OK" when done.

For guidance on estimating the weaving-specific variables, the user is referred to the weaving segment chapter. Special attention should be paid to the distinction between weaving segment length and the weaving short length. In FREEVAL, the effective segment length is entered in the Excel worksheets and is the length to which the calculated performance measures are applied. However, the performance measures are calculated based on the short length as discussed in Chapter 12. For example, a weaving segment may have a short length of 1,500', which is measured as the distances between the gores at the on and off-ramps. Following guidance given in Chapter 12, the operational effects of the weaving segment often extend a distance of 500' upstream and downstream of that short length. Consequently, the weaving segment length should be entered as 2,500' in the time period input worksheets.

The user can select "use defaults for all time periods" to skip the detailed data entry, but is required to enter data for each segment in the first time period. After entering all data for each time period, click "OK". If more than one weaving segment exists or more than one time period is used, the weaving dialog will move to the next set of inputs.

Exhibit 77: Weaving Dialog



To ensure that weaving segments are coded correctly, the reader is referred to Chapter 12 of the HCM2010 on "Weaving Segments" where definitions for weaving segment short length, the number of required lane changes, and the number of weaving lanes are provided. The user should not accept the default values in the weaving dialog before consulting with Chapter 12 variable definitions and analysis conventions. The total ramp density is automatically calculated from the overall facility geometry, but can also be user-adjusted. The ramp-to-ramp flow defaults to zero, representing a worst-case weaving scenario. The user can adjust any of the values in the flow diagram and the method will automatically calculate all remaining values when the user clicks the "update" button. A user-adjustment for ramp-to-ramp flow is especially important for two-sided weaves, which is selected using radio button at the top of the dialog. The weaving graphic shown in Exhibit 77 automatically changes when a two-sided weave is used.

STEP G: OUTPUTS

The summary worksheet labeled "WKS3" (Exhibit 78) contains aggregated results for all time periods. It provides average speed and travel time over all time periods and gives the maximum demand-to-capacity ratio (d/c) for each segment across all time intervals. Provided all segments operate below capacity (below a demand to capacity ratio, d/c, of 1.0) in all time periods, the facility operations will be labeled as "globally undersaturated". If that is the case, all individual segment results are obtained by the respective methodologies in HCM2010 chapters 11 through 13. Aggregation of performance is consistent with the computations presented in Chapter 10 and 25. If any segment during any time interval operates at d/c > 1.0, the facility is considered to be "oversaturated" and additional output is generated. This is discussed in more detail below. From the summary worksheet, the user can select any of the individual interval worksheets for detailed results (Exhibit 79). Additionally, a set of four summary graphs is created showing four key MOEs over all segments and all time intervals (Exhibit 80).

Exhibit 78: Facility Summary Worksheet

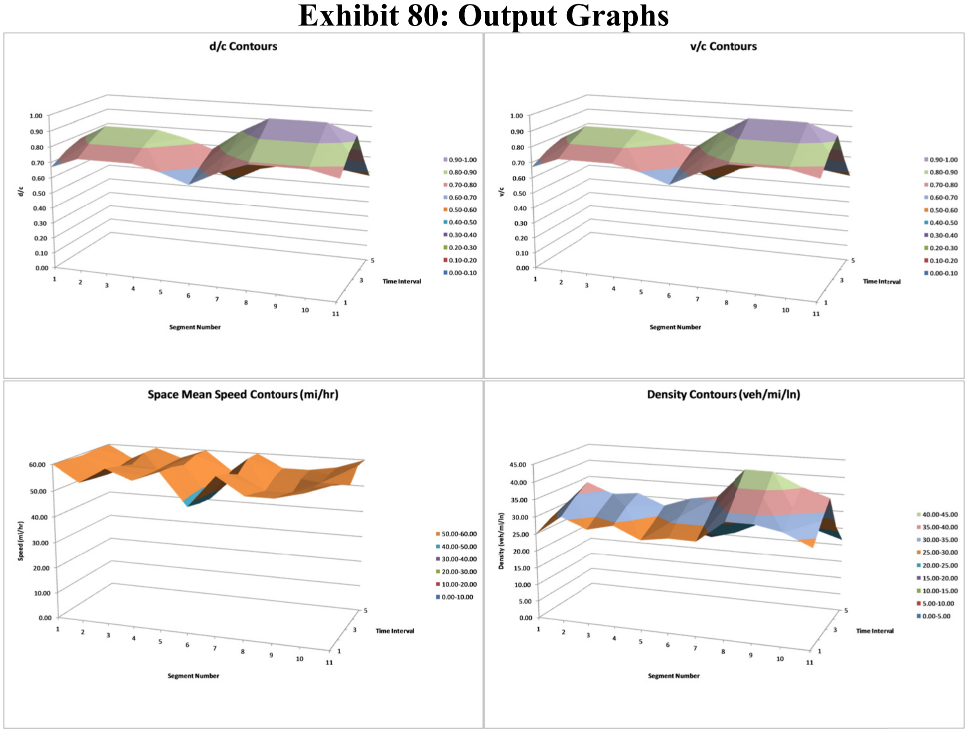
	Worksheet 3 - Facility-Level Summary												
Title	Chapter 10- Freeway Facilities-Example Problem 1- Undersaturated												
Number of ValidTime Intervals	5												
Period Duration (min)	75											SECTION AND PERIOD TOTALS	
SEGMENT NUMBER :	1	2	3	4	5	6	7	8	9	10	11		units
SEGMENT LABEL :	S01	S02	S03	S04	S05	S06	S07	S08	S09	S10	S11		
Input or estimated segment type (B,W,ONR,OFR)	B	ONR	B	OFR	B	W	B	ONR	R	OFR	B		
Segment length (ft)	5280	1500	2280	1500	5280	2640	5280	1140	360	1140	5280	6.00	miles
Number of lanes	3	3	3	3	3	4	3	3	3	3	3		
Free flow speed (mi/hr)	60	60	60	60	60	60	60	60	60	60	60		
Maximum d/c ratio**	0.78	0.87	0.87	0.87	0.83	0.77	0.90	0.99	0.99	0.99	0.92	Globally Undersaturated	
Time interval queueing begins													
Travel time per vehicle (min)	1.00	0.32	0.44	0.30	1.01	0.62	1.02	0.25	0.08	0.23	1.03	6.3	min
VMTD Veh-miles (Demand)	5788.8	1797.9	2732.9	1797.9	5968.8	3321.9	6238.8	1473.3	465.3	1473.3	6463.8	37,523	VMT
VMTV Veh-miles (Volume)	5788.8	1797.9	2732.9	1797.9	5968.8	3321.9	6238.8	1473.3	465.3	1473.3	6463.8	37,523	VMT
VHT travel (hrs)	96.8	33.6	46.4	32.1	100.3	69.0	106.3	28.0	8.8	26.4	111.3	659.0	VHT
VHD delay (hrs)	0.3	3.6	0.9	2.2	0.9	13.6	2.3	3.4	1.1	1.9	3.5	33.6	VHD
Space mean speed = VMTV / VHT (mph)	59.82	53.53	58.85	55.98	59.49	48.16	58.69	52.65	52.65	55.78	58.09	56.9	mph
Average density (vpmpl)	25.8	31.5	28.7	30.1	26.8	27.6	28.3	34.6	34.6	32.6	29.7	28.5	veh/mi/ln
Average density (pcpmpl)	26.4	32.3	29.4	30.9	27.4	28.3	29.1	35.4	35.4	33.4	30.4	29.2	pc/mi/ln
												All entry vehicles have cleared within the analysis period.	

Exhibit 79: Time Interval Performance

Input Worksheet (VKS 1) - Directional Freeway Facility													
FREEVAY SYSTEM TITLE:	Chapter 10- Freeway Facilities-Example Problem 1- Undersaturated												
SEGMENT NUMBER :	1	2	3	4	5	6	7	8	9	10	11		
SEGMENT LABEL :	S01	S02	S03	S04	S05	S06	S07	S08	S09	S10	S11		
Input or estimated segment type (B,V, ONR,OFR,R)	B	ONR	B	OFR	B	W	B	ONR	R	OFR	B		
Segment Length (ft)	5,280	1,500	2,280	1,500	5,280	2,640	5,280	1,140	360	1,140	5,280	6.00	miles
Number of lanes	3	3	3	3	3	4	3	3	3	3	3		
Free flow speed (mph)	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0		
Space mean speed (mph)	59.4	52.5	57.1	55.7	58.3	46.1	56.1	50.6	50.6	55.2	55.0		
Segment density (veh/mi/lane)	29.3	37.2	34.2	35.0	31.9	34.6	35.8	43.9	43.9	40.3	37.7	34.8	veh/mi/ln
Segment capacity (vph)	6,732	6,732	6,732	6,732	6,732	8,303	6,732	6,732	6,732	6,732	6,732		
Segment demand (vph)	5,225	5,855	5,855	5,855	5,585	6,395	6,035	6,665	6,665	6,665	6,215		
Segment volume served (vph)	5,225	5,855	5,855	5,855	5,585	6,395	6,035	6,665	6,665	6,665	6,215		
d/c ratio	0.78	0.87	0.87	0.87	0.83	0.77	0.90	0.99	0.99	0.99	0.92		
On-Ramp demand (vph)	0	630	0	0	0	810	0	630	0	0	0		
On-Ramp capacity (vph)		2,000				2,000		2,000					
Off- Ramp demand (vph)	0	0	0	270	0	360	0	0	0	450	0		
Off-Ramp capacity (vph)				2,000		2,000				2,000			
Ramp-to-Ramp demand (vph)						150							
Travel time per vehicle (min)	1.01	0.32	0.45	0.31	1.03	0.65	1.07	0.26	0.08	0.23	1.09	6.51	min
Free-flow travel time (min)	1.00	0.28	0.43	0.28	1.00	0.50	1.00	0.22	0.07	0.22	1.00	6.00	min
Freeway mainline delay (min)	0.01	0.04	0.02	0.02	0.03	0.15	0.07	0.04	0.01	0.02	0.09	0.51	min
System delay-- includes on-ramps (min)	0.01	0.04	0.02	0.02	0.03	0.15	0.07	0.04	0.01	0.02	0.09	0.51	min
VMTD Veh-miles / interval (Demand)	1,306.3	415.8	632.1	415.8	1,396.3	799.4	1,508.8	359.8	113.6	359.8	1,553.8	8,861	veh-mi
VMTV Veh-miles / interval (Volume served)	1306.3	415.8	632.1	415.8	1396.3	799.4	1508.8	359.8	113.6	359.8	1553.8	8,861	veh-mi
VHT travel / interval (hrs)	22.00	7.92	11.07	7.46	23.96	17.32	26.88	7.12	2.25	6.52	28.24	160.74	hrs
VHD delay /interval (hrs)	0.23	0.99	0.54	0.53	0.69	4.00	1.74	1.12	0.35	0.53	2.34	13.05	hrs
Space mean speed = VMTV / VHT (mph)	59.4	52.5	57.1	55.7	58.3	46.1	56.1	50.6	50.6	55.2	55.0	55.1	mph
Segment density (pc/mi/lane)*	30.1	31.8	35.0	31.5	32.7	35.5	36.7	35.8	36.9	36.9	38.6	35.6	pc/mi/ln
Density-based LOS on segment	D	D	D	D	D	E	E	E	E	E	E	E	
Demand-based LOS on segment													
* For Merge and Diverge Segments this Density is only for Ramp Influence Area!												Revise Input Data	

From any of the time interval sheets (Exhibit 79) the user can select "revise input data" to modify segment and time-interval specific data. However, the user cannot add/delete segments or time intervals at this stage, since the corresponding worksheets and columns have been customized in step B above. No attempt is made to characterize facility LOS across multiple time periods which may have very different operational performance and can therefore bias the resulting facility LOS value considerably.

