FINAL REPORT

Evaluation of Construction Work Zone Operational Issues: Capacity, Queue, and Delay

Project IVA-H1, FY 00/01

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16. Abstract

The Illinois Department of Transportation (IDOT) requires queuing analysis to determine traffic backups on interstate work zones. The monetary gains/losses in contractual procedures such as lane rental and incentive/disincentive depend on the queuing analysis. The statewide survey indicated that incentive/disincentive and lane rental procedures were more effective in reducing duration of work zones and delay. The survey of state DOTs indicated that for estimating capacity the Highway Capacity Manual (HCM) technique was used; for estimating queue length and delay, QUEWZ, QuickZone, and HCM technique were used; and for estimating road user costs, QUEWZ and spreadsheets were used more often than other techniques. About 57% of the DOTs said they use Intelligent Transportation Systems (ITS) technologies in work zones. Headway and traffic flow data were collected and analyzed for 14 work zones in Illinois. Field data were compared to the results from FRESIM, QUEWZ, and QuickZone software. QUEWZ overestimated the capacity and average speed, but underestimated the average queue length. Speeds computed in FRESIM were comparable to the average speeds from the field data when there was no queuing at the work zones. However, when there was queuing, FRESIM overestimated the speed. The queue lengths obtained from FRESIM were shorter than the field values in half of the cases and longer in the other half of the cases. The queue lengths from QuickZone did not match the field data and generally QuickZone underestimated the queue lengths. QuickZone consistently underestimated the total delay observed in the field. When demand is less than capacity QuickZone does not return any user delay because it does not consider the delay due to slower speeds in the work zones. A new methodology was developed to determine capacity, speed reduction, delay, queue length, and user costs. Speed reductions due to the work zone factors are used to compute operating speed. Then, capacity is determined using speed flow curves developed in this study. Finally, queue, delay and user costs are computed.

17. Key Words Work zone capacity, speed, queue, delay, user costs; Work intensity; QuickZone, QUEWZ, FRESIM; Construction zone survey; Queuing analysis; Work zone speed flow curve	**18. Distribution Statement** No restrictions. This document is available to the public through the National Technical Information Service (NTIS), Springfield, Virginia 22161

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EVALUATION OF CONSTRUCTION WORK ZONE OPERATIONAL ISSUES: CAPACITY, QUEUE AND DELAY

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The contents of this report reflect the views of the authors who were responsible for the facts and accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the Illinois Department of Transportation. This report does not constitute a standard, specification, or regulation.

EXECUTIVE SUMMARY

The Illinois Department of Transportation (IDOT) Bureau of Design and Environment (BDE) Manual requires that traffic control plans for freeway reconstruction projects include, as a minimum, a queuing analysis to determine the anticipated traffic backups. Based on the results of the queuing analysis a decision is made to consider restricting construction operations to off-peak or night hours, using alternative routes, making temporary capacity improvements, or providing real-time information to motorists. To reduce delay and inconvenience to motorists, contractual procedures (such as lane rental and incentive/disincentive (I/D)) are used to shorten the duration of construction time. The monetary gains/losses in the contractual procedures depend, to a large degree, on the results of the queuing analysis. A limited number of methods are available to estimate motorist delays and queuing in work zones, but they are not considered "user-friendly," do not give accurate estimates in all situations, and are not uniformly applied by all IDOT districts. The purpose of this research project was to study contract incentive/disincentive procedures for minimizing lane closures; to evaluate queuing analysis procedures and relevant factors affecting queue length and road user costs; to evaluate the performance of current techniques for estimating delays and queue lengths, to assess the role of intelligent transportation systems (ITS) in work zones, and to recommend a queuing analysis and road user cost estimation method.

Literature reviews on incentive/disincentive and lane rental, work zone capacity calculation, and role of ITS in work zones were conducted. A survey was conducted among the 9 IDOT districts offices on the issues of I/D, capacity, queue length, road user costs, and motorist signing. Also, another survey was conducted among all 50 state DOTs on contract procedures, techniques used for calculating capacity, queue, delay and road user costs, cost figures used, motorist signing, and use of ITS technologies in work zones. On 14 work zones in Illinois, data on traffic flow, speed, capacity, and queuing were collected. The sites included five short-term and 8 long-term work zones. Comparisons were made between field data and software that are used in the calculation of delay, queue length and road user costs. The three software programs selected for evaluations were FRESIM, QUEWZ and Quick Zone. New UIUC Models were developed to determine capacity, speed reduction, delay, and queue length. The UIUC Models consider effects of heavy vehicles, work intensity, narrow lanes and shoulders. Three examples based on actual field data are given to illustrate the application of the proposed methodology.

The findings of this study are:

- Incentive/Disincentive and lane rental procedures were more effective in reducing the delay in work zones. However, there was no consensus on the I/D or lane rental dollar amount to be used.

- Highway Capacity Manual (HCM) techniques to calculate capacity, queue length, delay and road user costs were used in five IDOT Districts. Their satisfaction level with the techniques varied from somewhat satisfied to very satisfied. Among the state DOTs, HCM technique for capacity calculation was used more often than other techniques. For estimating queue length and delay, QUEWZ, Quick Zone, and HCM technique were used more often than other techniques. For road users cost calculation, QUEWZ and spreadsheets were used more often than other techniques. States were very satisfied with their spreadsheets for road users cost calculations.
- About 68% of the responding DOTs said they used the vehicle operating costs and 38% said they used motorist delay costs in calculating the road user costs. However not many states use crash costs in such calculations.
- About 57% of the responding DOTs said they use ITS technologies in work zones.
- About 70% of DOTs said that major contributing factors for the loss of credibility of work zone signs are: failure to remove signs when there is no work going on, incorrect information, lack of enforcement, and overuse of signs.
- QUEWZ overestimated the capacity and average speed, but underestimated the average queue length. This was true with the default-input values as wells as modified capacity values.
- FRESIM requires calibration, which requires knowledge of how the model works. Speeds computed in FRESIM were comparable to the average speeds from the field data, when there is no queuing at work zones. However, when there was queuing, FRESIM overestimated the speed. FRESIM did not return the queue lengths directly. The queue lengths obtained from the suggested procedure were shorter than the field values in half of the cases and longer in the other half of the cases.
- QuickZone requires capacity as an input value. The queue lengths from QuickZone did not match the field data and generally QuickZone underestimated the queue lengths. QuickZone consistently underestimated the total delay observed in the field. When demand is less than capacity, QuickZone does not return any user delay because it does not consider the delay due to slower speeds in work zones.

Recommendations for Future Research

The following recommendations are made for future studies:

- A spreadsheet or other computer program should be written to make the proposed UIUC methodology more user friendly and more efficient.

- The data used in developing the UIUC models came from work zones on interstate highways with two lanes per direction. Similar studies or extension of this study is need for work zones on other types of highways or work zones with different number of lanes.
- Speed reduction models developed in this study were based on small number of participants and construction sites. It is recommended to do a future study with a larger number of participants and various work zone types and configurations.
- This study is based on data for one lane closure on interstate highway work zones. For work zones with crossover and different number of lane closures, the results may not be directly applicable. It is recommended to do further study for those conditions.
- The operating speed computed using the methodology discussed in this report is for conditions when there is no flow breakdown. A detailed study is needed to determine the causes of flow breakdown and its consequences on work zone speed.
- The speed – flow curve developed in this study did not have enough data to quantify the rapid decrease in capacity during flow breakdown. Further field data is needed to quantify the decrease in capacity for different work zone conditions.
- The adjustment values for lateral clearance, lane width, and passenger car equivalents (PCE) for trucks are directly taken form the HCM for basic freeway sections. There is a need to collect field data to determine if these values are applicable for work zones..
- There are other factors such as grade, weather conditions, road surface conditions that may affect capacity and speed in work zones. These effects need to be determined.
- Using ITS technologies may affect work zone capacity. Effect of using ITS technologies on speed-flow curve and capacity needs to be studied.
- A detailed analysis of benefits and costs of using ITS technologies in work zones is needed.
- The Department uses a procedure for calculating road user cost that relies on knowing speed and capacity of the work zone. However, it does not provide a procedure for determining speed and capacity. The models in this report provide procedures to estimate work zone operating speed and capacity. The UIUC methodology should be used on interim basis to see if it should be refined, modified, and improved before it is considered for inclusion in the BDE manual
- A long-term data collection effort should be initiated to answer many of the issues that need to be addressed about work zone traffic operations.

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CHAPTER 1 - INTRODUCTION

Every year the vehicle miles traveled on highways is growing at a considerable rate. To keep up with the growing demand and to provide a good level of service to motorists, work zones become an unavoidable aspect of the highway system. Work zones often reduce the efficiency of the highway system and driving through work zones is a fact of life for travelers on the US highways. There is a need to reduce the delay and improve safety in work zones. The Illinois Department of Transportation (IDOT) Bureau of Design and Environment (BDE) manual requires that traffic control plans developed for freeway reconstruction projects include, at a minimum, a queuing analysis to determine the anticipated traffic backups at particular times of the day. Based on the results of the queuing analysis a decision is made to consider restricting construction operations to off-peak or night hours, closing a ramp, using alternative routes, temporarily widening the roadway to increase capacity, or providing real-time information to motorists. There are a few computer programs or manual procedures to determine delay and queue lengths in work zones. However, it is not clear which technique is appropriate for Illinois conditions.

The IDOT has implemented a policy BDE Procedure Memorandum 15-00 “Procedures to Minimize Motorists' Costs and Inconvenience", intended to promote measures that reduce delay and inconvenience during highway construction. The recommended measures include geometric design features such as designing shoulders on high-volume routes to accommodate future construction. However, most are non-structural measures affecting construction operations through incentive/disincentive contract clauses, and increased public coordination. One recommended contractual technique for high volume, multi-lane projects is the lane rental contract. This relatively new technique specifies the number of days that lanes may be closed as part of the contract. If the actual number of days of lane closure is less than the specified number, an incentive is paid. If the contractor exceeds the number of days of lane closure allowed, a disincentive payment is deducted from the contract for each day in excess of the bid number of days. The intent is to force efficient scheduling of resources and timely completion of the work in order to reduce motorist delay. BDE 15-00 offers some guidance to IDOT District officials in determining an equitable amount for the incentive or disincentive payments in lane rental contracts. However, more accurate information on the actual motorist delay is necessary to estimate the cost to the public for each additional increment (days or hours) of lane closure. At present, computerized prediction methods for estimating motorist delays and queuing in work zones are available, but are not uniformly applied by the nine IDOT districts, are not considered "user-friendly," and do not appear to give accurate estimates in all situations. In addition, other methods that will help reduce motorist delay, such as real-time motorist information boards, alternate route information, and other techniques, need to be included in a systems analysis of work zone delay issues.

Research is needed to evaluate the issues in work zone delays and inconvenience to motorists, including more accurately predicting the length of queues and average motorist delay, and developing innovative procedures for minimizing the need for lane closure through improved traffic control techniques and/or construction operations.

The objectives of this study are:

- To study contract incentive/disincentive procedures currently in use for minimizing lane closures.
- To model road user costs for the variety of settings (urban, high-volume rural, suburban, 2-lane, multi-lane, etc.) for various work activities near the roadway centerline, identifying the relevant factors to be included in road user costs.
- To field-evaluate the performance of available computer models for estimating traffic delays and queue lengths for a variety of traffic and highway conditions.
- To evaluate the effectiveness and credibility of motorist signing, real-time traffic control technologies and alternative construction scheduling schemes in reducing traffic queuing in construction work zones.

This report contains the findings related to operational issues in work zones. The report consists twelve chapters. Chapter 1 gives an introduction and the background for this research study. It also describes the structure of the report.

Chapter 2 is a literature review of the contract procedures used in awarding freeway construction projects. The literature review concentrates on Incentive/Disincentive (I/D) and lane rental procedures. It also touches upon the determination of contract time and dollar amount for the procedures.

Chapter 3 gives a summary of responses for the survey conducted among the 9 IDOT Districts in Illinois. The survey responses were broadly classified into I/D, capacity, queue length and road user costs, and motorist signing.

Chapter 4 includes the responses for the survey conducted among the state DOTs. The survey consisted of questions about contract procedures, dollar amounts, techniques used for calculating capacity, queue, delay and road user costs, vehicular costs, motorist signing and ITS technologies.

Chapter 5 gives a description of the data collection and data reduction methodology used in this study. A list of sites, time and duration of data collection is also given in this chapter. Data regarding the traffic flow, speed and queuing in work zones was collected in 14 interstate work zones in Illinois. The sites included five short-term work zones and 8 long-term work zones.

Chapter 6 gives a comprehensive review of the capacity in construction work zones. In this review, issues like the definition of capacity and also the different models used in the estimation of capacity were studied. The review also gives a summary of a collection of capacity values obtained from the literature.

Chapter 7 compares different software used in the calculation of delay, queue length and road user costs. Three software models used for estimating delay in work zones were selected for evaluation. The models evaluated were FRESIM, QUEWZ and Quick Zone. The models were evaluated based on field data from 11 of the work zone sites.

In Chapter 8 a model was developed for the estimation of capacity in construction work zones. Using the data from 11 of the sites, models were developed to determine capacity, speed reduction, delay and queue length. The models consider effects of heavy vehicles, work intensity, narrow lanes and shoulders. The model was further calibrated using the remaining three sites.

Chapter 9 presents the application of the capacity model developed in chapter 8 to calculate delay and queue length. Three examples based on actual field data are given. The examples include both long term and short term sites. The chapter also gives the limitations of the model.

Chapter 10 consists of a literature on the real time technologies and motorist signing used in construction work zones. Driver understanding of motorist signs and effectiveness of signs were also discussed.

Chapter 11 reviews chapters 13, 55, 63 and 65 of the BDE manual 2000. The findings from this study may impact the procedures for calculating delay, queue length and user costs, depending on how the findings are adapted in BDE Manual.

Chapter 12 gives the conclusion and recommendations from this study.

CHAPTER 2 - LITERATURE REVIEW ON CONTRACT INCENTIVE/DISINCENTIVE PROCEDURES FOR MINIMIZING LANE CLOSURES

2.1 Objective

The objective of this literature review is to provide a comprehensive review of the contract incentive and disincentive procedures employed to minimize lane closures. The literature review is confined to the aspects of selection of projects, determination of contract time and the incentive/disincentive amount determination.

2.2 Incentive/Disincentive Procedures- an Overview

The BDE manual (2000, 66-2.04) describes the Incentive/Disincentive contracts as follows

" The term Incentive/Disincentive (I/D) describes a contract provision which compensates the contractor a prescribed amount of money for each day identified that critical work is completed ahead of schedule and assesses a deduction for each day the contractor overruns the schedule. The Incentive/Disincentive clause is used to motivate contractors to complete critical projects by an expedited work schedule on or before a specified date."

The objectives of contractual incentives are to induce the contractor to finish the project with minimum construction cost and minimum construction time with acceptable level of quality. In case the contractor fails to attain the objectives of the owner, disincentive clauses are employed. The disincentives should be accompanied with the incentives, because usage of only disincentives does not provide above standard performance (Arditi et al, 1994).

In the case of the highway projects, the objectives are mainly concerned with finishing the project ahead of time or attaining a particular standard of quality. The major findings from the literature study done by Newman et al (1984) are as follows:

- Most highway agencies include incentive provisions for early project completion although some use it for attaining standard of quality
- Contract times given in the contract documents are long enough to allow the contractors to finish work.
- The most prevalent method to encourage early completion of project is the assessing of liquidated damages. The liquidated damage is not a penalty but it is the amount the contractor shall pay to the department due to the overrun in completion of contract time. Section 108.09 of the Standard Specifications for Road and Bridge Construction says that the liquidated damages for failure to complete the contract on time establishes the cost of delay to account for administration, engineering, inspection and supervision during periods of extended and delayed performance.

- Liquidated damages are developed based on agencies' contract dollar amount included in the standard specification.
- Liquidated damages included additional inspection and engineering costs. Some agencies also use user costs.
- Highway agencies are less comfortable with providing incentives for early completion.
- Incentive provisions are mainly used for 4R (rehabilitation, restoration, resurfacing and reconstruction) and bridge rehabilitation projects.
- Contractors favor the use of incentives that balance the liquidated damages assessed for late completion. Most of the contractors were successful in getting incentives by early completion.
- Both the contractors and the highway agencies believe that the incentives should equal the liquidated damages.
- Based on the findings of the above study the recommendations that were given:
- Liquidated damages clause should be employed for all projects to enable the prompt completion of the project.
- Incentive clauses should be employed only for projects that cause excessive inconvenience to public and traffic.
- Amount of incentive should equal the amount of liquidated damages. For clarification purpose, Illinois DOT generally caps the total incentive at 5% of the awarded value and no cap on the disincentive.

The purpose of using I/D procedures in a highway construction project is to reduce the construction time with minimal cost. The reduction in construction time leads to minimizing lane closures, reduction in traffic congestion, delays and road user costs. On the other side, I/D provisions may increase construction cost, crew size, material inventory, inspection costs, cause environmental problems like night time noise, lighting problems and reduce quality.

The use of I/D in contracts demands the proper selection of the project for which the I/D provisions has to be used, the determination of construction time and the amount of the I/D provisions. The I/D procedures can be applied to either a single project or portions of a project.

2.3 Project Selection

The I/D procedures are mostly used for projects where early completion of the project will reduce the road user delays and benefit the travelling public. The BDE 2000 manual categorizes the projects for which I/D procedures can be applied in Illinois:

- Adverse Effects- Roads where there is heavy volume and which involve heavy road user costs due to the construction. Other effects such as disruption to business establishments and adverse travel and economic impacts.
- Timing- Projects in which the late completion is of more concern than early completion which affects the progress of the roadway (projects involving high volume roadways, beginning of holiday season).
- Urban River Crossings- River structures situated inside or adjacent to Central Business Districts.
- Nighttime Construction- Projects which involve night time construction on major roadways.

The I/D procedures may be either applied to a single project or parts of a project, to two or more projects combined. The BDE 2000 suggests the following conditions for I/D provisions: When I/D is applied to a single project, all the work must be completed before the application of disincentive amount. When I/D is applied to part of a project, a completion date is set for that part of the project and the other parts are subject to the liquidated damages. When I/D is applied for combined projects, Cooperative I/D procedures are used. In these procedures it is required that the work should be completed on all the projects before the I/D completion date.

In the FHWA Technical Advisory T5080.10 “I/D for early Contract Completion” (1989) states that the I/D phases should be limited to completion in one construction season at most. The effective use of I/D procedure depends on the establishment of a reasonable contract time, which will be acceptable to the contractor and the client. The following section deals with the estimation of contract time.

2.4 Determination of Contract time

The FHWA Technical Advisory T5080.10 “I/D for early Contract Completion” gives the following suggestions for I/D contract time determination.

- I/D time determined based on past performance requires good engineering judgement
- I/D time determined based on critical path methods (CPM) methods requires good work breakdown structure and identification of separate tasks
- Use calendar days instead of working days
- Consider weather and holidays

The BDE 2000 manual says that the contract time should be calculated based on an expedited schedule, which involves one or more of the following:

- Six-day work week, double shift with night illumination
- Extended work hours with 12 to 14 hours per day
- Expedited work schedule with 228 working days per calendar year ; and or

- Multiple work crews in multiple areas

The determination of contract time requires an experienced project scheduler who is able to judge which construction operations overlap, order in which the construction operation will proceed and the duration of all construction operations. The BDE 2000 manual gives guidance on the productivity rates of different construction operations.

A+B bidding has been adopted by number of state highway agencies (SHAs). A+B bidding has two bids, the cost bid (A) and the time cost bid (B). The time cost bid gives the time within which the work can be finished for the specified cost (A). There are two problems on the time bid range. A contractor can show a high cost bid (A) and a low time cost bid (B), so that he can use the excess cost bid to cover the disincentives arising out of the low time cost bid. Another possibility is that the contractor can have a low cost bid (A) and high time cost bid (B) so that he may make an unreasonable amount of money from the incentive payments. Fang Shr et al (2001) discussed the development of a quantified model between construction cost and time. Using the Florida Department of Transportation data, a construction cost vs. time curve was developed. The optimum lower time limit for a project is set using the contractor's price vs. time curve and the road user costs. The model was validated using projects completed by the Florida DOT.

The formulation of the model consists of arriving at two relations: construction cost vs. duration and time cost vs. duration. The sum of the construction cost equation and the time cost equation will give the total cost. The point representing the lowest construction cost is called the 'normal point'. The data used to establish this relation is taken from fifteen projects from the Florida DOT. Of the fifteen projects, six projects were done by A+B contract, four projects used Incentive/Disincentive contracts and five projects were based on No Excuse Bonus method. A relationship was developed using regression analysis, which is given as:

$$(C-C_o/C_o) = 0.03214 + 0.10481(D-D_o/D_o) + .46572(D-D_o/D_o)^2$$

Where,

C – present cost of the contract = final construction cost

C_o – award amount

D – number of days actually used by contractor

D_o – final contract time adjusted for weather and additional work.

The above equation gives the interrelationship between construction cost and construction time. The curve is arrived at after determining the present cost of the construction (C) and duration of contract (D). The curve is adjusted to match the normal point. The total time cost is the product of the unit time value and the contract time. Adding the two costs and after calculation the minimum C is found to occur when

$$\text{Minimum Contract Time} = Do - 1.0736[TD_o^2/Co]$$

Figure 2.1 gives the models for the different costs.

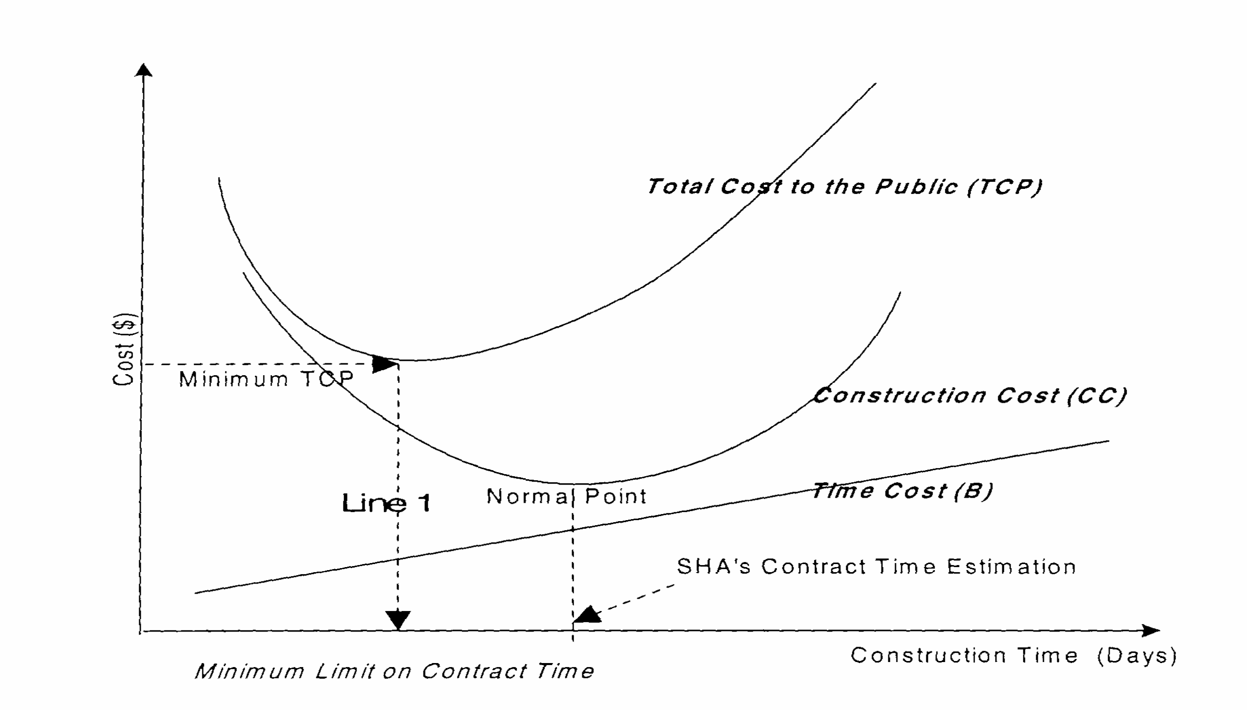

Figure 2.1 Process to Determine Minimum Limit on Contract Time (SHA Perspective)

Source: Jin-Fang Shr, Jeffrey S. Russell, Benjamin P Thompson, Bin Ran and Awad S. Hanna, ***Setting Time Limits for Florida DOT Highway Projects***, Transportation Research Board 1472, 2000.

The Kentucky Contract Time Determination System (KY- CTDS) was developed for Kentucky Department of Highways for the estimation of contract time. The previous system was based on a single project model with fourteen project-controlling activities and was developed as a mainframe computer application. The KY – CTDS was developed as a PC-based, user friendly application. The contract time estimation systems in other DOTs were evaluated. Both manual and computer based systems were evaluated. It was found that a pc-based computer system utilizing templates for productivity rate analysis and a software package for bar chart schedule would be consistent and accurate. The KY-CTDS uses Microsoft Excel for the template and Microsoft Project software for the bar chart schedule. The Microsoft Excel has six different project templates to calculate activity duration. The project templates in MS Excel contain the macro that has the project activity relationship logic and also transfers data to MS Project. The MS Excel project template macro calculates the project contract time and transfers the data to

MS Project. In MS Project the project duration is converted to bar chart scheduling based on the Kentucky workday calendar. (Werkmeister et al, 2000).

The logical relationships between the project controlling activities for each project classification were established. The relationships between activities were limited to one in order to work within the limitations of the MS Project software, and phasing allowance was provided to account for the time lost in phasing. The production rates for each of the activity were established using the expertise of the members of the working group. These rates were then compared to some already completed projects. These production rates produce default values that can be adjusted according to the local conditions.

2.5 Determination of I/D Amount

The I/D amount is the dollar amount per reduced day that should be paid to the contractor for the early completion of the work or assessed against the contractor for extending beyond the stated contract duration. According to the BDE 2000, the I/D amount is based on the road user delay costs and the liquidated damages. In projects where the I/D is applied to only a portion of the project the I/D amount is based on the road user cost alone. The road user delay cost consists of 3 components (BDE 2000)

- Travel Time- the difference between the travel time in normal conditions and during construction
- Passengers- number of passengers per vehicle, assumed to be 1.25
- Hourly cost- hourly cost per passenger, assumed to be $10.00.

The I/D amount is adjusted downward from the sum of the calculated road-user delay costs and the liquidated damages. The BDE 2000 gives the following restrictions on setting the I/D amount

- The I/D amount must provide a favorable benefit – cost ratio (B/C) of at least 1.0
- The final daily I/D amount must be large enough to motivate the contractor to work an accelerated schedule

The FHWA report called “Incentive/Disincentive Early Contract Completion” (OPR Report, 1989) specifies the following I/D daily amount criteria

The costs incurred in I/D amount are:

- Established construction engineering inspection costs
- State related traffic control and maintenance costs
- Detour costs
- Road user costs (cost of delays, added energy costs, accident costs)

In the case of A + B bidding contract, the contractor has to decide the contract cost and the contract time to satisfy the owner's need. The owner will select the contractor based on the contract time and the contract cost. The balance between the values of 'A' and 'B' depends on the owner's value of time for the project. This value is measured in terms of unit time value (UTV) of the owner. The calculation of "Unit Time Value" is significant because it determines the value of time to the owner. Different SHA's have different method of calculating UTV since there is no formal procedure. Some SHA's do not consider the indirect costs (loss of business, etc.) associated with a project. This is important, as they may become a significant part of the UTV.

. Shen et al (1999) developed a model to optimize the price time bid.

The Total Contract Bid (TCB=A + B) is given by the equation:

$$TCB = p + (UTV * t)$$

Where,

p = contractors tender price

UTV = unit time value (specified by owner)

t = contract time

Figure 2.2 gives the relation between TCB, p and t.

