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An Evaluation of Simulation Models To Assess Travel Delay In Work Zones

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AN EVALUATION OF SIMULATION MODELS TO ASSESS TRAVEL DELAY IN WORK ZONES

A Thesis Presented

by

FRANCIS FAN WU

Submitted to the Graduate School of the University of Massachusetts Amherst in partial fulfillment of the requirements for the degree of

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Civil Engineering

Transportation Engineering
AN EVALUATION OF SIMULATION MODELS TO ASSESS TRAVEL DELAY IN WORK ZONES

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I would like to thank my advisor, Dr. John Collura for his thoughts, patience, guidance, and support. I would also like to thank Dr. Ni and Dr. Knodler for serving on my thesis committee and for all that I have learned from them over the past one and a half years.

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A special thank you to those who provided support and friendship that helped me stay focused on this project when the going got tough.
About 20 percent of the U.S. National Highway System is under construction during the peak summer roadway season. Fifty percent of all highway congestion is attributed to nonrecurring conditions and work zones are estimated to account for nearly 24 percent of nonrecurring delay. Work zones account for two percent of roadway crashes and more than 1,000 fatalities per year.

Motorists across the United States have increasingly voiced their displeasure with work zones and the associated delay. This has posed a challenge to transportation officials and contractors as they are faced with finding ways to reduce work zone delay. A key to addressing this challenge to minimize motorist delay during construction and maintenance operations is to recognize these impacts well in advance. In order to meet this challenge, work zone strategy evaluations are necessary to understand the type, severity, and extent of impacts associated with various strategies. One major tool used to aid in conducting these evaluations is computer simulation.

There are many simulation packages in existence, some of which are designed specifically for work zone analysis. These packages include, for example, QUEWZ,
QuickZone, and CA4PRS. This research focuses on the evaluation of these three simulation packages along work zones located on four interstate highway segments on I-91 and I-95 in New England. The evaluation consists of comparing simulation results to field observations in the work zones. The queue lengths estimated by QuickZone and QUEWZ are compared to queue lengths observed in the work zone. Maximum rehabilitation production rates estimated by CA4PRS will be compared to actual production rates recorded in the work zone. This evaluation will allow for a determination to be made as to whether or not these simulation packages produce accurate estimates. In addition to accuracy, the evaluation also sheds light on the user-friendliness of each simulation model as well as other parameters such as data requirements and analysis time. Major results of this evaluation include:

- QUEWZ and QuickZone are user-friendly work zone simulation models.
- The estimations of queue length provided by QuickZone and QUEWZ for the four sites in this research were found to be comparable to the field observations.
- CA4PRS is a user-friendly simulation model. However, the data required to perform an analysis is not as always easy to obtain. In addition, these simulated results of maximum rehabilitation production rates are not easily compared to observed data which are not typically available.

This research should be helpful to guide state and local officials in New England in the selection of simulation models to assess work zone strategies for roadway reconstruction and rehabilitation projects in New England.
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CHAPTER 1

INTRODUCTION

This chapter gives an overview of the challenges engineers are facing when designing and managing work zones and concludes with a description of the goal of this research.

1.1 Background

Author Noelie Altito once said, “The shortest distance between two points is under construction.” Everyday that observation seems more apt. The highway infrastructure of the United States is coming of age and as a result the highway system must be rehabilitated and reconstructed with the use of a variety of work zone strategies. This increasing need to rehabilitate the roadway infrastructure had placed an emphasis on improving our ability to understand, anticipate, and predict work zone traffic conditions, patterns, and other impacts [1].

About 20 percent of the U.S. National Highway System today is under construction during the peak summer roadway season. Fifty percent of all highway congestion is attributed to nonrecurring conditions and work zones are estimated to account for nearly 24 percent of nonrecurring delay. Work zones account for two percent of roadway crashes and more than 1,000 fatalities per year. During the peak summer roadwork season of 2001, approximately 13 percent of the National Highway System (NHS) was under construction, resulting in the staging of 3,110 work zones. The presence of these work zones accounted for 20,876 miles of reduced roadway capacity. This reduction adds to the already existing problem of roadway congestion. Over the past
twenty years, route-miles of highway have increased by approximately five percent while vehicle-miles of travel have increased by 79 percent [1].

With the staggering increase in vehicle-miles of travel, motorists are increasingly exposed to work zones. In 2001, more than 11 billion vehicle-miles of travel have been estimated to pass through active work zones. On average, motorists encounter an active work zone one out of every 100 miles traveled on the NHS in 2001, representing over 12 billion hours of exposure during 2001. Additionally, on average, motorists experience a lane closure every 200 miles driven on the NHS in 2001, representing approximately 6 billion vehicle-miles of travel through work zones nationally [1].

1.2 Research Goal

“Improved computer-based simulation modeling techniques may prove to be a useful tool to help assess alternative work zone configurations and identify the optimal work zone strategy to balance traffic management with construction timelines [14].” It is in the interest of transportation engineers to be able to present reliable information regarding impacts that may occur with the implementation of a work zone strategy. The goal of this research is to provide transportation officials with an evaluation of the application of QuickZone, QUEWZ and CA4PRS to various work zone conditions. It is anticipated that this research will be helpful in making recommendations to transportation agencies in New England and/or New York State for the use of such simulation models on roadway reconstruction and rehabilitation projects under their supervision. The research goal is presented in a more specific set of research objectives in Chapter 3.
CHAPTER 2

LITERATURE REVIEW

2.1 Past Work Zone Simulation Modeling Development

2.1.1 Introduction

Simulation models are designed to duplicate the operation of an actual system. By simulation the functional characteristics of a system, these models are used to predict system performance for a variety of input scenarios. They make it possible to obtain information about the performance of a system through the running of simulated experiments. Performing similar experiments with actual systems may be cost prohibitive, disruptive, or impossible to complete [3].

Traffic operations are generally simulated through one of two categories of traffic simulations – microscopic simulation and macroscopic simulation models. Macroscopic simulation regards traffic flow as a continuum or a stream of fluid. Microscopic simulation examines traffic flow by modeling the behavior of individual vehicles. Since microscopic simulation treats each vehicle as a unique entity, it provides a better medium for understanding the impact individual drivers have on the performance of the entire system. This provides a more effective tool for examining the impact driver behavior has on the throughput of work zones [3].

CORSIM and INTEGRATION are the two most widely used microscopic traffic simulation models. CORSIM was developed under Federal Highway Administration (FHWA) sponsorship. INTEGRATION was developed at Queens University in Ontario, Canada, as an integrated simulation and traffic assignment model. Both models can
similarly predict the operational performance of an integrated traffic system consisting of local streets and freeway segments [3].

CORSIM and INTEGRATION can be adapted to simulate traffic operations around a work zone. This is done by assuming that a lane closure for a work zone results in the same type of impact on traffic carrying capacity as a lane blockage caused by an incident. Both programs are capable of simulation work zones through a prolonged incident blockage. This does not very accurately depict traffic behavior in the approach to a work zone. When modeling a lane blockage in CORSIM, the program assumes that drivers have no knowledge of the approaching blockage and there is no taper. INTEGRATION, on the other hand, does a better job of capturing an appropriate lane-changing behavior at work zones. It does not allow users to modify the location of advance warning signs [3].

These models do not allow the use to incorporate any external logic, which is necessary to simulate the impact of late merging and slow moving vehicles on the queue formation at work zones. These modeling limitations led to the decision to develop a work zone simulation model using Arena simulation software. Arena is a powerful simulation model with an advanced animation module and is typically used to simulation manufacturing processes [3].

2.1.2 Work Zone Simulation Model

The work zone model design is based on the existing geometry of a typical interstate work zone with a lane closure, reducing two lanes to one. The model was based specifically on a work zone on Interstate Highway 80, located in Scott County, Iowa, during the summer of 1998. It is, however, flexible enough to accommodate the potential
modifications of the work zone design and traffic characteristics. It also allows end-users to change parameters and conduct “what-if” analyses [4].

The work zone model is specifically designed to simulate traffic operations prior to and through a work zone. The two most important components of the model are the inclusion of car-following and lane-changing algorithms. The car-following logic models a driver’s behavior in response to speed changes of the lead vehicle. The lane-changing algorithm is more complex because the decision to change lanes depends on a number of factors. Prior to changing lanes, a driver determines whether it is possible, necessary, or desirable to do so. It is necessary, for example, for a vehicle to change lanes when it approaches a lane closure. It is, however, desirable to change lanes when a vehicle is behind a slow-moving vehicle. The car-following and lane-changing algorithms will be discussed in the next two sections in more detail [4].

Within the model each vehicle is generated according to an exponential distribution with an inter-arrival time of at least two seconds (i.e., two seconds headway). Upon its arrival, a number of attributes are assigned to the vehicle. These attributes include vehicle classification, speed, and lane assignment. The attributes are assigned following a discrete or continuous probability function. For example, if it is assumed that the traffic stream is composed of ten percent trucks, the model randomly assigns truck characteristics to ten percent of the vehicles [4].

Vehicles enter the model a few hundred feet upstream of the lane drop sign. It is therefore assumed that vehicles are well informed of the upcoming lane closure. A small percentage of vehicles, however, remain, on the terminating lane ever after the posted lane drop sign. These vehicles, called late mergers, will merge as soon as they find
adequate gaps in the traveling lane. Those vehicles that are not able to merge before the lane is terminated (where the barrels are located) must eventually stop and wait for the next acceptable gap. The waiting time for these vehicles is sometimes long because the through-lane vehicles are not modeled to recognize the vehicles in the terminating lane and provide them a gap. Vehicles in the through lane, however, respond to late mergers who merge immediately in front of them by adjusting their speed. The capacity impacts of the late mergers and other errant merging behavior are examined using simulation in a “before and after” study [4].

Drivers who join the queue at its end and wait to reach the head of the queue view those drivers who travel to the head of the queue in the terminating lane as “cheaters.” Two truck drivers have been commonly observed to block cheaters by collaborating. One truck will travel in the through lane while another truck will travel side-by-side in the closed lane. When the two trucks reach the lane closure taper, the truck in the terminating lane will merge ahead of the truck in the through lane. Usually the two drivers travel slowly through the queue creating a significant gap between their trucks and the vehicle immediately downstream. This errant behavior will be evaluated using the simulation [4].

Given the traffic volume and the population of trucks and slow-moving vehicles, the simulation model estimates the expected travel time and speed throughput the modeled work zone. The model enables a traffic engineer to visually present the impact of a scheduled road construction to public [4].

The model could also assist traffic engineers in rescheduling road construction if the estimated delay is unacceptable for the scheduled timeframe. A number of scenarios
can be examined under various traffic conditions and designs to select the best plan before executing the actual construction activities [4].