Exhibit 80: Output Graphs



The four graphs in Exhibit 80 show performance measures over the time-space domain. The v/c and d/c graphs in this case are identical, because the facility is globally undersaturated. The speed plot shows a slight reduction in speed in the weaving segment (segment 6) resulting from relatively high weaving volumes that still do not exceed capacity. The density plot shows elevated densities in segments 8 and 9. Note that the length axis in the graphs is categorical and the scale therefore does not reflect the different lengths of segments.

In addition to the graphical outputs, FREEVAL also gives summary tables of the same four performance measures (v/c, d/c, speed, and density), as well as Levels of Service. Exhibit 81shows only the LOS table, since other outputs are already represented in the previous exhibit.

Exhibit 81: Levels of Service Summary Table

DENSITY BASED Level Of Service

	Segment											FACILITY
Time	1	2	3	4	5	6	7	8	9	10	11	LOS
1	C	C	D	C	D	C	D	D	D	D	D	D
2	D	D	D	D	D	D	D	D	D	D	D	D
3	D	D	D	D	D	E	E	E	E	E	E	E
4	D	C	D	D	D	C	D	D	D	D	D	D
5	C	C	C	C	C	B	C	C	C	C	C	C

A B C D E F

DEMAND BASED Level Of Service

	Segment										
Time	1	2	3	4	5	6	7	8	9	10	11
1											
2											
3											
4											
5											

*IF ALL CELLS BLANK, D/C<1.0 ACROSS ALL SEGMENTS AND TIME PERIODS.

Consistent with the discussion in Chapter 10, FREEVAL provides two summary tables for Levels of Service. The upper table in Exhibit 81 gives the density-based levels of service criteria, which in this case are all at LOS=E or better. The bottom table gives supplemental LOS information for any segments where demand exceeds capacity. Since all segments operate below capacity, no entries are shown in the demand-based Level of Service Table.

STEP H: REVISING INPUT DATA

Step G above concludes the freeway facility methodology outlined in Chapter 10. It is however expected that analysts will use the methodology to test various scenarios or to perform sensitivity analyses. The FREEVAL computational engine has been designed to allow the user to revise input data and make changes to geometry, demand patterns or other input variables to test the effect of such changes on the operations of the facility. Reasons to revise inputs include:

- Testing sensitivity of increased volumes due to traffic growth or traffic diversion to other routes.
- Testing geometric changes such as added lanes, different ramp configurations, or alternate weaving patterns in select segments
- Testing the operational effects of work zones and/or incidents through changes in segment capacity and/or free-flow speeds

As stated earlier, the input revision does not allow the analyst to change the number of segments or time periods. This limitation is due to the way the engine customizes the segment columns and time period worksheets in step B. If the analyst wishes to modify the temporal or spatial analysis domain, the facility has to be re-coded.

FREEVAL provides two types of adjustment factors that are intended to assist the user in performing basic sensitivity analyses. These are:

- Origin/Destination Demand Adjustment Factors, and
- Capacity Adjustment Factors

The two adjustment factors are described in more detail below.

Origin/Destination Demand Adjustment Factors

The origin and destination demand adjustment factors are used to test the effect of an increase or decrease in the original demand volumes by a user-defined growth or shrinkage factor. Each segment contains one origin and one destination adjustment factor for each time period. They work as simple multiplicative factors that adjust the entering and exiting demands in the segment. For example, an origin adjustment factor of 1.10, increases the demand of mainline or an on-ramp segment by 10%. Similarly, a destination adjustment factor of 0.85 will reduce the demand at an off-ramp by 15%. For weaving segments, the entering and exiting demands can be changed with the applicable origin and destination adjustment factors, respectively.

The origin/destination demand adjustment factors are intended to run quick sensitivity analyses or what-if analyses of demand scenarios. For example, they can be used to quickly assess the impact of ITS treatments that cause a proportion of drivers to leave the freeway at an off-ramp upstream of a freeway bottleneck. Similarly, they could be used to model a quick surge in on-ramp traffic. The analyst can change all origin and destination demand adjustment factors by the same value to model general background traffic growth (e.g. 1.05 for 5% traffic growth).

Capacity Adjustment Factors

The capacity adjustment factors are used to increase or decrease the capacity of a segment in one or more time periods. The HCM capacity value for the segment in the selected time interval is multiplied by the factor. As a result, the speed-flow relationship on the segment is changed as is discussed in more detail in Chapters 10 and 25. Capacity adjustment factors can be used to model (short-term) incidents in a segment or to represent the effects of increased friction due to work zones. Capacity adjustment factors should generally only be used to reduce the per-lane capacity in a segment. The speed-flow and capacity relationships in Chapters 10-13 have been calibrated and an adjustment to higher capacities (e.g. greater than 2,400 vehicles per hour per lane) is not supported by the data.

The effect of advanced traffic management strategies such as temporary shoulder use should be modeled by adding a lane in the appropriate segments and time periods, and then reducing the capacity of the revised segment using a capacity adjustment factor (since the use of a shoulder is unlikely to result in a full lane of added capacity. For example, if the use of the shoulder on a 3-lane 70mph basic freeway segment (per-lane capacity is 2,400 veh/hour/lane) results in an additional half-lane of capacity (1,200 veh/hour/lane), it should be modeled as a four-lane segment with a capacity adjustment factor of 0.875 (=[3*2,400+1,200]/[4*2,400]).

4.INTERPRETING OVERSATURATED RESULTS

This section discusses the interpretation of results for an oversaturated freeway facility. A freeway facility is defined as oversaturated, if any segment experiences a d/c>1.0 during any analysis time interval. In the facility summary worksheet, this facility will be labeled as "oversaturated" as shown in Exhibit 82. If this is the case, the user should first assure that whatever queues that have formed during the analysis have dissipated by the end of the last time interval and that all vehicles were able to clear the facility. To check for this, the total vehicle-miles-traveled (VMT) based on demand flow (VMTD) should exactly match the actual VMT processed (VMTV) in Worksheet 3. If these two numbers match, a message appears indicating that "All Vehicles have cleared within the analysis period". If not, the analysis violates the underlying assumptions of Chapter 10, which requires that all queues should be fully contained within the time-space domain. If VMT-Demand does not equal VMT-Volume, this assumption is violated in the time-dimension.

If a violation in the space-dimension occurs, an additional warning message will alert the user that "The queue in time interval X extends beyond the analysis region". In either case, the analyst should start over and re-run the analysis with additional segments and/or time periods as appropriate. An alternative in the case of space-dimension violation is to artificially increase the length of the first upstream segment until the spillover queue is captured within the facility confines. A congested boundary of the time-space domain means that vehicles either remain on the facility by the end of the analysis, or in the case of extended queuing upstream of the first segment, that the impact is not accounted for in the delay and travel times computed for the facility.

The oversaturated facility shown in Exhibit 82 was caused by applying across the board origin/destination demand adjustment factors of 1.11 to all segments and time periods for the undersaturated facility presented above. This represents an 11% overall growth in traffic flow.

Exhibit 82: Summary Output for Oversaturated Facility

Worksheet 3 - Facility-Level Summary

Title: Chapter 10- Freeway Facilities-Example Problem 2- Oversaturated

												SECTION AND PERIOD TOTALS	
Number of ValidTime Intervals	5												
Period Duration (min)	75												
SEGMENT NUMBER :	1	2	3	4	5	6	7	8	9	10	11		units
SEGMENT LABEL :	S01	S02	S03	S04	S05	S06	S07	S08	S09	S10	S11		
Input or estimated segment type (B,W,ONR,OFR)	B	ONR	B	OFR	B	W	B	ONR	R	OFR	B		
Segment length (ft)	5280	1500	2280	1500	5280	2640	5280	1140	360	1140	5280	6.00	miles
Number of lanes	3	3	3	3	3	4	3	3	3	3	3		
Free flow speed (mi/hr)	60	60	60	60	60	60	60	60	60	60	60		
Maximum d/c ratio**	0.86	0.97	0.97	0.97	0.92	0.85	1.00	1.10	1.10	1.10	1.02	Oversaturated	
Time interval queueing begins					3	3	3						
Travel time per vehicle (min)	1.02	0.32	0.46	0.31	1.08	0.76	1.20	0.25	0.08	0.23	1.07	6.8	min
VMTD Veh-miles (Demand)	6425.5	1995.7	3033.5	1995.7	6625.3	3687.3	6925.0	1635.4	516.4	1635.4	7174.8	41,650	VMT
VMTV Veh-miles (Volume)	6425.5	1995.7	3033.5	1995.7	6625.3	3687.3	6925.0	1635.4	516.4	1635.4	7174.8	41,650	VMT
VHT travel (hrs)	109.0	38.0	53.5	35.8	119.2	93.1	138.8	31.7	10.0	29.5	128.0	786.6	VHT
VHD delay (hrs)	1.9	4.7	3.0	2.6	8.7	32.5	23.4	4.5	1.4	2.2	8.4	93.3	VHD
Space mean speed = VMTV / VHT (mph)	58.93	52.58	56.68	55.71	55.60	39.59	49.90	51.52	51.52	55.49	56.06	52.9	mph
Average density (vpmpl)	29.1	35.6	33.1	33.6	31.8	37.2	37.0	39.2	39.2	36.4	34.1	34.0	veh/mi/ln
Average density (pcpmpl)	29.8	36.5	33.9	34.5	32.6	38.2	37.9	40.2	40.2	37.3	35.0	34.9	pc/mi/ln

All entry vehicles have cleared within the analysis period.