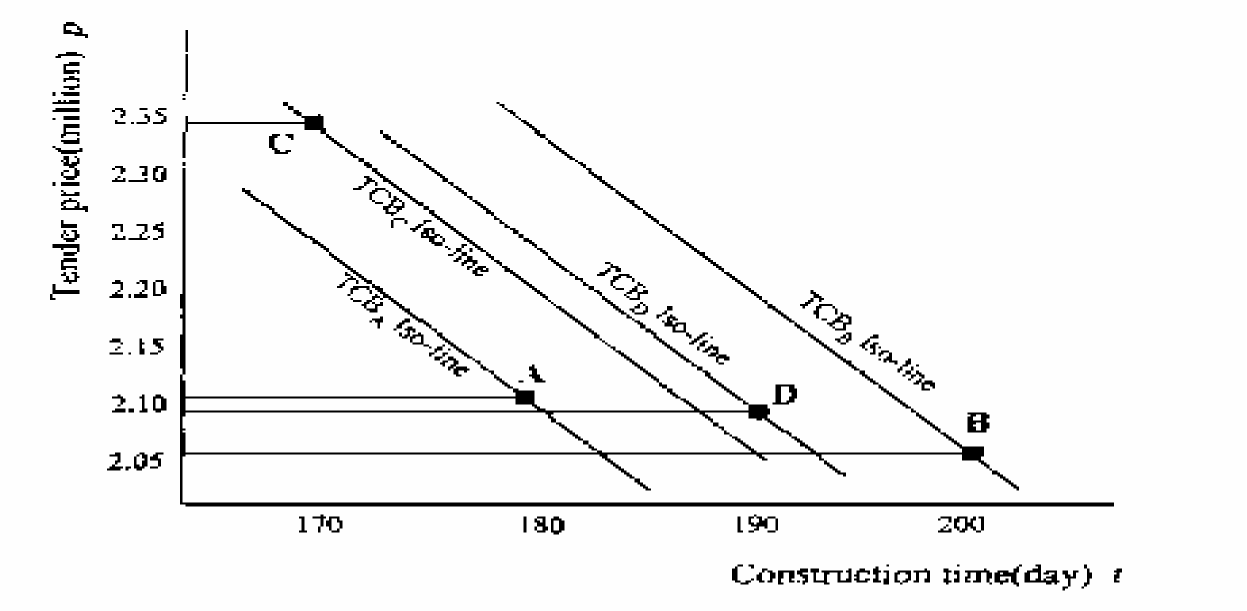

Figure 2.2 Contractors' Overall Competitiveness: TCB Iso-Line

Source: Liyin Shen, Derek Drew and Zhihui Zhang, ***Optimal Bid Model for Price-Time Biparameter Construction Contracts***, Journal of Construction Engineering and Management, 1999.

In this equation it can be seen that different strategies can be obtained for the same value of TCB, by varying the values of p and t. The contractor has to choose the best strategy among the different strategies, by considering factors like company practice, availability of resources, etc. If we plot the different strategies for a fixed TCB value, we will get a linear variation with slope UTV. All the points on this line indicate different values of p and t for a given UTV and TCB value. This line is called as an Iso-line. A graph containing a number of Iso lines is called an Iso-map. The quantities, construction cost and construction time are interrelated, and each contractor has a particular construction time for a project at minimum construction cost, i. This point is called the 'normal point' (i.e. the point of minimum construction cost and the construction time). This construction time and construction cost (normal point) doesn't take into account the UTV provided by the owner. The addition of the time cost into the system changes the variation between the tender price and the construction time. The variation due to the introduction of the UTV in the cost Vs time graph will be linear (UTV * t). If we superimpose the tender price Vs construction time on to the Iso map we will get a particular TCB value at which the Iso line will be tangential to the cost Vs time graph. This tangential point of intersection gives the value of the most competitive tender price and construction time the contractor can offer.

Ellis et al (1990) analyzed case studies relating to AB bidding in three states. The details for each case study consisted of the state, type or location of the site, original estimate of project cost and calendar days, road user costs (RUC) and the bidding costs and duration given by different bidders. It was found that in two of the cases the lowest combined bidder was not the lowest on a cost basis. Another comparison of data from 16 case studies, indicated that significant reduction of project duration was achieved by A+B bidding. It was also found that most of the awarded contracts did not bid the lowest construction cost and the savings from the reduction in duration of construction far outweighed the difference in construction cost. From the data, it was found that an average of 108 days reduction in construction time was achieved and the savings amounted to approximately $500,000 per project.

The savings to the public was calculated using the formula:

$$S_p = (T_E - T_C)(R) - (C_B - C_c)$$

Where,

S_p = savings to the public (dollars)

T_E = contract time determined by the engineers (days)

T_C = time bid by contractor (days)

R = road user cost (dollars/day)

C_B = bid price of successful or best bidder (dollars)

C_c = bid price of low bidder (dollars)

Also the comments of the owners and the contractors were found to be supportive of the A+B bidding system. Some of the issues associated with this system are

- Awarding incentives for early completion
- Restricting the project duration
- The cost factors to be considered in computing RUC

2.6 Limitations of I/D contract

The advantages and disadvantages of various contracting methods employed to reduce contract time were analyzed by Herbsman et al (1995). The analysis was based on data obtained from case studies. The contracting methods analyzed in this paper were:

- Bidding on cost/time
- Incentive/Disincentive (I/D)
- Bidding on cost/time combined with incentive/disincentive
- Lane rental.

Bidding on cost/time brought positive feedback from the owners. Fourteen case studies in this category were analyzed and it was found out that construction time was considerably reduced with little or no increase in construction cost. In 11 of 14 case studies, the project duration submitted by the contractor was less than that calculated by the engineer, with the time reduction ranging from 2.9 % to 68.4% (average of 29.87 %).

Incentive/Disincentive contract procedure is a well-established contract procedure. The calculation of incentive amount varies for different SHAs'. Sixteen SHA's were surveyed and it was found out the I/D amount varied from \$2500/day to \$5000/day. The most commonly used I/D amount was \$5000/day. In metropolitan areas, where the road user costs are high, the I/D amount will increase. Although the I/D amount is usually based on the road user costs, in some SHA's the I/D amount is calculated as percentage of the total project cost. Most states use the same amount for disincentive and incentive. Out of the 35 states surveyed, 28 states used I=D, two states used I>D, one state used I<D and four states said that they there is no specific relation between incentive and disincentive amount. The maximum limit on the I/D fees also varied from state to state. The limitation may be in terms of percentage of project cost (maximum 10% NewYork, majority=5%), dollar amount (\$100,000 New Jersey), and incentive/disincentive duration (30 days Arizona). It was also found that in 75% of the projects under this category an incentive amount was paid to the contractor.

The combination of the bidding on cost/time procedure and I/D procedure is called the "A+B plus I/D" procedure. In this procedure, once the successful bidder is chosen, the project duration specified by the contractor is taken as the contract duration based on which the I/D amount is paid. This type of contract procedure has two advantages. While choosing the bidder by the A+B method, the contract time is reduced from the engineer's estimated time. Once the successful bidder is chosen, he has the further chance of being paid an incentive, if he completes the project faster than specified in the bid. From the data collected from 10 recent projects from Missouri DOT, it was found that in each project was completed not only before the engineer's estimated time, but also before the time specified by the contractor in the bid.

In the lane rental method, the transportation agency will determine a cost for lane closure. The bidder has to submit the cost of construction and the duration of lane closure. The successful bidder will be the one who submits the least sum of the construction cost and the total lane closure cost. If the contractor exceeds the duration of lane closure specified he has to pay the owner the cost of the lane closure.

After analyzing the case studies, it was found that all the four methods were able to reduce construction time in the range of 20-50 %. Of the four methods, A+B bidding method was found to be economical than other because it reduces construction time by encouraging competition between contracts and not by paying estimates. The I/D method was more expensive and less effective.

The BDE manual specifies that the incentive amount should not exceed 5 percent of total construction cost. The I/D procedure should include an upper limit of 30 calendar days for which the incentive amount can be paid but the disincentives are not limited.

2.7 References

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CHAPTER 3 - RESULTS OF THE SURVEY OF IDOT DISTRICT OFFICES ABOUT WORK ZONE OPERATIONAL ISSUES

The University of Illinois at Urbana-Champaign in cooperation with the technical review panel (TRP) for the project developed a questionnaire and sent it to all 9 IDOT District offices to collect data on freeway construction work zone issues. The topics covered in the survey are:

- The contract procedures the districts used to award such contracts,
- The incentive/disincentive and lane rental specifications used,
- The techniques and software used to estimate capacity, delay, queue length and road user costs in the work zones, and
- The real time technologies used in freeway work zone control traffic.

All 9 districts responded to the survey. A summary of the responses is given at the end of this section. A copy of the survey questionnaire is included in Appendix A. Fig 3.1 shows the nine districts in the state of Illinois. The responses to each question are discussed here.

3.1 Incentives/Disincentives

1. What types of contract procedures does your District utilize for minimizing delay to motorists in construction work zones?

The different contract procedures used in IDOT districts are given in Table 3.1.

Table 3.1 Contract Procedures used by IDOT Districts

Districts	Contract Procedures			
	Incentive/ Disincentive	Lane Rental	A+B	Others
1	✓			✓
2	✓	✓	✓	✓
3	✓	✓		
4	✓	✓	✓	✓
5	✓	✓		✓
6	✓	✓	✓	✓
7	✓	✓	✓	✓
8	✓	✓		✓
9	✓	✓		

Figure 3.1 IDOT Highway District Offices

In terms of other procedures, District 1 has used “reverse lane rental” where they set the allowable lane closure hours and assess liquidated damages if lanes are not open. District 2 has used completion date + disincentive, District 4 has used restricted working hours, District 6 has used procedures like tight completion dates, night time work, no lane closure during peak hours and weekends, and no work during public events, and District 8 has used peak hour restrictions and night work schedule. District 7 evaluates the monthly/daily/hourly traffic to determine the best time of year, week, or day to allow lane closures.

2. Has your District used incentive/disincentive provisions in construction work zone projects?

All the districts answered that they have used incentive/disincentive procedures in construction work zone projects.

3. Is the use of incentive/disincentive provisions effective in reducing delay to motorists by reducing the construction time?

All nine districts answered that the incentive/disincentive procedures were effective in reducing disruption to motorists. All districts mentioned that the Incentive/Disincentive procedures are effective because of the financial advantage the contractors achieve by finishing the projects earlier. District 4 and 7 said that contractors almost always complete the work early to obtain the maximum incentive. District 6 said that the contractors would work long days/night time to complete the work in time to receive incentives because they do not like to have a disincentive on their records for bonding reasons. District 9 said that contractors have used accelerated schedules, extended work hours, preformed multiple operations simultaneously, and used larger crews with more equipment to reduce construction time.

4. What incentive/disincentive dollar amounts does your District use in calculating road user costs?

District 1 did not answer this question. Districts 2, 3, 4, 5, 7, and 8 responded to this question, but did not give any numerical values. District 3 said that the value depends on the ADT and percentage of trucks. District 2 and 4 said that they followed the Bureau of Design and Environment (BDE) manual to calculate the Incentive/Disincentive amounts based on user costs. District 4 feels that the disincentive needs to be $5,000 per day to be effective. District 5 said that the value depends on user costs. District 6 said that they used a value of $7.44 per passenger vehicle and $16.22 per single or multiple unit truck to calculate the delay cost only. District 7 said that the Incentive/Disincentive dollar amounts depend on the type of work, traffic data and the length of construction operations. District 7 used $7900 per day on one project. District 8 said that the amount varies depending on project conditions. District 9 said they use $10 /hr/person with an average of 1.5 persons per vehicle. This has resulted in costs up to $11,500 per day

5. Should the incentive/disincentive dollar amounts be revised?

Districts 1, 2, 3, 4, 5, and 8 said that the Incentive/Disincentive amounts should not be revised. District 6 said that the disincentive amount should be at least twice the incentive amount because in many cases the emphasis is on finishing the project on time before some event such as a holiday or state fair. District 7 mentioned that the incentive/disincentive amount should be based on motorist delay costs. District 9 uses an amount of $10/hr/person. It said that this value was based on old studies conducted by Chicago Motor Club and is out of date. It further said that when the commercial traffic reached 45% of the AADT, the road user cost must be affected.

3.2 Lane Rental

6. Has your District used lane rental provisions in highway construction projects?

All the districts said that they have used lane rental specifications. District 1 mentioned that they are using ‘Reverse lane rental’. They set the hours 8 or 9 PM for a one-lane closure and 11 PM or Midnight for a two-lane closure with all lanes open by 5:00 AM. They charge $1,000 to $2,000 per 15 minutes for one lane blocked and $3,000 to $5,000 per 15 minutes for two lanes blocked as liquidated damages.

7. Is the use of lane rental provisions effective in reducing disruptions to motorists?

All nine districts said that the lane rental provisions are effective in reducing disruption to motorists. District 1 said that the contractors abide by the scheduled work hours because of the liquidated damages and public pressure from traffic reporters. District 2 said it is effective because it reduces the duration of lane closures. District 3 said it works because contractors schedule more work within the closures, allowing for lanes to be reopened without necessitating an additional closure at a future date for another work effort in the same lane. District 4 said it works because contractors elect to keep lane closure to minimal length and work off peak hours. District 5 said it works because the contractor does not leave unnecessary lane closures in place and expedites construction. District 6 said it works because lanes are not closed when no work is being completed. Without lane rental it is hard for the resident engineers to keep the contractor from keeping lanes closed. The only other tool is ‘Traffic Control Deficiency Payment.’ District 7 said it works because the contractor always works in such a manner as to utilize the fewest lane rental days due to the built in incentive. District 8 said it works because it reduces time frame of the lane closure. District 9 felt lane rental works for much the same reasons as incentive/disincentive contracts.

8. What lane rental dollar amounts does your District utilize?

District 1 did not answer this question. Districts 2, 3, 4, 6, and 8 did not give any values. District 2 said that the amount varies based on ADT and motorist time. District 3 said that it varies based on ADT and percentage of trucks. District 4's single lane rental project was over 5 years ago and the information is archived. District 6 mentioned that the amount varies depending on the traffic; delay and user costs are used to determine the amount. District 8 said it varies depending on project conditions. District 5 said it varies and gave a range between $5000 and $15000 per lane rental day and said the amount depends on the user costs. District 7 gave a range from $7000 to $9000 per lane rental day (a day is full 24-hour period). District 9 uses the same amount they used for Incentive/Disincentive, which is $10/person/vehicle with an average of 1.5 persons per vehicle.

9. Should the lane rental dollar amounts be revised?

Districts 1 and 4 did not respond to this question. Districts 2, 3, 5, and 8 answered "no" to this question. District 7 said ”no comment." District 6 said in some situations that it is specified no work during rush hours, if the contractor does not get the lanes open he/she should be charged a rush-hour lane rental fee that should be 10-20 times the normal amount. District 9 said "yes" and gave the same response they gave for the Incentive/Disincentive amount. They said that the dollar figure they use is based on data that is out-dated; and when the commercial traffic reaches 45% of the ADT the road user cost must be affected.

3.3 Capacity, Queue Length, and Road User Costs

10. List up to three software programs or analytical techniques that your District utilizes to estimate the following items in construction work zones with lane closures: Lane capacity, queue length, motorist delay, and road user costs

Districts 1,4,5, and 6 said that they do not use any software to estimate the above variables. District 2 uses HCS 2000 to estimate lane capacity. District 3 uses HCS 2000 and SIG Cinema to estimate lane capacity, queue length and motorist delay. District 7 uses HCS 2000, Quickzone to estimate lane capacity, queue length and motorist delay. District 7 also uses the information from the FHWA Life Cycle Cost Analysis course to estimate all four variables. District 8 uses the plot of cumulative arrival and departure counts of vehicles over time to estimate delay and queue. This is basically the same procedure that was in the Highway Capacity Manual (HCM) 1985 and HCM 1994. District 9 formerly used QUEWZ, but is not using it currently because it was not user friendly. They use spreadsheet and longhand calculations that are based on the procedure in 1994 HCM to find queue and delay. They use the FHWA and BDE methods to estimate road user costs.

11. How satisfied are you that the estimated values you get from the software programs or analytical techniques to represent actual field conditions?

District 2 uses HCS 2000 to estimate lane capacity, but had no opinion as to how satisfied they are with the software. District 3 said that they are somewhat satisfied with HCS 2000 and SIG Cinema to estimate lane capacity, queue length and motorist delay. District 7 said that they are very satisfied with HCS 2000 in estimating lane capacity, queue length and motorist delay, but somewhat unsatisfied with Quick Zone and FHWA Life Cycle Cost Analysis course technique. District 9 is somewhat satisfied with the long hand calculations to find the queue and delay. They said the hand calculation underestimated the queues as the percentage of trucks increased. Also the queues developed earlier in the day than the predicted time. They pointed out that the most important part of any of the calculations is the traffic data as input.

12. Do you have field data available on lane capacity, queue lengths, delay, or road user costs for construction work zones with lane closures?

District 2 did not give any answer for this question. Districts 1, 3, 4, 5, 7, and 8 said that they have no field data available on lane capacity, queue lengths, delay or road user costs. District 6 said that they have traffic data to determine such items, but field data is not collected during construction. District 9 provided data on speed and volume for a one-lane closure on US-65.

3.4 General Questions

13. List the current and programmed construction projects for the 2002 season on interstate highways/freeways with lane reductions, and/or lane rental, and or incentive-disincentive contracts (i.e. project location, length, contract number, approximate beginning and end date, etc)

Most of the districts listed 4 or 5 construction projects, District 6 listed 6, and Districts 8 and 9 each had one construction project.

14. Which existing work zone projects create traffic queues during peak traffic times?

District 1,5,6, and 9 said that all of the listed work zone projects would create traffic backups. District 2 and 8 said four of the work zones would create traffic backups. District 3 and 7 each identified one of the work zones with traffic backups. District 4 did not give any response for this question.

15. List locations of the existing permanent lane drops (no construction) on interstate highways or freeways resulting in traffic queues during peak traffic times

Districts 2, 3, 4, 5, and 7 said that they did not have such permanent lane drops. Districts 1 and 8 said they had one such permanent lane drops. District 9 listed an interchange of two interstate highways where 4 lanes merge into 2 lanes that has queues during holidays and construction, but normally has no queues.

16. List four specific construction/maintenance operations (i.e. bridge repair, patching, resurfacing, etc) that exhibit the longest queue backups.

The most frequent cited items and their frequencies are: Patching (6), resurfacing (5), bridge repair or replacement or rehabilitation (5), milling (3), culvert replacement using flaggers (1), cutting detector loops (1), crack sealing (1), and partial depth patching of centerline of pavement repair (1). District 3 mentioned that they have not experienced backups on projects with ADT less than 20,000.

17. What kind of construction work scheduling (i.e. off peak hour operations, night operations, incentive/disincentive, lane rental, A+B, freeway closure, etc) does your District use to reduce delay and road user costs?

District 1 uses off peak and night hours for all work that can be done in such times. All contracts that have lane closures during peak have incentive/disincentive special provisions. Night hours vary depending on traffic volumes and work time. They allow a minimum of 8 hours for one-lane closures. District 2 said all listed had been used. District 3 used off-peak, night operations, incentive/disincentive, and lane rental. District 4 uses all items listed above, but uses freeway closure on rare situations (work on truss of river crossing). District 5 uses off-peak, night operations, incentive/disincentive, lane rental, and crossovers with restrictions on the contractor hauling in the open lanes. District 6 uses all of the listed items. District 7 uses off-peak hours, night operations, incentive/disincentive, lane rental, A+B contracts, and off-season project scheduling. District 8 uses night operations, incentive/disincentive, and lane rental. District 9 uses incentive/disincentive, lane rental, alternate signed routes, special features of the traffic control plan, and changeable message signs with cell phone control.

18. Has your District used Intelligent Transportation Systems (ITS) or real time traffic control systems in construction work zones?

District 1 uses permanent changeable message signs to display lane closures and congestion information. District 2 has been using an ITS system in Rock Island County to change the display on the changeable message sign when traffic speed decreases. Districts 3, 7, 8, and 9 have not used ITS or real time traffic control in construction work zones. District 4 is using changeable message boards in the McClugage Bridge rehabilitation project to inform drivers about delay. District 5 has used an Automated Information Management System (AIMS) in one of their projects on I-70. They say that it worked well but not fool proof. District 6 said they used ITS to inform motorist of delays. It is expensive and did not help in getting traffic to avoid the construction zone.

19. Does your District have policies/procedures for determining the construction projects needing real time traffic control?

Districts 1, 2, 3, 4, 5, 7, and 9 responded “No” to this question. District 6 said that they have internal meetings to discuss traffic control requirements. District 9 said Traffic Management Committee, with members from various bureaus, discusses applicable traffic management techniques for specific jobs.

20. In your District in the past three years, have you had construction lane reductions that created queues beyond anticipated/signed lengths?

All the districts said that they had queues beyond anticipated/signed lengths due to construction lane reductions. Actions taken by the districts for traffic management are listed below. District 1 adds signs if queues are consistently beyond regular signing. District 2 uses changeable message boards outside the standard warning sign locations. District 3 adjusted contracts to open lanes before rush hour. District 3 posted an alternate route. District 4 used additional message boards and utilized more press releases. District 5 used additional changeable message boards placed 5 miles and 3 miles before taper, lowered work zone speed limit 2 miles prior to taper, used flashing “Be Prepared to Stop” sign trailers 2.5 miles a head of the work zone. District 6 placed additional warning signs. District 7 said no extra measures were taken because by luck the signing was far enough in advance to accommodate the longer queue length. District 8 used restricted construction during peak hours. District 9 placed additional signs and changeable messages as appropriate.

21. In your District in the past three years, have you had traffic accidents in construction zones that created queues beyond anticipated/signed lengths?

District 4 did not respond to this question. All other districts, except District 7, said that they had traffic backups due to traffic accidents in construction zones. District 1 included portable CMS in all contracts that include work on the expressways. These signs can be moved where needed and programmed by cell phone. District 2 established alternate routes that were permanently signed. Detours and alternate routes were coordinated with local agencies. District 3 said that State police took care of accidents since it was not a normal occurrence. District 5 said that AIMS message boards were used which can be controlled from a cell phone or from the RE's field office. District 6 placed additional warning signs immediately. District 8 placed additional message boards, reduced speed limit, and had more state police present in the work zones. District 9 relocated the temporary concrete barriers to ease traffic movement, and State Police directed traffic to alternate routs.

22. Do you have additional comments/suggestions?

Districts 2, 3, 4, 5, 6, and 9 did not give any comments or suggestions. District 1 said that since there is heavy traffic on the Chicago Area Expressways, most of the work is done during the night. But they found that even the night time lane closures caused extreme unavoidable congestion. They also mentioned that the contractors need at least a minimum of 8 hours for a one-lane closure and 5 hours for a two-lane closure. District 7 responded by saying that they would like to have a better method to evaluate projects for potential backups and a better method for determining incentive/disincentive fee for contracts. District 8 said that they are considering moveable barriers and incident management pullouts.

3.5 Summary

All districts use I/D and lane rental and some districts use other procedures to minimize delay to motorists. All districts mentioned that the incentive/Disincentive procedure is effective because it encourages the contractors to complete the project on time or earlier for financial gains (or to avoid penalty for being late) thus reducing the disruption to motorists. The nine districts used a wide range of I/D dollar amounts that is mainly based on the project conditions. There was no consensus on the dollar figures to calculate I/D amount and most districts said that the I/D dollar amount need not be revised. Lane rental procedure was also found to be effective in reducing the disruption to motorists. Lane rental dollar amount is also found to be varying based on project conditions. Only two districts said that the lane rental dollar amount needs to be revised. The list of I/D and lane rental dollar amounts can be obtained from Table 3.2.

To determine capacity, queue length and road user costs, four districts do not use any software programs or analytical techniques. Five districts use the HCM technique or software that is based on HCM technique. One district used QUEWZ and another one used Quick Zone but on a limited basis. Their degree of satisfaction with the HCM based software varied from somewhat satisfied to very satisfied. The districts were somewhat dissatisfied with Quick Zone.

Construction activities such as patching, resurfacing, bridge repair are found to cause the maximum disruption to motorists. Also most districts use off-peak and night operations to reduce delay and user costs to motorists.

Five districts used ITS technologies in work zones. Seven districts said that they do not have policies/procedures for determining the construction projects needing ITS. Two districts said they consider it as a part of traffic control requirement. All districts said they had queue beyond anticipated-signed length due to construction lane reduction. Most districts took various actions to warn motorists about the queuing.

Seven districts said they had accidents in construction zone that caused queues beyond anticipated/signed length.

Table 3.2 gives a matrix of responses for the survey from the 9 districts.

Table 3.2 IDOT Districts responses to the survey

	Question	District 1	District 2	District 3	District 4	District 5	District 6	District 7	District 8	District 9
1	Contract Procedures	1. I/D	1.I/D 2.Lane Rental 3.A+B	1. I/D2.Lane Rental	1.I/D 2.Lane Rental 3.A+B	1.I/D 2.Lane Rental	1.I/D 2.Lane Rental 3.A+B	1.I/D 2.Lane Rental 3.A+B	1.I/D 2.Lane Rental	1. I/D 2. Lane Rental
2	Has I/D been used?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
3	Are I/D effective?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
4	I/D dollar amount?	-----	-----	-------	------	--------	7.44 per veh, 16.20 per single or multiple unit truck	-----	-------	$10.00 /hr/person
5	Should I/D dollar amount revised?	No	No	No	No	No	Yes	Yes	No	Yes

Table 3.2: Continued

6	Has Lane rental been used?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
7	Is Lane rental effective?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
8	Lane rental dollar amount?	------	--------	------	-----	$5000-- $15000	-------	A range from $7000 to $9000 per lane rental day (a day is the full 24 hour period).	-------	-------
9	Should Lane rental dollar amount revised?	-------	No	No	-------	No	Yes	-----	No	Yes

Table 3.2: Continued

10	Lane Capacity software used?	None	MCTRAN HCS 2000	1.HCS 2000 2. SIG Cinema	None	None	None	1. HCS 2000 2. Quick Zone 3. FHWA-Life cycle Cost Analysis Course	Analytical technique	-------
	Queue length software used?	None	None	1.HCS 2000 2. SIG Cinema	None	None	None	1. HCS 2000 2. Quick Zone 3. FHWA-Life cycle Cost Analysis Course	Analytical technique	--------
	Motorist Delay software used?	None	None	1.HCS 2000 2. SIG Cinema	None	None	None	1. HCS 2000 2. Quick Zone 3. FHWA-Life cycle Cost Analysis Course	Analytical technique	--------

Table 3.2: Continued

	Road User costs software used?	None	None	-----	None	None	None	1. FHWA-Life Cycle Cost Analysis Course	-----	1. FHWA 2. BDE
11	Lane Capacity software satisfaction?	No opinion	No opinion	1.some what satisfied 2.some what satisfied	No opinion	-------	No opinion	1. Very Satisfied 2. Somewhat Unsatisfied 3.Somewhat Unsatisfied	-----	Somewhat Satisfied
	Queue length software satisfaction?	No opinion	No opinion	1.some what satisfied 2.some what satisfied	No opinion	-------	No opinion	1. Very Satisfied 2. Somewhat Unsatisfied 3.Somewhat Unsatisfied	-----	------
	Motorist Delay software satisfaction?	No opinion	No opinion	1.some what satisfied 2.some what satisfied	No opinion	-------	No opinion	1. Very Satisfied 2. Somewhat Unsatisfied 3.Somewhat Unsatisfied	-----	---------

Table 3.2: Continued

	Road User costs software satisfaction?	No opinion	No opinion	No opinion	No opinion	-------	No opinion	1.Somewhat Unsatisfied	-----	Somewhat Satisfied
12	Field Data availability?	No	-------	No	No	No	Yes	No	No	Yes
13	Current and Programmed construction projects?	4	6	5	4	3	3	3	1	1
14	Work zones that create traffic queues during peak queues?	4	4	1	-----	3	3	1	4	1
15	Permanent Lane drops?	1	None	None	None	None	-------	None	1	1

Table 3.2: Continued

16	Construction operation exhibiting longest queue backup?	1. Milling Resurfacing 2. Bridge deck pours 3. Stopping traffic to remove or erect bridge beams	1.Patching/ Resurfacing interstate highways 2. Staged bridge replacements 3. Culvert replacement using flaggers 4. Pavement widening	--------	1.Patching 2.Resurfacing 3. Cutting detector loops 4. Bridge repairs	1. Paving 2. Patching 3. Milling	1.Bridge repairs 2. Work requiring lane closure during rush hour traffic	1. Pavement Patching 2. Bitumen removal via large milling machine 3. Center line of pavement repairs- Partial depth patching 4. Bitumen resurfacing	1.Resurfacing 2. Patching 3.Crack sealing	1. Bitumen Resurfacing 2. Pavement patching.