2.1.3 Current State of the Art in Work Zone Simulation

Sterzin, Toledo, and Ben-Akiva summarized the state of microsimulation of work zone activities in this way, “None of the simulators surveyed explicitly models work zones. Ten simulators capture work zone effects by modeling it as a pre-defined incident. However, this approach does not necessarily capture all of the effects of work zones.” This future identifies the need to improve microsimulation of work zones [5].

Many difficult questions must be answered to have an accurate simulation of work zone traffic conditions. The calculation of demand and capacity are two calculations that are the most difficult in the evaluation of work zones. Demand calculations are difficult due to the diversions caused by drivers delaying, canceling, or diverting trips to other routes. One difficulty in finding a true capacity is that different researchers have different definitions of how work zone capacity is defined. “Some researchers measured the mean queue discharge flow rate as work zone capacity when the upstream of work zones was in sustained congested traffic flow, while some other researchers defined work zone capacity as the traffic flow rate on the onset of congested traffic conditions.” One broadly employed method for evaluating the impacts of work zones is based on the FHWA developed software, QuickZone. QuickZone is a sketch level tool that supports assessment of work zone mitigation strategies and estimates the costs, traffic delays, and potential backups associated with these impacts. QuickZone can be used to evaluate traffic delays associated with work zone schedules in relation to peak and off-peak traffic periods and/or with the employment of diversion routes. The program
displays the amount of delay in vehicle hours and the maximum length of the projected traffic queue associated with the work activity [7].

2.2 Car-following Algorithm

The car-following theory is one of the most useful techniques for simulating vehicle interactions in a traffic flow. A driver constantly responds to the speed changes of the vehicle immediately downstream. He/she accelerates or decelerates as the lead vehicle speeds up or slows down. Car-following behavior has been formulated using differential equations by a number of researchers. These equations calculate a vehicle’s speed with respect to its distance from the front vehicle at a given time interval [6].

The traditional car-following theory represents space as a continuum and differential equations describe the relative position of vehicles with respect to one another. Microscopic simulation models, on the other hand, divide space into discrete positions. Car following is incorporated by updating the vehicles’ speed at designated points called stations. In our model, the stations are 100 feet apart. One hundred feet is believed to be a small enough increment of distance, at highway speeds, to closely model continuous space. Space intervals rather than time intervals are used to update vehicle assignments. The new car-following algorithm adjusts a vehicle’s speed based on the headway (in feet) and the speed of the lead vehicle. Each vehicle upon its arrival is randomly assigned, among other attributes, a desired speed, which is the speed that each vehicle ultimately wishes to achieve [6].

Controlling vehicles based on space intervals (stations) rather than time is done to be consistent with the requirement of the simulation software used and has enabled us to
take full advantage of Arena’s powerful animation module. Using Arena we are able to
developing a high fidelity microscopic simulation model to be used as a visual medium
for demonstration purposes [6].

A vehicle’s desired speed is calculated by using Equation 1. The first term of the
equation is the assigned work zone speed limit. The second term defines the additional
amount of speed that a vehicle is willing to travel above the speed limit under safe
conditions. The additional speed is assigned based on a driver’s type. Table 1 includes the
distribution of the desired speed above the work zone speed limit and the percentage of
drivers desiring each increment.

When a vehicle arrives at the very first station in the simulation model, it detects
the location and speed of the lead vehicle. It then accelerates or decelerates in response to
the detected information based on the incorporated car-following algorithm. Once the
vehicle reaches the next station, it again adjusts its speed relative to the lead vehicle’s
position and speed. This procedure will be repeated at every station throughout the
network [6].

The car-following algorithm is triggered each time a vehicle enters a station. By
detecting the location and speed of the lead vehicle, the car-following logic determines
whether or not a vehicle may accelerate (to reach its desired speed) or decelerate. The
logic begins by checking the vehicle’s distance from its lead vehicle \( h \). It then compares
the detected distance to two predetermined headways; \( h_1 \) and \( h_2 \). These two headways
divide the car-following algorithm into three regimes. When the headway is less than \( h_1 \n\) (the first regime), the vehicle is following the lead vehicle closely and cannot travel any
faster than the lead vehicle. The conditions for the first regime are in Equation 2.
Between headways $h_1$ and $h_2$, the following vehicle’s speed is greater than the lead vehicle (the second regime) and the following vehicle may travel at a speed faster than the lead vehicle, but its acceleration is governed by the speed of the lead vehicle and the relative distance to the lead vehicle. The conditions for the second regime are expressed in Equation 3. When the headway with the lead vehicle is between $h_1$ and $h_2$ and its speed is greater than the lead vehicle or the headway is greater than $h_2$ (the third regime), the following vehicle is able to travel at its desired speed (free flow conditions). The conditions for the third regime are shown in Equation 4. Based on experimentation with the model, values of 100 feet (one station) and 300 feet (three stations) were selected for $h_1$ and $h_2$, respectively [6].

Given the speed and vehicle type, the vehicle’s allowable speed increment can be determined from Table 2. This table is adapted from the speed-distance relationships for the passenger cars, which represents acceleration rates of approximately 3.5 ft/sec$^2$ and less. For example, a car in the car-following regime, when allowed to accelerate and travel at 47 miles per hour (mph), may add 3 mph to its speed. The normal acceleration rates for trucks at each speed increment are assumed to be half the rates for passenger cars.

As an illustration of the car-following logic, assume that a vehicle, shown in a gray box in Figure 1, arrives at a station located at 1,200 ft ($d$) at the speed of 55 mph ($v$). Its desired speed ($v_d$), however, is 70 mph. It detects its lead vehicle, shown in a black box in Figure 1, at 1,400 ft. Thus, the vehicle’s distance from the lead vehicle ($h$) is 200 ft (i.e., $1400 - 1200$) [6].
2.3 Lane-Changing Algorithm

The lane-changing algorithm is another new component in the work zone simulation model. There are two types of lane-changing – mandatory and discretionary. A mandatory lane-changing is when it becomes necessary for a vehicle to change lanes due to termination of one lane. A discretionary lane-changing is when a vehicle changes lanes to overtake a slower-moving vehicle or to allow an oncoming vehicle to merge. Changing lanes due to a lane closure at a work zone is an example of a mandatory lane-change [7].

Lane-changing is a complex driver behavior. The lane-changing logic in the model captures only the mandatory aspect of this behavior. Thus, only the vehicles on the terminating lane are modeled to change lanes. These vehicles will merge as soon as a sufficient gap in the traveling lane is found.

A vehicle that detects an adequate gap in the traveling lane immediately adjusts its speed with respect to the vehicle at the lead end of the gap by using Equation 5. A vehicle that, for example, is traveling 50 mph on the terminating lane reduces its speed when it verifies that the vehicle at the lead end of the detected gap is traveling at 45 mph. The changing vehicle as soon as a lane-changing maneuver is initiated, adhering to the implemented car-following logic [7].

2.4 Driver Behavior

Human factors considerations are extremely important to the modeling of driver behavior in work zones. Two of those considerations are the acceptable gap in merging and effect of added information and rubbernecking as a result of the work zone activity.
“In merging into traffic on an acceleration ramp on a freeway or similar facility, the situation data for a four lane facility at 90 km/h with a one second allowance for the ramp provides a baseline estimate of gap acceptance: 4.5 seconds. Theoretically as short a gap as three car lengths (14 meters) can be accepted if vehicles are at or about the same speed, as the would be in merging from one lane to another. This is the minimum, however, and at least twice that gap length should be used as nominal value for such lane merging maneuvers.

One of the problems that impede smooth traffic flow on congested facilities is that “rubber neck” problem. Drivers passing by accident scenes, unusual businesses or activities on the road side, construction or maintenance work, or other occurrences irrelevant to the driving task tend to shift sufficient attention to degrade their driving performance [8].”

2.4.1 Driver Expectancy

The concept of driver expectancy is one that is important to work zones. “When a driver’s expectancy is incorrect, either the driver takes longer to respond properly or he/she may respond poorly or wrongly. If, for example, a driver relies on a curve sign that shows a curve to the right but the road actually curves left, one can imagine the difficulty the driver may have in safely negotiating the curve – especially if he/she is a stranger to the area at night.” If drivers do not react correctly in the work zone, safety to the driver and the workers in the work area could be compromised [9].

“What the driver expects on a road is greatly influenced by the “roadway environment.” Studies have shown that what a driver experiences on a road section – presence or absence of traffic control devices, road surface type, condition and width,
narrow bridges or culverts, is what the driver expects to continue for the next one to two kilometers [9]. Work zone traffic control strategy changes the expectancy of the driver to be more ready for the downstream work zone [9].
CHAPTER 3

RESEARCH OBJECTIVE

A major interest among professionals in transportation agencies is to have the ability to present reliable information regarding impacts that may occur with the implementation of a work zone strategy. This ability provides decision makers in these agencies the information needed to make informed decisions on the best work zone implementation for the local conditions in the area of the work zone. An effective tool to aid in the evaluations of these anticipated impacts include user friendly computer based simulation models that are adaptable to the many work zone configurations being considered in the planning, design, and implementation of the work zone strategy [14].

There are three major objectives of this research project:

Objective 1 is to assess the strengths and limitations of readily available computer based simulation models designed to evaluate the impacts of alternative work zone strategies. The assessment will include the following simulation packages: QUEWZ (Queue and User Cost Evaluation of Work Zones), QuickZone, and CA4PRS (Construction Analysis for Pavement Rehabilitation Strategies). Criteria, constraints and parameters to be used in this assessment will be, for example,

- Minimum length of work zone
- Maximization of work zone productivity
- Optimal construction staging
- Maximum tolerable traffic delay
- Optimal work zone season
• Nightmare work zones
• Crash frequency
• Minimal user costs rehabilitation strategy
• Construction window lane closure tactic
• Material selection: curing time for concrete or cooling time for asphalt
• Pavement cross section: thickness of new concrete or asphalt concrete
• Contractor’s logistical resource: location, capacity, and numbers of rehabilitation equipment available
• Scheduling interface: mobilization/demobilization, traffic control time, and activity lead-lag time relationships and buffer sizes.
• Quantify corridor delay resulting from capacity decreases in work zones
• Identify delay impacts of alternative project phasing plans
• Support tradeoff analyses between construction costs and delay costs
• Examine the impacts of construction staging by location along mainline, time-of-day (peak vs. offpeak), and season (summer vs. winter)
• Assess travel demand measures and other delay mitigation strategies
• Help establish work completion incentives

Objective 2 is to make recommendations for the use of such simulations models on roadway reconstruction and rehabilitation projects in New England. The recommendations may include a software package or suite of packages and will consider the following factors and criteria:
• User Friendliness
• Convenient input with meaningful output
• Low software and hardware operating requirements

• Accurate for various work zone configurations

• Flexibility to adapt to staged construction

• Economically balanced work zone strategy with minimum traffic delay and minimum user costs
CHAPTER 4

RESEARCH APPROACH

To meet the objectives of this research, QuickZone Delay Estimation Program Version 1.01 will be used to analyze four work zone locations in New England. The first of these sites is located along Interstate 91 in Greenfield, Massachusetts. The second site is located along Interstate 91 in Windsor, Connecticut. The third site is situated along Interstate 95 in West Greenwich, Rhode Island and the fourth site is located along Interstate 95 in Bangor, Maine. In addition to QuickZone, the four sites will also be analyzed by using CA4PRS Version 1.5a and QUEWZ-98. The illustrative examples will provide both graphical and tabular output resulting from site-specific input data.