The summary output in Exhibit 125-11 gives insight on congestion patterns and severity. In the example, a total of 4 segments are shown to have a maximum d/c ratio greater than 1.0 (Segments 8,9,10, and 11). Segment 5, 6, and 7 all have queuing starting in time interval 3 suggesting an active bottleneck in segment 8. The downstream segments 9 and 10 are not exhibiting a queue, suggesting that demand is metered at the segment 8 bottleneck. The d/c ratios greater than 1.0 without any associated queuing indicate hidden bottlenecks.

More insight can be obtained by now looking at the output worksheet for interval 3 (the time period with queuing) which is shown in Exhibit 83. The exhibit shows that the d/c ratio in segment 8 is 1.10 and as a result a queue starts forming in segment 7. Within the 15-minute time period, the queue fills up all of segments 7 and 6, and extends 1,164 feet into segment 5. Queuing also occurs on the on-ramp at segment 6, with a 270 foot queue on the ramp. The queuing occurs because the calculated capacity of segment 8 (6,732 veh/hour) is less than the demand of 7,398 veh/hour. The actual segment volume and throughput to the next segment (segment 9) is limited to the capacity and thus also equals 6,732 veh/hour. FREEVAL-2010 always places the bottleneck at the upstream end of the segment.

Exhibit 83: Oversaturated Output for Time Interval 3

Input Worksheet (WKS 1) - Directional Freeway Facility

FREEWAY SYSTEM TITLE: Chapter 10- Freeway Facilities-Example Problem 2- Oversaturated

SEGMENT NUMBER :	1	2	3	4	5	6	7	8	9	10	11		
SEGMENT LABEL :	S01	S02	S03	S04	S05	S06	S07	S08	S09	S10	S11		
Input or estimated segment type (B,W, ONR,(	B	ONR	B	OFR	B	W	B	ONR	R	OFR	B		
Segment Length (ft)	5,280	1,500	2,280	1,500	5,280	2,640	5,280	1,140	360	1,140	5,280	6.00	miles
Number of lanes	3	3	3	3	3	4	3	3	3	3	3		
Free flow speed (mph)	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0		
Space mean speed (mph)	57.4	51.0	53.0	55.4	53.6	28.2	34.8	50.2	50.2	55.1	54.6		
Segment density (veh/mi/lane)	33.7	42.5	40.9	39.1	38.0	58.8	57.7	44.7	44.7	40.7	38.3	43.7	veh/mi/ln
Segment capacity (vph)	6,732	6,732	6,732	6,732	6,732	8,303	6,732	6,732	6,732	6,732	6,732		
Segment demand (vph)	5,800	6,499	6,499	6,499	6,199	7,098	6,699	7,398	7,398	7,398	6,899		
Segment volume served (vph)	5,800	6,499	6,499	6,499	6,111	6,625	6,032	6,732	6,732	6,732	6,277		
d/c ratio	0.86	0.97	0.97	0.97	0.92	0.85	1.00	1.10	1.10	1.10	1.02		
v/c ratio	0.86	0.97	0.97	0.97	0.91	0.80	0.90	1.00	1.00	1.00	0.93		
Queue length at end of time interval (ft)					1164	2640	5280						
On-Ramp demand (vph)	0	699	0	0	0	899	0	699	0	0	0		
On-Ramp volume served (vph)	0	699	0	0	0	874	0	699	0	0	0		
On Ramp delay (veh-hrs)		0.0				0.8		0.0					
On-Ramp queue length (ft)						270							
On-Ramp capacity (vph)		2,000				2,000		2,000					
Off- Ramp demand (vph)	0	0	0	300	0	400	0	0	0	500	0		
Off-Ramp volume served (vph)	0	0	0	300	0	393	0	0	0	455	0		
Off-Ramp capacity (vph)				2,000		2,000				2,000			
Ramp-to-Ramp demand (vph)						167							
Travel time per vehicle (min)	1.05	0.33	0.49	0.31	1.12	1.07	1.72	0.26	0.08	0.24	1.10	7.76	min
Free-flow travel time (min)	1.00	0.28	0.43	0.28	1.00	0.50	1.00	0.22	0.07	0.22	1.00	6.00	min
Freeway mainline delay (min)	0.05	0.05	0.06	0.02	0.12	0.57	0.72	0.04	0.01	0.02	0.10	1.76	min
System delay-- includes on-ramps (min)	0.05	0.05	0.06	0.02	0.12	0.78	0.72	0.04	0.01	0.02	0.10	1.98	min
VMTD Veh-miles / interval (Demand)	1,449.9	461.6	701.6	461.6	1,549.8	887.3	1,674.7	399.3	126.1	399.3	1,724.7	9,836	veh-mi
VMTV Veh-miles / interval (Volume served)	1449.9	461.6	701.6	461.6	1527.7	828.1	1508.1	363.4	114.7	363.4	1569.3	9,349	veh-mi
VHT travel / interval (hrs)	25.28	9.05	13.24	8.34	28.53	29.41	43.29	7.23	2.28	6.59	28.74	201.96	hrs
VHD delay /interval (hrs)	1.11	1.35	1.54	0.64	3.06	16.40	18.15	1.18	0.37	0.54	2.58	46.93	hrs
Space mean speed = VMTV / VHT (mph)	57.4	51.0	53.0	55.4	53.6	28.2	34.8	50.2	50.2	55.1	54.6	46.3	mph
Segment density (pc/mi/lane)*	34.5	35.0	41.9	34.9	39.0	60.3	59.2	36.5	37.4	37.4	39.3	44.8	pc/mi/ln
Density-based LOS on segment	D	D	E	D	E	F	F	E	E	E	E	E	
Demand-based LOS on segment								F	F	F	F		

* For Merge and Diverge Segments this Density is only for Ramp Influence Area!

Revise Input Data

In the same time period, it is evident that segments 9-11 also have d/c ratios greater than 1.0, but no queuing occurs since the demand is metered by segment 8. This occurs because the capacity of segment 8 is greater than or equal to the capacities of these downstream segments. For example, the demand in segment 11 is 6,899 veh/hour, which is greater than the segment capacity of 6,732 veh/hour (d/c = 1.02). However, due to the upstream (more severe) bottleneck the volume served in segment 11 during this time period is only 6,277 veh/hour and the served volume-to-capacity ratio is only 0.93. The bottleneck in segment 11 is therefore inactive or hidden. As a result the downstream segments operate at capacity, which is defined as density-based LOS E. The fact that these segments do have d/c ratios greater than 1.0 is reflected in the demand-based LOS, which is F for segments 9 through 11. This recognizes that the segment would fail if the upstream bottleneck didn't exist (or was alleviated through geometric changes to the facility).

The results for time-period 3 in Exhibit 83 show that not all the forecasted demand actually reaches segment 9-11, due to congestion in segment 8. Because some vehicles did not get served in time period 3, they are now added as residual demand in time period 4. Exhibit 84 shows this effect. While the segment 9-11 served volumes were lower than the demand in time interval 3, the volumes are greater than the demand in time interval 4. For example, the segment 11 demand is 5,500 veh/hour, but as the upstream queue clear the actual served volume is 6,121 veh/hour in this time period. The output further shows that due to a drop in demand from time periods 3 to 4 all queues have cleared at the end of the 15-minute interval.

Exhibit 84: Oversaturated Output for Time Interval 4

Input Worksheet (WKS 1) - Directional Freeway Facility

FREEWAY SYSTEM TITLE: Chapter 10- Freeway Facilities-Example Problem 2- Oversaturated