Table 3.2: Continued

17	Kind of construction scheduling?	1. I/D 2. Night work hours	1. I/D 2.Lane rental 3.A+B 4.Completion date + disincentive	1. Off-peak 2. Night operation 3. I/D 4. Lane rentals	1.off peak hour operations 2. Night operations 3. I/D 4. Lane rental 5. A+B	1. Off peak 2. Night operations 3. I/D 4. Lane rental 5.Crossovers with restrictions on the contractor hauling in the open lane	1. Tight completion dates 2. Night time work 3. No lane closure during rush hour, public events and weekends.	1. Off peak hour scheduling (which includes night operations) 2. I/D of interim and final completion dates 3. Lane rental 4. A+B Contracts 5. Off season project scheduling	1. Night Operations 2. I/D 3.Lane Rental	1. I/D 2. Lane Rental 3. Alternate road signals 4. Special features of the traffic control plan 5. Changeable message signs with cell phone control
18	Use of ITS or Real time traffic control?	Yes	Yes	No	Yes	Yes	Yes	No	No	No

Table 3.2: Continued

19	Policies/ Procedures for Real time Traffic control	No	No	No	No	No	Yes	No	Yes	No
More than anticipated queues in the past three years due to--										
20	--construction lane reductions?	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
21	--traffic accidents in construction zones?	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes	Yes
22	Additional Comments?	Yes	No	-----	------	No	No	Yes	Yes	-----

CHAPTER 4 - SURVEY OF DOTs ABOUT WORK ZONE ISSUES

The University of Illinois at Urbana-Champaign in cooperation with the TRP for this project developed a questionnaire and sent it to all state DOTs, District of Columbia and Puerto Rico. A copy of the questionnaire is included In Appendix B. The purpose of the survey was to collect information about:

- The contract procedures used to award freeway work zone contracts
- The Incentive/Disincentive and lane rental procedures used
- The techniques and software used to estimate capacity, queue length and road user costs in freeway construction zones
- ITS technologies used
- Motorist signing

Thirty-eight DOTs responded for the survey. The percentage response rate is about 73%. The responses from 37 DOTs were used (one survey came too late) as presented in the following sections.

1. Would you like to get a summary of the results of this survey?

About 92% of the DOTs said that they would like to get a summary of the results of this survey, 5 % said that they do not need a summary of the survey and 3% did not respond to this question.

4.1 Contract Procedures

2. Does your agency utilize any of the following contract procedures to minimize disruption to motorists in construction work zones?

As shown in Figure 4.1a, almost all of the responding DOTs (95%) used I/D, 78% used A+B, 54% used lane rental and 35% used other procedures. The ‘other procedures’ are mostly special clauses like night and weekend procedure, A + B + life cycle costs, design build etc. As it can be seen from Figure 4.1b, about 16% of the DOTs used all four procedures, 46% used three, 22% used two and only 16% used one procedure for awarding the contracts.

3. If YES to question 2, how effective are the procedures in minimizing disruption to motorists?

The number of responses in each category is given in Table 4.1. As shown in Figure 4.2, the I/D procedure was considered to be very effective by 41% of the DOTs that used this procedure. Around 27 % of the DOTs that used the lane rental procedure said that it was very effective and 24 % of the DOTs responded that the A+B procedure was very effective. In the other procedures used, about 11 % said that those procedures were very effective. The average effectiveness rating for I/D, lane rental, A+B and other procedures are 2.3, 1.9, 2.1 and 1.8, respectively on a scale of 1 to 3.

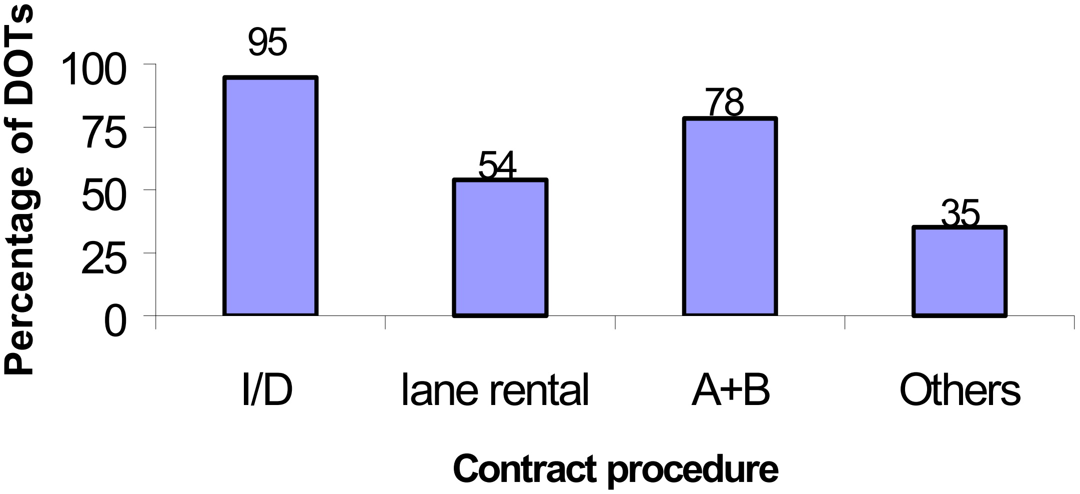

Figure 4.1a Percentage of DOTs using the Contract Procedures

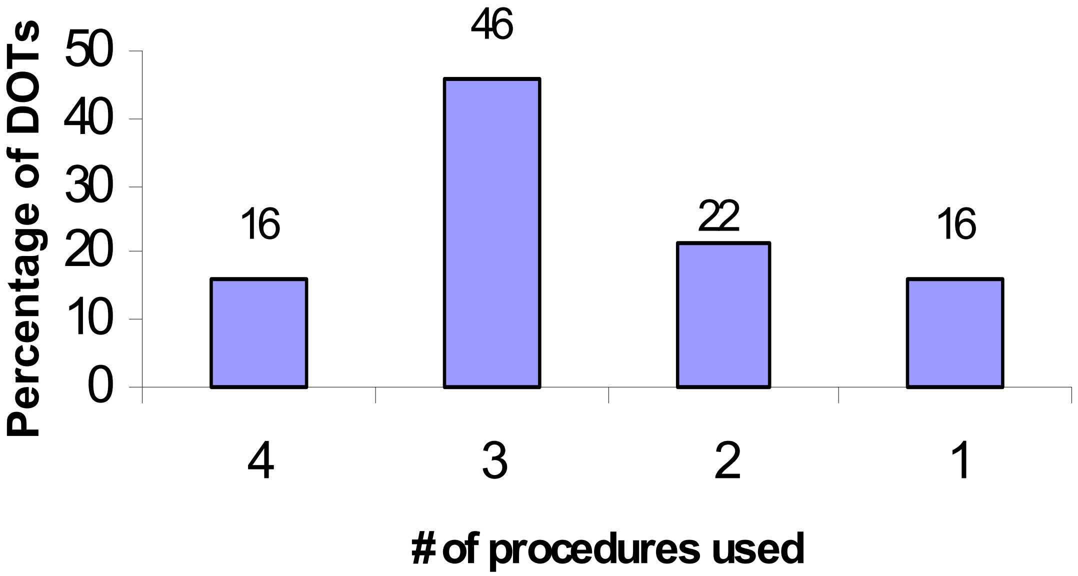

Figure 4.1b Percentage of DOTs using Multiple Procedures

Table 4.1 Responses for the Effectiveness of Contract Procedures

Contract Procedure	Effectiveness			
	Very Effective	Somewhat Effective	Not Effective	No Opinion
I/D	15	19	0	2
Lane Rental	10	11	0	6
A+B	9	19	1	3
Others	5	7	0	4

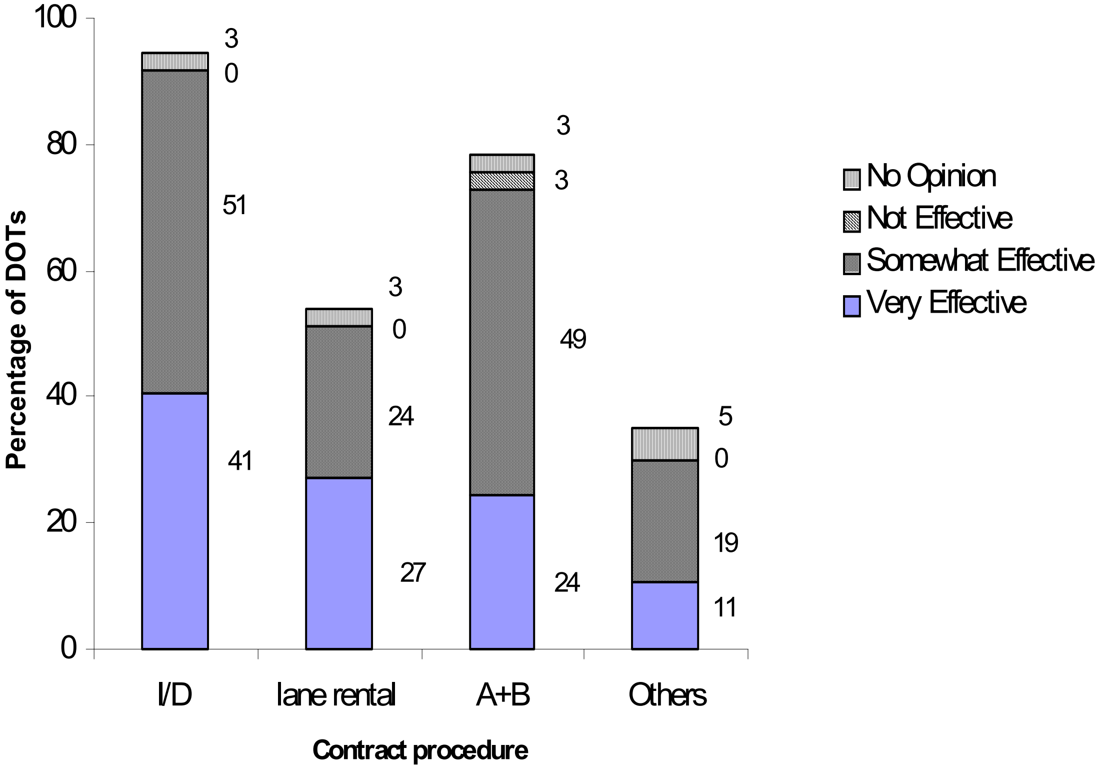

Figure 4.2 Effectiveness of Contract Procedures

4. What incentive/disincentive dollar amounts does your agency use in calculating road user costs?

Thirty-five DOTs responded to this question, but 71% of the DOTs did not give any single value and said that the road user cost varies for each project. The factors mentioned for this variation are ADT, time of day, anticipatory delay time, detour distance, energy costs and accident costs. Wisconsin and Washington DOTs said that they use QUEWZ to calculate the road user cost. Louisiana DOT estimated I/D amount based on the following values:

ADT	$value/day
<10 k	$1000
10-15K	$5000
15-25k	$10,000
>25k	$ 15,000

They also limit the maximum incentive to 5% of the engineer's estimate or 10% reduction in calendar days, whichever is less. Example: ADT>25k and engineers estimate is $10,000,000. 5% of $10,000,000 is 500,000. Contractor bids for 150 days. Contractor is eligible for 15 days incentive. The maximum incentive amount is 15*15,000 = 225,000.

5. What lane rental dollar amounts does your agency utilize?

Twenty-two DOTs responded to this question, and 56% of them said that the lane rental dollar amounts vary for each project depending on various factors. Wyoming DOT said that the lane rental dollar amount is calculated based on the "lane rental user delay cost table" developed by FHWA. Other DOTs gave values over a wide range based on different measures.

4.2 Capacity, Queue Length, Delay and Road User Costs

6. List up to three software programs or analytical techniques that your agency utilizes to estimate construction work zones:

Table 4.2 shows that the most commonly used software/analytical technique for estimating capacity is HCM, HCS and QUEWZ. For estimating queue length and delay, QUEWZ, Quick Zone and HCS are most commonly used. For estimating road user costs QUEWZ and Excel spread sheets are used.

Table 4.2 Software or Analytical Techniques Used by DOTs

	Software Used (# of states using each software)
Lane Capacity	HCM(6),HCS(5), Quewz(4), Quickzone(2), Hicap 2000(1) FRESIM(1), LOS plan(1), Excel spread sheets (1)
Queue Length	Quewz(5), Quickzone(5), HCS(4), Excel spread sheets(2), HCM(1), Hicap 2000(1), FRESIM(1), Passer(1), Synchro(1)
Delay	Quewz(5), Quickzone(4), HCS(4), Excel spread sheets(4), FRESIM(2), HCM(1), Hicap 2000(1), Passer(1),ITE manual traffic studies(1),
Road User Costs	Quewz(5), Excel spread sheets(5), Quickzone(1), FRESIM(1), PLANPAC(1), MicroBenCost(1), Quick Benefit Cost software(1), AASHTO red book 197(1), NCHRP 133(1), Offsite detour designs(1), Flagger program design(1),

7. How satisfied are you with the accuracy level of the software programs or analytical techniques (listed in the previous question) in representing the actual field conditions?

The satisfaction level of the most commonly used software for each factor is given in the Figures 4.3a-4.3d. The values are the average satisfaction level for that software (Very Satisfied =3, Somewhat Satisfied =2, Not Satisfied = 1, No Opinion =0). The users are not very satisfied with any of the software. For capacity calculation, QUEWZ was rated 2.3 (between very satisfied and somewhat satisfied) and HCM was rated 2 (somewhat satisfied). For queue length calculation; the respondent rated Quick Zone – 1.4, QUEWZ –1.8, HCM – 1.75 (below somewhat satisfied). The users gave a rating of 2.0 (somewhat satisfied) for QUEWZ delay calculation and 1.3 for Quick Zone and 1.75 for HCS. For road user cost calculation, the users gave a score of 2.8 (close to being very satisfied) for the spreadsheets and 1.8 for QUEWZ.

8. Does your agency use any of the following factors in calculating road user costs in construction work zones? (If "Yes", please give the dollar figure used)

About 60% of DOTs said that they use the vehicle operating costs in calculating the road user costs and 8% said they use crash costs in calculating road user costs. Motorist delay cost is used by 68% of DOTs. About 11% of DOTs said they also use other costs (like impact to businesses, safety, truck delay, and cost occupancy factor) to compute the road user costs.

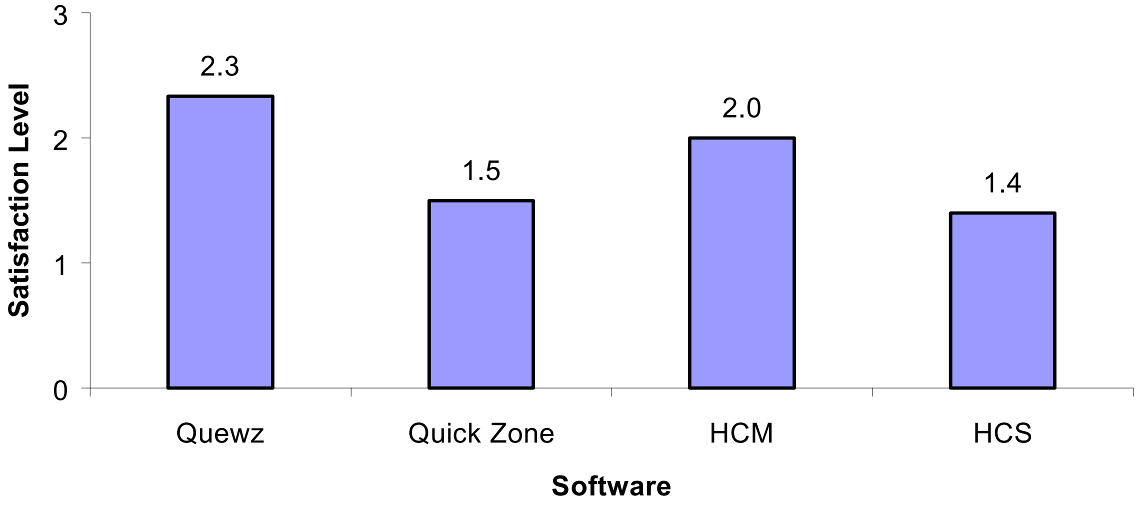

Figure 4.3a Satisfaction Level for Estimating Lane Capacity

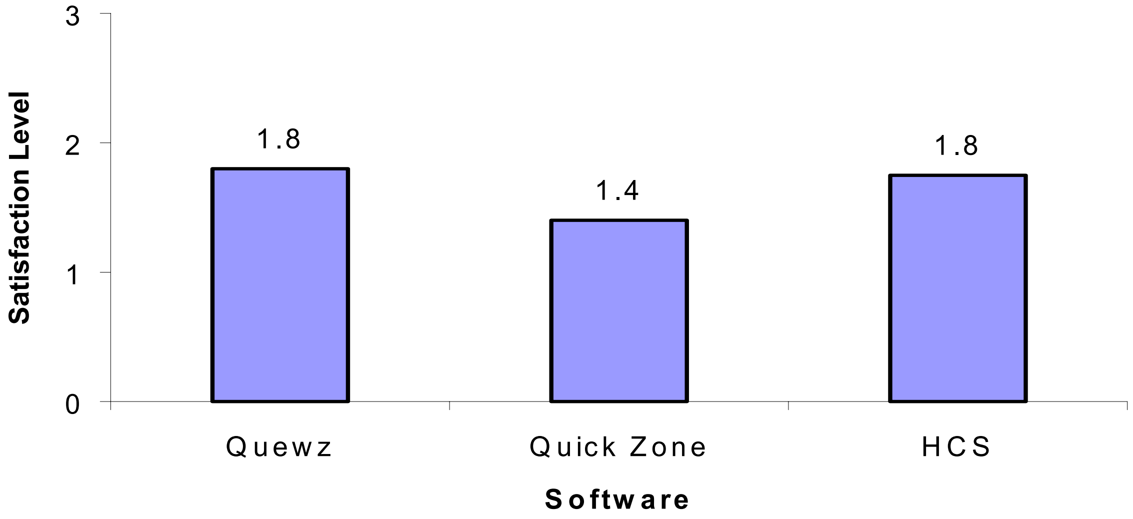

Figure 4.3b Satisfaction Level for Estimating Queue Length

Figure 4.3c Satisfaction Level for Estimating Delay

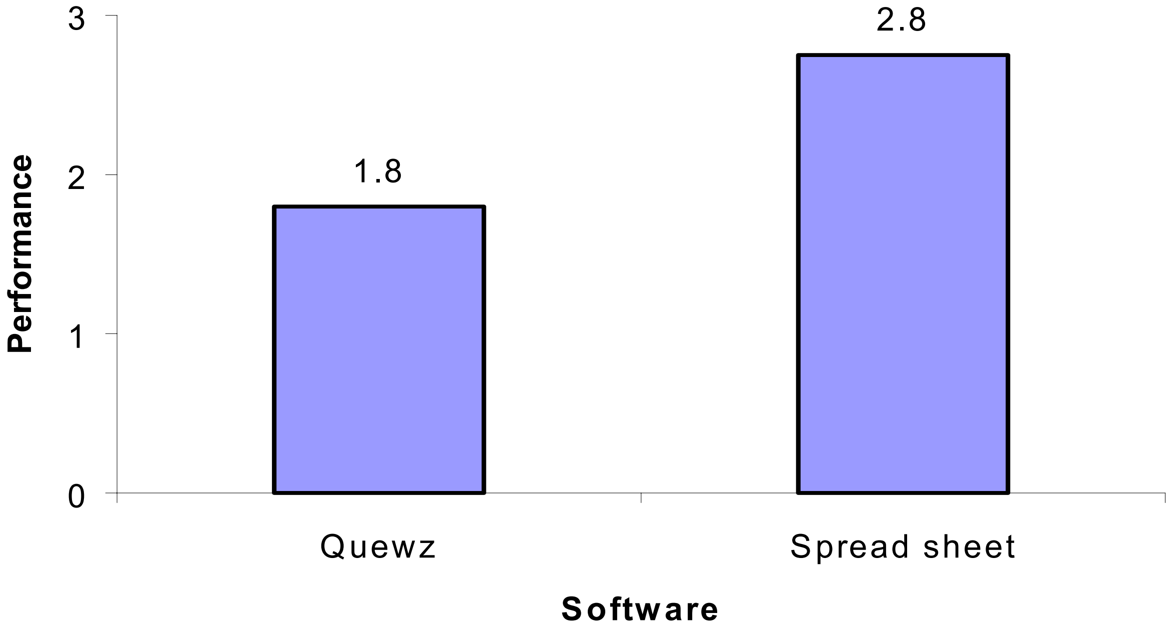

Figure 4.3d Satisfaction Level for Estimating Road User Costs

About 16% of DOTs responded by saying that the vehicle operating costs varies for each location. Arkansas DOT uses values given in AASHTO red book. Other DOTs gave a range of values based on different units such as cost per mile, cost per min, cost per vehicle (car/truck). The range of values is given below:

(i) Vehicle Operating Costs – \$0.13/mile - \$14.3/ mile for cars to trucks, \$0.30/min for trucks and \$0.15/min for autos

(ii) Motorist delay cost – \$8.8/hr - \$23.08/hr for cars to trucks, \$13.65/mile for cars and \$22.75/mi for trucks

(iii) Crash Costs - \$4000 per crash property damage

The list of different costs given by the various states is given in the Table 4.3.

Table 4.3 Road user costs used by DOTs

State	Vehicle Operating costs	Motorist delay costs	Crash Costs	Other costs
Alabama	0.13 /mile, we are currently updating these to the values in the FHWA interim technical bulletin	8.80/hr	-	-
Alaska	-	-	-	-
Arizona	-	-	-	Impact to businesses, Safety issues
Arkansas	Based on figures in AASHTO red book	Based on figures in AASHTO red book	-	-
California	For VOC we use two types: Idling cost for sitting in a queue and VOC for a forced detour.	Motorist delay: cars 49/hr, trucks \$24/hr	-	-
Colorado	-	-	-	-
Florida	Whatever is embedded in the software	Whatever is embedded in the software	Whatever is embedded in the software	Whatever is embedded in the software

Table 4.3: Continued

Georgia	-	-	-	-
Hawaii	-	-	-	To date only a few HDOT projects have utilized I/D or A+B. road user costs have been developed by consultants. Our in-house staff has not yet been tasked with this.
Idaho	-	0.19/0.46 per minute for cars/trucks, based on road user delay	-	-
Illinois	-	-	-	-
Iowa	-	-	-	0.36/mile
Kansas	-	-	-	-
Kentucky	-	13.75/hr	-	26.48/hr, Truck delay cost
Louisiana	Specific to each project based on publication cited above	Specific to each project based on publication cited above	-	-
Maine	-	-	-	-
Maryland	-	-	-	-
Minnesota	0.28, 1.43 per mile for auto, truck	9.92, 18.40 per hour for auto, truck	4000 per crash property damage	27,000 per crash c injury, 56,000 per crash B injury, 260,000 per crash A injury
Mississippi	-	-	-	-
Missouri	7.23, 22.7 per car, truck	Not applicable	-	-
Nebraska	0.13/min	0.02/min	-	0.16/min, cost/occupancy factor. User cost=ADT*delay(in minutes)*cost/occupancy factor

Table 4.3: Continued

Nevada	0.30/min -trucks, 0.15/min -autos	0.30/min -trucks 0.15/min –autos	-	-
New Hampshire	-	-	-	-
New Jersey	0.24, 0.48 per mile car, truck	13.65, 22.75 per mile-car, truck	-	-
New Mexico	Varies	Varies	-	-
North Carolina	-	-	-	-
Oklahoma	Varies	Varies	-	-
Pennsylvania	Varies	Varies	-	-
Puerto Rico	-	-	-	-
South Dakota	-	-	-	-
Tennessee	Unable to obtain values and units from program	Unable to obtain values and units from program	-	-
Texas	-	-	-	-
Vermont	-	-	-	-
Virginia	Varies by location	-	-	-
Washington	-	-	-	Only what is included in the Quewz software
Wisconsin	0.235, 0.619 /mi for cars, trucks	12.64, 23.08/hr for autos , trucks	-	-
Wyoming	-	-	-	$ amount varies depending on speed reduction I.e. more if we go from 75 to 35 then 75 to 55

9. Do you have field data available on traffic flow and/or queue lengths for construction work zones with lane closures?

To this question 62% of DOTs responded that they have no field data available on traffic flow in work zones, 11% indicated that they do not know whether any data is available, and the rest of the DOTs replied that they have some data on work zones. Arkansas DOT indicated that they have data for a 'Smart Work Zone' project.

10. Do you use any innovative methods to increase traffic capacity in construction work zones?

About 49% of DOTs do not use any method to increase traffic capacity, 27% use some kind of innovative method to increase traffic capacity. The rest of the DOTs did not respond for this question. Arkansas DOT gave the following six strategies the use:

"To improve capacity in CWZ we develop Transportation Management Plans (TMPs). TMPs are project specific and use 6 strategies: 1) Public information 2) Motorist information 3) Incident Management 4) Construction strategies 5) Demand management and 6) Alternate routes. Examples are: AWIS Automated Workzone Information Systems, GAWK Screens on K-Rail, Freeway service patrols for quick clearance of incidents and split traffic @ high demand periods."

About 8% of DOTs mentioned the use of moveable barriers to increase capacity. Also the use of temporary pavement is also mentioned by some DOTs.

4.3 ITS Technologies and Motorist Signing

11. Have you used any ITS technologies (or real-time technologies) for traffic control in construction work zones?

About 43% of DOTs responded that they do not use ITS in work zones, but 57% said that they do use ITS is work zones. Varieties of ITS technologies are being used by the DOTs. The different ITS technologies are given below (Number in brackets indicate the number of DOTs using the technology

- Variable Message Signs (8)
- Portable Variable Message signs (5)
- Travel time prediction system - video cameras (3)
- ATMS (2)
- ADAPTIR (2)

Other technologies include INTELLIZONE, IRD (work zone messenger system), smart work zone, information to motorists through website and advisory radio, advanced detectors (to detect traffic flow conditions) and management system.

12. If "Yes" to the previous question, please list the technologies used and indicate how effective they were in traffic control.

The effectiveness of the most commonly used ITS technologies as given by the DOTs are shown figure 4.4.