4.1 Advantages of Simulation

Simulation seems to be a very useful tool for evaluating the performance of systems under alternative strategies. Many advantages characterize simulation techniques and that impels transportation engineers and planners to use them. Some of the advantages of simulation include:

- Provides a cost effective way of testing and evaluating different scenarios
- Allows user to test scenarios faster than in real life
- Offers an insight into the characteristics of traffic system operations that are important, allowing the user to make a more informed decision
- Provides outputs/animation that the public can understand.
• All the above advantages comprise the reasons that simulation was chosen for this research.

4.2 QuickZone

QuickZone Delay Estimation Program was developed in response to the 1998 FHWA report *Meeting the Customer’s Needs for Mobility and Safety During Construction and Maintenance Operations (FHWA-PR-98-01-A)* [11]. QuickZone is a traffic impact analysis tool used to estimate work zone delays in all phases of the project development process (i.e. policy, planning, design, and operation). Target users include state and local planners, traffic operations and construction staff, and construction contractors [12].

QuickZone has been found suitable to analyze both urban and non-urban corridors. Primary functions include [13]:

• Quantifying corridor delay resulting from capacity decreases in work zones
• Identifying delay impacts of alternative project phasing plans
• Supporting tradeoff analyses between construction and delay costs
• Examining impacts of construction staging by location, time of day (peak vs. off-peak), and season (summer vs. winter)
• Assessing travel demand measures and other delay mitigation strategies
• Establishing work completion incentives

QuickZone has also been applied to evaluate proposed changes to lane closure schedules during construction, identify work that could be scheduled during nighttime
hours, explore the feasibility of completely closing a road during construction, and schedule work around seasonal traffic demands.

QuickZone analysis requires four critical user-defined components. Network Data describes the mainline facility under construction as well as alternatives present within the corridor (i.e. detours). Project Data describes the plan for the work zone strategy and phasing, including capacity reductions resulting from the work zone. Travel Demand Data describes the patterns of pre-construction corridor utilization. Corridor Management Data describes various mitigation strategies to be implemented in each phase, including estimates of capacity changes resulting from these strategies [14]. Specific inputs for analysis include node coordinates, link characteristics, demand characteristics (e.g. AADT, hourly demand, and seasonality), project and phasing information, work zone information (e.g. affected links, capacity decreases, mitigation strategies, and changes in travel behavior), and delay cost parameters [17].

QuickZone provides users with four forms of output. The Project Delay Summary profiles the expected delay by time of day in each phase, as well as total delay and length of the mainline queue. The Travel Behavior Summary displays the expected changes in volume on both the mainline and adjacent facilities. The Amortized Delay and Construction Costs Graph shows the amortized project costs over the total expected life of reconstruction operations. The Summary Worksheet provides an analysis of queue, delay, travel behavior, cost, and input [17]. Output is displayed in both tabular and graphical forms. Tabular performance measures include the total average daily delay per phase in vehicle-hours, the maximum length of mainline queue in miles, and the total travel time in minutes. A road user cost report presents the average road user cost per
day, detour delay costs, and incentive/disincentive equivalence. Graphical performance measures include a delay graph, which displays the average delay by time of day for project phases in vehicle-hours. The output also indicates changes in travel behavior due to the presence of work zones, both in volume and in percentage [17].

QuickZone output is helpful in identifying project phases likely to be generators of delay throughout the project duration. It also helps to determine if the amount of delay is reasonable and acceptable. If delay is acceptable, then the project proceeds as planned. If delay is unacceptable, then QuickZone helps to make changes to the construction strategy to make the project more cost-effective for both motorists and contractors [17].

4.3 CA4PRS

CA4PRS was developed to aid California’s Department of Transportation (Caltrans) in their 1998 Long-Life Pavement Rehabilitation Strategies (LLPRS) program. CA4PRS is a systematic construction engineering and management tool for the rehabilitation and reconstruction of highways. The software is used to estimate the maximum probable length of highway pavement that can be rehabilitated or reconstructed given various project constraints. Target users include state highway agencies, design and construction engineers, consultants, and paving contractors [19].

CA4PRS has been found to be beneficial for highway agencies, especially during the design stages when resulting analysis can be used to optimize pavement, construction, and operations. It is also useful to optimize rehabilitation strategies that balance the construction schedule with driver inconvenience and costs. One of the major benefits of
CA4PRS is its ability to be integrated with micro- and macroscopic traffic simulation models to quantify road user costs during construction.

CA4PRS requires four user-defined inputs. Project Details include project descriptions, route names, station miles, location, and the total lane-miles to be rehabilitated. Scheduling includes mobilization and demobilization times, lead-lag relationships, and alternative closure timeframes. The Resource Profile specifies contractor logistics and resource constraints such as the location and size of batch plants and the number and capacity of hauling trucks. Analysis allows for selection of a number of construction windows, rehabilitation sequences, mix designs, and cross-sectional changes. Specific analysis input variables include pavement strategy (i.e. PCC, CSOL, FDAC), construction window, lane closure tactics, material constraints, pavement cross section, concrete pavement base types, contractor logistical resource constraints, and scheduling interfaces [19].

CA4PRS is capable of performing both deterministic and probabilistic analysis. Deterministic analysis treats input parameters as constants. This analysis mode seeks a single maximum distance of pavement that can be rehabilitated within the construction window under the given project constraints. On the other hand, probabilistic analysis treats input parameters as random variables. Each variable is described using one of several statistical distributions, permitting the review of the likelihood of achieving different production rates using Monte Carlo simulation.

Output is displayed in graphical and tabular form for both deterministic and probabilistic analysis. Production Details include a user input summary, the maximum production of each rehabilitation scenario in terms of lane-miles, and the total number of
lane closures required to finish the entire rehabilitation project scope based on the
maximum production of each scenario. The Production Chart shows the optimally
balanced maximum duration of demolition and paving activities within the given closure
time limit. It illustrates the linear progress of the main rehabilitation operations over
time. The difference is that probabilistic output plots the distribution of maximum
production, showing the most likely maximum production as the mean and productions at
± 0.5 standard deviations as the lower and upper bounds.

CA4PRS output allows various traffic lane closure strategies and pavement design
alternatives to be evaluated. The goal is to maximize new pavement life expectancy and
construction production while minimizing traffic delay and costs. Additionally, CA4PRS
is used to check construction staging plans, identify critical resources constraining
production, and quantify the probability of meeting work incentives/disincentives as well
as cost plus schedule (i.e. A + B) contracts [19].

4.4 QUEWZ-98

QUEWZ, Queue and User Cost Evaluation of Work Zones, is a tool for
evaluating freeway work zones lane closures. QUEWZ-98 is the most recent
microcomputer version of the QUEWZ program. This version was developed as part of
Study No. 0-1745, “Air Quality Impacts of Highway Construction and Scheduling.” The
study was performed under the sponsorship of the Texas Department of Transportation
(TxDOT) in cooperation with the U.S. Department of Transportation, Federal Highway
Administration.
QUEWZ-98 is a computerized version of a commonly used manual techniques for estimating the queue lengths and additional road user costs resulting from work zone lane closures. It simulates traffic flows through freeway segments both with and without a work zone lane closure in place and estimates the changes in traffic flow characteristics and additional road user costs resulting from a lane closure whose time schedule and lane configuration are described by the model user. QUEWZ098 can also apply the same traffic flow simulations to identify time schedules for lane closures that will not produce excessive queue lengths and delays [22].

QUEWZ-98 operates on IBM-compatible, DOS-based microcomputers. Hardware requirements are a microcomputer with a minimum of 256K Random Access Memory (RAM) and a suitable disk drive configuration (at least one 3 ½-inch floppy diskette drive). Three executable files, which can be stored on one 360K floppy disk, are required to run the program: QUEWZ98.EXE, Q98MENU.EXE, and DISPLAY.EXE. QUEWZ98.EXE is a compiled version of the model that can be run in batch mode. Q98MENU.EXE is a menu-driver procedure for using QUEWZ-98. DISPLAY.EXE generates a graphical display of acceptable lane closure schedules [22].

QUEWZ-98 compares traffic flows through a freeway segment with and without a work zone lane closure and estimates and changes in traffic flow characteristics (average speeds and queue lengths) and road user costs resulting from the lane closure. The model can be applied to freeway facilities or multilane divided highways with as many as six lanes in each direction and can analyze work zones with any number of lanes closed in either one or both directions. The model can analyze 24 consecutive hours of operations [22].
4.4.1 Output Options

QUEWZ-98 has two output options:

1. Road user cost option, and
2. Lane closure schedule option.

The road user cost output option analyzes a user-specified lane closure configuration and schedule of work activities. The output consists of estimates of traffic volumes, capacities, speeds, queue lengths, and additional road user costs for each hour affected by the lane closure. A diversion algorithm may be used with this option to estimate the volume of traffic that might divert from the freeway in response to work-zone-related delays.

The road user cost output option also includes an estimate of base emissions, construction related emissions and excess emissions.

The lane closure schedule option summarizes the hours of the day when a given number of lanes can be closed without causing excessive queuing. The user may define what constitutes excessive queuing. This option evaluates each possible number of closed lanes. For example, when analyzing a work activity in the outbound direction of a freeway that has 3 lanes, QUEWZ-98 would evaluate schedules for closing both 1 and 2 lanes. QUEWZ-98 considers each hour as a possible starting hour for the lane closure and for each starting hour determines the number of hours that lanes could remain closed before queuing becomes excessive.

4.4.2 Speed and Queue Estimation

Both output options use the same speed and queue estimation procedures. QUEWZ-98 estimates speed and queuing using procedures presented in the 1994
Highway Capacity Manual (HCM). Average speeds are estimated based on the speed-volume relationship for freeway facilities. When demand volumes exceed the capacity of the work zone, queuing characteristics are estimated using input-output analysis.

4.4.3 Road User Cost Estimation

The additional road user costs associated with a freeway work zone lane closure are estimated as the difference between the road user costs with versus without the lane closure. Three components of road user costs are included: vehicle operating costs, travel time costs, and excess emissions. Costs are estimated in 1990 dollars. The cost estimating equations are derived from Memmott. The dollar value of time is $12.64 per vehicle hour for passenger cars (with an average occupancy of 1.3 persons per car) and $23.09 per vehicle hour for trucks.

Excess emission are based on MOBILE5a average values. The default values are representative of San Antonio in the summer of 1998.