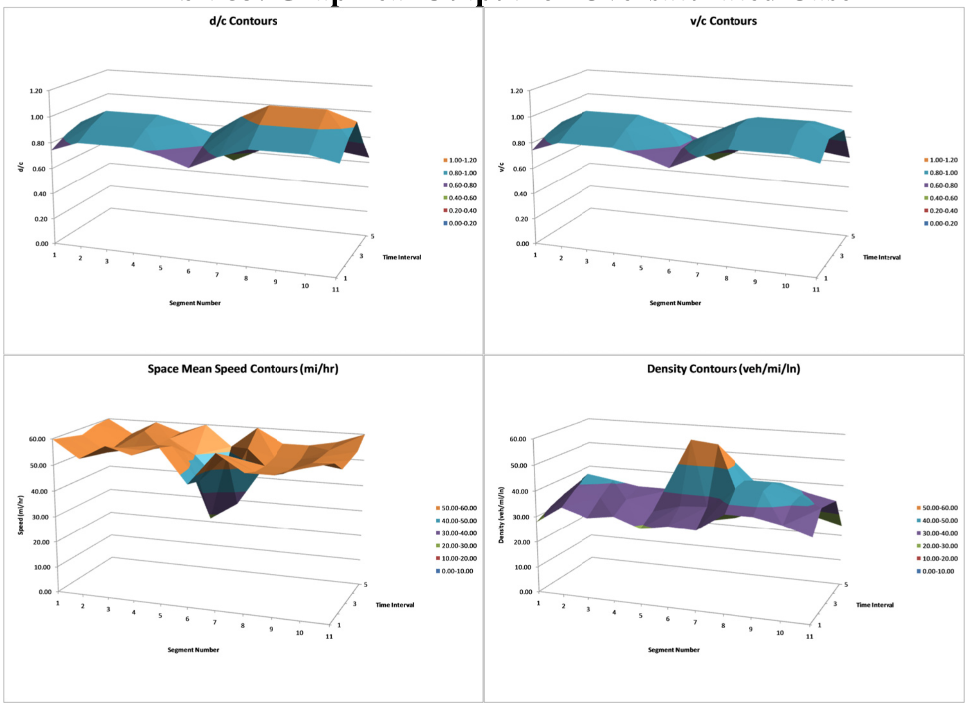
SEGMENT NUMBER :	1	2	3	4	5	6	7	8	9	10	11		
SEGMENT LABEL :	S01	S02	S03	S04	S05	S06	S07	S08	S09	S10	S11		
Input or estimated segment type (B,W, ONR,(	B	ONR	B	OFR	B	W	B	ONR	R	OFR	B		
Segment Length (ft)	5,280	1,500	2,280	1,500	5,280	2,640	5,280	1,140	360	1,140	5,280	6.00	miles
Number of lanes	3	3	3	3	3	4	3	3	3	3	3		
Free flow speed (mph)	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0	60.0		
Space mean speed (mph)	59.4	53.0	58.2	55.8	49.9	39.2	53.9	51.2	51.2	55.3	55.6		
Segment density (veh/mi/lane)	29.2	35.2	32.1	33.4	36.0	39.4	36.9	42.1	42.1	38.9	36.7	35.5	veh/mi/ln
Segment capacity (vph)	6,732	6,732	6,732	6,732	6,732	8,382	6,732	6,732	6,732	6,732	6,732		
Segment demand (vph)	5,200	5,600	5,600	5,600	5,300	5,700	5,300	5,800	5,800	5,800	5,500		
Segment volume served (vph)	5,200	5,600	5,600	5,600	5,389	6,173	5,967	6,466	6,466	6,466	6,121		
d/c ratio	0.77	0.83	0.83	0.83	0.79	0.68	0.79	0.86	0.86	0.86	0.82		
v/c ratio	0.77	0.83	0.83	0.83	0.80	0.74	0.89	0.96	0.96	0.96	0.91		
Queue length at end of time interval (ft)													
On-Ramp demand (vph)	0	400	0	0	0	400	0	500	0	0	0		
On-Ramp volume served (vph)	0	400	0	0	0	425	0	500	0	0	0		
On Ramp delay (veh-hrs)		0.0				0.0		0.0					
On-Ramp queue length (ft)													
On-Ramp capacity (vph)		2,000				2,000		2,000					
Off- Ramp demand (vph)	0	0	0	300	0	400	0	0	0	300	0		
Off-Ramp volume served (vph)	0	0	0	300	0	406	0	0	0	345	0		
Off-Ramp capacity (vph)				2,000		2,000				2,000			
Ramp-to-Ramp demand (vph)						89							
Travel time per vehicle (min)	1.01	0.32	0.45	0.31	1.20	0.77	1.11	0.25	0.08	0.23	1.08	6.81	min
Free-flow travel time (min)	1.00	0.28	0.43	0.28	1.00	0.50	1.00	0.22	0.07	0.22	1.00	6.00	min
Freeway mainline delay (min)	0.01	0.04	0.01	0.02	0.20	0.27	0.11	0.04	0.01	0.02	0.08	0.81	min
System delay-- includes on-ramps (min)	0.01	0.04	0.01	0.02	0.20	0.27	0.11	0.04	0.01	0.02	0.08	0.82	min
VMTD Veh-miles / interval (Demand)	1,300.1	397.7	604.5	397.7	1,325.1	712.5	1,325.1	313.1	98.9	313.1	1,375.0	8,163	veh-mi
VMTV Veh-miles / interval (Volume served)	1300.1	397.7	604.5	397.7	1347.2	771.7	1491.7	349.0	110.2	349.0	1530.4	8,649	veh-mi
VHT travel / interval (hrs)	21.88	7.50	10.38	7.12	27.02	19.70	27.70	6.82	2.15	6.31	27.52	164.10	hrs
VHD delay /interval (hrs)	0.21	0.87	0.31	0.50	4.57	6.85	2.84	1.00	0.32	0.49	2.01	19.96	hrs
Space mean speed = VMTV / VHT (mph)	59.4	53.0	58.2	55.8	49.9	39.2	53.9	51.2	51.2	55.3	55.6	52.7	mph
Segment density (pc/mi/lane)*	29.9	29.9	32.9	30.5	36.9	40.4	37.9	34.3	34.8	34.8	37.6	36.4	pc/mi/ln
Density-based LOS on segment	D	D	D	D	E	E	E	D	D	D	E	E	
Demand-based LOS on segment													

* For Merge and Diverge Segments this Density is only for Ramp Influence Area!

Revise Input Data

The effects of congestion are also evident in the graphical output provided as part of FREEVAL2010. The graphs in Exhibit 85 are the same as already introduced in Exhibit 125-9, but now show the effect of congestion. Most importantly, while the under-saturated d/c and v/c graphs in Exhibit 125-9 were identical, the oversaturated v/c graph limits the throughput of the active bottleneck in segment 8 to 1.0 and further shows the metering effect in segments 9 through 11. The speed graph shows a significant drop in speed as a result of the active bottleneck, but further shows that operating conditions downstream of segment 8 are acceptable. This point is critical, since an individual segment analysis of segments 9-11 would have predicted a much lower and congested speed. The density plot further shows areas of queuing with densities exceeding 45 veh/mile/lane in the queued segments.

Exhibit 85: Graphical Output for Oversaturated Case



The LOS summary table for the oversaturated scenario now clearly shows the distinction between the density-based LOS that uses the actual volumes served on the facility and the demand-based LOS table that shows the presence of all segments with d/c greater than 1.0, including all active and hidden bottlenecks (Exhibit 86).

Exhibit 86: LOS Summary Table for Oversaturated Scenario

DENSITY BASED Level Of Service

	Segment											FACILITY
Time	1	2	3	4	5	6	7	8	9	10	11	LOS
1	D	D	D	D	D	D	D	D	D	D	D	D
2	D	D	E	D	D	E	E	E	E	E	E	E
3	D	D	E	D	E	F	F	E	E	E	E	F
4	D	D	D	D	D	E	E	D	D	D	E	E
5	C	C	C	C	C	C	C	C	C	C	C	C

LEGEND: A, B, C, D, E, F

DEMAND BASED Level Of Service

	Segment										
Time	1	2	3	4	5	6	7	8	9	10	11
1											
2											
3								F	F	F	F
4											
5											

*IF ALL CELLS BLANK, D/C<1.0 ACROSS ALL SEGMENTS AND TIME PERIODS.

The density-based Level of Service Table in Exhibit 86 shows that segments 6 and 7 operate at LOS F in time period 3. In this case Segment 8 is the active bottleneck and since FREEVAL places the bottleneck at the beginning of the segment, it operates at capacity or LOS=E. Since all downstream segments have capacity less than or equal to that of the active bottleneck, they also operate at LOS=E. The bottom portion of Exhibit 86 shows the demand-based LOS, which emphasizes that segments 8 through 11 all have demand-to-capacity ratios greater than 1.0 in time period 3. The comparison between the density-based and demand-based LOS tables allows a quick and easy analysis of which bottlenecks are active and which segments are inactive or hidden bottlenecks due to an upstream metering effect of traffic demand. The overall facility LOS is F in time period 3, since one or more individual segments have $d/c > 1.0$.

Appendix C: Overview of Study Sites

This appendix contains details on NC work zone sites identified as part of NCDOT project 2010-08. The initial focus of site selection was on work zones that were instrumented with automated data collection devices through Traffic.Com in the Raleigh, NC area. Other sites will be supplemented as necessary.

TABLE #: Work Zone Diary Candidates, Scenarios, and Locations

Date	Direction	Closure Description	NC040300	NC040290	NC040280	NC040270	NC040260	NC040250	NC040240	NC040230	NC040220
8/10/2009	WB	1 Left Lane							3 to 2		
8/11/2009	WB	1 Left Lane							3 to 2		
8/12/2009	WB	1 Left Lane							3 to 2		
8/16/2009	WB	1 Left Lane						3 to 2			
8/17/2009	WB	1 Left Lane						3 to 2			
8/18/2009	WB	1 Left Lane					3 to 2	3 to 2			
8/19/2009	WB	1 Left Lane				2 to 1	3 to 2	3 to 2			
8/20/2009	WB	1 Left Lane				2 to 1	3 to 2	3 to 2			
8/23/2009	WB	1 Left Lane		4 to 3	4 to 3						
8/24/2009	WB	1 Left Lane		4 to 3	4 to 3						
8/25/2009	WB	1 Left Lane	4 to 3	4 to 3	4 to 3						
8/26/2009	WB	1 Left Lane	4 to 3	4 to 3	4 to 3						
8/27/2009	EB	1 Left Lane			4 to 3						
8/30/2009	EB	1 Left Lane			4 to 3						
8/31/2009	EB	1 Left Lane						3 to 2	3 to 2		
9/1/2009	EB	1 Left Lane						3 to 2	3 to 2		

Date	Direction	Closure Description	NC040300	NC040290	NC040280	NC040270	NC040260	NC040250	NC040240	NC040230	NC040220
9/3/2009	EB	1 Left Lane			4 to 3						
9/9/2009	EB	1 Left Lane			4 to 3						
9/10/2009	EB	1 Left Lane			4 to 3						
9/13/2009	EB	1 Left Lane			4 to 3						
9/14/2009	EB	1 Left Lane			4 to 3						
9/15/2009	EB	1 Left Lane			4 to 3	3 to 2	3 to 2				
9/16/2009	EB	1 Left Lane					3 to 2	3 to 2			
9/17/2009	EB	1 Left Lane					3 to 2	3 to 2			
3/7/2010	EB	2 Left Lanes			4 to 2*						
3/8/2010	WB	2 Right Lanes							3 to 1*	3 to 1	
3/9/2010	EB	3 Right Lanes	4 to 1	4 to 2	4 to 1						
3/14/2010	EB	3 Right Lanes	4 to 1	4 to 2*	4 to 1*						
3/15/2010	WB	2 Right Lanes						3 to 1	3 to 1*	3 to 2*	
3/16/2010	WB	2 Right Lanes							3 to 1*	3 to 1	
3/17/2010	EB	1 Right Lane			4 to 3						
3/17/2010	EB	1 Left Lane			4 to 3						
3/18/2010	EB	1 Left Lane			4 to 3	3 to 2*	3 to 2				
3/19/2010	EB	1 Right Lane					3 to 2	3 to 2	3 to 2		
3/19/2010	EB	1 Left Lane					3 to 2	3 to 2	3 to 2		
3/20/2010	WB	Right Lane				2 to 1					
3/23/2010	EB	1 Right Lane							3 to 1*	3 to 2	
3/24/2010	WB	1 Right Lane					3 to 2	3 to 2*	3 to 2*		
3/26/2010	EB	2 Left Lanes		4 to 2*							
3/27/2010	WB	1 Right Lane						3 to 2			
3/31/2010	WB	1 Left Lane			4 to 3	2 to 1*	3 to 2				
3/31/2010	EB	1 Left Lane		4 to 3*	4 to 3*						
3/31/2010	EB	Ramp Lane					3 to 2				
4/6/2010	WB	1 Right Lane									3 to 2