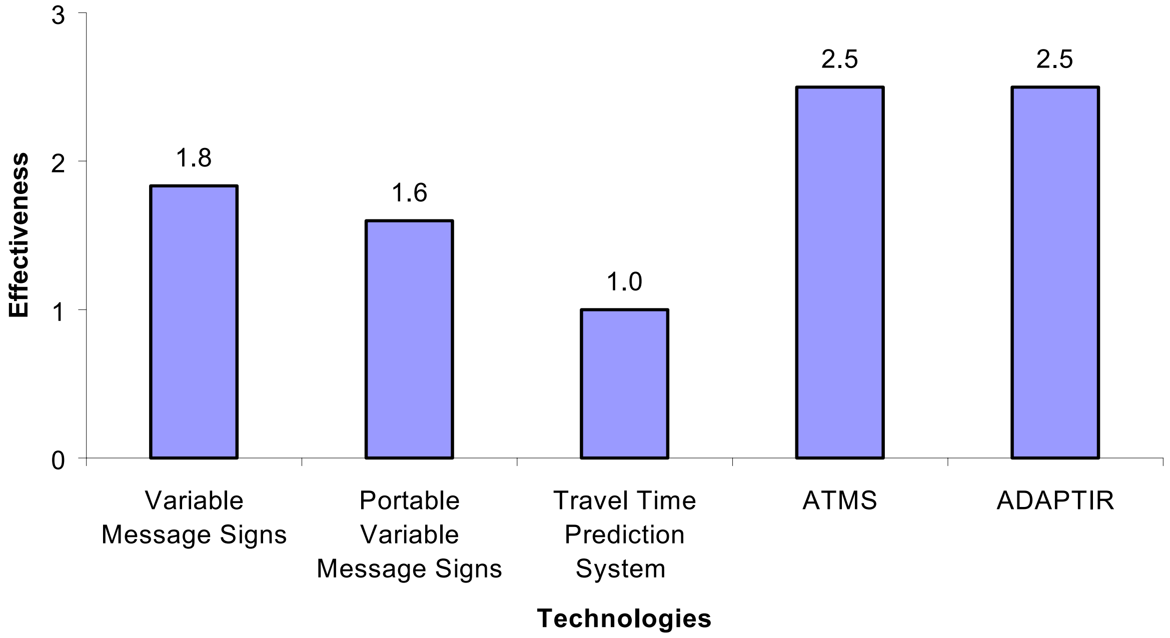

Figure 4.4 Effectiveness of Technologies in Work Zones

13. Are there any benefit-cost analysis done for these technologies?

None of the DOTs said that there was any benefit-cost analysis done for these technologies. Minnesota DOT indicated that

"Another problem with evaluating these systems is the difficulty in determining if they are cost effective. The cost of the systems were $500 per day but the overall cost of these real-time warning systems were under 2% of the overall cost of the project."

14. Have you used any other innovative methods for traffic control in construction work zones?

About 41% of DOTs responded that they do not use any other methods for traffic control, 27% indicated that they use other innovative methods to control traffic in work zones, and the rest of the DOTs did not respond to this question. Some of the methods are given below

- All lane closures are right lane closure (Arkansas)
- Extra law enforcement and 24 hr traffic control & incident response (Iowa)
- Information website, phone help desk and advertisements

15. Do you use any motorist signing other than those in the MUTCD?

About 32% of DOTs responded that they do not use motorist signing other than that given by the MUTCD. The remaining DOTs have used signs other than that given in the MUTCD. Some of the commonly used signs are given below:

- Double fine signs for speeding
- Signs indicating road closure periods
- Identical signs on each side of lane
- Message signs with non MUTCD messages
- Direction signs to adjacent businesses and properties

16. Do you know what are the contributing factors to the lack of credibility of the motorist signs?

About 70% of DOTs mentioned that they know what factors contribute to the lack of credibility of the motorist signs. The rest of the DOTs did not respond to this question. Some of the very common factors identified by the DOTs are given below:

- Failure to remove signs when work activity is done
- Incorrect information
- Lack of enforcement
- Over use of signs

New Jersey DOT indicated that a study has been in initiated in this regard.

17. Do you have suggestions for improving the effectiveness of motorist signs?

Fifteen DOTs gave suggestions for improving the effectiveness of motorist signs. The suggestions are summarized below:

- Correct information
- Timely placement and removal of signs
- Proper enforcement
- Large signs with better reflectivity

18. Do you have additional comments/suggestions?

The comments given by some of the DOTs are shown below:

> “FHWA ' Work Zone Operations Best Practices Guidebook' has many good ideas on improving mobility in the work zone.”

"The University of Kentucky Transportation Center developed the Excel spreadsheet that we use based on the FHWA report . FHWA-SA-98-079 "Life Cycle cost Analysis in Pavement Design". We have used this extensively to develop costs for Incentives/Disincentives and lane rentals."

"Louisiana DOT formed a work zone task force consisting of numerous agencies and completed phase I, task force recommendations currently in Phase II, 5 year program, to implement 50 task force recommendations"

"Missouri's 'Work Zone Guidelines' may be found on MoDOT's website - webmaster@mail.modot.state.mo.us"

"We sometimes require that certain work be done at night that would otherwise create unacceptable motorist delay."

"Our detail manuals on road user costs and construction scheduling are available at the following user site: www.state.nj.us/transportation/cpm/baselinedocuments go to "Others (T)" and search for BDC01T-7 and BDC01T-5, respectively"

"FHWA has established software which may help you, The name of the software is Quick Zone."

4.4 Summary and Conclusions

The responses from 37 state DOTs are used in this chapter. Almost all of the responding DOTs (95%) used Incentive/disincentive (I/D), 78% used cost – plus – time (A+B), 54% used lane rental and 35% used other procedures. The 'other procedures' are mostly special clauses like night and weekend procedure, A + B + life cycle costs, design build etc. The I/D procedure was rate as "very effective" by 43%, the lane rental by 50 %, the A+B by 31 %, and the other procedures by 38 % of the DOTs that used them. About 71% of the DOTs did not give any single value to calculate I/D dollar amount and said that the road user cost varies for each project. The factors mentioned for this variation are ADT, time of day, anticipatory delay time, detour distance, energy costs and accident costs. For lane rental dollar amounts, 56% of the DOTs said that the lane rental dollar amounts vary for each project depending on various factors.

The most commonly used software/analytical technique for estimating capacity is HCM, HCS and Quewz. For estimating queue length and delay, Quewz, Quick Zone and HCS are most commonly used. For estimating road user costs Quewz and Excel spread sheets are used. For capacity calculation, Quewz was rated 2.3 (on a scale of very satisfied=3, somewhat satisfied=2, and not satisfied=1) and HCM was rated 2. For queue length calculation, the respondent rated Quick Zone as 1.4, Quewz as 1.8, HCM as 1.75. The users gave a rating of 2.0 for Quewz delay calculation and 1.3 for Quick Zone and 1.75 for HCS. For road user cost calculation, the users gave a score of 2.8 for the spreadsheets and 1.8 for Quewz.

About 60% of DOTs said that they use the vehicle operating costs in calculating the road user costs and 8% said they use crash costs in calculating road user costs. Motorist delay cost is used by 68% of DOTs. About 11% of DOTs said they also use other costs (like impact to businesses, safety, truck delay, and cost occupancy factor) to compute the road user costs.

About 43% of DOTs responded that they do not use ITS in work zones, but 57% said that they do use ITS is work zones. Varieties of ITS technologies are being used by the DOTs. About 32% of DOTs responded that they do not use motorist signing other than that given by the MUTCD. The remaining DOTs have used signs other than that given in the MUTCD. About 70% of DOTs mentioned that they know what factors contribute to the lack of credibility of the motorist signs. Some of the very common factors identified by the DOTs are given below:

- Failure to remove signs when work activity is done
- Incorrect information
- Lack of enforcement
- Over use of signs

In conclusion, the I/D procedure was used more than lane rental and A + B, however lane rental was rated “very effective” by nearly half the DOTs compared to 43% for I/D procedure. The dollar amount for I/D and the lane rental were based on road user costs that varied by the project conditions. A majority of DOTs take into account the motorist delay and vehicle operating costs in calculating the road user costs. There were no fixed values for these costs and they widely varied among DOTs.

Quewz, Quickzone and HCM software were used more than other techniques for calculating capacity, queue and delay in work zones. Quewz was rated better than other techniques. For calculating road user costs, Quewz and spreadsheets were used more than other techniques and the spreadsheets were better rated than Quewz.

Less than half of the DOTs used ITS technologies in work zone and changeable message signs were used by most. Other technologies like ADATIR and ATMS were used by very few DOTs. There was not benefit cost analysis done for these technologies and this may be one reason for the low utilization of these technologies. Most DOTs pointed out that the main reason for the lack of credibility of work zone signs was the failure to remove the signs after work had stopped. Another reason for the lack of credibility was giving incorrect information. Most DOTs used motorist signing other than the ones given in the MUTCD

CHAPTER 5 - FIELD DATA COLLECTION AND REDUCTION

5.1 Data Collection Sites

After consulting with the TRP for this project and based on information from IDOT District offices on work zone activities, the research team selected 14 sites in Illinois for data collection. The location of the sites, date, and time of data collection are given in Table 5.1. All sites were located on interstate highways with two lanes per direction, except in two sites as shown in Table 5.1. At all sites except the two, in the direction of data collection, one of the lanes was closed due to construction and the other lane was open. Five of the data sites were short-term work zone sites and the remaining were long-term work zone sites. A short term work zone is defined as a construction or maintenance work site that lasted less than a few days and the closed lane was delineated using cones, barrels and barricades (but not barriers) at the work activity area. A long term work zone is defined as a construction or maintenance work site that lasted more than a few days and the closed lane delineated using concrete barriers at the work activity area. Five sites had queues (I-74 EB MP5, I-290/IL53 EB MP4, I-74 EB MP5, I55 SB MP56&55, I55 NB MP55&56, I-270 EB MP9). The location of the 14 data collection sites is given in Fig 5.1.

5.2 Field Data Collected

The data collected for this project may broadly be classified into four categories; general, geometric, traffic, and construction. The list of various data elements collected in the field are given below: General data

1) Location of work zone
2) Type of traffic – Inbound or Outbound
3) Weather conditions
4) Police presence
5) Flagger presence

Geometry data

1) Lane width
2) Total number of lanes in each direction
3) Number of open lanes
4) Presence of ramps
5) Length of lane closure
6) Position of closed lane
7) Length of work activity

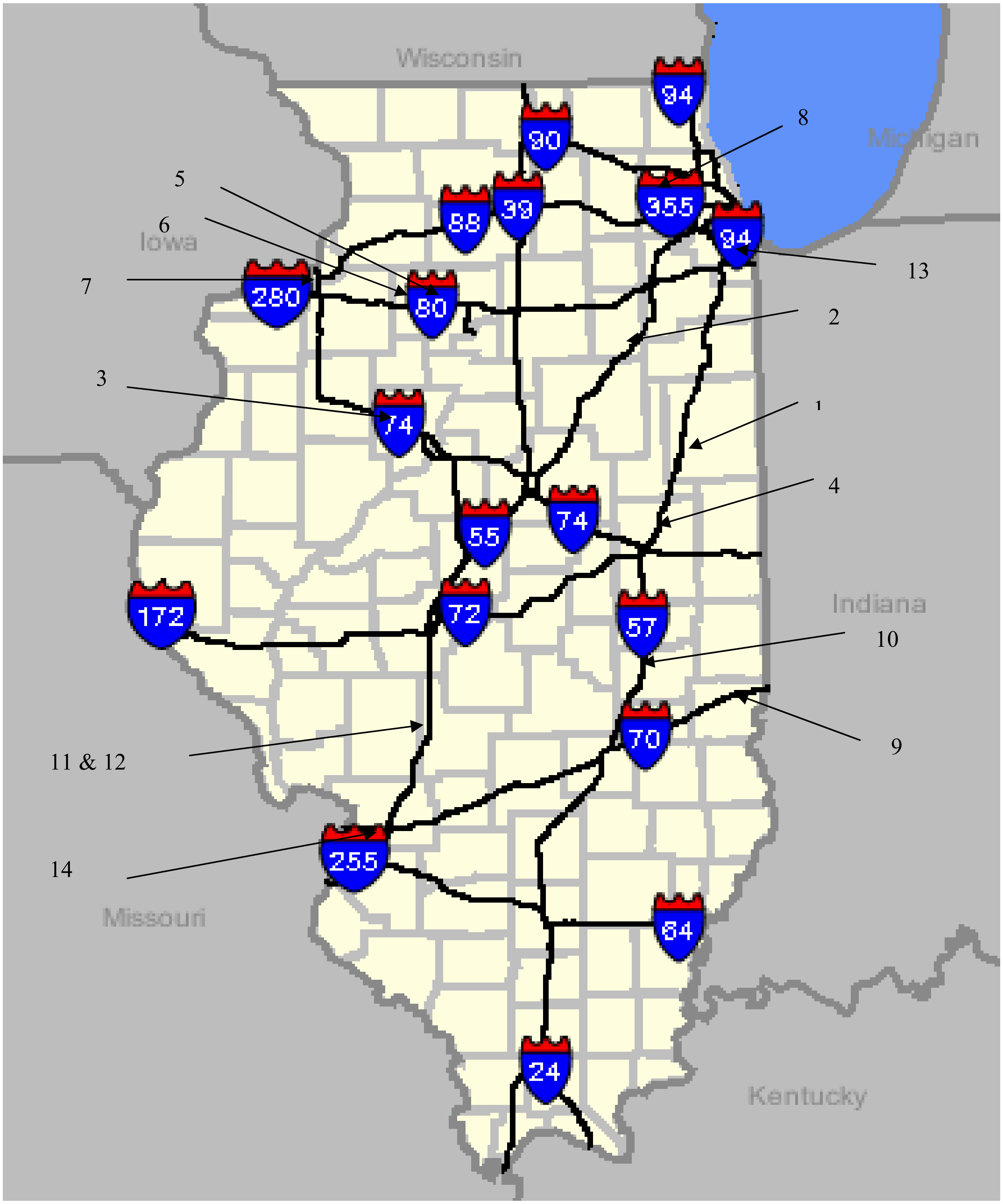

Figure 5.1 Data Collection Sites

Table 5.1 Data Collection Sites

No.	HWY	Mile Post	Direction	ADT	Total no of Lanes	No of Open Lanes	Position of closed lane	Short or Long term	Date	Time of data collection
1	I-57	271	NB	13,100	2	1	Left	Short	July 18, 2002	9:40 a.m. – 2:00 p.m.
2	I-55	224 ½	NB	24,000	2	1	Left	Short	July 23, 2002	10:30 a.m. – 2:40 p.m.
3	I-74	79	WB	16,900	2	1	Right	Long	July 23, 2002	4:00 p.m. – 6:00 p.m.
4	I-57	250	NB	18,500	2	1	Right	short	July 24, 2002	9:00 a.m. – 11:00 a.m.
5	I-80	44 & 43	EB	14,700	2	1	Right	Long	July 25, 2002	9:40 a.m. – 11:50 a.m.
6	I-80	39 & 40	WB	14,700	2	1	Right	Long	July 25, 2002	12:00 p.m. – 2:10 p.m.
7	I-74	5	EB	43,200	2	1	Left	Long	July 25, 2002	3:50 p.m. – 5:50 p.m.
8	I-290/ IL-53	4	EB	191,000	4	3	Left	Long	July 26, 2002	1:30 p.m. – 3:40 p.m.
9	I-70	145 & 146	EB	21,800	2	1	Left	Long	August 1, 2002	9:40 a.m. – 11:40 a.m.
10	I-57	212	SB	18,300	2	1	Right	Long	August 1, 2002	3:00 p.m.- 5:00 p.m.
11	I-55	56 & 55	SB	25,100	2	1	Right	Long	August 2, 2002	10:30 a.m. – 2:30 p.m.
12	I-55	55 & 56	NB	25,100	2	1	Left	Long	August 2, 2002	4:40 p.m. – 8:10 p.m.
13	I-57	355	SB	105,000	3	2	Left	Short	August 22, 2002	2:20 p.m. – 6:20 p.m.
14	I-270	9	EB	48,900	2	1	Right	Short	September 26, 2002	12:25 p.m. – 2:25 p.m.

Work activity data

1) Type of work activity
2) Number of workers present
3) Number and size of construction equipment
4) Proximity of work activity to the travel lanes in use
5) Traffic control devices used

Traffic data

1) Headways
2) Speed of the vehicles in work zone
3) Volume of traffic
4) Queue length

5.3 Data Collection Methodology

Data regarding the general conditions, geometry and work activity were recorded on paper by an observer. Any changes in conditions during the course of the data collection period were also written down. In the case of traffic data, a video camera was used to capture the time at which vehicle passed two specific markers placed at a fixed distance. The general arrangement of the data collection is shown in Figure 5.2 The distance between the markers was around 250 ft but varied for different sites. In three of the sites (I-290/IL53 EB MP4, I57 SB MP355, I-270 EB MP9), where traffic was heavy and the markers could not be established, two observers collected the speed data over a longer distance. An observer noted the presence of any queue and the length of the queue for every one minute. Data was collected from 2 hrs to 4 hrs depending on the traffic conditions.

5.4 Data Reduction

The traffic data captured using the video cameras were reduced in the lab and various data elements were obtained. Initially, the videotapes were time coded. Time coding of the videotapes allowed us to read the travel time more accurately (1/30 seconds). The time-coded videotapes were then played in industrial type VCR and the following data elements for each vehicle were entered into spreadsheets:

1) Vehicle type (1-cars, 2-large pickup trucks, 3-semi trucks)
2) Time at markers 1 and 2
3) Whether the vehicle is close enough to its predecessor that can be considered as in a group (0 meant not in-group, 1 meant in group)

Determination whether a vehicle was in a group or not was based on visual examination of the distance between the two vehicles. We did not use the headways at this point to make that determination.

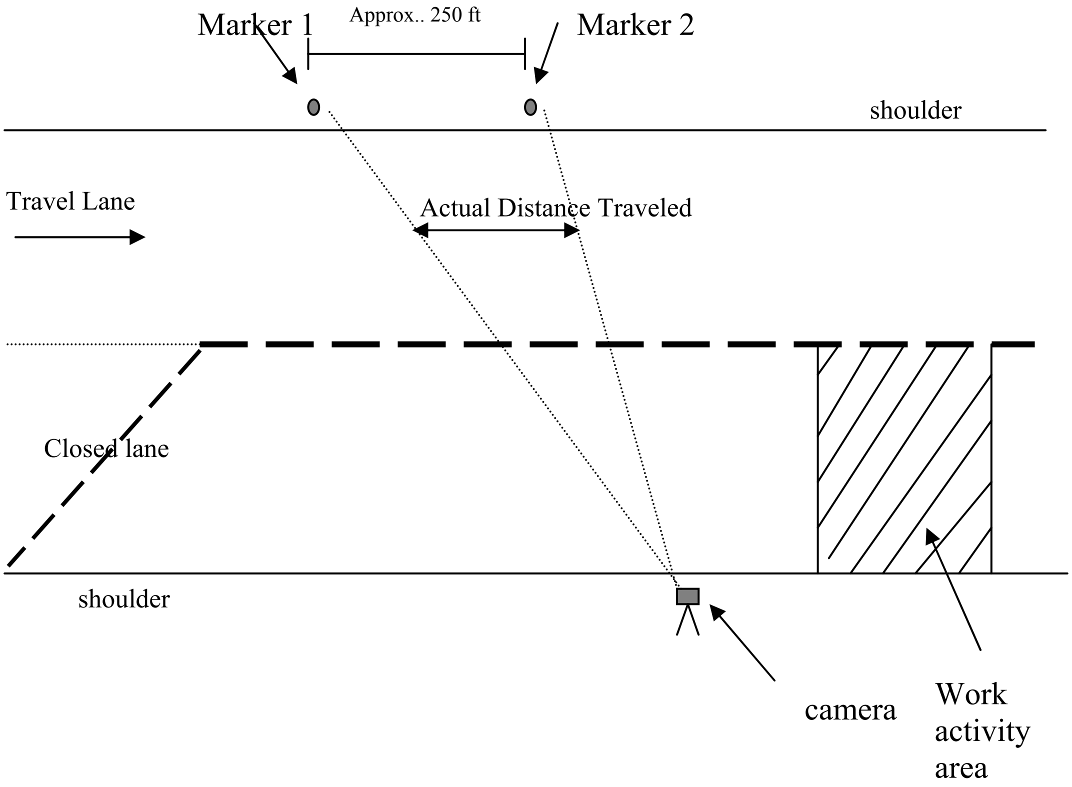

Figure 5.2 Setup for Data Collection

5.4.1 Headways

The headway for each vehicle was computed based on the times measured at marker 2 (the marker close to camera location). We measured the time when the front bumper of a vehicle passed over the line of sight between the camera and Marker 2. The time headway for a following vehicle is the time difference between the passing of the front bumper of leading and following vehicles over the line of sight. The accuracy of the headway measurements is 1/30 seconds.

5.4.2 Speed

The speed of a vehicle was computed based on the travel time between the two markers and the distance between the markers after applying the necessary corrections for the line of sight. The computed speeds are accurate to 1 mph. We tried to keep the Markers as lined up as possible to reduce any error due to unequal lateral distance.

5.5 Why Manual Data Collection Method

The data collection and reduction approach used was very time consuming, but the decision was made that it was worth the time and effort. The use of automatic devices would have given data based on different class of vehicles or range of speed values but we decided not to do that because we wanted to get more detailed information about each vehicle, its headway, and speed. The automatic data collection devices would not give you such data. They give you aggregated data that is not as detailed as this one we obtained. The queue length was manually observed and noted down for each minute of data collection.

CHAPTER 6 - LITERATURE REVIEW ON CAPACITY IN WORK ZONES

This chapter reviews the literature available in the area of work zone capacity definition, measurement and estimation. The queue and delay models are discussed in chapter 7.

6.1 Definition of Capacity

The definition of capacity in work zones has different forms. There is still not a clear definition of capacity in work zones. There are two ways of approaching freeway capacity, as a mean flow or expected maximum flow. According to Persaud et al (1991), defining the capacity as the mean queue discharge is the most suitable way because expected maximum flow is useless in the prediction of congestion. In work zone conditions, the concept of maximum flow is not suitable because when congestion occurs the flow will be no longer the maximum flow but will be governed by the queue discharge rate. Also when there is a formation of upstream queue there will also be a drop in flow in the bottleneck. A number of studies have given different notions of capacity in work zones.

Definition of capacity at lane closures:

1. Full hour volumes counted at lane closures with upstream queue
2. Expressed as hourly traffic volume from the maximum five-minute flow rate
3. Measured as two three-minute volumes with a one-minute interval under congested conditions. The average of the two volumes is then multiplied by 20 to give one-hour capacity
4. Traffic volume immediately before the queue begins.

Jiang (1999) measured lane closure capacity as the flow before a sharp speed drop followed by low speeds and fluctuating traffic flows and he indicated that, Texas Transportation Institute (TTI) measures queue discharge rate instead of lane closure capacity.

6.2 Measurement of Capacity and the Effect of Other Factors

According to the work done by TTI, it is assumed that the maximum flow is attained at the end of the taper when there is a queue upstream of the work zone. From the studies of Dixon et al (1996), it can be concluded that once a queue is formed the maximum flow happens upstream of the work zone governed by the merging activity. This study examined the speed-flow relationship, the evaluation of a work zone on the basis of lane configuration and site location, and the identification of the part of a work zone where the capacity is lowest. The study included both rural and urban sites. The work zone capacity used in the Highway Capacity Manual is based on studies conducted in Texas. These values may not be applicable to work zones in other states due to the large number of frontage roads in Texas.

The Dixon study was conducted in North Carolina and the lane closure configurations studied were

- Unidirectional two-lane reduced to single lane
- Unidirectional three-lane reduced to single lane
- Unidirectional three-lane reduced to 2 lanes
- Divided freeway (2 lane each direction) to two-way two lane operation by use of crossovers

Other factors like time of construction (day or night) and the intensity of work activity (heavy, moderate or light), closeness of work to traffic lanes, closeness of interchanges to the work zones. All the lane closures studied were temporary lane closures.

A total of 24 work zone sites throughout North Carolina were studied for this purpose. The sites varied in lane closure configurations and physical conditions such as (type of activity and use of message signs etc). The data about physical conditions were collected employing a checklist and also by filming the location. The information that was required for capacity analysis was number of vehicles, distribution of vehicles across lanes, percentage of heavy vehicles and average speed of vehicles. The data was collected using Nu-Metrics counters and classifiers. Classifiers were placed at advanced warning area, end of the transition and the activity area. Counters were used at the beginning of the transition area. The data was collected in 5-min time intervals. The 95-th percentile value of 5-min within-a-queue observations is taken as the end of transition capacity. The capacities at the end of transition area and the activity area were compared for different scenarios like rural-urban, day-night, proximity to active work. The capacities at the transition end were compared with the capacities at the work activity area. The capacity at the work activity area showed more variability than the capacity at the end of transition area because of the dynamic work activity. Also the activity area capacity values were smaller than the transition area capacity values. This difference was more significant in rural areas.

Maze et al (2000) mentioned that when a queue is formed the maximum flow in the entire work zone is controlled by the rate at which the vehicles discharge from the queue and this flow will be of lower value because of the capacity drop. For this study, a site in Iowa on the Interstate 80 between U.S. 61 and Interstate 74 was chosen. The date was collected using two cameras mounted on two trailers with 30-foot booms. The two trailers were stationed in the site for 19 days. During this period congestion was observed for 4 days. A plot of the data showed that under queuing conditions, the volume remained constant before and after queuing while the average speed dropped. Also, there was no capacity drop observed in this case. The maximum capacity of the lane closure was calculated by taking the average of the 10 maximum traffic volumes before and after queuing conditions. It was found that the capacities for the rural highway work zones in Iowa ranged from 1400 Passenger Car Units (PCUs) to 1600 PCUs. The data also showed considerable similarity in traffic volumes for same day of the week and time of the day.

Yi Jiang's (1999) study reports that during congestion, traffic flows at a much lower rate than the work zone capacity. In order to assess the traffic delays, characteristics of traffic flows and speeds are essential. This study analyzes the traffic flow characteristics on Indiana's four lane highways. Data were collected from work zones on interstate highways during the period between October 1995 and April 1997. Data like vehicle speed, traffic volume and classification were collected at 5-min intervals during peak traffic and1-hour intervals during low traffic. Traffic volume was collected at three places:

- before the transition area –> free flow traffic
- within the transition area -> merging traffic
- within in the activity area -> work zone traffic

Data was collected for 4 days from 8 work zones. In this study, the work zone capacity was defined as " the traffic flow rate just before a sharp speed drop followed by a sustained period of low vehicle speed and fluctuating traffic flow rate". This is because, in Indiana, traffic flows in work zones changed from congested to uncongested with a sharp speed drop. The capacity values were found by plotting a graph between time, and volume for each day. The volume at the time where the speed drops sharply is taken as the capacity. The values of capacity in two cases were compared.

i) Case where the congestion occurred within the transition area

ii) Case where the congestion occurred within the activity area.

The comparison was made using the analysis of variance. The tests showed that the mean capacity values of the four work zones were statistically equal. The analysis of variance tests were also performed for capacity values categorized by intensity of work zones. Three categories of work zones were classified based on work zone intensity; medium intensity, work not adjacent to traffic, high intensity. The tests showed that the mean capacity values were statistically equal for the three categories.

In a 1970 study conducted by Kermode et al, the capacity at work zone lane closures was determined by taking a number of three-minute counts under congested conditions. The authors gave a curve for determining the delay, based on relationships between volume and speed. The delay is related to the average speed in the back up. There was some effect on delay due to the presence of on ramps and off ramps. On ramps in the back up increased the delay and off ramps in the back up decreased the delay due to the diversion of some traffic. To find delay using this curve, one has to measure the volume per lane in back up and the length of the back up. The volume per lane back up is found by taking two 3-minute volume readings (with one-minute interval) at the site during congestion. The volume per hour is then obtained by multiplying the average of these two values by twenty, which is further divided by the number of lanes to obtain the volume per lane. Once the volume per lane in back up and the length of back up is obtained, the delay can be calculated using the curve. The delay value obtained from the curve is thus an average of all lanes and an approximate value only.

Rouphail et al (1985) studied the basic flow characteristics at freeway lane closures. Field studies were conducted in Illinois and the speed-flow relationship in the open lane of traffic was examined. The effect of work zone activity descriptors such as, location of work zone relative to traffic flow lanes, crew size and equipment was quantified using a normalizing procedure. To study the geometric impact the field study samples were confined to four-lane interstate type facilities with a single lane closure and no crossovers. This sample was chosen due to the following reasons

- The effect of lane geometry is likely to be combined with the impact of work site activity
- Four-lane roadways are most prevalent in rural freeways

Four sites were used for this study. The study sites were located within 60 miles of the Chicago area. Data elements collected were

- Traffic speed and composition upstream of the work zone
- 5-minute counts of speeds at the start and end of the lane closure
- work area activity descriptors

Numerical codes were used for the work activity descriptors. The work activity descriptors considered were

- Proximity of work activity to travel lane (PL). Numerical code used 0-4
  - 0- no work activity (e.g. lunch break)
  - 4- work activity carried out at the lane edges

Code increases by one unit for each 3-ft shift in construction activity closer to the travel lane.