4.4.4 Diversion Algorithm

The diversion algorithm is used in conjunction with the road user cost output option to provide more realistic estimates of the additional road user costs resulting from freeway work zone lane closures. The algorithm estimates the volume of traffic that would divert from the freeway in response to work-zone-related delays.

The algorithm is based upon observations of work zone lane closures on urban freeways with continuous parallel frontage roads in Texas. It was observed that queue lengths and delays tended to reach threshold levels throughout the duration of the lane closure. Therefore, the diversion algorithm calculates the traffic volume that must divert from the freeway so that delays do not exceed either a maximum queue length in miles or
delay to motorist in minutes. On average, the maximum queue engulfed 5 ramps, and the queue length varied according to the average ramp spacing. The maximum delay averaged approximately 20 minutes.

The additional road user costs for diverting traffic are estimated using the following assumptions: (1) the length of the alternative route equals the length of the work zone plus the critical length of queue, (2) the travel time for diverting traffic equals the time for a vehicle at the end of the critical length of queue to travel through the queue and the work zone, (3) the diverting traffic maintains a uniform speed equal to the length of the alternative route divided by the travel time, and (4) trucks do not divert. The additional costs for diverting traffic are included in the total additional road user costs resulting from the freeway work zone lane closure.
CHAPTER 5

CASE STUDY

The case study sections presented here give a detailed perspective of the use of QuickZone, CA4PRS and QUEWZ software packages. The four different work zone strategies are respectively located in Interstate 91 in Greenfield, MA, Interstate 95 in West Greenwich, RI; Interstate 91 near Windsor, CT; and Interstate 95 in Bangor, ME.

The first section of this chapter illustrates the use of these programs as applied to a work zone strategy employed along Interstate 91 in Greenfield, MA. The second section of this chapter is structured to give the same illustration of these three programs as applied to a different work zone strategy utilized along Interstate 95 in West Greenwich, RI. Thirdly, the section of this chapter is structured to give the same illustration of these three programs as applied to another different work zone strategy utilized along Interstate 91 in Windsor, CT. At last, the fourth section illustrates the use of only QuickZone and QUEWZ as applied to a work zone strategy employed along Interstate 95 near Bangor, ME. QuickZone Delay Estimation Program Version 1.01 and CA4PRS Version 1.5a and QUEWZ-98 were used to analyze the effects of the proposed work zone on driver mobility and the maximum possible rehabilitation production, respectively. The following paragraphs explain how these three simulation models are being used to evaluate the different work zone segments in different locations.
5.1 Modeling Interstate 91, Greenfield, MA

Project BR# G-12-058, Bridge Rehabilitation Route I-91 Northbound and Southbound over the B&M Railroad, was established under the direction of the Massachusetts Highway Department. The work zone is approximately one-quarter mile in length and is located as shown in Figure 1.

![Figure 1: I-91 Work Zone Location](image)

5.1.1 QuickZone Analysis of I-91, Greenfield, MA

As described in the previous chapter, QuickZone has four critical user-defined input components for analysis. For this research, only the southbound direction of travel was selected for analysis. Starting with Network Data, node information was entered to define the beginning and end of each link in the roadway section. Node information is based upon an X-Y coordinate system defined by the user and is used to graphically generate the analysis network, as shown in Figure 2.
Links are identified by the nodes defined previously and possess several attributes. These include the number of lanes, length, freeflow speed, capacity, jam density, and type (e.g. mainline, work zone, or detour). For this location, two lanes are normally available for travel in the southbound direction. Link lengths were adopted from work previously done by the author, but could also have been easily scaled from construction documents. Freeflow speed was determined to be 70 miles per hour (mph) as recommended by the Highway Performance Monitoring System Field Manual. Using the freeway capacity estimation procedure described by the same resource, capacity was calculated as 2395 vehicles per hour per lane (vphpl). The resulting jam density was calculated as 135 vehicles per mile per lane (vpmpl). Figure 3 provides an image this link characteristic input as seen in QuickZone.
Figure 3: I-91 Link Characteristics

**Travel Demand Data** is essential to producing accurate analysis results.

Depending on the availability or quantity of such data, this portion of input may be the most extensive and time consuming. The user specifies either the average annual daily traffic (AADT) or hourly counts in terms of vehicles. The travel demand data for this analysis was adopted from work previously completed by Heaslip [24]. This data was in the form of hourly counts and was entered for each link over a seven day, 24-hour period. Additionally, truck percentages of 1.67 percent were applied to each link over the same time period. A snapshot of the traffic demand as entered in QuickZone is shown in Figure 4.

![Table of Link Characteristics](image)

<table>
<thead>
<tr>
<th>Link</th>
<th>A Node</th>
<th>B Node</th>
<th>Lanes</th>
<th>Capacity (VPH)</th>
<th>Length (Miles)</th>
<th>Free Flow Speed (mph)</th>
<th>Jam Density (V/mi/ln)</th>
<th>Type</th>
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<td>8</td>
<td>1</td>
<td>1100</td>
<td>0.16</td>
<td>50</td>
<td>98</td>
<td></td>
</tr>
</tbody>
</table>

Figure 4: I-91 Network Demand

**Project Data** includes both global parameters as well as specific construction phase data. The global parameters provide basic project information that will later be
used in the analysis of defined construction phases. For this research, a number of assumptions were made with regard to global parameters. A project start date of May 1, 2005 was randomly chosen with a construction phase duration of 42 weeks. The yearly demand increase was assumed to be the default value of 2 percent and the yearly capacity decrease was assumed to be 0 percent. The project infrastructure cost of $1.85 million was obtained from project information provided by the Massachusetts Highway Department.

The construction phase data describes the major capacity reducing activities throughout the project’s duration. For analysis purposes, the left lane in the southbound direction was considered closed, mirroring the actual staged lane drop. Work zones were established 24 hours a day, seven days a week for the duration of this project phase. Details for Construction Phase 1 as entered in QuickZone are shown in Figure 5. Within this window, the work zone plan editor allows the user to describe individual work tasks during the defined construction phase. The work zone plan defines the capacity impact of a specific construction activity and how the traffic on individual links will react to the construction. Modifications can be made to the start and end time of each day’s activity, to the affected link’s associated capacity decreases, to mitigation strategies, and to changes in travel behavior. For this analysis, capacity decreases were estimated using the 2000 Highway Capacity Manual function within the QuickZone program. Due to the presence of the work zone and the lane drop, the capacity of each of the defined work zone links was reduced by a total of 3190 vehicles per hour. This resulted in a work zone capacity of 1600 vehicles per hour for the one available lane. An example work zone plan for Construction Phase 1 is shown in Figure 6.
Delay mitigation strategies and changes in travel behavior represent inputs to *Corridor Management Data*. This analysis employed no mitigation strategies along the study corridor. Additionally, travel behavior changes were unchanged from the QuickZone default values.

Lastly, the delay cost parameters affix a dollar value to the effects of the construction project. The data entered is used to estimate delay costs resulting from the construction project.
work zone activity. For this project, several assumptions were made for the delay cost parameters. All input was based on default values of $8 per car hour and $24 per truck hour. Additionally, the default amortization period of 10 years and inflation rate of 6.00 percent was used for analysis. These parameters are shown in Figure 7.

![Figure 7: Delay Cost Parameters](image)

QuickZone’s goal in terms of ease-of-use is less than three hours to prepare and input a network, and less than three minutes to analyze the data and produce delay profiles over the project duration. For this analysis, data entry took approximately two and one-half hours and analysis took under one minute.

The analysis results show Sunday at 4:00 pm to have the highest delay in vehicle-hours per hour for this particular phase of the Interstate 91 project. The delay graph in Figure 8 shows the delay value to be 982.2 vehicle-hours per hour. This same figure shows how delay varies over a seven day, 24-hour period. The QuickZone output reveals that motorists traveling through this work zone will experience delay caused by its existence on Sunday only. The capacity reductions as calculated by the HCM 2000 method cause this section of Interstate 91 to have a greater demand than it can support.
only during the afternoon hours of Sunday. Users have the ability to analyze a particular construction phase if more than one are defined and may select the exact days which they wish to review. The daily delay graph shown in Figure 9 illustrates the propagation of delay for Sunday. It can be seen that the delay starts to generate around 11:00 am, reaching a maximum at 4:00 pm. QuickZone estimates the delay to be totally dissipated by 7:00 pm.

![Figure 8: I-91 Weekly Delay Estimation](image)
The analysis also shows how traveler behavior changes in response to the work zone activity. The results reveal that 95 percent of travelers will endure mainline traffic through the work zone, 4 percent will shift their travel time by ± one hour, 1 percent will shift travel modes, and 1 percent will cancel their trip. Figure 10 shows a pie chart that illustrates these percentages of changes in travel behavior. As with the delay graph, users have the option to view only one or more project phases and to view a specific day. Additionally, changes in travel behavior can also be viewed as a bar graph. Shown in Figure 11, the bar graph allows users to view the number of vehicles that modify their travel behavior on an hour-by-hour basis. For this analysis, one can see that the greatest change occurs Sunday between 4:00 and 5:00 pm, corresponding with the period of highest delay.
The delay costing graph presents the user with a summary of the infrastructure and delay costs for each year of the project’s duration. For this phase of the project, the user-defined infrastructure cost was $1.85 million. From the analysis, the amortized cost...
per year over 10 years is $0.32 million. This is broken down into an infrastructure cost of $0.185 million per year and a delay cost of $0.135 million per year.

The summary table provides data on four key elements relative to the project: queue, delay, traveler behavior, and cost. For this analysis, the summary table reveals that the weekly maximum queue occurs on Sunday with a value of 3.85 miles. The resulting weekly maximum delay is estimated as 13 minutes. Additionally, the table reveals that the expected weekly queue will total 14.1 miles. A snapshot of the queue, delay, travel behavior, and cost for this project as estimated by QuickZone is shown in Figure 12.

<table>
<thead>
<tr>
<th>Queue Both</th>
<th>Delay Both</th>
<th>Phase Travel Behavior (Weekly Inbound - Outbound)</th>
<th>Cost In Millions $</th>
<th>Both</th>
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<tbody>
<tr>
<td>Weekly</td>
<td>Weekly</td>
<td>Weekly Total/In/Out</td>
<td>Total/In/Out</td>
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Figure 12: I-91 Analysis Summary Table

It should be noted that QuickZone is capable of analyzing full lane closures. In order to conduct such an analysis, however, detour routes must be defined as part of the analysis network. The definition of these routes includes starting and ending points, link lengths and characteristics, daily demands, etc. Analyzing a full lane closure for this portion of Interstate 91 is possible, but is not included within this research.