Date	Direction	Closure Description	NC040300	NC040290	NC040280	NC040270	NC040260	NC040250	NC040240	NC040230	NC040220
4/7/2010	WB	1 Right Lane									
4/7/2010	WB	1 Left Lane	4 to 3	4 to 3	4 to 3	2 to 1	3 to 2				
4/7/2010	EB	1 Left Lane					3 to 2	3 to 2	3 to 2		
4/9/2010	EB	2 Left Lanes			4 to 2						
4/10/2010	WB	2 Right Lanes						3 to 2*			
4/12/2010	WB	1 Left Lane						3 to 2*	3 to 2*		
4/12/2010	EB	1 Left Lane			4 to 3						
4/13/2010	EB	1 Left Lane			4 to 3*	3 to 2*					
4/13/2010	WB	1 Left Lane						3 to 2	3 to 2		
4/13/2010	EB	1 Left Lane							3 to 2	3 to 2	
4/13/2010	EB	1 Right Lane									3 to 2
4/14/2010	WB	1 Left Lane						3 to 2*	3 to 2*		
4/14/2010	EB	1 Left Lane			4 to 3						
4/14/2010	WB	1 Right Lane									3 to 2
6/5/2010	EB	Left Lane			4 to 3						
6/7/2010	WB	Left Lane					3 to 2	3 to 2	3 to 2		
6/7/2010	EB	Left Lane			4 to 3						
6/8/2010	WB	Left Lane					3 to 2	3 to 2	3 to 2		
6/8/2020	EB	Left Lane			4 to 3						
6/9/2010	EB	Left Lane			4 to 3						
6/10/2010	WB	Left Lane					3 to 2	3 to 2	3 to 2		
6/10/2010	EB	Left Lane			4 to 3						
6/10/2010	WB	Left Lane					3 to 2	3 to 2	3 to 2		
6/11/2010	EB	Left Lane			4 to 3						
6/11/2010	WB	Left Lane					3 to 2	3 to 2	3 to 2		
6/12/2010	EB	Left Lane			4 to 3						
6/12/2010	WB	Left Lane					3 to 2	3 to 2	3 to 2		
6/14/2010	EB	Left Lane			4 to 3						

Date	Direction	Closure Description	NC040300	NC040290	NC040280	NC040270	NC040260	NC040250	NC040240	NC040230	NC040220
6/14/2010	WB	Left Lane					3 to 2	3 to 2	3 to 2		
6/16/2010	WB	Left Lane					3 to 2	3 to 2	3 to 2		
6/17/2010	WB	Left Lane					3 to 2	3 to 2	3 to 2		
6/18/2010	WB	Left Lane					3 to 2	3 to 2	3 to 2		
6/18/2010	EB	Left Lane			4 to 3						
6/19/2010	EB	Left Lane			4 to 3						
6/20/2010	EB	Left Lane			4 to 3						
6/21/2010	WB	Left Lane							3 to 2	3 to 2	
6/21/2010	EB	Left Lane			4 to 3						
6/21/2010	EB	Left Lane							3 to 2	3 to 2	
6/22/2010	EB	Left Lane			4 to 3						
6/22/2010	WB	Left Lane							3 to 2	3 to 2	
6/22/2010	EB	Left Lane					3 to 2	3 to 2	3 to 2		
6/23/2010	EB	Left Lane							3 to 2	3 to 2	
6/23/2010	WB	Left Lane							3 to 2	3 to 2	
6/24/2010	EB	Left Lane							3 to 2	3 to 2	
6/24/2010	WB	Left Lane							3 to 2	3 to 2	
6/25/2010	EB	Left Lane			4 to 3						
6/25/2010	WB	Left Lane							3 to 2	3 to 2	
6/25/2010	EB	Left Lane							3 to 2	3 to 2	
6/27/2010	EB	Left Lane							3 to 2	3 to 2	
6/27/2010	WB	Left Lane							3 to 2	3 to 2	
6/28/2010	WB	Left Lane							3 to 2	3 to 2	
6/28/2010	EB	Left Lane							3 to 2	3 to 2	
6/30/2010	EB	Left Lane			4 to 3						
6/30/2010	WB	Left lane							3 to 2	3 to 2	
6/30/2010	EB	Left Lane					3 to 2	3 to 2	3 to 2		
7/6/2010	EB	Right lane			4 to 3	3 to 2	3 to 2				

Date	Direction	Closure Description	NC040300	NC040290	NC040280	NC040270	NC040260	NC040250	NC040240	NC040230	NC040220
7/6/2010	EB	Left Lane			4 to 3				3 to 2	3 to 2	
7/6/2010	WB	Left Lane							3 to 2	3 to 2	
7/7/2010	WB	Left Lane					3 to 2	3 to 2			
7/7/2010	EB	Left Lane							3 to 2	3 to 2	
7/7/2010	WB	Left Lane							3 to 2	3 to 2	
7/8/2010	EB	Left Lane			4 to 3	3 to 2					
7/9/2010	EB	Left Lane			4 to 3				3 to 2	3 to 2	
7/9/2010	WB	Left Lane							3 to 2	3 to 2	
7/9/2010	WB	Left Lane					3 to 2	3 to 2			
7/10/2010	EB	Left Lane							3 to 2	3 to 2	
7/10/2010	WB	Left Lane							3 to 2	3 to 2	
7/11/2010	EB	Left Lane							3 to 2	3 to 2	
7/11/2010	WB	Left Lane							3 to 2	3 to 2	
7/11/2010	WB	Left Lane					3 to 2	3 to 2			
7/11/2010	EB	Right lane			4 to 3	3 to 2					
7/12/2010	EB	Left Lane			4 to 3		3 to 2				
7/12/2010	WB	Right lane									3 to 2
7/12/2010	EB	Left Lane							3 to 2	3 to 2	
7/12/2010	WB	Left Lane							3 to 2	3 to 2	
7/13/2010	WB	Left Lane	4 to 3	4 to 3	4 to 3	2 to 1	3 to 2				
7/13/2010	WB	Left Lane							3 to 2	3 to 2	
7/14/2010	WB	Left Lane							3 to 2	3 to 2	
7/14/2010	EB	Left Lane							3 to 2	3 to 2	
7/14/2010	EB	Left Lane			4 to 3	3 to 2					
7/14/2010	WB	Right lane			4 to 3	2 to 1	3 to 2				
7/15/2010	WB	Right lane				2 to 1	3 to 2				
7/15/2010	WB	Left Lane							3 to 2	3 to 2	
7/15/2010	EB	Left Lane							3 to 2	3 to 2	

Date	Direction	Closure Description	NC040300	NC040290	NC040280	NC040270	NC040260	NC040250	NC040240	NC040230	NC040220
7/16/2010	WB	Left Lane							3 to 2	3 to 2	
7/16/2010	EB	Left Lane							3 to 2	3 to 2	
7/18/2010	WB	Left Lane							3 to 2	3 to 2	
7/18/2010	EB	Right lane						3 to 2			
7/19/2010	EB	Right lane						3 to 2			
7/19/2010	WB	Right lane						3 to 2	3 to 2	3 to 2	
7/20/2010	WB	Left Lane						3 to 2	3 to 2	3 to 2	
7/22/2010	EB	Left Lane							3 to 2	3 to 2	
7/22/2010	WB	Left Lane							3 to 2	3 to 2	
7/22/2010	EB	Left Lane			4 to 3						
7/23/2010	EB	Left Lane			4 to 3						
7/23/2010	EB	Left Lane							3 to 2	3 to 2	
7/23/2010	WB	Left Lane							3 to 2	3 to 2	
7/25/2010	WB	Left Lane							3 to 2	3 to 2	
7/25/2010	EB	Left Lane					3 to 2	3 to 2	3 to 2		
7/26/2010	WB	Left Lane				2 to 1	3 to 2	3 to 2			
7/26/2010	WB	Left Lane						3 to 2	3 to 2	3 to 2	
7/26/2010	EB	Left Lane					3 to 2	3 to 2	3 to 2		
7/26/2010	WB	Left Lane					3 to 2	3 to 2			
7/28/2010	WB	Left Lane	4 to 3	4 to 3	4 to 3		3 to 2				
7/28/2010	WB	Right lane					3 to 2	3 to 2			
7/28/2010	WB	Left Lane					3 to 2		3 to 2	3 to 2	
7/28/2010	EB	Left Lane					3 to 2	3 to 2	3 to 2		
7/28/2010	EB	Left lane			4 to 3		3 to 2				
7/29/2010	EB	Left Lane					3 to 2	3 to 2	3 to 2		
7/29/2010	WB	Left Lane					3 to 2		3 to 2	3 to 2	
7/29/2010	WB	Left Lane	4 to 3	4 to 3	4 to 3	2 to 1	3 to 2				
7/29/2010	EB	Left Lane			4 to 3						