- Crew size (CS)
- Equipment code (EC). Numerical code 0-3
  - 0- no operating equipment
  - 3- heavy equipment usage
- Flagman code (FC).
  - 0- presence of flagman
  - 1- absence of flagman
- Noise level code (NL). Numerical code 0-3 based on relative noise level
- Dust level code (DL). Numerical code 0-3 based on relative dust level

The sum of the numerical codes is termed as the activity index (AI) of the work zone. The work activity data were collected manually in five-minute intervals corresponding to the speed flow observations.

Except in site 3, the upstream speed distribution followed normal distribution. In site 3 the upstream traffic was operating in stop-and-go conditions and this made it impossible to measure the approach speeds because free-flow conditions did not occur. Speed data from the starting and ending of the lane closure exhibited skewness. Speed-flow relations followed the typical speed-flow curve given by

HCM. From the speed-flow curve the capacity and optimum speed were 975 vph and 41.3 mph respectively. These unrealistic values indicate that derivation of capacity and level of service without regard to individual site variation results in excessive scattering of data. To eliminate site variations individual site models were generated to include of space mean speed and observed flow rate.

$$S= a + bV$$

Where,

S – space-mean speed

V – observed flow rates

a and b are the regression coefficients

The effect of construction activity on speed was determined using the following model

$$S_{ot} = S_{pt} - S_t$$

Where,

S_o – observed space-mean speed in time interval (t) at the lane closure area

S_p - predicted space-mean speed in time interval (t) for given geometric, traffic, lane width, and clearance restrictions with work activity

S_t - speed reduction in time interval (t) due solely to the presence and intensity of the work activity

The analysis consisted of testing two hypothesis (a) S_t is indeed significantly different from zero and the (b) the degree to which S_t is functionally correlated to the activity index or to one of its components. The analysis will also determine whether S_t is dependent on of flow rate. The analysis was done in four steps

1. The observed flow rates were converted were adjusted for trucks (Q_w) and the lane width restrictions (W_w)
2. The computed workzone capacity was defined as

$$C_c = 2000\ V_h\ Q_h$$

The observed capacity in the field was defined as C_o. A regression analysis was done with (C_o-C_c) as dependent variable and a set of independent variables involving lane geometric, traffic and type of work activity gave the following equation

$$C_o - C_c = 1262 - 228.6\ N_t - 1230\ Q_h + 167.4\ A + 90\ N_o$$

Where Nt – total number of lanes before closure, per direction

A - work activity type, 1 –long term, 2- short term

N_o – number of open lanes in work zones

For the studied sites N_t=2, A= 1, and N_o = 1.

$$Co = 2000\ Q_h W_h + 1062.2 - 1230\ Q_h$$

Applying a similar definition for C_0 as C_c the above equation becomes

$$2000\ Q_wW_w = 2000\ Q_hW_h + 1062.2 - 1230\ Q_h \quad \text{------}\ (1)$$

The above equation can be solved for W_w with Q_w=Q_h= 1 for stream of traffic consisting entirely of passenger cars. This gives

$$W_w = W_w - 0.084 \text{ -------} (2)$$

Substituting equ (2) in equ (1) we get

$$Q_w = 0.531 + Q_h\ (W_h - 0.615) / (W_h - 0.084)$$

3. The service volume is now calculated as SV_t (pcph/l) = 12 f_t / (W_w * Q_w)

   Where f_t is the observed 5-min flow rate in interval t.

   The regression equations of S_{pt} were derived on the basis of the HCM speed-flow curve.

4. The equations for SV_t and S_{pt} are substituted into the model

   $$S_{ot} = S_{pt} - S_t$$

   The interval estimates of S_t were derived and analyzed.

A total of 103 5-min observations from the four sites were analyzed. It was found that on an average the observed mean speed at lane closure was 3 mph lower than the predicted mean speed. T-tests were performed to identify the difference in mean speed reduction due to the presence and intensity of work activity associated with different work zone descriptors. The difference was found to increase with increasing AI but the difference was less than 1 mph. The difference in speed increased significantly as the proximity of work zone moved to within 6 ft of the traffic lane.

A study done by Al-Kaisy et al (2000) analyzed freeway capacity at work zones based on emprical data. This study is restricted to long term work zones. The work zone site studied was situated near downtown Toronto on Gardiner Expressway. The data were collected from two directions on the same work zone with lane-closure configuration 3 normal – 2 open. The effect of heavy vehicles was not considered (i.e. freeway capacity was measured in terms of vphpl). The freeway capacity was measured as queue discharge rate under congested conditions, the 'congested-freeway capacity" which is slightly lower than the "free-flow capacity". The data were measured in 20-sec time intervals and capacity values were measured during congestion. The congestion was identified using time-mean speed. Even though the values of capacity varied widely, 90 % of the values were in the range of 1800 to 2050 vphpl with a standard deviation of 99 vphpl. The capacity values were tested for normality and found to be highly similar. The mean value of capacity 1943 vphpl was reasonably close to HCM value 1860 given that the HCM values were based on limited field studies in Texas during the late 1970's and early 1980's.

The capacity observations were also compared for different days and there was a wide variation in the distribution. This might be due to the variation in the flow of heavy vehicles and also the variation in the intensity of the work activity. The authors also discuss the influence of some of the factors involved, such as temporal variation (more capacity during peak hours) and day of week (less capacity during weekends).

Findings:

- Driver population and the work activity have significant effect on the capacity of work zones.
- The average capacity got from this study is significantly closer to the value given by HCM under the condition that HCM values were taken from studies in Texas.
- Temporal variation, grade variation and day of the week had significant effect on the capacity.

The paper published by Dudash et al (1983) focuses on the capacity of a single lane of urban freeway during reconstruction. The traffic flows were measured for different traffic movement scenarios. The traffic flow was greatly reduced when the proximity between the opposing vehicles increased. This also affects the capacity, which indicates the influence of traffic movement on capacity.

Al-Kaisy et al (2001) studied the effect of driver population on capacity of freeway reconstruction zones. The study site was on the QEW near Toronto. Capacities were measured during congested conditions, thereby giving the queue discharge rate. Comparison with 10 weekday data sets gave a driver population factor of 0.93 (ratio of PM to AM capacities) with no work activity. Comparison of AM for weekdays with PM for weekends gave a driver population factor of 0.84.Comparison of weekends AM peak and weekday AM peak gave a driver population factor of 0.84. Although freeway work zone capacity varies depending on different factors, the measurement of capacity in the field has two basic views, the measurement of queue discharge rate and the measurement of maximum flow rate. The consideration of queue discharge rate as the capacity of freeway work zone is followed by many traffic engineers and is well established. The consideration of maximum flow rate as freeway capacity has to be studied further, since much less analysis has been done on this approach.

6.3 Estimation of Capacity

For a long time, researchers have been working to establish a model for estimating capacity in freeway work zones that would take into account all the factors affecting capacity. A number of new and old models are available in this regard. Most of these models are based on the theory that after establishing a base capacity for some fixed conditions, new capacity estimates can be made by applying correction factors to the base capacity to suit the lane closure condition. The base capacity will be based on data collected from the field. All though these kind of models may not be suitable for all the states, because of the variations in the base capacity values and construction procedures in different states. Memmott et al (1984) gave one of the earliest models. The model was established as:

$$C = a - b\,(CERF)$$

Where,

C= estimated work zone capacity (vphpl)

CERF = capacity estimate risk factor suggested in the research

a,b = coefficients given in the research.

Abrams et al (1981) developed a model, which is given as:

$$C = 2000 * TF * WCF + WZF$$

Where,

C= estimated work zone capacity (vphpl)

TF = truck adjustment factor given in the HCM

WCF = lane width and lateral clearance adjustment factor given in the HCM

WZF = work zone capacity adjustment factor determined in the research

Krammes et al (1994) later developed a model based on data collected from Texas freeway construction zones. The capacity values for short-term freeway lane closures given by the 1985 Highway Capacity Manual were based on data collected in Texas during the late 1970s and early 1980s. The capacity values were based on lane closure configuration and the values tend to vary considerably for each lane closure configuration. This variability may be due to the differences in type and intensity of work activity, the proximity of work activity to traffic, percentage of heavy vehicles, lane width and lateral clearance to obstructions, and the alignment. This model gives new capacity values for short-term freeway work zones. The data used for arriving at these capacity values were collected for more than 45 hr of capacity counts from 33 work zones in Texas between 1987 and 1991.

Five different lane closure configurations were considered for data collection. The lane closure configurations considered were [3 to 1], [2 to 1], [4 to 2], [5 to 3], and [4 to 3]. All the work zones were short-term and most were maintenance activities. The capacity counts were made at the point of intersection of transition area and the activity area. The capacity counts were taken only at the upstream side of the work zone in order to eliminate the variability in the number and traffic volumes of ramps within different work zones. The effect of the presence of ramps was treated separately. Thus the base capacity will be the capacity for the work zone without the presence of ramps. The capacity was measured as the mean queue discharge entering a freeway bottleneck. Therefore the data were used for the time period only when the traffic was queued in all lanes upstream of the activity area.

The observed capacities for [3 to 1] and [2 to 1] were found to be of significantly higher than that given in the 1985 HCM. For all lane closure configurations combined the overall average capacity was found to be 1600 pcphpl. Comparing these data with previous observations it was suggested that factors causing below-average capacity include unusually intense work activities and the presence of ramps. The overall average capacity found did not consider the effect of presence of ramps in the work zone.

From the new data, it was observed that entrance ramps within transition area or a short distance into the activity area had more impact on capacity than entrance ramps farther downstream. A detailed study was undertaken at one work zone to study the effects of placement of work zones relative to the presence of entrance ramps. It was suggested that it is desirable to locate the lane closure such that any entrance ramp is at least 152 m (499 ft) downstream from the start of the lane closure.

The overall average capacity of 1600 pcphpl is used as the base capacity for the work zone capacity value. Adjustments were made for effects of heavy vehicles, intensity of work activity and presence of ramps. The heavy vehicle adjustment factor given in the 1985 HCM was used to account for the effect of heavy vehicles. It is given as

$$H=100/[100+p*(E-1)]$$

Where,

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

P= percentage of heavy vehicles

E= passenger car equivalent (passenger cars/heavy vehicle)

It was found that the capacities of individual work zones fell within a range of +/- 10 percent of 1600 pcphpl. Effect of intensity of work activity on the capacity was adjusted for this +/- 10 percent (160 pcphpl) since the available data were not sufficient to establish a relationship between intensity of work activity and the base capacity value.

The equation suggested for work zone capacity was given as:

$$C = (1600 \text{ pcphpl} + I - R) * H * N$$

Where,

C = estimated work zone capacity

I= adjustment for type and intensity of work activity, range (-160 to +160), depending on type, intensity and location of work activity

R= minimum of average entrance ramp volume in pcphpl during lane closure period for ramps located within chanellizing taper or within 152 m (500 ft) downstream of the beginning of full lane closure, or one-half of capacity of one lane open through work zone (i.e., 1,600 pcphpl/2N);

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

N= number of lanes open through work zone

Al-Kaisy et al (2002) developed two different models and studied them. Two site specific models were developed based on long-term reconstruction zones. The capacity for long-term construction zone was found to be higher than that for short term work zones. This difference in capacity was attributed to the presence of concrete barriers and driver familiarity with the work zone

A total of seven sites where considered for this study. Out of this seven, six were long term freeway reconstruction sites and one is a normal freeway site. The normal freeway site was chosen to study the effect of heavy vehicles on freeways during congestion. For this study, the capacity is considered as the mean of queue discharge flow rate, based on previous studies. The model to be established was based on the HCM method, in which a base capacity was adjusted for site-specific conditions. Base capacity conditions are commuter drivers, passenger cars, daytime light conditions, no work activity, clear weather, right side lane closure, level train with grades no greater than 2 percent, lane width of at least of 12 ft. Mean capacities for the sites chosen under the above-mentioned conditions were measured. The base capacity was fixed at 2000 pcphpl. The base capacity was used to formulate a model for estimating capacity by applying corrections for various factors. Passenger Car Equivalent (PCE) factors for heavy vehicles were based on an optimization approach, minimizing the variation in capacity measured in passenger cars. A PCE of 2.4 was established for level grade. It was found that the capacity was higher when there were more commuters, so a reduction factor of 7 % during weekdays and 16% during weekends was established. For nighttime construction a reduction of 5% was established. There was not enough data to establish the effect of lane closure configuration on capacity, but it was found out that shifting lane closures from right lanes to left lanes reduced the capacity by around 6%. There was a capacity reduction of about 4.4 % to 7.8% due to rains. Also the reduction in capacity was found out to be varying largely between 1.85% to 12.7% for the presence of work activity. Two models were considered, a multiplicative model and an additive model. The multiplicative model was evaluated using the minimization of sum of squared errors, whereas multivariate regression was used to evaluate the additive model. Two additive models were evaluated; one in which the heavy vehicle factor is expressed as a number of heavy vehicles in the traffic stream and in the other was the heavy vehicle factor was expressed as percentage of the total traffic. The second additive model had lower standard error than the first additive model. After comparing the additive model values with the observed data it was found out that the combined effect of two factors cannot be the addition of the individual effects. This was also supported by the previous researches. Finally the multiplicative model was established as the suitable model for estimating capacity.

Another model developed by Kim, Lovell and Paracha (2001) was based on multiple regression. In this model seven factors were taken into account:

- Number of closed lanes
- Location of closed lanes (right =1, otherwise =0)
- Proportion of Heavy vehicles

- Lateral distance to the open lanes
- Work zone length
- Work zone grade
- Intensity of work activity (1 or 0 for medium intensity, and 1 or 0 for heavy intensity)

Traffic and geometric data were collected from 12 construction sites to establish this model. The correlation between the independent variables showed that the number of lanes closed and the work intensity in the work zone are major factors in estimating capacity. The model established was as follows:

$$\text{CAPACITY} = 1857 - 168.1\ \text{NUMCL} - 37.0\ \text{LOCCL} - 9.0\ \text{HV} + 2.7\ \text{LD} - 34.3\ \text{WL} - 106.1\ \text{WI}_H - 2.3\ \text{WG}^*\ \text{HV}$$

Where,

NUMCL – number of lanes closed
LOCCL – location of closed lanes
HV – proportion of heavy vehicles
LD – lateral distance to open lanes
WL – work zone length
WI_H – intensity of work
WG – work zone grade

The authors compared the capacity values obtained from this model with other models and found out that this model gave more accurate results than other models.

6.4 Capacity Values

This section gives capacity values for work zones found in the literature review.

North Carolina Work Zone Capacities

Number of Lanes		**Rural or Urban**	**End of Transition Capacity [vphpl]**	**Activity area Capacity [vphpl]**	**Intensity of Work Activity**	**Comparison of Activity Area to End of Transition Capacity [Percent]**
Normal	**Open**					
2	1	Rural	1300	1210	Heavy	93
2	1	Urban	1690	1560	Moderate	93
				1490	Heavy	88
3	1	Urban	1640	1440	Moderate	88

Source: *Capacity for North Carolina Freeway Work Zones,* Karen K. Dixon, Joseph E. Hummer, and Ann R. Lorscheider Transportation Research Record 1529, 1996.

Short-Term Freeway Work Zone Lane Closure Capacity

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

* Calculated using a passenger car equivalent for heavy vehicles of 1.7

Notes: Heavy vehicle adjustment factor used H = 100/[100+P*(E-1)]

The data was collected from 33 work zones in Texas during the years 1987 to 1991.

The data was obtained at the end of transition area as the queue discharge rate.

Source: *Updated Capacity Values for Short-Term Freeway Work Zone Lane Closures,* Raymond A. Krammes and Gustavo O. Lopez, Transportation Research Record 1442, 1994.

Capacity Rates for Some Typical Operations

Work Activity	**No. of Lanes in One Direction**		**Observed Capacity(vph)**
	In Normal Operation	**In Work Area**	
Median barrier or guardrail repair	2	1	1500
	3 or 4	2	3200
	4	3	4800
Pavement repair, mud-jacking, pavement grooving	2	1	1400
	3 or 4	2	3000
	4	3	4500
Striping, resurfacing, slide removal	2	1	1200
	3 or 4	2	2600
	4	3	4000
Installation of pavement markers	2	1	1100
	3 or 4	2	2400
	4	3	3600
Middle lanes(for any lanes)	3 or 4	2	2200
	4	3	3400

Source: *Freeway Lane Closures,* Richard H. Kermode and William A. Myyra, Traffic Engineering, 1970.

Average Capacity for Different Lane Configurations

No. of Lanes		**No. of Studies**	**Average Capacity**	
Normal	**Open**		**Vehicles Per Hour**	**Vehicles Per Hour Per Lane**
3	1	5	1130	1130
2	1	8	1340	1340
5	2	8	2740	1370
4	2	4	2960	1480
3	2	8	3000	1500
4	3	4	4560	1520

Notes: The study was conducted in Texas. The data was obtained from 34 studies at different work zones in Texas. The effect various factors like on ramps, off ramps, percentage of heavy vehicles, grades etc were not considered. The data includes work zones with and without work crew.

Source: Traffic Capacity through Urban Freeway Work Zones in Texas, Conrad L. Dudek and Stephen H. Richards Transportation Research Record 869, 1982.

Work Zone Capacity Data-Indiana

Work Zone, Type and Location	**Capacity (Vehicles /Hour)**	**Heavy Vehicle Percent**	**Equivalent Capacity (Passenger Cars/Hour)**	**Construction Type and Work Intensity**	**Congestion Starting Location**
Zone # 1 – Partial Closure (Right Lane Closed) on I-65 N. of SR-32	1500	25	1689	Bridge Rehabilitation, Medium Intensity	Transition Area
Zone # 1 – Partial Closure (Right Lane Closed) on I-65 N. of SR-32	1572	12	1665	Bridge Rehabilitation, Medium Intensity	Transition Area
Zone # 1 – Partial Closure (Right Lane Closed) on I-65 N. of SR-32	1190	11	1258	Bridge Rehabilitation, Medium Intensity	Transition Area
Zone # 2 Crossover (In opposite Direction) on I-70 E. of SR-9	1823	39	2142	Pavement Overlay, Not Adjacent to Traffic	Within Work Zone
Zone # 2 Crossover (In opposite Direction) on I-70 E. of SR-9	1475	22	1598	Pavement Overlay, Not Adjacent to Traffic	Transition Area
Zone # 2 Crossover (In opposite Direction) on I-70 E. of SR-9	1595	10	1672	Pavement Overlay, Not Adjacent to Traffic	Transition Area
Zone # 2 Crossover (In opposite Direction) on I-70 E. of SR-9	1386	6	1566	Pavement Overlay, Not Adjacent to Traffic	Transition Area
Zone # 3- Crossover(In Median Crossover Direction) on I-69 S. of SR-332	1404	28	1601	Pavement Overlay, Not Adjacent to Traffic	Within Work Zone
Zone # 3- Crossover(In Median Crossover Direction) on I-69 S. of SR-332	1536	7	1590	Pavement Overlay, Not Adjacent to Traffic	Within Work Zone

Work Zone Capacity Data-Indiana: Continued

Zone # 3- Crossover(In Median Crossover Direction) on I-69 S. of SR-332	1488	21	1644	Pavement Overlay, Not Adjacent to Traffic	Within Work Zone
Zone # 4 – Partial Closure (Left Lane Closed) on I-69 at SR-14	1308	32	1517	Bridge Rehabilitation, High Intensity	Within Work Zone
Zone # 4 – Partial Closure (Left Lane Closed) on I-69 at SR-14	1320	31	1525	Bridge Rehabilitation, High Intensity	Within Work Zone

Source: *Traffic Capacity, Speed, and Queue-Discharge Rate of Indiana's Four-Lane Freeway Work Zones,* Yi Jiang, Transportation Research Record 1657, 1999.

Mean Capacity Observations at Ontario, Canada

During Weekdays, Commuter Peak Period, Daylight, and Clear Weather Conditions

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

Work Zone Capacity by Location of Lane Closure (Left Lanes Versus Right Lanes) at the Burlington Bay Skyway Reconstruction Sites

	Capacity (pcphpl)		**% Difference**	**t-test**
	Right Lanes Closed	**Left Lanes Closed**		
Total				
All Observations	1948	1782	8.5	Significant
No rain, no work activity	1947	1807	7.2	Significant
Weekdays, no rain, no work	1987	1872	5.8	Significant
Toronto-Bound				
All Observations	1905	1805	5.2	Significant
No rain, no work activity	1892	1829	3.3	Significant
Weekdays, no rain, no work	1936	1987	2.5	Significant
Niagara-Bound				
All Observations	2110	1747	17.2	Significant
No rain, no work activity	2198	1767	19.6	Significant
Weekdays, no rain, no work	2108	1841	12.6	Significant

Work Zone Capacity with and Without Work Activity on Site (Burlington Bay Skyway Reconstruction Sites)

	Capacity (pcphpl)		**% Capacity Drop**	**Data Sets (Total hrs)**	**t-test**
	No Work Activity	**Work Activity**			
All Observations	1875	1739	7.25	31 (143)	Significant
Weekdays, left-lane closure, no rain	1883	1647	12.7	13 (58)	Significant
Weekdays(AM Peak), right lane closure, no rain	2003	1966	1.85	7 (28)	Not significant
Weekends, left-lane closure, no rain	1659	1621	2.3	3 (15)	Not Significant

Source: *Guidelines for Estimating Freeway Capacity at Long-Term Reconstruction Zones,* Ahmed Al-Kaisy & Fred Hall, Transportation Research Board 81st Annual Meeting, 2002.

Work Zone Capacity – Maryland

Site	# of closed lanes	Loc. of closed lanes	# of open lanes	Heavy Veh. (%)	Driver Pop.	On-ramp at work	Lateral distance (feet)	Work zone length (mile)	Grade (%)	Work intensity	Work duration (short, long)	Weather (sun, rain)	Work time (day, night)	Avg. speed (mph)	Capacity (vphpl)
1	1	Right	3	8.2	0	Yes	0.5	1.2	-2	Shoulder pavement (Low)	Short	Sun	Day	22	1612
2	1	Right	3	8.1	0	Yes	0.5	0.45	-2	Shoulder pavement (Low)	Short	Sun	Day	37	1627
3	1	Right	3	9.0	0	Yes	0	0.15	+3	Bridge repair (Med)	Short	Sun	Day	31	1519
4	1	Left	3	10.3	0	N/A	0.5	0.15	-5	Median barrier repair (Low)	Short	Sun	Day	31	1790
5	1	Left	3	8.0	0	N/A	0.5	0.18	-5	Median barrier repair (Low)	Short	Sun	Day	30	1735

Work Zone Capacity – Maryland: Continued

6	1	Left	3	10.1	0	Yes	1.0	1.9	-3	Median barrier repair (Low)	Short	Sun	Day	37	1692
7	2	Right	2	14.3	0	Yes	1.0	1.8	0	Pavement (Heavy)	Short	Sun	Night	23	1290
8	2	Right	2	8.5	0	Yes	0	2.2	0	Pavement (Heavy)	Short	Sun	Night	21	1228
9	2	Left	2	11.0	0	Yes	0.5	1.3	0	Pavement (Med)	Short	Sun	Night	22	1408
10	2	Left	2	11.3	0	Yes	0	0.9	0	Pavement (Heavy)	Short	Sun	Night	24	1265
11	2	Left	2	4.6	0	Yes	0.5	2.0	0	Pavement (Med)	Short	Sun	Night	17	1472
12	2	Left	2	9.9	0	Yes	0	0.9	0	Pavement (Heavy)	Short	Sun	Day	20	1298

Notes: Data was collected after the peak hour both during day and night.

The driver population was assumed to be non-commuters. All the work zones were short term.

Driver population: commuter =1, otherwise = 0.

Source: *A New Methodology to Estimate Capacity for Freeway Work Zones*

Taehyung Kim and David J. Lovell, Transportation Research Board 80th Annual Meeting, 2001.

Summary of Capacity Values for Long -Term Construction Zones:

No. of Normal Lanes	**Lanes Open**	**Number of Studies**	**Range of Values (veh/h/ln)**	**Average per Lane (Veh/h/ln)**
3	2	7	1780-2060	1860
2	1	3	-	1550

Notes: If the lane closure involves a crossover then the capacity values are closer to the average value 1550 veh/h/ln. Whereas lane closures with a merge to a single lane will have higher capacity values close to the average of 1750 veh/h/ln.

Source: *HCM 2000,* Exhibit 22-4, and pg. 22-8.

Reference: *Notes on Work Zone capacity and level of Service*
Dudek C.L., Texas Transportation Institute, 1984.

6.4.1 Summary

The capacity values given in the tables presented above are measured based on different definitions of capacity followed by the researchers. Not all the capacity tables presented above may be obtained based on extensive and detailed data collection. The capacity values given by Dixon et al (1996) ware based on 24 short-term work zone sites in North Carolina. The low capacity values (1210-1650 vphpl at the activity area) given in the table are characteristic of short term work zones. The transition area capacity is comparatively higher than the activity area capacity. This trend indicates that in a work zone the bottleneck is at the work activity area and not the transition area, which further implies that the location of measurement of capacity also becomes and issue in giving a solid definition for capacity. Krammes et al (1994) gave the short term work zone capacity values based on study from 33 sites in Texas. The capacity values were measured at the intersection of transition area and activity area. The values are low (1460-1580 vphpl) since the values are for short-term work zones. As the percentage of trucks increased the capacity values decreased. Dudek et al (1982) did some capacity studies at Dallas and Houston. The values measured indicated that the number of lanes open during a lane closure very much affected the per lane capacity. It could be observed from the table that capacity per lane for 3 lanes open was higher than that for two lanes open and so on. One of the disadvantages of this study is that the effect of other factors like percentage of trucks, grades etc were not considered. Jiang (1999) conducted capacity studies in Indiana. The study sites were a good mixture of crossover sites and partial closure. Surprisingly the capacity values for crossover sites (1566-2142 pcphpl) are higher than those for the partial lane closure sites (1256-1689 pcphpl), even though one would expect the other way. Al-kaisy et al (2002) measured capacity values at Ontario, Canada in long-term construction zones. The values measured were higher (1747 - 2252 pcphpl) which is characteristic of long-term construction zones. A maximum difference of 19.6 % is found between the right lane closure and left lane closure. The right lane closure tends to show higher capacity values than left lane closure. There may be other factors for such high variation which may not have been taken into account. Kim et al (2001) did a short term work zone capacity study in Maryland. Several factors were measured in eleven different cases. The values range from 1228 –1790 vphpl which is indicative of the short term work zones. In summary, how capacity is measured, under what traffic and roadway conditions it is measured, to what purpose it is measured, and where in the work zone it is measured affect its value. One should be very careful is borrowing capacity values from other sites. If the above-mentioned factors are similar then the borrowed value may be reasonable. Otherwise, the borrowed capacity value may not represent the capacity of the site.

6.5 References

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CHAPTER 7 - EVALUATION OF COMPUTER MODELS

In this chapter, the comparison of the field data with the three software packages, QUEWZ, FRESIM and QuickZone is discussed. An explanation of the way in which the values for the required parameters were computed from the field data follows the discussion of the three software packages. This is followed by sections that discuss how the results returned by the three software packages compared with the field data.

7.1 QUEWZ

QUEWZ, Queue and User Cost Evaluation of Work Zones, evaluates freeway work zone lane closures. QUEWZ-98 is the most recent version of the QUEWZ family of programs, which have been developed by the Texas Transportation Institute. It was developed as part of a study: "Air Quality Impacts of Highway Construction and Scheduling."

QUEWZ-98 is a menu driven program and operates on IBM-compatible, DOS-based microcomputers with a minimum of 256K Random Access Memory (RAM) and a suitable disk drive configuration.