The following section discusses the use of CA4PRS to analyze the same work zone location. Instead of using the software to generate estimates of delay, this software package will be used to estimate maximum possible rehabilitation production.
5.1.2 CA4PRS Analysis of I-91, Greenfield, MA

CA4PRS also requires four user-defined inputs. Basic information regarding the rehabilitation project is entered in the Project Details window. For this portion of the research, work zone beginning and end mile-posts were estimated from construction documents. These values were entered as 1493.00 and 2011.00, respectively. Additionally, the total lane-miles to be rehabilitated was entered as 0.25, reflecting the approximate length of the work zone. Figure 13 shows all of the Project Detail information as entered into the software program.

![Figure 13: I-91 Project Details](image)

The Scheduling window required a number of assumptions to be made. Mobilization and demobilization times were assumed to be 3.0 hours and 6.0 hours, respectively. Lead-lag relationships were also established within this window, specifying the time required between the end of demolition activities and the beginning of
rehabilitation operations. For this analysis, this period of time was defined as 24.0 hours. Lastly, construction timeframes are specified for several different scenarios. This analysis utilized a continuous closure/shift operation form of activity. Work was defined to begin each day at 7:00 am, Monday through Friday. Nine hours were allotted for each day’s operations to occur. Figure 14 shows the Scheduling window and Figure 15 shows the possible construction activity timeframes.

![Figure 14: Scheduling Window](image)
As with scheduling, the *Resource Profile* inputs also required several assumptions. Many of the values were adopted from an example contained within the CA4PRS installation disc, as much of this information is more accurate and readily available to contractors than to transportation agencies. For demolition activities, the capacity of the hauling trucks was assumed to be 26.0 tons. It was also assumed that 4 trucks per hour would be utilized, each with a packing efficiency of 0.85. One team would be completing the demolition activities with an efficiency of 0.75. The capacity of the asphalt batch plant was assumed to be 440.0 tons per hour. Four trucks per hour would be hauling the asphalt, each with a capacity of 26.0 tons and a packing efficiency of 0.90. Additionally, the non-paving speed of the paver was assumed to be 18.0 miles per hour. Figure 16 shows this data as input into the Resource Profile window.
Lastly, the Analysis window allows the user to define the desired rehabilitation activity. The construction timeframe and the lane closure strategy are selected. In addition, the pavement cross section is defined. For the analysis of Interstate 91, the pavement cross section was adopted from the Interstate 95 construction documents, as no other comparable information was available. The cross section consisted of three lifts: binder course, surface course, and friction course. The binder and friction courses are each 1.75 inches thick and assumed to have a cooling time of 3.00 hours each. The friction course is 1.25 inches thick and assumed to have a cooling time of 6.00 hours. Based on the Resource Profile input, the paving speed was automatically calculated by the software. Figure 17 shows the Analysis information and Figure 18 shows the pavement cross section as defined in CA4PRS.
As mentioned in Chapter 4, CA4PRS is capable of running either a deterministic or probabilistic analysis to generate estimates for maximum possible rehabilitation production. For this research, a deterministic Full-Depth Asphalt Concrete (FDAC) analysis was used. The results given in the *Production Details* estimated the maximum
possible rehabilitation production to be 0.80 lane-miles. These results as produced by CA4PRS are shown in Figure 19. Additionally, the software provides a Production Chart to show the progress and interrelationship of the proposed rehabilitation activities over time. Figure 20 illustrates this output for the Interstate 91 work zone.

![Figure 19: I-91 Production Details](image1)

![Figure 20: I-91 Production Chart](image2)
5.1.3 QUEWZ analysis of Interstate 91, Greenfield, MA

Q98MENU is the main program of the simulation package of QUEWZ-98. Q98MENU is called by typing Q98MENU at the DOS prompt and by striking the Enter key. A menu driven procedure leads the user through the process of entering data and running QUEWZ-98. This section explains the use of each screen as applied to the work zone strategy utilized along Interstate 91, Greenfield, MA.

After Q98MENU is called, the introductory screen is automatically displayed in Figure 21. This screen will move to the main menu screen when we press any key. QUEWZ-98 has two output options. The research first task in creating a new file for this specific work zone strategy is to select among the primary model options: (1) road user cost estimates for a specified lane closure configuration and schedule of work activities, and (2) acceptable lane closure schedules for all possible lane closure configurations.

![QUEWZ-98 Introductory Screen](image)

Figure 21: QUEWZ-98 Introductory Screen

*Input Section Illustration*
For this research, the first output option Road User Cost Estimates is chosen. Since we are provided the directional hourly volume, we choose the first option in Volume Data Input Options. The model options screen is in Figure 22.

The second screen shot is named Model Constants Screen, Figure 23. This screen allows the user to either accept the model default values or specify new values for several model constants. We made a few assumptions. Cost Update Factor is to be 1.0 while the Percentage of Heavy Vehicles is written on the documents to be 8%. The Free Flow Speed is 60mph and LOS D/E Breakpoint Speed is set to be 46mph. Because of the specific traffic demand, the Speed at Capacity can only by 30mph, while the LOS Breakpoint Volume is 1850vphpl. At last, in this screen, we enter the Volume at Capacity 2000vphvl, which is provided in the documents.
When the road user cost output option is selected, the first section that appears after the two preliminary screens is the Diversion Algorithm screen in Figure 24. This screen allows us to choose whether or not engage the diversion algorithm. The diversion algorithm computes how much traffic must divert from the freeway to avoid excessive queuing. There are two alternatives for defining excessive queuing, so excessive queuing may be defined in terms of either (1) a critical length of queue in miles, or (2) a maximum acceptable delay to motorists in minutes. We made assumptions about the queue length and delay. The assumption is a queue length of 2 miles for selection 1 and a delay of 20 minutes for selection 2.
The diversion algorithm diverts traffic when queueing exceeds a critical length. The default length of queue is 2 miles based on a ramp spacing of 0.4 miles and 5 ramps engulfed in queue on average. An alternative is to compute a critical length based on a maximum acceptable delay in minutes, for which the default is 20 minutes. The default values are based on data collected on urban freeway with continuous frontage roads in Texas. For rural areas, the diversion algorithm is not recommended.

<table>
<thead>
<tr>
<th>Present Value</th>
<th>New Value</th>
</tr>
</thead>
</table>

Basic for Diversion Algorithm (1 or 2)----------> 0 7
1. Critical length of queue (miles)
2. Maximum acceptable delay (minutes)

Description of Lane Closure Configuration is the next screen. Figure 25 is Lane Closure Configuration Screen for the Road User Cost Output Option. According to the provided information in Heaslip’s dissertation [24], the number of directions is given and the total lanes and open lanes and length of the lane closure are known.
Figure 25: Lane Closure Configuration Screen for the Road User Cost Output Option for I-91 Greenfield, MA

Figure 26 is the schedule of work activity screen, which illustrates the screen displayed to obtain the necessary data on the schedule of work activity for the road user cost option. Data are requested for both the hours when the lane closure begins and ends and the hours when the work activity begins and ends. From the talks with field engineers and the documents, we know when the closures begin and end, and when the work activities begin and end. Then this information is entered onto the screen.
After we choose the option of directional hourly volume data, for this situation, the screen of Directional Hourly Volume Data appears once. The closures are in both directions, then two screens (one for each direction) are displayed sequentially. Figure 27 and Figure 28 are respectively for northbound and southbound hourly volume data.
Figure 28: Directional Hourly Volume Data Screen (Southbound) of I-91 Greenfield, MA

Output Section Illustration

This section presents the project of Interstate 91, Greenfield, MA of the use of QUEWZ-98 to illustrate the various input described before and output options that are available. The output for this project is provided in Figure 30.

5.2 Modeling Interstate 95, West Greenwich, RI

Project 2004-CB-060, Comprehensive Bridge Rehabilitation Program Group 2: Robin Hollow Road Bridge No. 588, was established under the direction of the Rhode Island Department of Transportation. The work zone is approximately one-quarter mile in length and is located as shown in Figure 31. Photographs of the work zone taken during a site visit are structured in Appendix A.
QuickZone Delay Estimation Program Version 1.01 and CA4PRS Version 1.5a and QUEWZ-98 were used to analyze the effects of the proposed work zone on driver mobility and the maximum possible rehabilitation production, respectively. The following paragraphs explain how these three simulation models are being used to evaluate the different work zone segments in different locations.

5.2.1 QuickZone Analysis of I-95, West Greenwich, RI

The QuickZone analysis procedure for this work zone was carried out in the same manner as for Interstate 91. For this portion of the research, only the northbound direction of travel was selected for analysis. Node information was entered to define the beginning and end of the roadway section, as shown in Figure 30.

Link characteristics for this location vary slightly from those in the previous analysis. This segment of Interstate 95 has two lanes available for normal travel in the northbound direction. Link lengths were scaled from construction documents provided
by the Rhode Island Department of Transportation. As with the first case, freeflow speed was determined to be 70 miles per hour (mph) based on the recommendations of the Highway Performance Monitoring System Field Manual. The freeway capacity was estimated as 2395 vehicles per hour per lane (vphpl) with a resulting jam density of 135 vehicles per mile per lane (vpmpl). Figure 31 provides an image of the link characteristic input screen.

Figure 30: I-95 Analysis Network

<table>
<thead>
<tr>
<th>Link #</th>
<th>A-Node</th>
<th>B-Node</th>
<th>Lanes</th>
<th>Capacity (vphpl)</th>
<th>Length (Miles)</th>
<th>Freeflow Speed (mph)</th>
<th>Jam Density (vpmpl)</th>
<th>In/Out</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2395</td>
<td>0.26</td>
<td>70</td>
<td>135</td>
<td>1</td>
<td>M</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>2395</td>
<td>0.06</td>
<td>70</td>
<td>135</td>
<td>1</td>
<td>W/Z</td>
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<td>2</td>
<td>2395</td>
<td>0.21</td>
<td>70</td>
<td>135</td>
<td>1</td>
<td>W/Z</td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>5</td>
<td>2</td>
<td>2395</td>
<td>0.26</td>
<td>70</td>
<td>135</td>
<td>1</td>
<td>W/Z</td>
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<td>5</td>
<td>6</td>
<td>2</td>
<td>2395</td>
<td>0.26</td>
<td>70</td>
<td>135</td>
<td>1</td>
<td>M</td>
</tr>
</tbody>
</table>

Figure 31: I-95 Link Characteristics

The travel demand data for this analysis was provided by the Rhode Island Department of Transportation. This data was in the form of hourly counts and was entered for each link over a seven day, 24-hour period. Truck percentages of 2 percent
were assumed for this location and applied to each link over the same time period. A snapshot of the traffic demand as entered in QuickZone is shown in Figure 32.