Date	Direction	Closure Description	NC040300	NC040290	NC040280	NC040270	NC040260	NC040250	NC040240	NC040230	NC040220
7/30/2010	WB	Left Lane	4 to 3	4 to 3	4 to 3	2 to 1	3 to 2				
7/30/2010	WB	Left Lane							3 to 2	3 to 2	
7/30/2010	EB	Left Lane							3 to 2	3 to 2	
8/1/2010	WB	Left Lane							3 to 2	3 to 2	
8/1/2010	EB	Left Lane					3 to 2	3 to 2	3 to 2		
8/2/2010	WB	Left Lane							3 to 2	3 to 2	
8/2/2010	EB	Left Lane					3 to 2	3 to 2	3 to 2		
8/2/2010	WB	Left Lane	4 to 3	4 to 3	4 to 3						
8/2/2010	EB	Left Lane			4 to 3						
8/3/2010	EB	Left Lane					3 to 2	3 to 2	3 to 2		
8/3/2010	WB	Left Lane							3 to 2	3 to 2	
8/4/2010	WB	Left Lane							3 to 2	3 to 2	
8/4/2010	EB	Left Lane					3 to 2	3 to 2	3 to 2		
8/6/2010	EB	Left Lane			4 to 3						
8/6/2010	WB	Left Lane	4 to 3	4 to 3	4 to 3						
8/7/2010	WB	Right Lane				2 to 1	3 to 2				
8/9/2010	EB	Left 2 Lanes			4 to 2						
8/9/2010	EB	Left Lane					3 to 2	3 to 2	3 to 2		
8/9/2010	WB	Left Lane							3 to 2	3 to 2	
8/13/2010	EB	Left 3 Lanes			4 to 1						
8/14/2010	WB	Left 3 Lanes	4 to 1	4 to 1	4 to 1						
8/17/2010	EB	Left Lane			4 to 3						
8/19/2010	EB	Right Lane			4 to 3						
8/22/2010	WB	Left Lane				2 to 1					
8/23/2010	WB	Left Lane				2 to 1					
8/26/2010	EB	Right Lane			4 to 3						
8/26/2010	WB	Left Lane				2 to 1					
8/27/2010	WB	Left Lane							3 to 2	3 to 2	

Date	Direction	Closure Description	NC040300	NC040290	NC040280	NC040270	NC040260	NC040250	NC040240	NC040230	NC040220
8/29/2010	WB	Left Lane							3 to 2	3 to 2	
8/30/2010	WB	Left Lane							3 to 2	3 to 2	
8/30/2010	EB	Right 2 Lanes			4 to 2						
8/31/2010	EB	Right 2 Lanes			4 to 2						
8/31/2010	WB	Left Lane							3 to 2	3 to 2	

STUDY AREA INFORMATION

The map in figure 2 shows the layout of Traffic.Com sensors in the Raleigh, NC. The map shows all available sensors (green) and highlights those that are associated with one or more work zones to be studied through this project (orange).

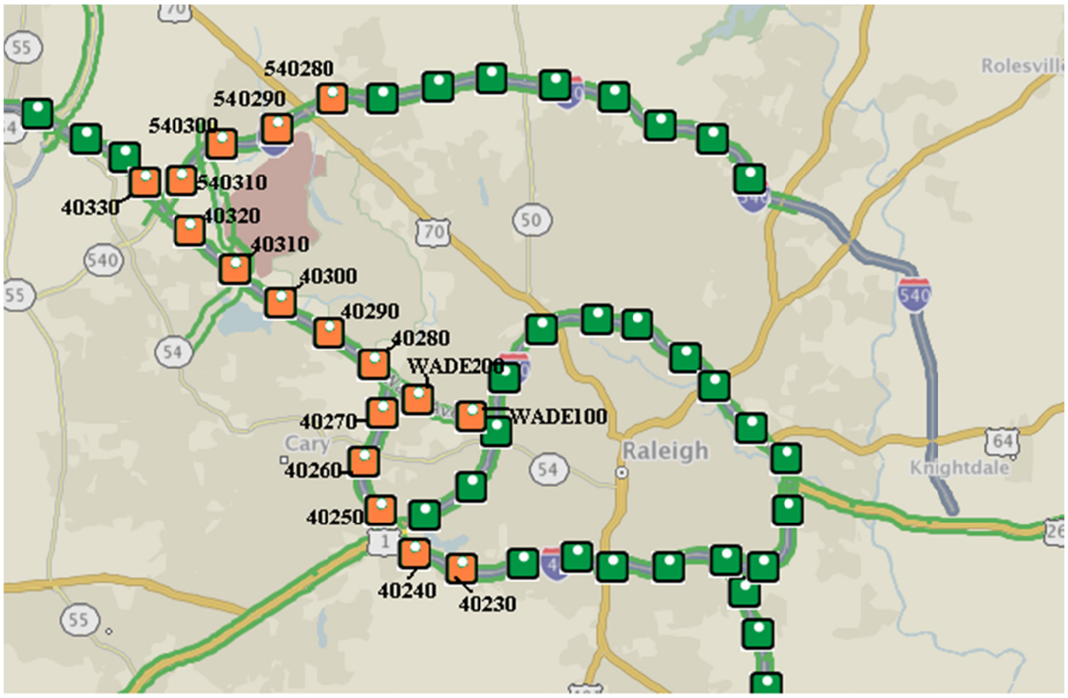


FIGURE 2 Study Area Map.

Table 2 shows details of all (orange) sensors in Figure 2 that provide data for one or more work zones for NCDOT project 2010-08.

TABLE 2 Sensor List and Description

Row	Sensor ID	Mile Post	Location Description	# of Lanes (W/E)
1	NC040330	281.9	1.92 Mile West of Airport Blvd	5/5
2	NC040320	283.2	0.39 Mile North of Airport Blvd	4/4
3	NC040310	284.5	0.22 Mile North of Aviation Pkwy	5/5
4	NC040300	285.9	0.08 Mile North of Old Reedy Creek Rd	4/4
5	NC040290	287.2	1.37 Mile West of Trenton Rd	4/4
6	NC040280	288.5	0.08 Mile West of Trenton Rd	4/4
7	NC040270	289.7	0.08 Mile South of Trinity Rd	2/3
8	NC040260	291.0	0.57 Mile West of Western Blvd	3/3
9	NC040250	289.7	0.15 Mile North of Buck Jones Rd	3/3
10	NC040240	288.5	0.62 Mile West of Avent Ferry Rd	3/3
11	NC040230	287.2	0.05 Mile North of Lake Dam Rd	4/3
12	NC040220	296.1	1.02 Mile North of Lake Wheeler Rd	3/3
13	NC540310	0.7	1.0 Mile East of Slater Rd	4/4
14	NC540300	2.0	0.17 Mile West of Globe Rd	5/5
15	NC540290	3.4	0.79 Mile West of Glenwood Ave	5/5
16	NC540280	4.8	1.87 Mile West of Leesville Rd	3/5
17	NCWAD200	---	0.22 Mile West of Edwards Mill Rd	3/3
18	NCWAD100	---	0.57 Mile West of I-440	2/3

Table 3 contains details on three initial work zones identified for further study as part of NCDOT project 2010-08: I-4744, I-5112, and I-5116. For each project, the table identifies construction time frames, mileposts, and associated traffic.com sensors.

TABLE 3: Work Zone Projects Information

Project		Description	Project Time Frame		Data Collection Time Frame (During Construction)		Mile Post		Sensors	
			Start Date	End Date	Start Date	End Date	Start	End	Start	End
I-4744	East Bound	I-40 Widening from Jones Franklin Rd. to Harrison Ave.	8/16/09	9/17/09	8/1/09	9/30/09	286	292	40290	40260
	West Bound						293	289	40250	40270
I-5112	East Bound	I-40 Rehab from Wade Ave. to I-540	6/1/09	10/4	7/1/09	10/4/09	283	287	40320	40300
	West Bound						289	286	40270	40290
I-5116	East Bound	Milling and resurfacing project on I-540 between I-40 and US-70	9/2/09	9/25/09	9/1/09	9/30/09	0.7	3.4	540310	540290
	West Bound						3.4	0.7	540290	540310

Figure 3 through 7 contain detailed project-specific sensor maps for the three work zone projects currently identified.

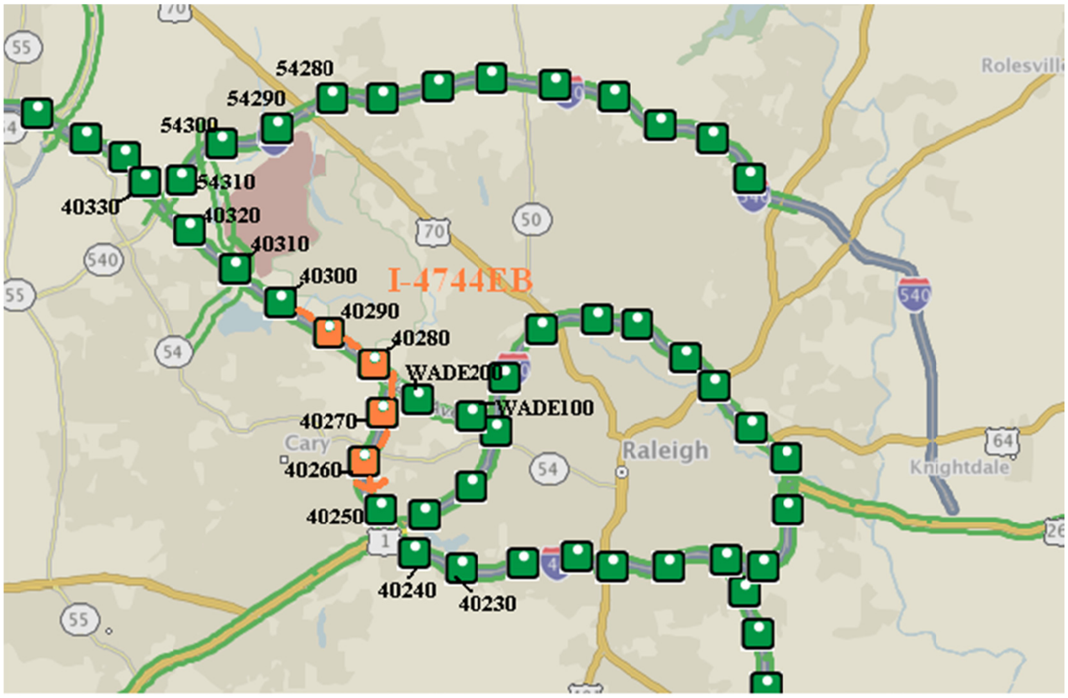


FIGURE 3: I-4744 East Bound.