7.1.1 Capabilities

QUEWZ-98 estimates the changes in traffic flow characteristics on freeway segments with lane closures. It can compute the additional road user costs due to the lane closure for a given closure configuration and schedule of closure. Three components considered in road user cost are vehicle operating costs, travel time costs and emission costs. QUEWZ-98 can also identify hours of a day when a given number of lanes can be closed without causing excessive queuing which can be defined by the user. This model is applicable to work zones on freeways or multilane divided highways with up to six lanes in each direction and any number of lanes closed in one or both of the directions.

7.1.2 Data Input

The data required could be classified in to four categories: lane closure configuration, schedule of work activity, traffic volumes approaching the freeway segment, and alternative values to the default model constants.

Lane closure configuration includes information such as number of directional roadways in which lanes are closed (1 or 2), total number of lanes in each direction, number of open lanes through the work zone in each direction, length of the lane closure, and capacity of the work zone.

Schedule of work activity includes the hours the lane closure begins and ends and the hours the work activity begins and ends. The hours of work activity can be different from the hours of lane closure but must be totally contained within the hours of lane closure.

QUEWZ-98 requires directional hourly traffic volumes to do the analysis. The user can provide these volumes directly or instead provide the AADT of the roadway, the day of the week when the lane closure will be in effect, and the general location of the freeway (urban or rural). QUEWZ-98 estimates the directional hourly volume from the AADT using the adjustment factors, which are based on data collected in Rural and Urban Interstates in Texas in 1985.

QUEWZ-98 uses default values for the model constants unless the user specifies otherwise. The model constants used are cost update factor, percentage of trucks, speed-volume relationship, work zone capacity, definition of excessive queuing and pollutant emissions rank.

Cost Update Factor

The cost update factor adjusts the road user costs for the effect of inflation. All the costs computed in QUEWZ-98 are expressed in 1990 dollars. To adjust the cost to another time period, the user can modify the Cost Update Factor. It is computed from the Consumer Price Index for the month of interest by using the equation (Copeland 1998):

$$\textit{Cost Update Factor} = \textit{Consumer Price Index} / 130.7 \tag{7.1}$$

The default value is 1.00

Percentage of Trucks

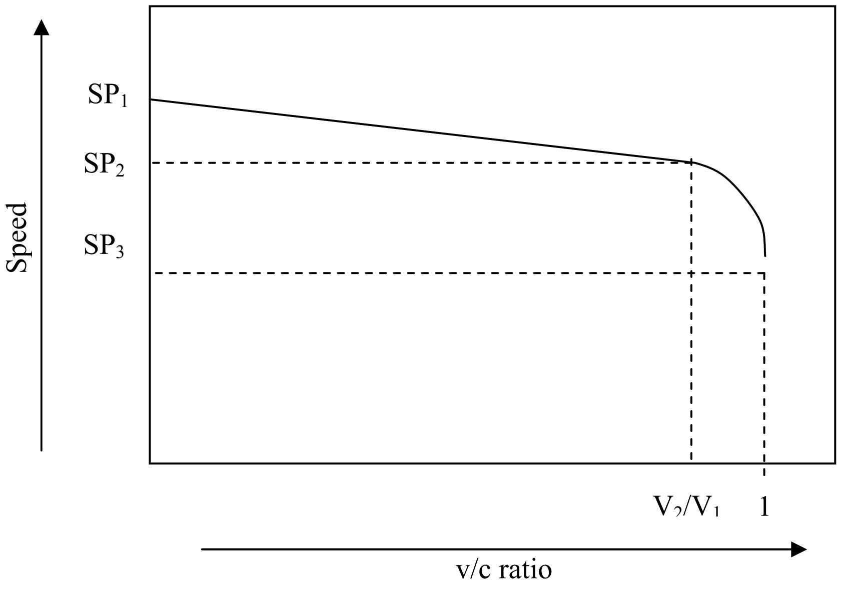
The percentage of trucks significantly affects the work zone capacity and road user costs. QUEWZ-98 uses a default value of 8 percent trucks, which is the average percentage of trucks observed during work zone capacity studies on urban freeways in Texas (Krammes et al., 1992).

7.1.3 Speed-Volume Relationship

QUEWZ-98 assumes a linear speed-volume relationship for v/c ratios less than or equal to the v/c ratio corresponding to the level of service D/E breakpoint, and a quadratic relationship for v/c ratios greater than the v/c ratio corresponding to the level of service D/E breakpoint but less than or equal to 1. The model is defined by five parameters free-flow speed (SP_1), the level of service D/E breakpoint speed (SP_2), the speed at capacity (SP_3), the normal capacity (V_1), and the level of service D/E breakpoint volume (V_2). The default values, based on the 1985 Highway Capacity Manual, for the parameters are SP_1 = 60 mph, SP_2 = 46 mph, SP_3 = 30 mph, V_1 = 2000 vphpl and V_2 = 1850 vphpl.

7.1.4 Work Zone Capacity

It was observed that work zone capacity varies depending on whether or not there is work activity in the work zone. Therefore QUEWZ-98 uses two different work zone capacities if the duration of work activity is less than the duration of the lane closure (Memmott et al., 1982).



SP_1 : Free flow Speed
SP_2 : LOS D/E Breakpoint Speed
SP_3 : Speed at Capacity
V_2 : LOS D/E Breakpoint Volume
V_1 : Normal Capacity

Figure 7.1 Speed-Flow relationship in QUEWZ

The per-lane capacity during the hours when lanes are closed but there is no work activity is assumed to be 90 percent of the normal per-lane capacity (Ullman, 1992). The work zone capacity for the hours work activity is present, is estimated using the work zone capacity model presented in Updated short-term Freeway Work Zone Capacity Values (Krammes et al., 1992). However, the user can modify the values of the parameters to adjust the capacity of the work zones with work activity. The model is presented in the Algorithm section.

7.1.5 Definition of Excessive Queuing

QUEWZ-98 has two output options: road user cost and lane closure schedule. QUEWZ-98 uses excessive queuing parameter in both the output options. Excessive queuing is used to estimate the amount of traffic that will divert away from the freeway in the road user cost option. The diversion algorithm calculates the traffic volume that must divert to avoid excessive queuing. The lane closure schedule option uses excessive queuing to identify the hours of day when a specific number of lanes can be closed without causing excessive queuing for each lane closure configuration.

Excessive queuing may be defined as a critical queue length (in miles) or as a maximum acceptable delay to motorists (in minutes). The default critical queue length is 2.0 miles, and maximum acceptable delay is 20 minutes. These are based on diversion studies at temporary freeway work zone lane closures on urban freeways with continuous frontage roads in Texas (Ullman, 1992).

7.1.6 Pollutant Emission Rates

QUEWZ-98 considers the emission effects of cruise and idle operations, but does not consider the impacts of acceleration and deceleration. The pollutants considered are hydrocarbons (HC), carbon monoxide (CO), and Nitrogen Oxide (NOX). The QUEWZ-98 default emission values are representative of San Antonio, Texas values estimated for summer 1998 using MOBILE5a, software that can generate default emission rates for each pollutant.

7.1.7 Algorithm

QUEWZ-98 estimates the capacity of the work zone when work activity is present using the HCM 2000 model for short-term work zone capacity. The model uses the following equation to compute the capacity of the work zone with work activity.

$$C = (1600 + I - R) * H * N \tag{7.2}$$

Where,

C: estimated capacity of the work zone (vph)

I: effect of work intensity (-160 to +160 vehicles; default value is 0)

R: effect of entrance ramps (0 to 160 vehicles; default value is 0)

H: effect of heavy vehicles

N: Number of open lanes through the work zone

Where

$$H = 100 / [100 + P * (E - 1)] \tag{7.3}$$

E: Passenger car equivalent (veh/pc) (default is 1.7)

The parameter I represent the effect of work intensity on the capacity of the work zone. It can take a value between -160 and +160. The parameter R is for the effect of entrance ramps within the lane closure. It can take a value between 0 and 160.The default value for both these parameters are zero. The user can modify the values for these parameters. However no guidelines have been provided regarding the appropriate values for these parameters under different conditions.

The factor H is used to convert the capacity from pcph to vph. E represents the passenger car equivalence and the default value is 1.7. The user can modify the value of E. Modifying these three parameters, the user can change the value of the capacity of work zone with work activity. But QUEWZ-98 does not execute if the capacity of work zone with work activity is greater than capacity of work zone without work activity. As mentioned earlier, 90% of the normal capacity (capacity of the freeway without lane closure) is the capacity for work zones without work activity.

QUEWZ-98 uses the Speed-Volume relationship described in the previous section to estimate the average speed of the vehicles. Knowing the capacity (under normal and lane closure conditions) and the volume for every hour, v/c ratios for both the cases are computed and these v/c ratios are used to estimate the average speed of the vehicles under normal and lane closure conditions for every hour of the closure.

Once the speeds have been estimated QUEWZ computes the travel time costs and vehicle operating costs. The travel time costs include the delay encountered while travelling at a lower speed through the work zone and also any queuing delay (which occurs when demand is greater than capacity). The queuing delay and queue lengths are computed using input-output analysis technique presented in the 6th chapter of 1994 HCM. Number of vehicles in queue is estimated as the difference between demand and the work zone capacity. The queue length in mile is calculated by assuming average vehicle length (40 ft) and the queue spreads equally on all the open lanes upstream of the site. The total delay for all the vehicles (in vehicle hours) is simply the average of number of queued vehicles at the beginning and the end of the hour. Vehicle operating costs include the cost of speed change cycles and change in vehicle running costs. The actual equations for estimating the cost are derived from Memmott, 1991.

The user has the choice of using the Diversion Algorithm in QUEWZ-98 while estimating the road user cost. On urban freeway (with parallel frontage roads) lane closures in Texas, it was observed that queue lengths and delays tend to reach threshold levels soon after the lane closure and remain near those threshold levels thereafter. So, 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 motorists in minutes. Use of the diversion algorithm is not recommended for rural areas. Even for urban areas the diversion algorithm has to be used with caution because this diversion phenomenon was observed under certain conditions such as the presence of parallel frontage roads.

7.1.8 Output

The user can choose between two output options: road user cost and lane closure schedule. The road user cost output includes input data summary (lane closure configuration, traffic parameters, schedule of work activity), summary of user costs (additional road user costs for each hour of the day and for each direction), summary of traffic conditions (approach volume, capacity, approach speed, work zone speed and average queue length during each hour of the closure) and the summary of traffic volumes (volume remaining on and the volume diverting the freeway as estimated by the diversion algorithm)

The lane closure schedule output option indicates the hour to which work activity can continue without causing excessive delay from any starting hour for each possible number of closed lanes. The output is provided in tabular and graphical form.

7.2 FRESIM

Federal Highway Administration (FHWA) conceived the concept of a single integrated simulation system that can provide the user the capability to simulate traffic flow in large urban networks, which include freeways, and surface street networks. The result of this initiative by FHWA is the TRAF family of simulation models. The TRAF family includes CORSIM (for corridor microscopic simulation) and CORFLO (for corridor macroscopic simulation) simulation models. FRESIM performs microscopic simulation of freeway networks and is a part of CORSIM. In FRESIM, FRE indicates freeway network and SIM indicates that it is a microscopic simulation. Traffic Software Integrated System (TSIS) provides a user-friendly interface for executing CORSIM.

7.2.1 Capabilities

The FRESIM model can simulate most of the prevailing geometric conditions on freeways. It can simulate one to five through lanes of mainline freeway, one to three lane ramps, variations in grade, lane additions and drops on the freeway, and freeway blockage incidents. The simulation model also includes a lane-changing model, and can model a freeway surveillance system, traffic-responsive metering, ten different driver types and nine different vehicle types. For simulating work zones, the incident capability of the model is recommended.

7.2.2 Data Input

ITRAF (Interactive traffic network data editor for the integrated TRAFfic simulation system) provides a graphical interface for the user to create and edit input files to the TRAF family of simulation models, which includes FRESIM. The Data input required for FRESIM can broadly be classified into the following three categories: Geometric, Traffic and Run Control.

Geometric data: The user has to graphically create the network in ITRAF and provide network information. This includes geometric information, detector information, add or drop lanes for the link. In addition the user has to model the lane closures as incidents on the freeway.

Traffic: This information includes the volume entering the system, exiting the freeway and ramp metering information.

Run Control: This information indicates the user preferences for running the simulation model and is used to control the execution of FRESIM. Among many things, the input includes, the time periods for which the simulation has to be performed, the random number seeds that are to be used for generating the random numbers in the simulation, the probability distribution to be used, the intervals at which the reports have to be generated by the program and the warm up period to bring the network to an equilibrium, before the statistics are collected.

7.2.3 Simulating work zones in FRESIM

FRESIM does not have the capability to directly model work zones. However, it can simulate the effect of incidents on freeways. This feature of FRESIM is used to simulate work zones. The incident information includes the duration of incident, the length of the roadway affected by the incident, the lanes affected and the rubbernecking factor to be applied for the adjacent lanes.

7.2.4 Output

FRESIM returns the data for each link of the network at the end of the simulation period. This data includes total travel time, move time, average speed, number of vehicles that entered and exited the link, number of vehicles on the link at the end of the simulation time period. FRESIM also returns vehicle miles and vehicle minutes traveled for the whole network. In addition FRESIM also returns the Fuel Consumption and emission estimates.

7.3 QUICKZONE

The 1998 Federal Highway Administration (FHWA) report “Meeting the Customer’s Needs for Mobility and Safety During Construction and Maintenance Operations” identified the need to consider the cost of traveler delay when key decisions about project staging and duration are made. The report also recommended the development of an analytical tool to estimate and quantify work zone delays. Toward this end, the FHWA developed QuickZone, an analytic tool for estimation of work zone delay supporting all four phases of the project development process (policy, planning, design and operation). QuickZone is an open-source software product and it is written as a small program within Microsoft Excel.

With QuickZone the users can: 1) Quantify corridor delay resulting from capacity decreases in work zones; 2) Identify delay impacts of alternative project phasing plans; and 3) Support tradeoff analyses between construction costs and delay costs. QuickZone quantifies work zone impacts in terms of queues, user delay, travel behavior and costs.

The prospective user of QuickZone need only have Excel97 or higher running on a Windows-based PC (Windows 95 or higher) with minimal memory and processing speed requirements.

7.3.1 Structure of QuickZone

QuickZone uses Microsoft Excel dialog sheets and worksheets for accomplishing its goals. There are four major modules and for navigation between these modules a master control dialog sheet is used. The four modules are: Input Data, Program Controls, Output Data and Open/Save. The Input Data interface is used to give the necessary input data for QuickZone and is structured as a series of linked worksheets. The Program Controls initiate QuickZone to execute the analysis and is directly accessed from the master control dialog sheet. Output Data, which include queues, user delay, travel behavior and costs, are displayed using Excel charts, tables and dialog sheets. The Open/Save allows QuickZone network data to be saved outside of the program and the network data read from files.

7.3.2 Data Input

The following data is necessary for running a QuickZone analysis.

1. Network (Nodes and Links)—A complete description of network with nodes links with their attributes and the Mainline and Detour links identified.
2. Project Information— Starting date and duration of the Project.
3. Construction Phase Data—Duration and Infrastructure Cost.
4. Work Zone Plan— A complete description of the various plans. This includes Start Date, End Date, Links affected by the construction, capacity decrease of each affected link, mitigation strategy to be used, if any, day(s) and time of the week, work is in effect.

7.3.2.1 Network

The network is described in terms of nodes and links connecting the nodes and the attributes of the links. The following six modules are used to input the network data.

Nodes Module: All the nodes of the network are defined here. A node is necessary at the intersection of two links or the starting/ending points of the network. Each node is defined by a node number and the xy coordinates of the node. A network can have a maximum of 100 nodes.

Links Module: A Link connects a pair of nodes. All links are directional, and its upstream and downstream nodes define each link. A maximum of 200 links is permitted. The attributes required for each link are: link number, upstream node (called A node), downstream node (called B node), number of lanes, capacity (in vehicles/hr/lane), length (in miles), free flow speed (in mph), jam density (vehicles/mile/lane), Inbound or Outbound, Type of link (Mainline or Work Zone or Detour or ramp) and description (optional).

Inbound and Outbound Demand Patterns: QuickZone requires Inbound and Outbound Demand patterns along with AADT for all the links if hourly demand is not available, to calculate the hourly demand on various links of the network. The user may define up to seven different Inbound (and Outbound) Demand Patterns for the Inbound (and Outbound) direction over a 24-hour period. Each pattern is defined by hourly demand factors (the sum over 24 hr period should equal 100%) and daily demand distribution factors (the sum over the seven days should equal 7). The user may choose to use the default Demand Patterns available in the supplied sample network or change them.

Demand Module: QuickZone needs accurate hourly demand on each of the links of the network to perform the analysis. Accurate demand is required because QuickZone performs conservation of flow calculations. The user has to provide either hourly demands or the AADT and Demand Patterns for all the links. If the user does not provide hourly demand on each link, this module generates hourly demand on each link using the AADT values and the Demand Patterns provided by the user in Inbound and Outbound Demand Patterns.

Seasonality Demand Pattern Module: Link travel demands may be adjusted for seasonal variations based on the seasonality demand pattern. The user can use the default pattern, which is based on HCM, or specify a pattern. The average of the seasonality over 12 month period must equal 100%.

7.3.2.2 Project Information

Project Information consists of Project Description, Start Date (QuickZone adjusts the start date so that it is a Sunday), duration of the project (in weeks, limited to 520 weeks or 10 years), yearly increase in demand over base year demand, yearly decrease in capacity over base year capacity.

7.3.2.3 Construction Phase Data

Project is divided into construction phases, where each phase represents a major capacity reducing activity. The sum of all construction phases must equal the Project duration. The construction phases cannot overlap and must be sequential. Each project must have at least one construction phase and can have a maximum of 15 phases. Each phase is defined by a phase description, duration (in weeks) and infrastructure cost.

7.3.2.4 Work Zone Plan

Work Zone Plans are a subset of the Construction Phase data and describe distinct tasks of the construction phase and their impact on capacity of the links and the reaction of travelers. Each

Construction phase must have at least one work zone plan and can have up to seven plans. The plans cannot overlap and must be sequential. The data required for each plan can be classified in four categories: Work Zone information, Links Information, Mitigation Strategies and Traveler Behavior.

Work Zone Information: This includes a brief description of the plan and the start and end times.

Links information: This includes the links affected by the plan, the capacity decrease. The user can enter the decrease in capacity or the reduced capacity can be computed using the work zone capacity models of HCM 1997 or HCM 2000. The user can also indicate a full road closure for the links. However, QuickZone performs checks to ensure that there is a detour exiting at the beginning of the road closure and entering at the end of the road closure. Also it checks to ensure that the aggregate weekly 24 hour capacity of the detour is greater than the sum of the mainline demand and the detour demand. This is done to ensure that queues do not persist week-to-week indefinitely and become too large for QuickZone to compute.

Mitigation Strategies: QuickZone can consider the effect of six mitigation strategies. While route re-timing, VMS/HAR/Pre-trip and lane widening can only be used for detour links, ramp metering, media campaign and reversible lanes can only be used for mainline links.

For route re-timing and lane widening, the detour link that is affected and the percent increase in the capacity are the input values. When the VMS/HAR/Pre-Trip toggle is off, it is assumed that mainline diversion to the detour route will not occur until the tail of the queue reaches back to the diversion point. With the toggle on, volume will divert onto the detour when the queues delay encountered on the mainline exceeds the additional time it takes to traverse the detour rather than the mainline. Because these services can provide information on congestion along the detour route as well, QuickZone assumes a more efficient diversion split of up to 100% of detour capacity.

Ramp metering improves the capacity of the link it is feeding along the Mainline and its input includes the link affected and the percent increase in capacity. The media campaign distributes travel demand evenly around the times of day when the work zone is active. Without the media campaign, QuickZone conducts a more heuristic split designed to mimic small adjustments made to trip timing be travelers who alter their trip making in response to queuing delays that result from the work zone. However, users can change the effects of the media campaign to encourage mode shift or trip cancellation by making those travel behavior inputs larger. Media campaign is available for the mainline links only. Reversible lanes increase the inbound direction by 1 lane and reduce the outbound direction by 1 lane and apply only to the mainline links.

Travel Behavior Information: Travel Behavior is separated into two categories: Start Demand and Excess Demand. The Start Demand applies percent reductions to all vehicles regardless of whether or not they experience higher than baseline delay on the Mainline. The Excess Demand applies only to those vehicles that experience higher than baseline delay on the Mainline. Various types of traveler behavior considered in QuickZone are Mode Shift Change (percentage of travelers who change mode during the project), Cancel Trip (percentage of travelers who cancel their trip during the project), Time Shift within One Hour (percentage of travelers that will not be on the affected links due to changing their departure time by up to an hour and applies only to Excess Demand) and Endure the Mainline Traffic (percentage of travelers that will endure the mainline). It should be noted that these four numbers should sum to 100.

Amortized Delay and Construction Cost Module: This module allows the user to input cost parameters that are used to estimate delay costs resulting from the construction project. The parameters are Inflation Rate (in %), Delay Cost per Car Hour (in $/car-hour) Delay Cost per Truck Hour ($/truck-hour) and Life of improvement (in years).

7.3.3 QuickZone Algorithm

QuickZone takes the input data from the user and estimates delay and mainline queue growth by comparing travel demand against capacity for every link on an hour-by-hour basis for the life of the project. Time-of-day and seasonal variations in travel demand are accounted for in the travel demands. Links that are downstream from bottlenecks should see lower travel demand because vehicle flow is reduced by the upstream bottleneck. This effect of bottlenecks on downstream demand is also considered.

QuickZone estimates the number of queued vehicles on the mainline, which is comprised of several consecutive links including the links with lane closure. The model essentially applies input-output analysis (procedure in Chapter 6 of 1994 HCM) for every link on the mainline. Hourly traffic volumes and capacities of the links are required as input data. Either on site measured hourly volume or AADT-based hourly volume can be used.

As an initialization step, QuickZone calculates the recurrent queue length assuming no construction on the mainline. For the first link of the mainline, demand volume for each hour is calculated as the sum of number of vehicles in queue from the previous hour and the demand for this hour. For all the other downstream links, demand volume for every hour is the sum of number of vehicles in queue from the previous hour and inflow from upstream mainline link and the inflow from other (not on the mainline) upstream links for this hour. Using the same procedure, queue lengths due to lane closure are calculated using the reduced capacity values for the work zone links.

Next Quick Zone computes the number of vehicles that would time shift to avoid congestion. As mentioned earlier QuickZone estimates the number of queued vehicles when there is no construction and when there is construction for every hour. QuickZone assumes that the number of vehicles changing the departure time is equal to a fraction of the difference in the number of queued vehicles in these two cases (with and without construction). The fraction that would shift can be specified by the user. When media campaign is used for informing the public of the construction, QuickZone distributes the shifting vehicles evenly over the work zone time period. When there is no media campaign, QuickZone assumes that half the vehicles would leave an hour earlier and half would leave an hour later. The demand that would shift for every hour is added to the demand for the first mainline link. For the other mainline links the demand and queue computation is the same as before.

Next QuickZone computes the number of vehicles that would use the detours to avoid congestion. This volume is the minimum of spare capacity available on detour route and the number of vehicles in queue after considering the time shifting of the vehicles. This volume is added to all the links downstream of the diversion point and the queue lengths are recomputed. QuickZone assumes that if there are no traveler information services like Variable Message Signs (VMS), Highway Advisory Radio (HAR), Pre-Trip traveler information, only 90% of the capacity on the detours would be utilized. If they are present 100% of the detour capacity would be utilized.

QuickZone then computes the number of vehicles that would change mode and cancel mainline trip for every time period in which total queue length due to lane closure is longer than that of normal condition. The fractions that would cancel trips or change mode are user inputs to the program. This volume is reduced for the first mainline link and all demands and queue lengths for all the downstream links are recomputed.

Aggregate mainline delay for every hour is computed as the average of the total number of vehicles in queue at the beginning and the ending of the hour. The max user delay is computed as the ratio of the number of vehicles in queue to the smallest of capacity available on the mainline links.

7.3.4 Output

QuickZone provides four primary outputs: Project Delay Summary, Travel Behavior Summary, Amortized Delay and Construction Costs and Summary Table.

7.3.4.1 Project Delay Summary

Profiles expected delay by time-of-day in two chart types. The first compares multiple construction phases while the second shows delay for a single construction phase. Within each chart type, the user has the option of which days to show on the graph. The options include: Whole Week or any specific day of the week. The Delay Graph has day and time (24-hour) as the X-axis and Delay/Hour (in Vehicle-Hours) as the Y-axis.

7.3.4.2 Travel Behavior Summary

Displays the number of vehicles that choose one of the four travel behaviors determined for each phase: Cancel Trip, Mode Shift, Hour Time Shift and Takes Detours. It is presented as either a bar graph or as a pie graph. The bar graph shows the number of vehicles that modify their travel behavior on an hour-by-hour basis while the pie graph shows the percentage of vehicles throughout the entire day that modify their travel behavior. The user has the option of which days to show on the graph. The options include: Whole Week or any specific day of the week.

7.3.4.3 Amortized Delay and Construction Costs

Shows the user a summary of the cost, both delay and infrastructure, for the project by year. Each bar in the graph represents the costs for that year. A summary of the total cost per year over a ten year period is provided in a summary box at the bottom of the graph.

7.3.4.4 Summary Table

Provides two tables summarizing the output and user inputs for all the construction phases of the project and broken down further to each of the work zone plans. The output table includes data for Queue, Delay, Travel Behavior and Cost for each construction phase as well as for the individual work zone plans within each construction phase.

The summary table can display different data depending on the user's need. Users can choose from three directions and three cases. The three directions are Inbound, Outbound and both. The three cases are: Baseline (does not take into account the work zone) After (associated only with the work zone) Sum (combination of the baseline and after). The default data values are both directions for the after case.

The Input Data Summary Table provides information on the user input for General Data, Travel Behavior and Mitigation Strategies. The General Data includes Start Time, Ending Time of the Work Zone Plan, Days in Effect, Work Zone Links Affected and change in capacity of all links for each Work Zone Plan within each Construction Phase. Travel Behavior includes Mode Shift Percentage, Cancel Trip Percentage, One-Hour Shifting Percentage, and Endure Mainline Percentage. Mitigation Strategy includes information on Signal Retiming, VMS, Lane Widening, Ramp Metering, Media Campaign, and Reversible Lanes.

7.3.5 Users' Comments on QuickZone

QuickZone version 1.01 was released in late 2002. The authors contacted some of the users of QuickZone for getting information about their experience with QuickZone, if they faced any problems, how reliable the results were and if they had any documentation. We contacted personnel in the departments of transportation of Maryland, North Carolina, Wisconsin and Ohio. Ohio and North Carolina have not used the software at all. Maryland DOT has modified it and that will be discussed in the following section. A consultant for Wisconsin tried using QuickZone for a project on I-94 near Hudson, Wisconsin. However due to the difficulties faced with its use, the consultant switched to FRESIM. Based on that experience they found that inputting the information for the nodes of a big network was a very time consuming job. Also QuickZone needs estimates of the capacity of the work zone, which most users don't know. One other limitation that was found was that QuickZone does not indicate which specific entrances or exits are causing the queuing and which links are most affected. In addition to these users the authors also contacted the developers of QuickZone for any information regarding the validation of QuickZone using field data. It appears that field validation has not been performed.

7.3.6 MD-QuickZone

MD-QuickZone is a customized version of QuickZone. This version was developed by the University of Maryland under contract to the Maryland State Highway Administration as a part of the study entitled "Guidelines to Improve Traffic Operations in Work Zones". MD-QuickZone uses the same algorithm as QuickZone to estimate the queue lengths and user delays. But, MD-QuickZone improves upon QuickZone by adding a few extra capabilities to the QuickZone software. These extra capabilities include Closure Analysis, Work Zone Optimization, Economic Analysis and Capacity Analysis.

The user can define the capacity decrease on individual links affected by the work zone explicitly by choosing the user-defined capacity option.

Closure Analysis

This feature determines the hours during the day when the lanes should be closed without causing excessive queuing and delay for the users. This feature is identical to the Lane Closure Schedule option in QUEWZ 98. The user can specify the maximum acceptable queue lengths and delay values.