<table>
<thead>
<tr>
<th>Week</th>
<th>1st O</th>
<th>AADT</th>
<th>6AM</th>
<th>7AM</th>
<th>8AM</th>
<th>9AM</th>
<th>10AM</th>
<th>11AM</th>
<th>12PM</th>
<th>1PM</th>
<th>2PM</th>
<th>3PM</th>
<th>4PM</th>
<th>5PM</th>
<th>6PM</th>
<th>7PM</th>
<th>8PM</th>
<th>9PM</th>
<th>10PM</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>283</td>
<td>259</td>
<td>223</td>
<td>189</td>
<td>195</td>
<td>327</td>
<td>952</td>
<td>976</td>
<td>1152</td>
<td>1428</td>
<td>1733</td>
<td>1733</td>
<td>2018</td>
<td>2070</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>283</td>
<td>259</td>
<td>223</td>
<td>189</td>
<td>195</td>
<td>327</td>
<td>952</td>
<td>976</td>
<td>1152</td>
<td>1428</td>
<td>1733</td>
<td>1733</td>
<td>2018</td>
<td>2070</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>1</td>
<td>283</td>
<td>259</td>
<td>223</td>
<td>189</td>
<td>195</td>
<td>327</td>
<td>952</td>
<td>976</td>
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<td>1428</td>
<td>1733</td>
<td>1733</td>
<td>2018</td>
<td>2070</td>
<td></td>
<td></td>
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<tr>
<td>4</td>
<td>1</td>
<td>283</td>
<td>259</td>
<td>223</td>
<td>189</td>
<td>195</td>
<td>327</td>
<td>952</td>
<td>976</td>
<td>1152</td>
<td>1428</td>
<td>1733</td>
<td>1733</td>
<td>2018</td>
<td>2070</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>1</td>
<td>283</td>
<td>259</td>
<td>223</td>
<td>189</td>
<td>195</td>
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<td>1733</td>
<td>1733</td>
<td>2018</td>
<td>2070</td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>

Figure 32: I-95 Network Demand

As with Interstate 95, several assumptions were also made with regard to global parameters. A project start date of April 29, 2007 was randomly chosen. The phase duration was estimated by the Rhode Island Department of Transportation to be 36 weeks. The yearly demand increase was assumed to be the default value of 2 percent and the yearly capacity decrease was assumed to be 0 percent. The project infrastructure cost of $1.05 million was obtained from an estimate provided by the Rhode Island Department of Transportation.

For this analysis, the left lane in the southbound direction was considered closed. This location, however, utilized the existing 12-foot right shoulder to maintain two lanes of flow. Upon approaching the work zone, the 12-foot lanes shifted to two 11-foot lanes. As with Interstate 95, these work zones were established 24 hours a day, seven days a week for the duration of this project phase. Details for Construction Phase 1 as entered in QuickZone are shown in Figure 33. Capacity decreases were estimated using the 2000 Highway Capacity Manual function within the program. Due to the presence of the work zone, the capacity of the defined work zone links was reduced by a total of 1590 vehicles per hour. This resulted in a two-lane capacity of 3200 vehicle per hour for the work zone.
area. As an example, the work zone plan for Sunday in Construction Phase 1 is shown in Figure 34.

Similarly to Interstate 91, no mitigation strategies were employed along the study corridor. Additionally, travel behavior changes were unchanged from the QuickZone default values.

![Figure 33: I-95 Construction Phasing Information](image)
All delay cost parameter input was based on default values of $8 per car hour and $24 per truck hour. Additionally, the default amortization period of 10 years and inflation rate of 6.00 percent was used for analysis.

Again, QuickZone’s goal in terms of ease-of-use is less than three hours to prepare and input a network, and less than three minutes to analyze the data and produce delay profiles over the project duration. For this analysis, data entry took approximately one and one-half hours and analysis took under one minute.

The analysis results show this particular work zone to create no delay to motorists. The capacity reductions as calculated by the HCM 2000 method never cause this section of Interstate 95 to have a greater demand than it can support. For this reason, the only associated project cost is the infrastructure cost of $1.05 million. The 10-year amortized project cost would be $0.105 million per year. To illustrate these results, the weekly delay graph in Figure 35 shows that QuickZone did indeed estimate no delay to
occur. Additionally, the summary table has been included as Figure 35 to show that there is no queue or delay associated with this work zone and that the only cost is related directly to the infrastructure.

![Figure 35: I-95 Weekly Delay Estimation](image)

![Figure 36: I-95 Analysis Summary Table](image)

Two additional QuickZone analyses for Interstate 95 reviewed the impact on driver mobility given different lane closure windows. This scenario was presented to simulate the effect of the necessity to close a lane for construction activity or a vehicle crash the work zone area. The motivation behind these additional analyses stemmed from a conversation with a site worker who claimed that the only time a traffic backup
occurs is when conditions force the closure of a lane. The claim was that queues may extend all the way back to I-295, approximately 10 miles from the work zone location.

For these analyses, all of the original input parameters remained the same. The capacities of the defined work zone links were reduced using the HCM 2000 method function within the QuickZone program. It was estimated that a lane closure would result in a total capacity decrease of 3190 vehicles per hour for each link, leaving a capacity of 1600 vehicles per hour.

The first alternative analysis considered a 24-hour lane closure. This closure window in conjunction with the estimated capacity reduction showed significant queueing and delay compared to the original analysis scenario. QuickZone revealed a maximum queue length of 12.73 miles with an associated 43.1 minute delay to occur on a Friday. The next highest queue length occurred on a Saturday with a queue length of 10.99 miles and an associated delay of 37.2 minutes. Sunday experiences a 10.85-mile queue, resulting in a 36.7 minute delay. If the lane closure were to occur Monday through Thursday, queuing and delays would still be experienced but on a much smaller scale. These figures show the weekly delay graph, the daily delay graph for Friday, and the summary table for this scenario, respectively.

The second alternative analysis considered a 1-hour lane closure between 4:00 pm and 5:00 pm. This period of time was selected for analysis as the highest traffic demand is experienced during this timeframe. Again, the results of the QuickZone analysis showed the formation of queuing and delays compared to the original analysis scenario. The longest queue was 5.47 miles on a Friday, resulting in 18.5 minutes of delay. The second largest delay under these conditions occurred on a Sunday, showing a 3.39-mile...
queue and an associated 11.5-minute delay. The remaining days of the week, Monday through Thursday and Saturday, also produced delay but on a smaller scale. These figures show the weekly delay graph, the daily delay graph for Friday, and the summary table for this scenario, respectively.

It should be noted that QuickZone is capable of analyzing full lane closures. In order to conduct such an analysis, however, detour routes must be defined as part of the analysis network. The definition of these routes includes starting and ending points, link lengths and characteristics, daily demands, etc. Analyzing a full lane closure for this portion of Interstate 95 is possible, but is not included within this research.

The next section of this chapter will describe the use of the CA4PRS software package in the analysis of Interstate 95.

5.2.2 CA4PRS Analysis of I-95, West Greenwich, RI

Due to the large number of assumptions made in the CA4PRS analysis for the Interstate 91 portion of this research, the Interstate 95 portion of the analysis is practically the same. Work zone beginning and end mile posts were estimated from construction documents. These values were entered as 329.45 and 340.55, respectively. Similar to Interstate 91, the total lane-miles to be rehabilitated was entered as 0.25, reflecting the approximate length of the work zone. Figure 37 shows all of the Project Detail information as entered into the software program.
All of the same assumptions were made for the Scheduling and Resource Profile windows as for Interstate 91. Additionally, all of the parameters defined in the Analysis window remained unchanged from the Interstate 91 portion of this research.

As with Interstate 95, a deterministic Full-Depth Asphalt Concrete (FDAC) analysis was used for Interstate 95. The results given in the Production Details estimated the maximum possible rehabilitation production to be 0.80 lane-miles based on the logistical and resource inputs provided. These results as produced by CA4PRS are shown in Figure 38. Additionally, the Production Chart showing the progress and interrelationship of the proposed rehabilitation activities over time is shown in Figure 39 for the Interstate 95 work zone.
5.2.3 QUEWZ Analysis of I-95, West Greenwich, RI

As with the Interstate 95 in West Greenfield, RI work zone, the mechanics of entering data are similar. Preliminary Screens are the first group of screens. In this group, the first screen that appears when main menu item 1 is selected is the Model Options.
Screen. For this second specific work zone location, a series of screens are captured and illustrated. Figure 40 through Figure 43 are the screens for the project of work zone segment in Interstate 95, West Greenwich, RI.

![Model Options Screen, I-95 West Greenwich, RI](image)

Due to information provided by Rhode Island Department of Transportation, we have directional hourly volume available. For this research, the output is expected to be road user cost estimates.
The free-flow was determined to be 70 miles per hour (mph) based on the recommendations of the Highway Performance Monitoring System Field Manual. The freeway capacity was estimated as 2395 vehicles per hour per lane (vphpl) with a resulting jam density of 135 vehicles per miles per lane (vpmpl). LOS D/E Breakpoint Volume was determined to be 2100 vehicles per hour per lane (vphpl).

The lane closure configuration is specified by the number of directions in which lanes are closed, the total number of lanes and number of lanes open in each direction, and the length of the work zone lane closure.
5.3 Modeling Interstate 91, Windsor, CT

Project No. 63-577 is the project of Interstates I-91 Resurfacing and Safety Improvements. The work zone located on the pedestrian bridge in Hartford to north of Capen Street in Windsor, which is approximately one quarter to one third mile in length and is located as shown in Figure 41.

As with the Interstate 91, Windsor, CT, QuickZone Delay Estimate Program Version 1.01 and CA4PRS Version 1.5a and QUEWZ-98 were also used to analyze the effects and productivity of this site. The following sections explain the use of these three simulation models regarding to this specific section.
5.3.1 QuickZone Analysis of I-91, Windsor, CT

The QuickZone analysis procedure for this work zone was carried out in the same way as for Interstate 91 in Greenfield, MA, and Interstate 95 in West Greenwich, RI. For this portion of the research, only the southbound direction of travel was selected for analysis. Node information was entered to define the beginning and end of the roadway section, as shown in Figure 42.
Figure 45: I-91 in Windsor, CT analysis network

Link lengths were scaled from construction documents provided by the Connecticut Department of Transportation.

<table>
<thead>
<tr>
<th>Link #</th>
<th>A Node</th>
<th>B Node</th>
<th>Lines</th>
<th>Capacity (VPL)</th>
<th>Length (Miles)</th>
<th>Freeflow Speed (mph)</th>
<th>Jam Density (V/hr/L)</th>
<th>Flow</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2395</td>
<td>0.26</td>
<td>70</td>
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<td>M</td>
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<td>5</td>
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<td>2395</td>
<td>0.21</td>
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<td>5</td>
<td>6</td>
<td>2</td>
<td>2395</td>
<td>0.26</td>
<td>70</td>
<td>135</td>
<td>1</td>
<td>M</td>
</tr>
</tbody>
</table>

Figure 46: I-91 in Windsor, CT Link Characteristics

The travel demand data for this analysis was also provided by the Connecticut Department of Transportation. This data was in the form of hourly counts and was entered for each link over a seven day, 24-hour period. Truck percentages of 2 percent
were assumed for this location and applied to each link over the same time period. A snapshot of the traffic demand as entered in QuickZone is shown in Figure 44.