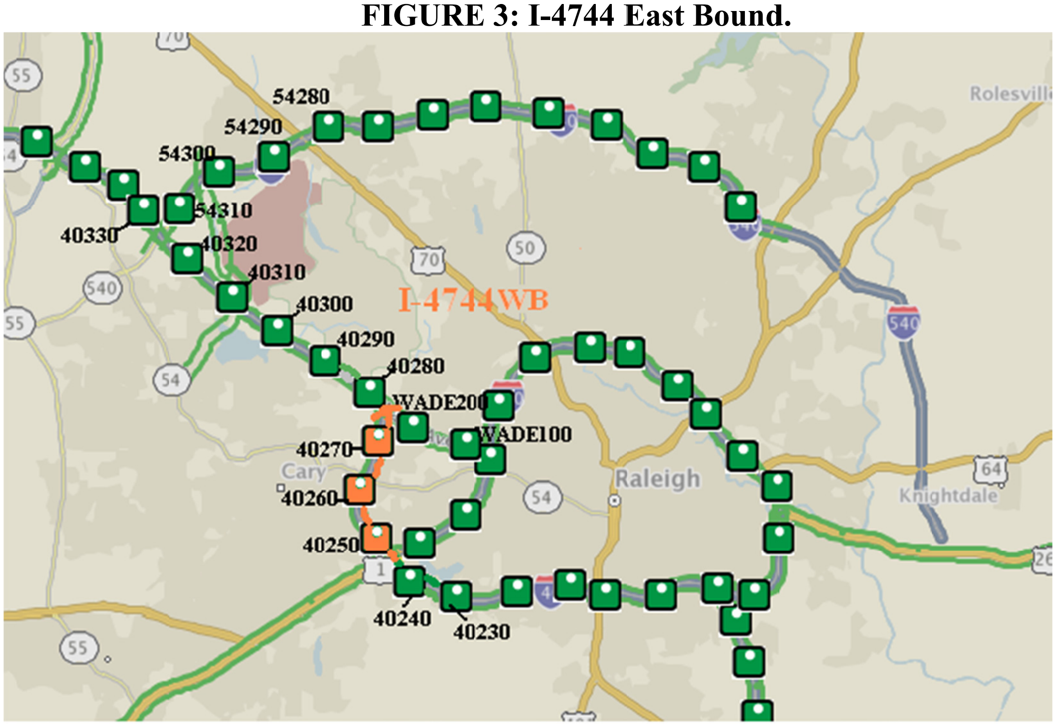


FIGURE 4: I-4744 West Bound.

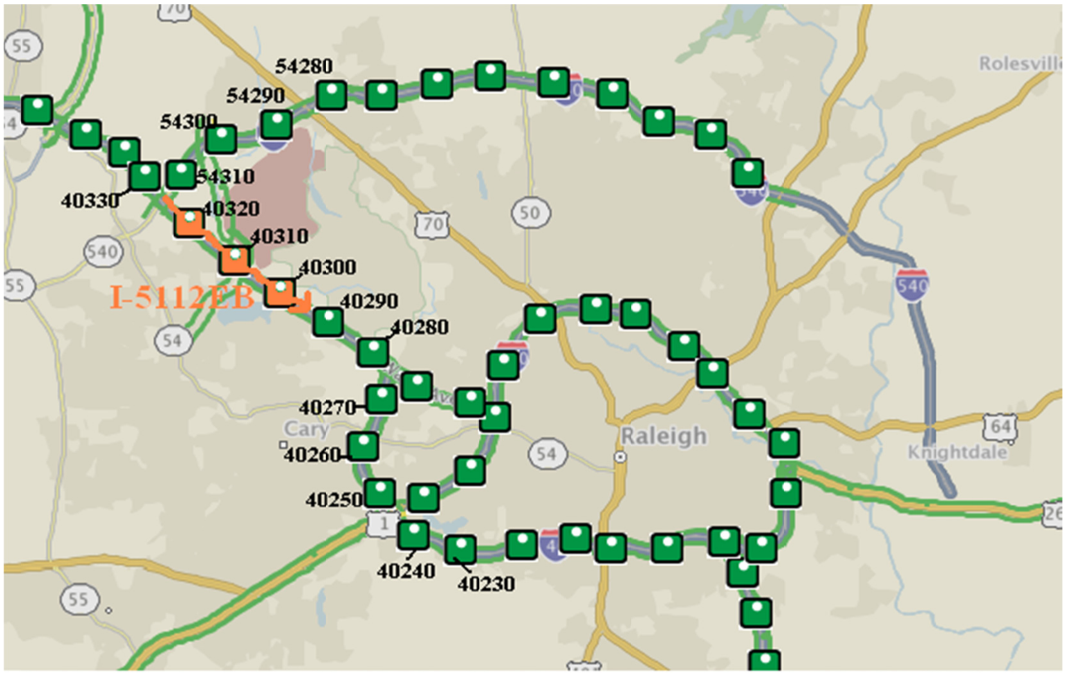


FIGURE 5: I-5112 East Bound.

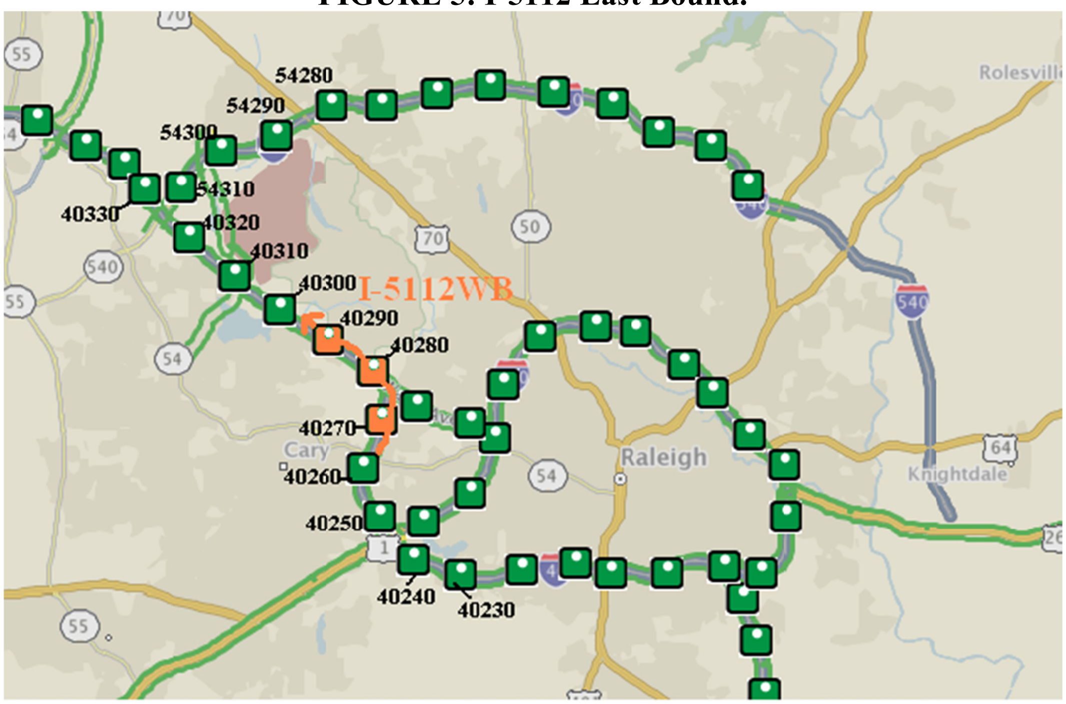


FIGURE 6: I-5112 West Bound.

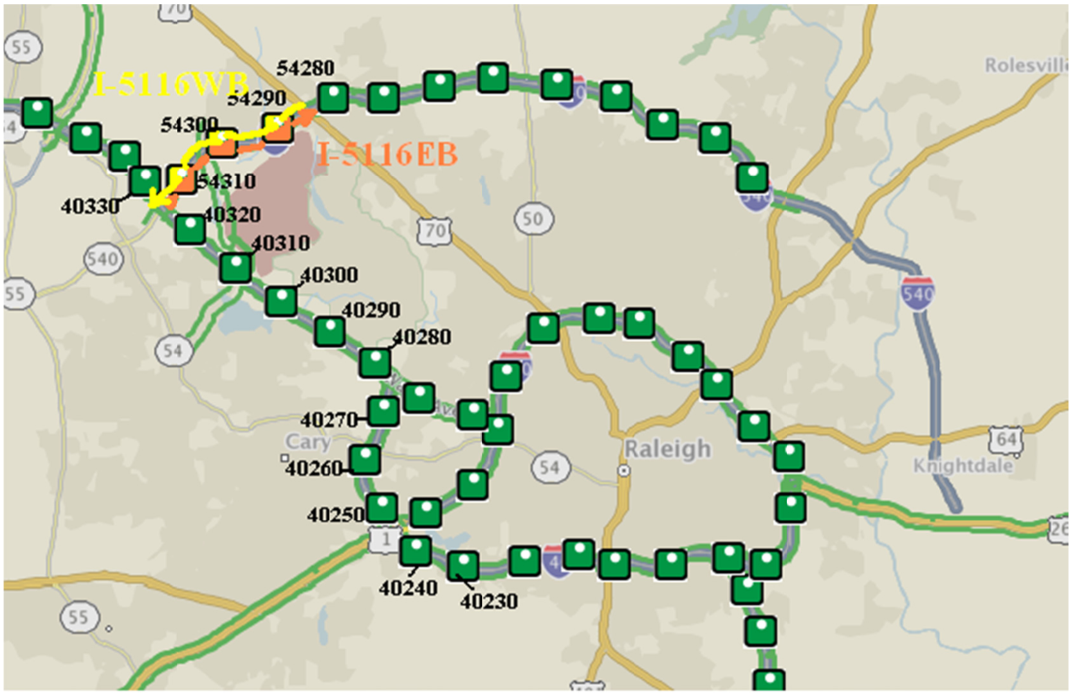


FIGURE 7: I-5112 West Bound.