Work Zone Optimization

This option can be used to determine an optimal work zone length for varying work zone configurations with different road types. The program determines a minimum cost work zone length and a cycle phasing plan. Presently the program can optimize work zone lengths and cycle times for two-way two-lane rural highways, and only work zone lengths for four-lane divided rural highways.

Economic Analysis Modules

The Economic Analysis Module considers the costs of various work zone traffic control strategies and helps select the most economic work zone traffic control strategy. This module requires input parameters for computing vehicle delay costs, vehicle operating costs, accident costs, traffic control costs, and construction costs. The output data module has two components: economic analysis summary and selection of preferred control strategy. The economic analysis summary table provides the total traffic impact costs and the total construction costs of each alternative.

Capacity estimation

This software gives the user the option to choose from UMCP Model, HCM 2000 or 1997 and User input for estimating the capacity of work zones.

UMCP Model is presented in Kim et al., 2001. This model is a multiple regression model, which expresses work zone capacity as a function of several factors such as the number of closed lanes, the proportion of heavy vehicles, grade and the intensity of work activity. The independent factors considered are

- Number of closed lanes (NUMCL)
- Location of closed lanes (right = 1, otherwise = 0) (LOCCL)
- Proportion of heavy vehicles (HV)
- Lateral distance to the open lanes (LD)
- Work zone length (WL)
- Work zone grade (WG)
- Intensity of work activity (1 or 0 for medium intensity, and 1 or 0 for heavy intensity) (WI)

The model equation is

$$\begin{aligned} CAPACITY = 1857 - 168.1\ NUMCL - 37.0\ LOCCL - 9.0\ HV + 92.7\ LD \\ - \quad 34.3\ WL - 106.1\ WI - 2.3\ WG*HV \end{aligned} \tag{7.4}$$

When the user chooses HCM 1997, the user has to select appropriate work zone capacities that are recommended by 1997 Highway Capacity Manual (HCM) under different lane closure configurations. If the user chooses HCM 2000, capacity is computed using equation 7.5

$$C = (1600 + I - R) * H * N \tag{7.5}$$

C: estimated capacity of the work zone (vehs/hour)

I: effect of work intensity (-160 to +160 vehs/hour)

R: effect of entrance ramps (vehs/hour)

H: effect of heavy vehicles

N: Number of lanes open through the work zone

From the perspective of queue length and user delay estimation, the most attractive feature of MD-QuickZone is the UMCP capacity estimation model. However on reviewing the literature for the UMCP model, concerns with the validity of the model arose. In particular the results of the regression analysis used to get the model are shown in Table 7.1. From Table 7.1 it can be seen that the p-values associated with location of closed lanes (LOCCL), proportion of heavy vehicles (HV), lateral distance to the open lanes (LD), work zone length (WL) are greater than 0.10 (p-value associated with 90% confidence level). Statistically this implies that the coefficients of these factors are not different from zero. Therefore the UMCP model in the present form is inappropriate.

Table 7.1 Results of regression analysis for the UMCP capacity estimation model

Factor	Variable	t – stat	p – value
	CONSTANT	24.49	1.65 E-05
Number of closed lanes	NUMCL	-4.43	0.011
Location of closed lanes	LOCCL	-1.54	0.199
Proportion of heavy vehicles	HV	-1.48	0.212
Lateral distance to the open lanes	LD	1.93	0.125
Work zone length	WL	-1.69	0.166
Intensity of work activity	WI	-2.7	0.054
Work zone grade * Proportion of Heavy vehicles	WG * HV	-3.38	0.028

In this study it was found that QuickZone couldn't be used to estimate the queue lengths and delays at work zones. Though MD-QuickZone has extra capabilities, it is not useful because it used the same algorithm as QuickZone to estimate the queue lengths and user delays and there are genuine and valid concerns with the validity of the UMCP model.

7.4 Parameters from field data for comparison with the software packages

7.4.1 Service capacity of the sites

Capacity of a work zone is one of the most important factors that affect the estimations of queue lengths and user delays experienced at the work zones. QUEWZ has an in-built capacity estimation model. But FRESIM and QuickZone need the capacity of the work zone as user input. To verify the validity of the capacity estimation model in QUEWZ as well as to use FRESIM and QuickZone, it was imperative to estimate the capacity at which the sites were operating when the data was collected in the field.

At the sites without queuing, because the demand was much lower than the capacity, queues were not observed. Naturally the number of departures video taped during the data collection underestimates the service capacity of the site. For this reason the number of departures cannot be used as the service capacity of the site for sites without queuing.

To determine service capacity for sites without queues, the number of departures during every minute of the data collection period was computed from the field data. The five and fifteen minutes that had the highest departure volumes were identified. On closer scrutiny of the headways during these minutes it was found that even in the minutes that had the highest departure volumes there were vehicles with headways longer than four seconds and/or spacing greater than 250 feet. Under capacity discharge conditions, such long headways and large spacings are unexpected. Therefore just considering the average headways of the vehicles in the five or fifteen minutes that had the highest departure volumes would not be a reasonable estimate of the capacity of the sites where there was no queuing. Consequently, the vehicles that were not traveling in platoon condition were removed before computing the average headway of the vehicles. Having computed the average headway of the vehicles, the service capacity was estimated as the inverse of the average headway.

To determine capacity for sites with queues, it was observed that there were occurrences of headways greater than four seconds and/or spacings greater than 250 ft. Therefore, even though there was sufficient demand, the departure volume underestimates the capacity of the work zone. Consequently the procedure that was followed for estimating the service capacity of the sites without queuing was used to estimate the service capacities of the sites with queuing also. The only difference was that the top fifteen minutes were considered rather than the top five minutes for the sites with queuing because there was more consistent demand.

Table 7.2 shows the hourly departure volumes, service capacity calculation based on the top five minutes and the top fifteen minutes of departures. It can be seen that for sites without queuing, if the departure volumes were used as capacity values they would be too low. For sites with queuing the departure volumes are nearer to the service capacity values. Also the service capacity values computed based on the top five minutes and the top fifteen minutes support each other.

Table 7.2 Service Capacity computations

Site	Service Capacity (vph) based on		Hourly throughput (vph)
	Top 5 min	Top 15 min	
I 55 NB 224	1250	1229	597
I 57 NB 250	1706	1750	585
I 57 NB 271	1600	1502	456
I 55 NB 55	1364	1341	1027
I 55 SB 55	1308	1220	982
I 57 SB 212	2035	1882	845
I 74 WB 79	1708	1700	750
I 80 WB 39	1835	1694	524
I 80 EB 44	1528	1551	556
I 70 EB 145	1741	1653	688
I 74 EB 5	1540	1459	1294

7.4.2 Total User Delay

Total User Delay has two components: delay due to slower speed in the work zone and delay due to waiting in queue when the demand exceeds the capacity.

Delay due to slower speed

At sites without queuing, since there is no queue, the only delay is due to the slower speed of travel in the work zone. For each vehicle video taped, the times they arrived at the two markers were noted while reducing the data from the videotapes. Therefore the average speed of every vehicle is known. So the delay for all the vehicles can be computed using equation 7.6.

$$d_{spd} = \sum_{i} \left(\frac{L}{v_i} - \frac{L}{v_{\lim}}\right) \tag{7.6}$$

Where,

d_{spd} = Delay due to slower speed

L = Length of the work zone

v_i = Average speed of the vehicle

v_{lim} = posted speed limit

Delay due to queuing

While collecting the data in the field, queue length information was noted at the beginning of every minute. So the number of vehicles in queue at the beginning and the end of every minute is known. Therefore the total queuing delay (in veh-mins) experienced by the users in that minute is the average of the number of vehicles in queue at the beginning and at the ending of every minute. Therefore the total queuing delay experienced by the users over the duration of data collection can be computed by using equation 7.7.

$$d_q = \sum_{i=1}^{t} \left(\frac{n_i + n_{i+1}}{2} \right) \tag{7.7}$$

Where,

d_q = Delay due to queuing (in veh-minutes)

t = Duration of data collection

n_i = Number of vehicles in queue at the beginning of every minute

However, at the end of the data collection period, if the queue still persists, the delay for these vehicles, can be computed provided the rate at which they are getting discharged is known. If the discharge rate (in vehs/hr) is called r_e, the queuing delay for the i^{th} vehicle in queue at the end of the hour can be computed as i/r_e. Therefore, the queuing delay for the n_e vehicles that are in queue at the end of the data collection period, d_{qe} can be computed using equation 7.8. Also the delay due to slower speed for these vehicles has been computed by making a reasonable assumption that these vehicles would travel at the average speed of the vehicles that departed during the last fifteen minutes of data collection period. There is no data to estimate the discharge rate after the end of the data collection period. So a reasonable estimate of that discharge rate was taken to be the discharge rate observed during the last fifteen minutes of the data collection period.

$$d_{qe} = \frac{n_e \times (n_e + 1)}{2} \times \frac{1}{r_e} \tag{7.8}$$

Similarly, if there were queue at the beginning of the data collection period, the queue waiting delay for these users must be accounted for, in the total delay experienced by the users. If the rate at which those vehicles arrived, r_b were known, the waiting delay for the i^{th} vehicle in queue is given by i/r_b. Therefore, the queuing delay for the n_b vehicles that are in queue at the beginning of the data collection period, d_{qb} can be computed using equation 7.9. There is no data to estimate the arrival rate before the data collection period. So a reasonable estimate of that arrival rate was taken to be the current arrival rate.

$$d_{qb} = \frac{n_b \times (n_b + 1)}{2} \times \frac{1}{r_b} \tag{7.9}$$

Using the methodology described above the total delay for the three sites with queuing was computed. Table 7.3 shows the delay due to slower speed, waiting delay and total delay at the three sites in vehicle-hours.

Table 7.3 Delays from the field data

Site	Delay in Field		
	Delay due to slower speed (veh hrs)	Delay due to waiting in queue (veh hrs)	Total delay (veh hrs)
I 74 EB 5	78	386	464
I 55 SB 55	197	364	561
I 55 NB 55	99	958	1056

7.5 Comparison of Field data with QUEWZ

Among the three software packages evaluated in this study, QUEWZ has a built-in model for estimating the capacity of the work zone, based on default values for the model's parameters. Therefore, the first approach taken in using QUEWZ was to plug in the site data and not to change the default values for the parameters. The second approach was to modify the parameters in QUEWZ to get the service capacity observed in the field for the different sites.

The measures of effectiveness (MOEs) used for comparing the QUEWZ output to field data are average speed of the vehicles and the average queue length.

7.5.1 Default QUEWZ

QUEWZ uses default values of zero for the parameters I (effect of work intensity on capacity) and R (effect of the presence of ramps within the lane closure), and a default value of 1.7 for E (passenger car equivalence) in estimating the capacity of the work zone. These values were unaltered in order to evaluate the work zone capacity estimation model of QUEWZ.

For each of the sites, data files were created using the following data observed in the site during the data collection period:

- Hourly volume
- Percentage Heavy vehicles
- Lane closure data
    - Length
    - Configuration (i.e., number of lanes closed)
    - Closure schedule (hours during which the lanes were closed)

7.5.1.1 Sites without queuing

Of the eleven sites that were used for evaluating the software, in eight sites no queues were observed during the data collection. The results of running QUEWZ with the default values, for the eight sites where there was no queuing are shown in Table 7.4. Table 7.4 shows the percentage heavy vehicles observed hourly volume, service capacity, and average speed for the eight sites along with the QUEWZ estimates of capacity and average speed.

The difference between the service capacity and the capacity estimated by QUEWZ ranges from –38 to 665 vphpl. On the average the capacities estimated by QUEWZ were less than the service capacities observed in the field by 363 vphpl. Figure 7.2 compares the capacity estimated by QUEWZ versus the service capacity that was observed in the field. From the figure we can see that QUEWZ consistently underestimates the capacity of the work zone. Paired t-test was performed to verify if the capacity estimated by QUEWZ was statistically less than the service capacity observed in the field. The t-statistic for paired t-test is 4.658, which is greater than the critical t-value for 95% confidence level. Therefore QUEWZ significantly underestimated the service capacity.

Table 7.4 Results of Default QUEWZ for non-queuing sites

Site	P (% HV)	1 st hour volume (vph)	2nd hour volume (vph)	Service Capacity (vphpl)	QUEWZ Default Capacity (vphpl)	Average Speed returned by QUEWZ in default case (mph)	Average speed in field (mph)
I 55 NB 224	35.37	605	588	1250	1288	53	33.63
I 57 NB 250	24.95	574	596	1706	1362	53.5	47.18
I 57 NB 271	27.22	446	465	1600	1343	55	42.22
I 57 SB 212	23.98	837	853	2035	1370	51	56.07
I 74 WB 79	21.01	771	729	1708	1394	52	44.04
I 80 WB 39	42.25	505	542	1835	1234	53.5	53.84
I 80 EB 44	41.53	519	592	1528	1239	53.5	48.31
I 70 EB 145	37	641	735	1741	1270	51.5	49.85

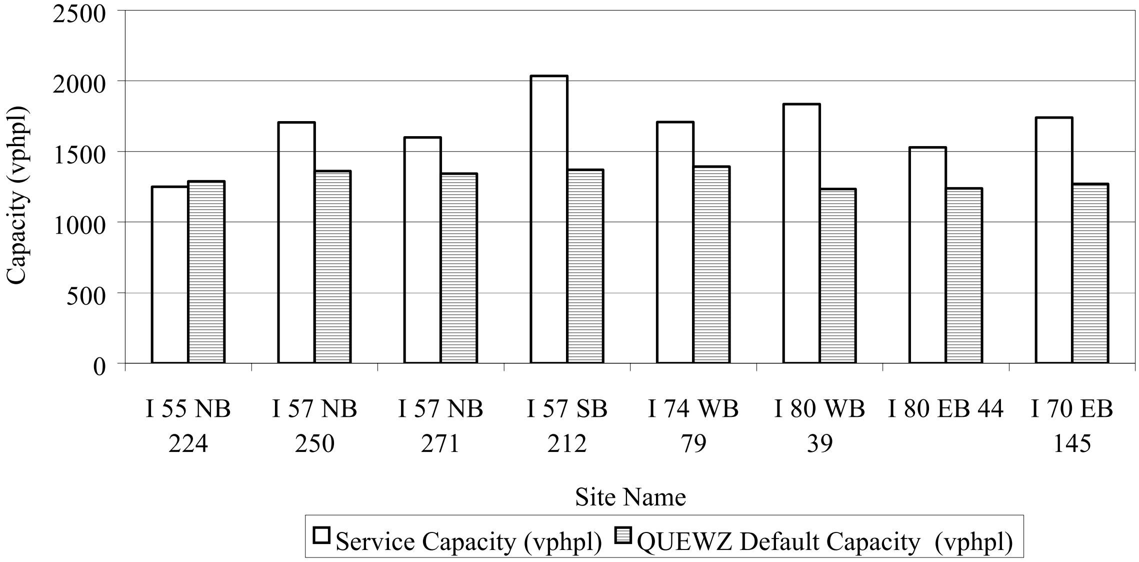


Figure 7.2 Service Capacity in Field Vs Default Capacity returned by QUEWZ for sites without queuing

Only for I55 NB 224 site is the capacity estimated by QUEWZ (1288 vphpl) very close to the service capacity (1250 vphpl). On reviewing the site notes it was noted that of the two hours the data was collected, for one and a half-hour there was a flagger slowing down the vehicles. The average speed of the vehicles when there was no flagger was 41.48 mph and when the flagger was present the average speed was 31.15 mph. This significant reduction in speed due to the flagger resulted in a lower service capacity at this site.

The difference between the average speed observed in the field and the average speed estimated by QUEWZ ranges from –0.34 to 19.37 mph. On the average the speeds estimated by QUEWZ were greater than the speeds observed in the field by 5.98 mph. Paired t-test was performed to verify if the speed estimated by QUEWZ was statistically greater than the speed observed in the field. The t-statistic for paired t-test is 2.208, which is greater than the critical t-value for 95% confidence level. Therefore QUEWZ consistently overestimated the speed when there was no queuing. Figure 7.3 compares the average speed estimated by QUEWZ versus the average speed that was observed in the field.

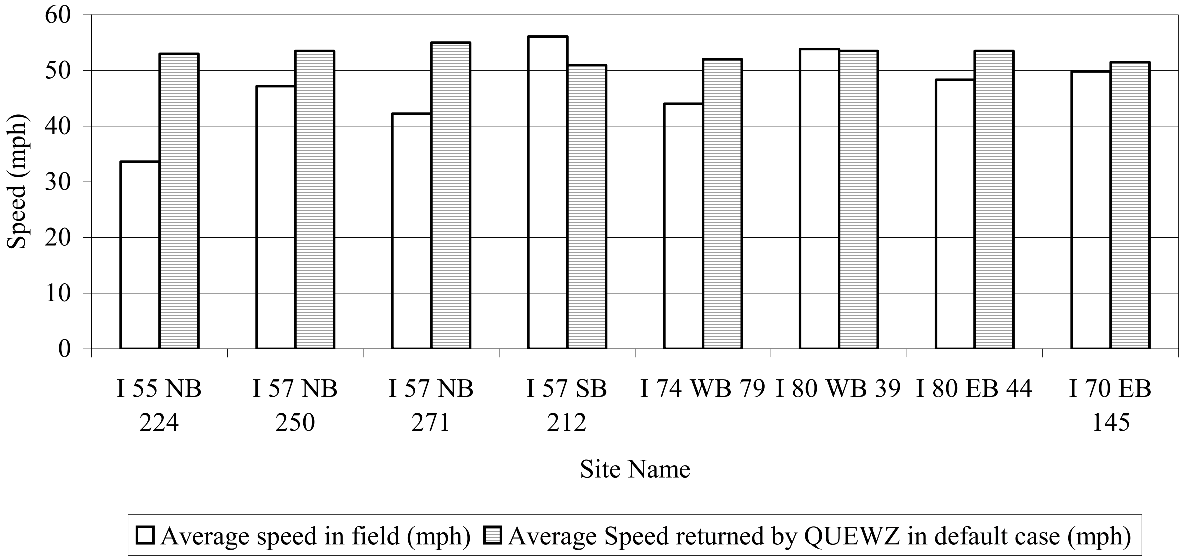


Figure 7.3 Average Speed in Field Vs Average speed returned by QUEWZ in Default case for sites without queuing

7.5.1.2 Sites with queuing

The results of running QUEWZ with the default values, for the three sites where there was queuing are shown in Table 7.5.

Table 7.5 Results of Default QUEWZ for queuing sites

Site	P (% HV)	Default Capacity in QUEWZ (vphpl)	Service Capacity in Field (vphpl)	1st hour volume (vph)	2nd hour volume (vph)	Average Speed for 1st hour returned by QUEWZ (mph)	Average Speed for 2nd hour returned by QUEWZ (mph)	Average speed in field in 1st hour (mph)	Average speed in field in 2nd hour (mph)	Average queue length returned by QUEWZ (m)	Average queue length in field (m)
I 55 NB 55	13.06	1465	1341	1568	975	30	46	24.04	26.44	0.2, 0.2	1.94,1.5
I 55 SB 55	18.08	1420	1220	1320	n/a	46	n/a	19.18	n/a	0	1.91
I 74 EB 5	3.9	1557	1459	1860	n/a	30	n/a	20.88	n/a	0.6	0.93

Table 7.5 shows the percentage heavy vehicles, observed hourly volume, service capacity, average speed and average queue length for the three sites along with the QUEWZ estimates of capacity, average speed and average queue length.

The difference between the capacity estimated by QUEWZ and the service capacity ranges from 98 to 200 vphpl. On the average the capacities estimated by QUEWZ were greater than the service capacities observed in the field by 141 vphpl. Figure 7.4 compares the capacity estimated by QUEWZ versus the service capacity that was observed in the field. From the figure we can see that QUEWZ consistently overestimates the capacity of the work zone when there is queuing. Because of the small sample size of three, statistical test was not performed to verify that the estimated capacity is higher than the observed service capacity.

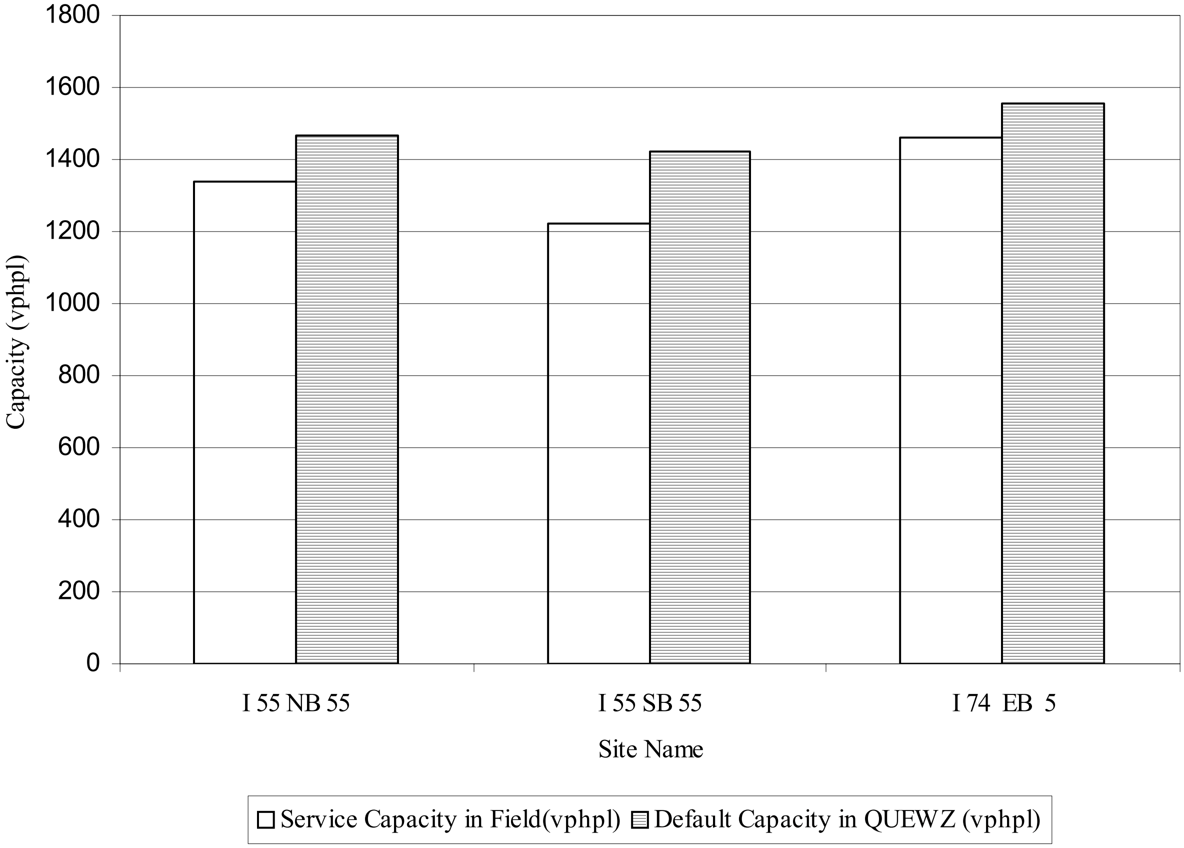


Figure 7.4 Service Capacity in Field Vs Default Capacity returned by QUEWZ for sites with queuing

The difference between the average speed estimated by QUEWZ and the average speed observed in the field ranges from 5.96 to 26.82 mph. On the average the speeds estimated by QUEWZ were greater than the speeds observed in the field by 15.36 mph. Figure 7.5 compares the average speed estimated by

QUEWZ versus the average speed that was observed in the field. It can be seen that for sites with queuing QUEWZ consistently overestimates the speed in the default case. Because of the small sample size of three, statistical test was not performed to verify that the estimated speed is higher than the observed speed.

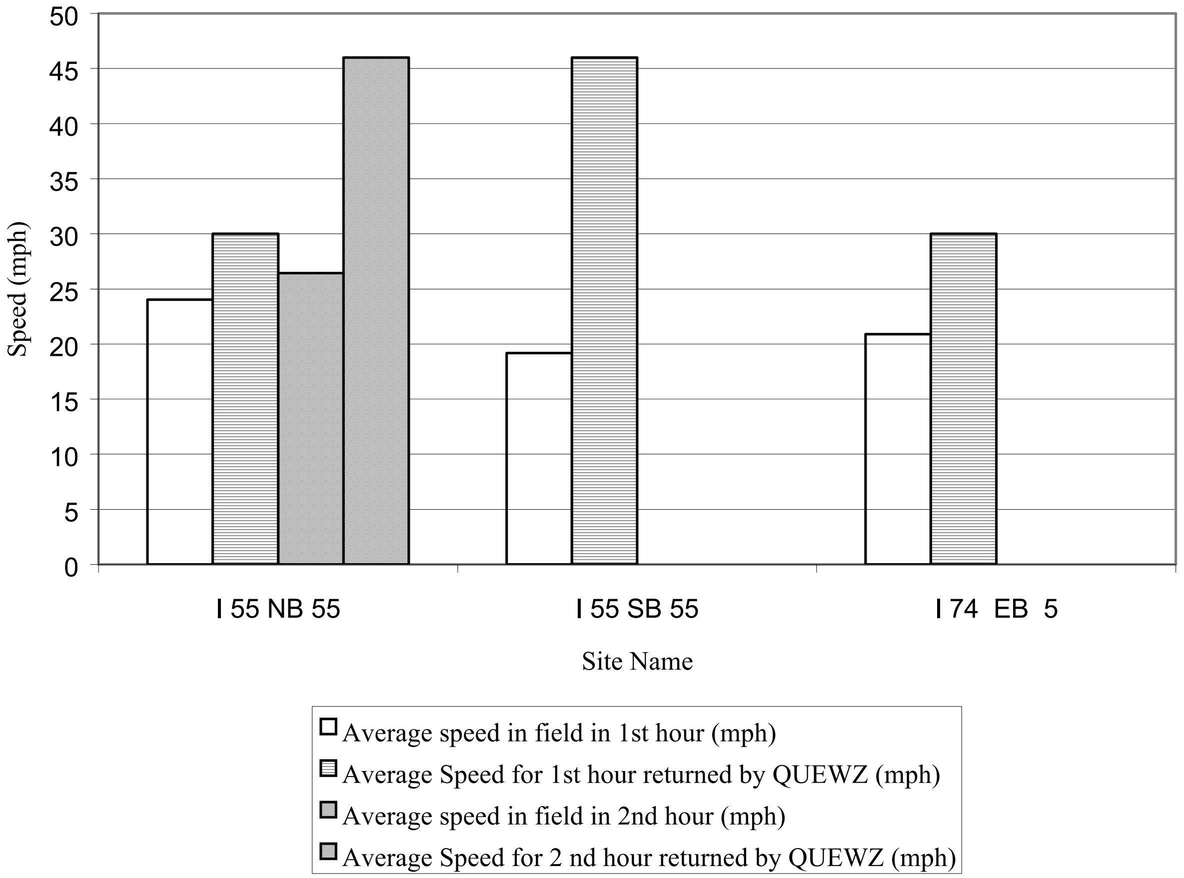


Figure 7.5 Average Speed in Field Vs Average speed returned by QUEWZ in default case for sites with queuing

The difference between the average queue length observed in the field and the average queue length estimated by QUEWZ ranges from 0.33 to 1.91 miles. On the average the queue lengths estimated by QUEWZ were less than the queue lengths observed in the field by 1.32 mile. Figure 7.6 compares the average queue lengths estimated by QUEWZ versus the average queue lengths that were observed in the field. It can be seen that QUEWZ consistently underestimates the queue length in the default case. For I 55 SB 55 site QUEWZ does not return any queue length because the default capacity estimated by

QUEWZ is greater than the demand. Because QUEWZ uses the Input-Output analysis method for computing the queue lengths, the estimated average queue lengths for that site is zero.