As with Interstate 91 Windsor, CT, several assumptions were also made with regard to global parameters. The phase duration was estimated by the Connecticut Department of Transportation to be 36 weeks. The yearly demand increase was assumed to be the default value of 2 percent and the yearly capacity decrease was assumed to be 0 percent. The project infrastructure cost of $1.05 million was obtained from an estimate provided by the Connecticut Department of Transportation.

5.3.2 CA4PRS Analysis of I-91 in Windsor, CT

Interstate 91 in Windsor, CT portion of the analysis is practically based on a few assumptions. Work zone beginning and end mile posts were estimated from construction documents These values were entered as 251.67 and 277.54, respectively. Similar to the previous two cases, the total lane-miles to be rehabilitated was entered as 0.25, reflecting the approximate length of the work zone. Figure 45 shows all of the Project Detail information as entered into the software program.
All of the same assumptions were made for the Scheduling and Resource Profile windows as for Interstate 91 in Windsor, CT. Additionally, all of the parameters defined in the Analysis window remained unchanged from the previous two portions of this research.

The Scheduling window required a number of assumptions to be made. Mobilization and demobilization times were assumed to be 2.0 hours and 4.0 hours, respectively. Lead-lag relationships were also established within this window, specifying the time required between the end of demolition activities and the beginning of rehabilitation operations. For this analysis, this period of time was defined as 24.0 hours.
Lastly, construction timeframes are specified for several different scenarios. This analysis utilized a continuous closure/shift operation form of activity. Work was defined to begin each day at 8:00 pm till 4:00am of the next morning, Monday through Friday. Nine hours were allotted for each day’s operations to occur.

As with scheduling, the Resource Profile inputs also required several assumptions. Even though this information is more accurate and readily available to contractors than to transportation agencies, many of the values were still adopted from the example contained within the CA4PRS installation disc. For demolition activities, the capacity of the hauling trucks was assumed to be 26.0 tons. It was also assumed that 4 trucks per hour would be utilized, each with a packing efficiency of 0.85. One team would be completing the demolition activities with an efficiency of 0.75. The capacity of the asphalt batch plant was assumed to be 440.0 tons per hour. Four trucks per hour would be hauling the asphalt, each with a capacity of 26.0 tons and a packing efficiency of 0.90. Additionally, the non-paving speed of the paver was assumed to be 18.0 miles per hour. Lastly, on Analysis the construction timeframe and the lane closure strategy are selected. In addition, the pavement cross section is defined. The cross section consisted of three lifts: binder course, surface course, and friction course. The binder and friction courses are each 1.75 inches thick and assumed to have a cooling time of 3.00 hours each. The friction course is 1.25 inches thick and assumed to have a cooling time of 6.00 hours. Based on the Resource Profile input, the paving speed was automatically calculated by the software. Figure 49 shows the Analysis information and also shows the pavement cross section as defined in CA4PRS.
CA4PRS is capable of running either a deterministic or probabilistic analysis to generate estimates for maximum possible rehabilitation production. As with the previous two cases, a deterministic Full-Depth Asphalt Concrete (FDAC) analysis was used for Interstate 91 in Windsor, CT. Additionally, the Production Chart showing the progress and interrelationship of the proposed rehabilitation activities over time is shown in Figure 55 for the Interstate 95 work zone. The results given in the Production Details estimated the maximum possible rehabilitation production to be 2.46 lane-miles. This is the maximum production expected based on the logistical and resource inputs provided. Additionally, the software provides a Production Chart to show the progress and interrelationship of the proposed rehabilitation activities over time. These results as produced by CA4PRS are shown in Figure 50.
**Figure 49: I-95 Production Details**

<table>
<thead>
<tr>
<th>Construction Window</th>
<th>Continuous Closure/Shift Operation (96 Hours/Closure)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Working Method</td>
<td>Single Lane Paving (11)</td>
</tr>
<tr>
<td>Section Profile</td>
<td>Profile A</td>
</tr>
<tr>
<td>Closing Time</td>
<td>User Specified</td>
</tr>
<tr>
<td>Objective (lane-km)</td>
<td>4.59</td>
</tr>
<tr>
<td>Maximum Profile (kmax)</td>
<td>2.46</td>
</tr>
<tr>
<td></td>
<td><strong>Maximum Possible (k/A-lane)</strong> 2.46</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Resource</th>
<th>Allocated</th>
<th>Utilized</th>
</tr>
</thead>
<tbody>
<tr>
<td>Demolition Hauling Truck (per hour per lane)</td>
<td>10.0</td>
<td>10.0</td>
</tr>
<tr>
<td>Batch Plant (ton/hour)</td>
<td>560.0</td>
<td>560.0</td>
</tr>
<tr>
<td>HPA Delivery Truck (per hour)</td>
<td>15.0</td>
<td>15.0</td>
</tr>
</tbody>
</table>

| Construction Windows Needed to Meet Objective | 1.83 |
| Demolition Quantity (cu. yd) | 4915.0 |
| ZCP Quantity (lane) | 9856.3 |
| Constraint Resources | DT0(demo), Batch Plant |
| Demolition to Paving | 146.77 |
| Demolition Hours | 45.3 |
| Paving Hours | 34.0 |
| Total Suspended Hours for Calking | 0.0 |

---

**Figure 49: I-95 Production Details**
5.3.3 QUEWZ Analysis of I-91, Windsor, CT

The procedures of entering data are similar. Preliminary Screens are the first group of screens. In this group, the first screen that appears when main menu item 1 is selected is the Model Options Screen. For this second specific work zone location, a series of screens are captured and illustrated. Figure 51 through Figure 54 are the screens for the project of work zone segment in Interstate 91, Windsor, CT.
Due to information provided by Connecticut Department of Transportation, we have directional hourly volume available. For this research, the output is expected to be road user cost estimates.

The free-flow was determined to be 70 miles per hour (mph) based on the recommendations of the Highway Performance Monitoring System Field Manual. The
freeway capacity was estimated as 2395 vehicles per hour per lane (vphpl) with a resulting jam density of 135 vehicles per miles per lane (vpmpl). LOS D/E Breakpoint Volume was determined to be 2100 vehicles per hour per lane (vphpl).

---

**Lane Closure Configuration**

The lane closure configuration is specified by the number of directions in which lanes are closed, the total number of lanes and number of lanes open in each direction, and the length of the work zone lane closure.

<table>
<thead>
<tr>
<th>Present Value</th>
<th>New Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of directions (1 or 2)</td>
<td>0</td>
</tr>
<tr>
<td>Total lanes (2 - 6 are acceptable)</td>
<td></td>
</tr>
<tr>
<td>Inbound</td>
<td>0</td>
</tr>
<tr>
<td>Outbound</td>
<td>0</td>
</tr>
<tr>
<td>Open lanes</td>
<td></td>
</tr>
<tr>
<td>Inbound (1 - 2 are acceptable)</td>
<td>0</td>
</tr>
<tr>
<td>Outbound</td>
<td>0</td>
</tr>
<tr>
<td>Length of the lane closure (miles)</td>
<td>0.0</td>
</tr>
</tbody>
</table>

Type the key: [ESC]→Main Menu [R]→Re-entry [ENTER]→Next Screen

---

Figure 53: Lane Closure Configuration Screen for the Road User Cost Output Option, Interstate 91 in Windsor, CT

---

**Schedule of Work Activity**

The Road User Cost option evaluates a time schedule specifying when lanes are closed and when work activity is actually underway. Work activity may be conducted during any part or all of the time that lanes are closed.

<table>
<thead>
<tr>
<th>Present Value</th>
<th>New Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hour lane closure begins</td>
<td>0</td>
</tr>
<tr>
<td>&lt; 0 - 23 are acceptable&gt;</td>
<td></td>
</tr>
<tr>
<td>Hour lane closure ends</td>
<td>0</td>
</tr>
<tr>
<td>&lt; 9 - 24 are acceptable&gt;</td>
<td></td>
</tr>
<tr>
<td>Hour work activity begins</td>
<td>8</td>
</tr>
<tr>
<td>&lt; 9 - 15 are acceptable&gt;</td>
<td></td>
</tr>
<tr>
<td>Hour work activity ends</td>
<td>16</td>
</tr>
<tr>
<td>&lt; 9 - 16 are acceptable&gt;</td>
<td></td>
</tr>
</tbody>
</table>

Type the key: [ESC]→Main Menu [R]→Re-entry [ENTER]→Next Screen

---

Figure 54: Schedule of Work Activity Screen, I-91, Windsor, CT
5.4 Modeling Interstate 95, Bangor, ME

This work zone located on the two lane interstate highway in Bangor, Maine, which is approximately one quarter to one third mile in length and is located as shown in Figure 60.

QuickZone Delay Estimate Program Version 1.01 and QUEWZ-98 were used to analyze the effects and productivity of this site. The following sections explain the use of QuickZone regarding to this specific section.

Figure 55: I-95 Bangor, ME Work Zone Location
5.4.1 QuickZone Analysis of I-95, Bangor, ME

The QuickZone analysis procedure for this work zone was carried out in the same way as for Interstate 91 in Greenfield, MA, and Interstate 91 in Windsor, CT. For this portion of the research, only the southbound direction of travel was selected for analysis. Node information was entered to define the beginning and end of the roadway section.

Link lengths were scaled from construction documents provided by the Maine Department of Transportation.

The travel demand data for this analysis was also provided by the Maine Department of Transportation. This data was in the form of hourly counts and was entered for each link over a seven day, 24-hour period. Truck percentages of 2 percent were assumed for this location and applied to each link over the same time period.

As with Interstate 95 in Bangor, ME, several assumptions were made. The phase duration was estimated by the Maine Department of Transportation to be 12 weeks. The yearly demand increase was assumed to be the default value of 5 percent and the yearly capacity decrease was assumed to be 0 percent. The project infrastructure cost of $1.15 million was obtained from an estimate provided by the Maine Department of Transportation.

The analysis results show Monday at 6:00 pm to have the highest delay in vehicle-hours per hour for this particular phase of the Interstate 95 Bangor, ME project. The QuickZone output reveals that motorists traveling through this work zone will experience delay on Monday evening and Friday evening. The capacity reductions as calculated by the HCM 2000 method cause this section of Interstate 91 to have a greater demand than it can support only during the afternoon hours of Sunday.
5.4.2 CA4PRS Analysis of I-95, Bangor, ME

The analysis on the Interstate 95 portion in Bangor, ME is practically similar to the previous three analyses, due to the large number of assumptions made in the CA4PRS. The total lane-mile to be rehabilitated was entered as 0.33, reflecting the approximate length of the work zone, according to the information provided by Redington Robbins, the engineer in Maine Department of Transportation. All of the same assumptions were made for the Scheduling and Resource Profile windows as for Interstate 91 Maine. A deterministic Full-depth Asphalt Concrete analysis was again used for Interstate 95 Bangor, Maine.