Appendix D Detailed Listing of Work Zone Data Extracted

Date	Time	Project Code	Sensor ID	Mile Post	Direction	Scenario	# of 15-Min Data Points
8/10/2009	9p-530a	I-4744	40230	294.6	WB	4-3	34
8/10/2009	9p-530a	I-4744	40240	293.4	WB	4-3	34
8/11/2009	9p-530a	I-4744	40230	294.6	WB	4-3	34
8/11/2009	9p-530a	I-4744	40240	293.4	WB	4-3	34
8/12/2009	9p-12a	I-4744	40230	294.6	WB	4-3	12
8/12/2009	9p-12a	I-4744	40240	293.4	WB	4-3	12
8/16/2009	9p-530a	I-4744	40240	293.4	WB	4-3	34
8/16/2009	9p-530a	I-4744	40250	292.1	WB	4-3	34
8/17/2009	9p-12a	I-4744	40240	293.4	WB	4-3	12
8/17/2009	9p-530a	I-4744	40250	292.1	WB	4-3	34
8/18/2009	9p-12a	I-4744	40250	292.1	WB	4-3	12
8/18/2009	9p-12a	I-4744	40270	289.7	WB	4-3	12
8/19/2009	9p-530a	I-4744	40270	289.7	WB	4-3	34
8/19/2009	9p-530a	I-4744	40280	288.5	WB	4-3	34
8/20/2009	9p-430a	I-4744	40270	289.7	WB	4-3	30
8/20/2009	9p-430a	I-4744	40280	288.5	WB	4-3	30
8/23/2009	9p-430a	I-4744	40270	289.7	WB	4-3	30
8/23/2009	9p-430a	I-4744	40280	288.5	WB	4-3	30
8/24/2009	9p-12a	I-4744	40270	289.7	WB	4-3	12
8/24/2009	9p-12a	I-4744	40280	288.5	WB	4-3	12
8/25/2009	9p-12a	I-4744	40280	288.5	WB	4-3	12
8/25/2009	9p-530a	I-4744	40290	287.2	WB	4-3	34
8/26/2009	9p-12a	I-4744	40280	288.5	WB	4-3	12
8/26/2009	9p-5a	I-4744	40290	287.2	WB	4-3	32
8/27/2009	9p-12a	I-4744	40280	288.5	EB	4-3	12
8/30/2009	9p-1130p	I-4744	40280	288.5	EB	4-3	10
8/30/2009	9p-1130p	I-4744	40290	287.2	EB	4-3	10
8/30/2009	9p-1130p	I-4744	40300	285.9	EB	4-3	10
8/31/2009	9p-5a	I-4744	40230	294.6	EB	4-3	32
8/31/2009	9p-5a	I-4744	40240	293.4	EB	4-3	32
8/31/2009	9p-5a	I-4744	40250	292.1	EB	4-3	32
9/1/2009	9p-330a	I-4744	40230	294.6	EB	4-3	26
9/1/2009	9p-330a	I-4744	40240	293.4	EB	4-3	26
9/1/2009	9p-330a	I-4744	40250	292.1	EB	4-3	26
9/3/2009	9p-12a	I-4744	40280	288.5	EB	4-3	12
9/3/2009	9p-12a	I-4744	40290	287.2	EB	4-3	12
9/3/2009	9p-12a	I-4744	40300	285.9	EB	4-3	12
9/9/2009	9p-12a	I-4744	40280	288.5	EB	4-3	12

Date	Time	Project Code	Sensor ID	Milepost	Direction	Scenario	# of 15-Min Data Points
9/9/2009	9p-12a	I-4744	40290	287.2	EB	4-3	12
9/10/2009	9p-5a	I-4744	40270	289.7	EB	4-3	32
9/10/2009	9p-5a	I-4744	40280	288.5	EB	4-3	32
9/13/2009	9p-5a	I-4744	40270	289.7	EB	4-3	32
9/13/2009	9p-5a	I-4744	40280	288.5	EB	4-3	32
9/14/2009	9p-5a	I-4744	40270	289.7	EB	4-3	32
9/14/2009	9p-5a	I-4744	40280	288.5	EB	4-3	32
9/15/2009	9p-12a	I-4744	40270	289.7	EB	4-3	12
9/15/2009	9p-12a	I-4744	40280	288.5	EB	4-3	12
9/16/2009	9p-130a	I-4744	40250	292.1	EB	4-3	18
9/16/2009	9p-130a	I-4744	40270	289.7	EB	4-3	18
9/17/2009	9p-12a	I-4744	40250	292.1	EB	4-3	12
9/17/2009	9p-5a	I-4744	40270	289.7	EB	4-3	32
3/7/2010	9p-1a	I-4744	40280	288.5	WB	4-2	16
3/7/2010	9p-1a	I-4744	40290	287.2	WB	4-2	16
3/7/2010	9p-1a	I-4744	40300	285.9	WB	4-3	16
3/8/2010	9p-10p	I-4744	40220	296.1	WB	4-3	4
3/8/2010	10p-6a	I-4744	40220	296.1	WB	3-1	32
3/8/2010	9p-6a	I-4744	40230	294.6	WB	4-2	36
3/8/2010	9p-10p	I-4744	40240	293.4	WB	3-2	4
3/8/2010	10p-6a	I-4744	40240	293.4	WB	3-1	32
3/9/2010	9p-12a	I-4744	40210	297.3	WB	5-4	12
3/9/2010	9p-12a	I-4744	40220	296.1	WB	3-2	12
3/9/2010	9p-12a	I-4744	40230	294.6	WB	4-2	12
3/9/2010	9p-930p	I-4744	40240	293.4	WB	3-2	2
3/9/2010	930p-12a	I-4744	40240	293.4	WB	3-1	10
3/14/2010	9p-3a	I-4744	40270	289.7	EB	3-2	24
3/14/2010	10p-3a	I-4744	40280	288.5	EB	4-1	20
3/14/2010	9p-10p	I-4744	40290	287.2	EB	4-2	4
3/14/2010	10p-3a	I-4744	40290	287.2	EB	4-1	20
3/14/2010	9p-3a	I-4744	40300	285.9	EB	4-3	24
3/15/2010	9p-5a	I-4744	40230	294.6	WB	4-3	32
3/15/2010	9p-930p	I-4744	40240	293.4	WB	3-2	2
3/15/2010	930p-5a	I-4744	40240	286.9	WB	3-1	30
3/15/2010	10p-5a	I-4744	40250	292.1	WB	3-2	28
3/16/2010	9p-12a	I-4744	40230	294.6	WB	4-3	12
3/16/2010	9p-12a	I-4744	40240	293.4	WB	3-1	12
3/16/2010	10p-12a	I-4744	40250	292.1	WB	3-2	8
3/17/2010	9p-12a	I-4744	40270	289.7	EB	3-2	12

Date	Time	Project Code	Sensor ID	Milepost	Direction	Scenario	# of 15-Min Data Points
3/17/2010	9p-12a	I-4744	40280	288.5	EB	4-3	12
3/17/2010	9p-12a	I-4744	40290	287.2	EB	4-3	12
3/18/2010	9p-3a	I-4744	40270	289.7	EB	3-1	24
3/19/2010	9p-12a	I-4744	40240	293.4	EB	3-2	12
3/19/2010	10p-12a	I-4744	40250	292.1	EB	3-2	8
3/19/2010	9p-12a	I-4744	40270	289.7	EB	3-2	12
3/20/2010	9p-12a	I-4744	40280	288.5	WB	4-3	12
3/23/2010	9p-1a	I-4744	40240	293.4	EB	3-1	16
3/23/2010	9p-1a	I-4744	40250	292.1	EB	3-2	16
3/24/2010	9p-12a	I-4744	40240	293.4	WB	3-2	12
3/24/2010	9p-12a	I-4744	40250	292.1	WB	3-2	12
3/26/2010	9p-830a	I-4744	40270	289.7	EB	3-2	46
3/26/2010	10p-830a	I-4744	40280	288.5	EB	4-2	42
3/26/2010	10p-830a	I-4744	40290	287.2	EB	4-2	42
3/31/2010	930p-12a	I-4744	40270	289.7	WB	2-1	10
3/31/2010	9p-12a	I-4744	40280	288.5	WB	4-3	12
3/31/2010	9p-12a	I-4744	40290	287.2	WB	4-3	12
4/6/2010	930p-12a	I-4744	40200	298.2	WB	4-3	10
4/7/2010	9p-430a	I-4744	40210	297.3	WB	5-4	30
4/9/2010	9-5 4/11	I-4744	40280	288.5	EB	4-3	128
4/9/2010	9-5a 4/11	I-4744	40290	287.2	EB	4-2	128
4/9/2010	10-5 4/11	I-4744	40300	285.9	EB	4-3	124
4/10/2010	9p-2a	I-4744	40250	292.1	WB	3-1	20
4/12/2010	9p-5a	I-4744	40240	293.4	WB	3-2	32
4/12/2010	9p-5a	I-4744	40250	292.1	WB	3-2	32
4/12/2010	9p-5a	I-4744	40270	289.7	WB	2-1	32
4/13/2010	9p-6a	I-4744	40280	288.5	EB	4-1	36
4/14/2010	9p-12a	I-4744	40230	294.6	WB	4-2	12
4/14/2010	9p-12a	I-4744	40240	293.4	WB	3-1	12
4/14/2010	9p-12a	I-4744	40250	292.1	WB	3-2	12
4/6/2010	9p-12a	I-5112	40290	287.2	WB	4-3	12
4/6/2010	9p-6a	I-5112	40300	285.9	WB	4-3	36
4/6/2010	9p-6a	I-5112	40310	284.5	WB	5-4	36
4/7/2010	9p-12a	I-5112	40290	287.2	WB	4-3	12
4/7/2010	9p-12a	I-5112	40300	285.9	WB	5-4	12
4/7/2010	9p-12a	I-5112	40310	284.5	WB	4-3	12
4/12/2010	9p-6a	I-5112	40300	285.9	WB	4-3	36
4/12/2010	9p-6a	I-5112	40310	284.5	WB	5-3	36
4/13/2010	9p-12a	I-5112	40300	285.9	WB	4-3	12

Date	Time	Project Code	Sensor ID	Milepost	Direction	Scenario	# of 15-Min Data Points
4/13/2010	9p-12a	I-5112	40310	284.5	WB	5-3	12
4/13/2010	9p-12a	I-5112	40320	283.2	WB	4-3	12
4/29/2010	9p-6a	I-5112	40290	287.2	EB	4-3	36
4/29/2010	9p-6a	I-5112	40310	284.5	EB	5-4	36
4/30/2010	9p-12a	I-5112	40300	285.9	EB	4-1	12
4/30/2010	9p-12a	I-5112	40310	284.5	EB	5-2	12
4/30/2010	9p-12a	I-5112	40320	283.2	EB	4-1	12
5/1/2010	9p-6a	I-5112	40300	285.9	WB	3-1	36
5/1/2010	9p-6a	I-5112	40310	284.5	WB	5-2	36
5/1/2010	9p-6a	I-5112	40320	283.2	WB	4-1	36