5.4.3 QUEWEZ Analysis of I-95, Bangor, ME

Due to the information provided by Maine Department of Transportation, we have directional hourly volume available. For this research, the output is also expected to be road used cost estimates. The free-flow was determined to be 70 miles per hour (mph) based on the recommendations of the Highway Performance Monitoring System Field Manual. The freeway capacity was calculated as 2400 vehicles per hour per lane with a resulting jam density of 140 vehicles per miles per lane. LOS D/E Breakpoint Volume was determined to be 2100 vehicles per hour per lane. Dates are requested for both the hours when the lane closure begins and ends the hours when the work activity begins and ends. From the talk with the engineers by phone, we know it starts from 8 am till 4 pm on each day of the week. The values then are entered into the simulation model. The output for the Interstate 95 Bangor, Maine project is presented in the evaluation section.
5.5 Evaluation of Simulation Results

Table 1 and Table 2 provide an evaluation of the results of this research for the QuickZone and QUEWZ simulation models [23] [24].

Table 3 is presented to compare the criteria, constraints, and parameters of the three software packages.

For QuickZone, the parameter used for comparison is queue length. Beginning with Interstate 91 in Windsor, CT, QuickZone estimated a maximum queue of 0.3 miles to occur on both Monday and Friday. The queue begins to build at around 8:00 pm on the Monday that was modeled and at around 9:00 pm on the Friday that was modeled. The queue is estimated to be dissipated by the early morning of the following day. Comparing these estimates to real-world data provided by the resident engineer working for Connecticut Department of Transportation, QuickZone provides a fairly accurate estimate of the actual queue length.

QUEWZ’s estimates are very similar to QuickZone’s. QUEWZ provides fairly accurate estimation of the queue length too. QUEWZ estimated a maximum queue of 0.3 miles to occur on Monday and 0.4 miles on Friday. The queue begins to build at around 8:00 pm on the Monday that was modeled and at around 9:00 pm on the Friday that was modeled. These results are consistent with the real-world date.

QUEWZ’s estimates are very similar to QuickZone’s. QUEWZ provides fairly accurate estimation of the queue length too. QUEWZ estimated a maximum queue of 0.3 miles to occur on Monday and 0.4 miles on Friday. The queue begins to build at around 8:00 pm on the Monday that was modeled and at around 9:00 pm on the Friday that was modeled. These results are consistent with the real-world date.
Table 1: Comparison of Queue Length between Field Observation and QUEWZ-98 Simulation Results (in miles)

<table>
<thead>
<tr>
<th>MON</th>
<th>1 lane closed</th>
<th>Wu</th>
<th>Khanta</th>
<th>Field Observation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.8 (8pm)</td>
<td>0.3 (8pm)</td>
<td>0-0.5</td>
<td>3.75 (6:7pm)</td>
</tr>
<tr>
<td>2</td>
<td>0.7 (8pm)</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>FRI</td>
<td>1 lane closed</td>
<td>0.4 (4pm)</td>
<td>0</td>
<td>2.5</td>
</tr>
<tr>
<td>2</td>
<td>0.2 (4pm)</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

Notes: 1. Provided by Leon Affol, the Resident Engineer in Connecticut DOT
3. Provided by Redington R Robbins, the lawyer at Maine DOT

QUEWZ’s estimates are very similar to QuickZone’s. QUEWZ provides fairly accurate estimation of the queue length too. QUEWZ estimated a maximum queue of 0.3 miles to occur on Monday and 0.4 miles on Friday. The queue begins to build at around 8:00pm on the Monday that was modeled and at around 9:00pm on the Friday that was modeled. These results are consistent with the real-world date.

QuickZone estimated that Interstate 91 in Greenfield, MA had a 3.85-mile queue to occur on a Sunday. The queue begins to generate around 11:00 am, reaching its maximum at approximately 4:00 pm. The queue is estimated to be dissipated by 7:00 pm. Comparing these estimates to real-world data, QuickZone provides a fairly accurate estimate of the actual queue length. Heaslip’s reports that, “On most Sundays, the queue would be 4 to 6 miles with propagation beginning at about 11:30 am. The queues would dissipate between 4 to 6 pm, depending on demand for that afternoon [24].” It was also reported that the media and conversations with the Massachusetts State Police revealed queues of
approximately 12 miles had formed at the beginning of the project. QUEWZ's results are also fairly comparable to the real-world data. The simulated results are in the same order of magnitude with the field observed results. Therefore, QUEWZ provides fairly accurate estimation of queue length.

Table 3: Work Zone Software Analysis Comparison

<table>
<thead>
<tr>
<th>Feature</th>
<th>CA4PRS</th>
<th>QuickZone</th>
<th>QUEWZ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Minimum length of work zone</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Maximum number of productivity</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Optimal construction staging</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum tolerable traffic delay</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>Optimal work zone season</td>
<td></td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>Nighttime work zones</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Crash frequency</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimal user costs/rehabilitation strategy</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>Construction window time of concrete bridge</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Material selection: curing time for concrete</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concrete mix thickness of new concrete or asphalt</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Concrete's logistical constraints, location,</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>capacity, and randomness of rehabilitation</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rehabilitation interface, mobilization, traffic</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>control, lane, and activity breakdown</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Quantify curb delay resulting from capacity</td>
<td>X</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>reductions on small roads</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Identify delay impacts of alternative project</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>planning plans</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Support shield analyses between construction</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>costs and delay impacts</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>To ensure the impacts of construction by location</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>and alternative strategies</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Assessment of design measures and other delay</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>mitigation strategies</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Help establish work completion timelines</td>
<td>X</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

About CA4PRS, it is much more difficult to make a comparative evaluation of the maximum rehabilitation results provided. For both Interstate 91 and Interstate 95, CA4PRS estimated the maximum rehabilitation production to be 0.80 lane-miles. Many of the input parameters for the analyses using CA4PRS were assumed values. The reason for so many assumptions is that these values are more directly related to the construction contractor rather than the state and local transportation professional. The maximum
rehabilitation production and the construction activity timeframe appear to be reasonable estimates, but there is no data available to make a direct comparison to real-world production. The real-world data would be best captured by visiting the site on a day when rehabilitation activity is taking place. For this research, the accuracy of a direct comparison would have to be questioned due to the large number of assumptions made.
CHAPTER 6

SUMMARY AND CONCLUSIONS

This study has focused on the application and evaluation of QuickZone, QUEWZ and CA4PRS to simulate the interstate highway work zone strategies implemented in four states of New England. The four studies, respectively analyzes Interstate 91 in Greenfield, MA, Windsor, CT and Interstate 95 in West Greenwich, RI and Bangor, ME. The research has explained and illustrated both the data input and output procedures of the three available software packages. Finally, the simulated results compare closely with the field observations.

The results produced by QuickZone provide the user with meaningful information, from queue length to time delay to user costs. The benefit of QuickZone is that these results are provided in both tabular and graphical form, allowing users to have multiple means of interpretation. Overall, it would be recommended that New England Departments of Transportation consider QuickZone for future work zone strategy assessments.

The results produced by QUEWZ also provide the user with meaningful information in terms of queue length. The biggest benefits being realized is accurate delay information which has resulted in more efficient construction phasing and maintenance of traffic planning. Also, it would be recommended that New England Departments of Transportation consider QUEWZ for future work zone strategy evaluation.
Future research involving QuickZone and QUEWZ could include:

- Application and evaluation of QuickZone and QUEWZ to various roadway classifications (i.e. rural or urban arterials, two- or three-lane interstates, local roads, etc)
- Analyzing the effect of work zone intensity as adjusted within the HCM capacity reduction function
- Analyzing the effects of altering pre-construction travel behaviors and work zone mitigation strategies
- Developing a way to account for speed differentials upon approach, passage, and exit of the work zone and analyzing the associated effects related to speed.

Table 4: Comparison of User Friendliness of Simulation Models

<table>
<thead>
<tr>
<th>Simulation Model</th>
<th>PC Operating Requirements</th>
<th>Work Zone Site Location</th>
<th>Data Assembly Time</th>
<th>Data Input Time</th>
</tr>
</thead>
<tbody>
<tr>
<td>QUEWZ</td>
<td>DOS system</td>
<td>Interstate 91, Greenfield, MA</td>
<td>2 - 3 hours</td>
<td>2 hours</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Interstate 85, West Greenwich, RI</td>
<td>5 - 6 hours</td>
<td>2 hours</td>
</tr>
<tr>
<td>QuickZone</td>
<td>Windows 95/98/2000/XP</td>
<td>Interstate 91, Enfield, CT</td>
<td>4 - 5 hours</td>
<td>2 hours</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Interstate 91, Greenfield, MA</td>
<td>2 - 3 hours</td>
<td>2.5 hours</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Interstate 85, West Greenwich, RI</td>
<td>4 - 5 hours</td>
<td>2.5 hours</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Interstate 91, Enfield, CT</td>
<td>5 - 6 hours</td>
<td>2.5 hours</td>
</tr>
<tr>
<td>CA4PRS</td>
<td>Windows 95/98/2000/XP</td>
<td>Interstate 91, Greenfield, MA</td>
<td>1 - 2 hours</td>
<td>1 hour</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Interstate 85, West Greenwich, RI</td>
<td>1 - 2 hours</td>
<td>1 hour</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Interstate 91, Enfield, CT</td>
<td>1 - 2 hours</td>
<td>1 hour</td>
</tr>
</tbody>
</table>

Table 4 above provides a summary of the time required to assemble, input and analyze the data for the QUEWZ, QuickZone and CA4PRS simulation models. It is anticipated that the information presented will shed light on the user-friendliness of each simulation model. It should be noted that these times will vary from project to project due to the availability of the necessary data. The times will also vary relative to the user’s familiarity with a given simulation model. Among the these simulation models, CA4PRS
requires least data input time, while QUEWZ and QuickZone need longer time for the
data input. CA4PRS also requires least time for the data assembly work.
APPENDIX A

INTERSTATE 95, RHODE ISLAND WORK ZONE PHOTOS

Interstate 95 Work Zone Area as of 6/19/07 (Southbound)

Interstate 95 Work Zone Staging Layout as of 6/19/07 (Southbound)
Interstate 95 Work Zone Staging Layout as of 6/19/07 (Northbound)

View of Interstate 95 from Robin Hollow Road (I-95 S in foreground)
APPENDIX B

INTERSTATE 91 WINDSOR, CT WORK ZONE PHOTOS

Interstate 91, CT work zone area photo I (taken by ConnDOT)

Interstate 91, CT work zone area photo II (taken by ConnDOT)
Interstate 91, CT work zone area photo III (taken by ConnDOT)

Interstate 91, CT work zone area photo IV (taken by ConnDOT)
REFERENCES