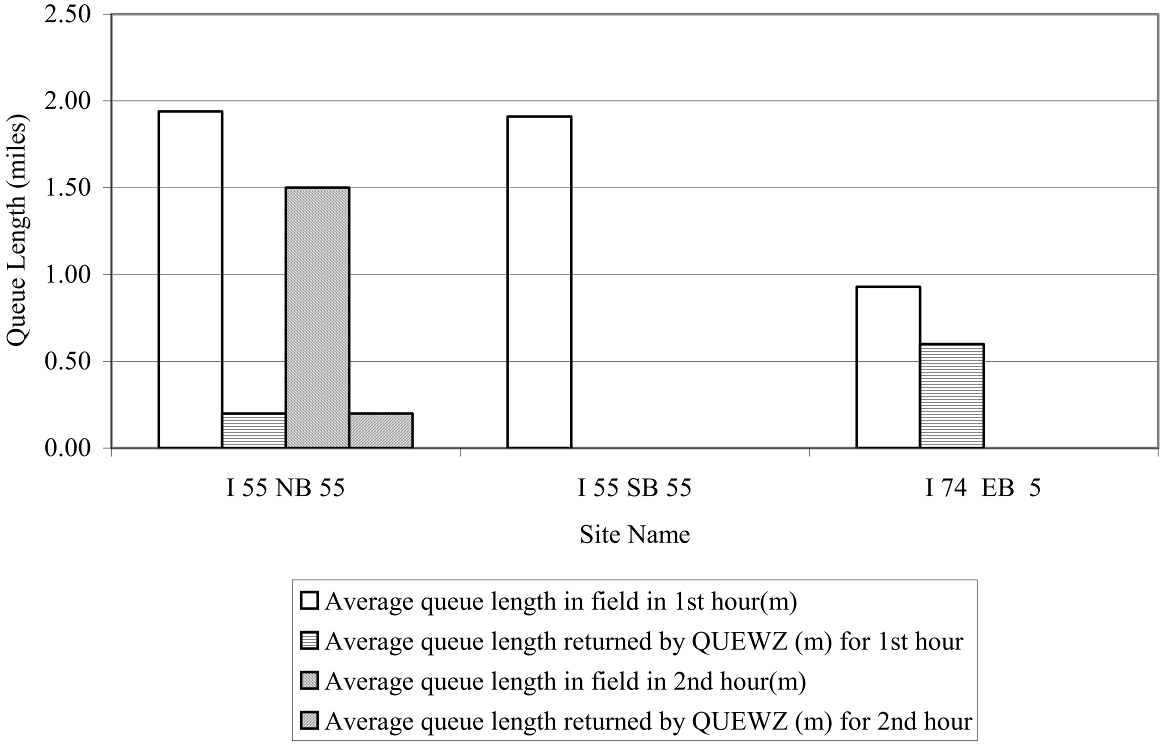


Figure 7.6 Average Queue length in Field Vs Average Queue length returned by QUEWZ in default case for sites with queuing

7.5.1.3 Findings for Default QUEWZ

In the default case it was found that QUEWZ underestimated the service capacity and overestimated the average speeds when there was no queuing in the site. When there was queuing, QUEWZ overestimated the capacity and the average speed and underestimated the average queue length in the default case. From the statistical tests it can be concluded with 95% confidence that the estimates of QUEWZ are different from the observed field data when there is no queuing. Since QUEWZ estimate of capacity does not match the field capacity, the discrepancy in the results is expected. Therefore the next logical approach would be to check if any reasonable modifications of QUEWZ would result in QUEWZ estimating the capacity correctly.

7.5.2 Modified QUEWZ

As has been explained earlier, QUEWZ uses default values of zero for the parameters I (effect of work intensity on capacity) and R (effect of the presence of ramps within the lane closure), and a default value of 1.7 for E (passenger car equivalence) in estimating the capacity of the work zone. The user can modify these default values and it is possible to get the service capacity observed in the field as the capacity estimated by QUEWZ.

The model estimates the capacity per lane using equations 7.10 and 7.11 (Same as equations7.2 and 7.3)

$$C = (1600-I-R)*H \tag{7.10}$$

Where,

$$H = 100/[100+P*(E-1)] \tag{7.11}$$

P represents the percentage of heavy vehicles.

As the first step towards this modification, the default values for I and R (zero) were not changed. The passenger car equivalence factor (E) was modified so that we could get the desired capacity value. The value of the factor H was back calculated to get the desired service capacity using the equation 7.12

$$H = C/1600 \tag{7.12}$$

Table 7.6 Passenger car equivalence (E) values used for different sites

Site	P (% HV)	C (desired Capacity in vphpl)	H = C/1600	E
I 55 NB 224	35.37	1250	0.78	1.79
I 57 NB 250	24.95	1706	1.07	0.75
I 57 NB 271	27.22	1600	1.00	1.00
I 55 NB 55	13.06	1341	0.84	2.48
I 55 SB 55	18.08	1220	0.76	2.72
I 57 SB 212	23.98	2035	1.27	0.11
I 74 WB 79	21.01	1708	1.07	0.70
I 80 WB 39	42.25	1835	1.15	0.70

Table 7.6: Continued

I 80 EB 44	41.53	1528	0.96	1.11
I 70 EB 145	37	1741	1.09	0.78
I 74 EB 5	3.9	1459	0.91	3.48

Knowing the percentage heavy vehicles in the site (P) and H, equation 7.11 was used to calculate the value of E. This value of E was used to get the service capacity as the QUEWZ estimate of capacity. Table 7.6 shows the values that were used for E for the different sites. These calculated values for E were used and QUEWZ was run again.

7.5.2.1 Sites without queuing

The results of running QUEWZ with the modified values for passenger car equivalence, for the eight sites where there was no queuing are shown in Table 7.7.

Table 7.7 Results of QUEWZ for non-queuing sites in service capacity case

Site	P (% HV)	1 st hour volume (vph)	2nd hour volume (vph)	Service Capacity (vphpl)	Average Speed returned by QUEWZ in Service Capacity case (mph)	Average speed in field (mph)
I 55 NB 224	35.37	605	588	1250	53	33.63
I 57 NB 250	24.95	574	596	1706	55	47.18
I 57 NB 271	27.22	446	465	1600	56	42.22

Table 7.7: Continued

I 57 SB 212	23.98	837	853	2035	n/a	56.07
I 74 WB 79	21.01	771	729	1708	53.5	44.04
I 80 WB 39	42.25	505	542	1835	n/a	53.84
I 80 EB 44	41.53	519	592	1528	54.5	48.31
I 70 EB 145	37	641	735	1741	54	49.85

Table 7.7 shows the percentage heavy vehicles, observed hourly volume, service capacity, and average speed for the eight sites along with the QUEWZ estimates of capacity and average speed when service capacity is given as the input.

QUEWZ assumes that capacity of a work zone with work activity cannot be greater than 90% of the normal capacity when there is no lane closure. In QUEWZ the normal capacity is assumed to be 2000 vphpl. Consequently QUEWZ does not permit the capacity of a work zone (with work activity) to be greater than 1800. So QUEWZ could not be used to evaluate I 57 SB 212 and I 80 WB 39 sites with their service capacities. However to get a rough estimate of the speeds, QUEWZ was used for the two sites with a service capacity of 1800 vphpl. QUEWZ estimated the average speeds for the two sites to be 55.5 and 53 mph.

The difference between the average speed observed in the field and the average speed estimated by QUEWZ ranges from 4.15 to 19.37 mph. On the average the speeds estimated by QUEWZ were greater than the speeds observed in the field by 10.13 mph. Figure 7.7 compares the average speed estimated by QUEWZ versus the average speed that was observed in the field. It can be seen that QUEWZ consistently overestimated the speed in the sites. Paired t-test was performed to verify if the speed estimated by QUEWZ was statistically greater than the speed observed in the field. The t-statistic for paired t-test is 4.058, which is greater than the critical t-value for 95% confidence level. Therefore QUEWZ consistently overestimated the speed when there was no queuing.

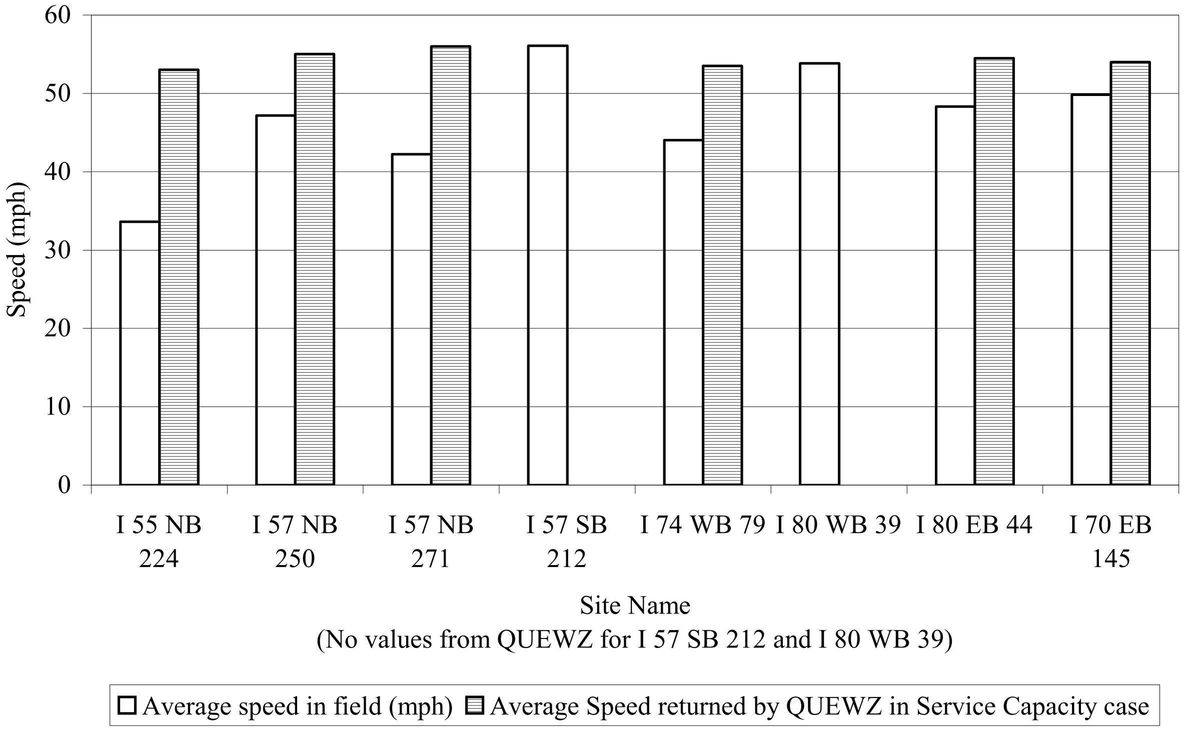


Figure 7.7 Average Speed in Field Vs Average speed returned by QUEWZ in Service Capacity case for sites without queuing

7.5.2.2 Sites with queuing

The results of running QUEWZ with the modified values for passenger car equivalence, for the three sites where there was queuing are shown in Table 7.8.

Table 7.8 Results of QUEWZ for queuing sites in service capacity case

Site	P (% HV)	Service Capacity (vphpl)	1 st hour volume (vph)	2nd hour volume (vph)	Average Speed returned by QUEWZ for 1st hour (mph)	Average Speed returned by QUEWZ for 2nd hour (mph)	Average speed in field in 1st hour (mph)	Average speed in field in 2nd hour (mph)	Average queue length returned by QUEWZ (m)	Average queue length in field (m)
I 55 NB 55	13.06	1341	1568	975	30	37	24.0374	26.4440	0.4,0.4	1.94,1.5

Table 7.8: Continued

I 55 SB 55	18.08	1220	1320	n/a	30	n/a	19.1813	N/A	0.2	1.91
I 74 EB 5	3.9	1459	1860	n/a	30	n/a	20.8817	n/a	0.8	0.93

Table 7.8 shows the percentage heavy vehicles observed hourly volume, service capacity, average speed and average queue length for the three sites along with the QUEWZ estimates of average speed and average queue length.

The difference between the average speed estimated by QUEWZ and the average speed observed in the field ranges from 5.96 to 10.82 mph. This is better than the default case when the range was from 5.96 to 26.82 mph. On the average the speeds estimated by QUEWZ were greater than the speeds observed in the field by 10.56 mph, which is better than 19.56 mph overestimation in the default case. Figure 7.8 compares the average speed estimated by QUEWZ versus the average speed that was observed in the field. It can be seen that for sites with queuing QUEWZ consistently overestimates the speed in the default case. Because of the small sample size, statistical test was not performed.

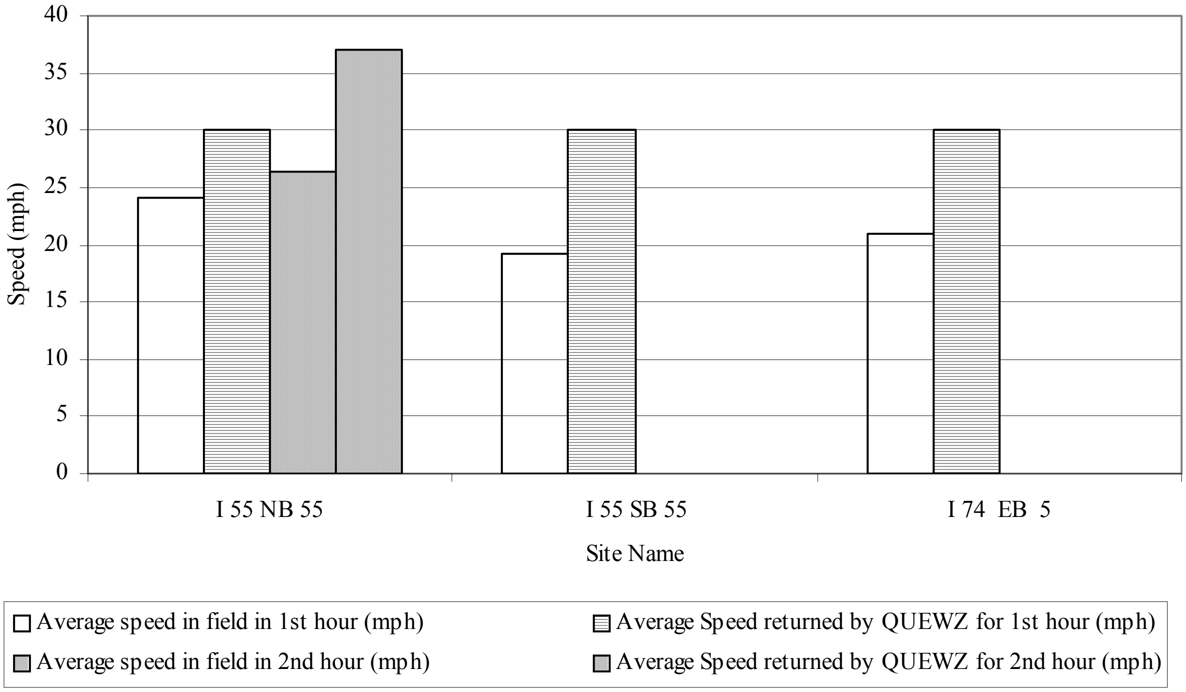


Figure 7.8 Average Speed in Field Vs Average Speed returned by QUEWZ in service capacity case for sites with queuing

The difference between the average queue length observed in the field and the average queue length estimated by QUEWZ ranges from 0.13 to 1.71 miles. On the average the queue lengths estimated by QUEWZ were lesser than the queue lengths observed in the field by 1.12 mile. Figure 7.9 compares the average queue lengths estimated by QUEWZ versus the average queue lengths that were observed in the field. It can be seen that QUEWZ consistently underestimates the queue length even after inputting the service capacity. Because of the small sample size, statistical test was not performed.

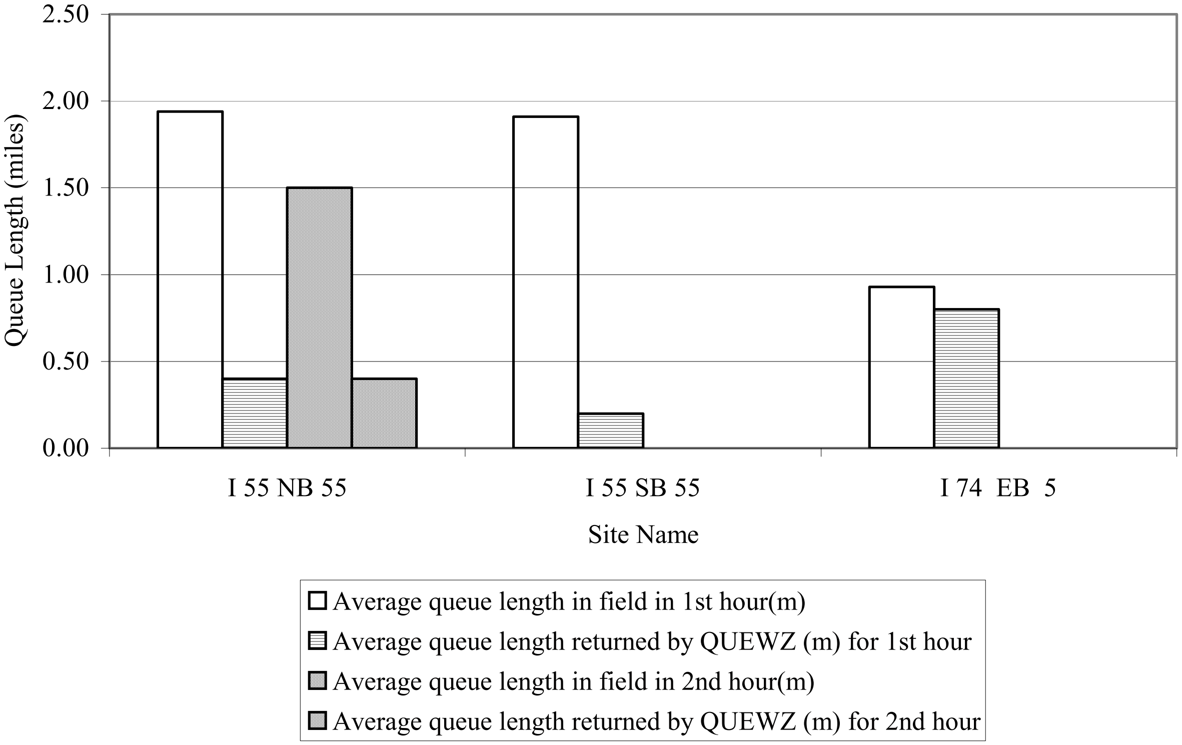


Figure 7.9 Average Queue length in Field Vs Average Queue length returned by QUEWZ in service capacity case for sites with queuing

7.5.2.3 Findings for Modified QUEWZ

In this case the passenger car equivalence was modified, even though some were not unreasonable, to get the service capacity observed in the field as the value estimated by QUEWZ. Nevertheless, it was found that QUEWZ overestimated the average speed of the vehicles in both queuing and non-queuing sites. Also the QUEWZ estimates of queue length were much below the observed queue lengths. So even after fixing the problem with capacity QUEWZ results do not match the field data.

7.5.3 Findings for QUEWZ

In the default case QUEWZ underestimated the service capacity and overestimated the average speed when there was no queuing in the site. When there is queuing, QUEWZ overestimated the capacity and the average speed and underestimated the average queue length in the default case. The passenger car equivalence was modified to get the service capacity observed in the field as the value estimated by QUEWZ. Nevertheless, it was found that QUEWZ overestimated the average speed of the vehicles in both queuing and non-queuing sites. Also the QUEWZ estimates of queue length were much below the observed queue lengths. Having found that Default QUEWZ results do not match field data, reasonable and logical modifications were made to QUEWZ. Despite this the results from QUEWZ did not match the field data.

7.6 Comparison of field data with FRESIM

Each of the sites was modeled in FRESIM with the following data observed in the field

- Hourly volume
- Percentage Heavy vehicles
- Lane closure data
    - length
    - configuration (i.e., number of lanes closed)
- Free-flow speed

The free flow speed of the drivers in the different sites was taken to be the speed limit posted at the different sites. However to verify this assumption, the average speed of the vehicles that were not travelling in platoon was computed (when there was no queuing for sites with queuing). If this value differed from the speed limit by more than 10%, then the average speed of the non-platoon vehicles was used as the free flow speed. Table 7.9 compares the average speed of non-platoon vehicles with the speed limit posted at the sites.

Table 7.9 Comparison of average speed of non-platoon vehicles with posted speed limit

Site	Average speed of non-platoon vehs	Posted Speed Limit
I 55 NB 224	37.51	45
I 55 NB 224 A	35.20	45
I 55 NB 224 B	43.79	45
I 57 NB 250	48.21	45

Table 7.9: Continued

I 57 NB 271	43.06	45
I 55 NB 55	n/a	55
I 55 SB 55	43.55	45
I 57 SB 212	57.18	55
I 74 WB 79	45.75	45
I 80 WB 39	53.91	55
I 80 EB 44	50.17	55
I 70 EB 145	51.32	55
I 74 EB 5	49.03	55

From the table it can be seen that for I 55 NB 224 and I 74 EB 5, the average speeds of non-platoon vehicles differed from the speed limit by more than 10%. At the I 55 NB 224 site a flagger was present for one and one half-hour of the two hours the data was collected. The presence of the flagger reduced the speed at which the drivers were traveling through the work zone. So the data was considered on I 55 NB 224A when a flagger was present and on I 55 NB 224B when the flagger was absent. When this distinction is made we can see that the average speed of non-platoon vehicles without the flagger is very close to 45 mph, the posted speed limit. No such factors were present in the I 74 EB 5 site. At I 55 NB 55, queuing was present all through the data collection period. So the speed limit was assumed to be the free flow speed.

7.6.1 Specifying capacity in FRESIM

Since FRESIM is a microscopic simulation model, the user cannot directly specify macroscopic parameters such as capacity. The capacity of a link in FRESIM is a function of several different parameters. However, Car Following Sensitivity Factor (CFSF) is the prime factor that affects the capacity of a link. The car following sensitivity factor is like the desired headway of the drivers. The lower the value of CFSF, the higher would be the capacity.

FRESIM uses the Pitt car following model (Halati et al., 1997) developed by the University of Pittsburgh. Earlier research (Crowther, 2001) has established the speed-flow relationship that evolves from the Pitt steady-state car following behavior.

$$q_c = \frac{u_f}{h_j + c_3 u_f}$$

where,

q_c = capacity (vph)

u_f = free-flow speed (mph)

h_j = vehicle spacing when traffic is completely stopped (mi)

c_3 = car following sensitivity factor (h)

From the field data we have the service capacity, the free flow speed and the proportion of heavy vehicles at every site. The vehicle spacing, h_j was computed as the sum of the effective vehicle length and the minimum vehicle separation distance of 10 ft (default value in FRESIM). FRESIM computes the effective vehicle length by adding three feet to the actual vehicle length. The average vehicle length was computed as the weighted average of the vehicle lengths plus three feet. The passenger car and heavy vehicle lengths were taken to be 20ft and 55 ft respectively.

This data was used in the above relationship to estimate the CFSF factor for getting the service capacity observed in the field in FRESIM. Table 7.10 shows the CFSF factors computed based on the percentage of heavy vehicles, average vehicle length, service capacity, and free flow speed at the different sites. Simulation runs were performed to verify that the resulting capacity was the service capacity observed in the field. It was observed that using the computed CFSF factors shown in Table 7.10 resulted in capacity values that were not close enough to the service capacity. The CFSF factor was modified and more simulation runs were performed before the CFSF factor for the site was fixed. Table 7.10 also shows the actual value used for CFSF for the different sites. These CFSF factors were used and 10 simulation runs were performed to ensure that the average of the capacity observed in the ten runs did not differ significantly from the service capacity in the field. Table 7.10 also shows the average capacity of the ten runs along with the service capacity observed in the field. The maximum difference in service capacity and average capacity is 16 vphpl and the average difference was 6 vphpl. These values of CFSF were used in all subsequent simulation runs.

As has been mentioned earlier, FRESIM models ten different driver types. Potentially each driver type can be assigned a different CFSF factor. Very scant research has been performed to study the effect of mean and variance of the distribution of car following sensitivity factors on the capacity. However, earlier research (Halati et al., 1997) has concluded that the mean value of the distribution of CFSF was important and the variance had a lesser impact on the capacity. Consequently, the same CFSF factor was used for all the ten different driver types.

Table 7.10 Comparison of average capacity of 10 runs of FRESIM with service capacity

Site	P (% HV)	Average vehicle length (ft)	Service Capacity (vphpl)	Free flow speed (mph)	Calculated CFSF Factor	CFSF Factor used	Mean discharge of 10 runs (vphpl)
I 55 NB 224	35.37	32	1250	45	2.19	2.19	1240
I 55 NB 224 A	34.45	32	1250	34.5	1.99	1.95	1235
I 55 NB 224 B	38.14	33	1250	45	2.18	2.19	1240
I 57 NB 250	24.95	29	1706	45	1.48	1.43	1706
I 57 NB 271	27.22	30	1600	45	1.61	1.57	1593
I 55 NB 55	13.06	25	1341	55	2.22	2.19	1339
I 55 SB 55	18.08	26	1220	45	2.36	2.34	1211
I 57 SB 212	23.98	28	2035	55	1.26	1.2	2023
I 74 WB 79	21.01	27	1708	45	1.50	1.45	1707
I 80 WB 39	42.25	35	1835	55	1.37	1.29	1834
I 80 EB 44	41.53	35	1528	55	1.77	1.73	1534
I 70 EB 145	37	33	1741	55	1.50	1.45	1737
I 74 EB 5	3.9	21	1459	49	1.99	1.99	1443

7.6.2 Sites without queuing

Eight of the eleven sites did not have any queuing during the time the data was collected. Each of the sites was modeled in FRESIM as a series of three links, the entry link, the work zone link and the exit link. Ten simulation runs were performed for each of the sites. Table 7.11 shows the mean of the average speeds in the ten runs along with the associated estimate of error based on a 95% confidence level. As the error is less than 0.10 mph, more simulation runs were not performed.

Table 7.11 Average speeds returned by 10 runs of FRESIM

Site	Average speed in field (mph)	Mean of average speed of 10 runs (mph)	Error based on 95% confidence level (mph)	Average speed from Run #									
				1	2	3	4	5	6	7	8	9	10
I 55 NB 224	33.63	43.91	0.04	43.93	43.98	44.06	43.91	43.78	43.76	43.93	43.98	43.87	43.94
I 55 NB 224 A	31.01	33.12	0.02	33.09	33.16	33.15	33.12	33.11	33.15	33.09	33.19	33.01	33.10
I 55 NB 224 B	41.33	43.98	0.04	44.04	43.95	44.07	43.94	43.93	44.02	43.81	44.07	43.97	44.04
I 57 NB 250	47.18	43.94	0.07	44.08	44.01	44.04	43.73	43.84	43.99	44.16	44.01	43.81	43.70
I 57 NB 271	42.22	44.17	0.05	44.10	44.18	44.11	44.25	44.26	44.02	44.25	44.37	44.06	44.13
I 57 SB 212	56.07	52.58	0.05	52.54	52.74	52.63	52.65	52.61	52.73	52.49	52.43	52.59	52.43
I 74 WB 79	44.04	42.56	0.05	42.55	42.64	42.61	42.47	42.44	42.76	42.62	42.59	42.51	42.43
I 80 WB 39	53.84	53.72	0.04	53.78	53.81	53.75	53.82	53.79	53.66	53.65	53.70	53.60	53.68
I 80 EB 44	48.31	53.67	0.07	53.76	53.46	53.79	53.67	53.94	53.60	53.76	53.72	53.45	53.57
I 70 EB 145	49.85	51.93	0.06	51.98	52.01	52.08	52.00	51.90	51.66	52.03	51.80	51.89	51.92

Table 7.12 Comparison of average speeds returned by FRESIM with average speed observed in the field for sites without queuing

Site	Average speed in field (mph)	Mean of average speed of 10 runs (mph)	Difference (mph)
I 55 NB 224 A	31.01	33.12	2.10
I 55 NB 224 B	41.33	43.98	2.65
I 57 NB 250	47.18	43.94	-3.24
I 57 NB 271	42.22	44.17	1.95
I 57 SB 212	56.07	52.58	-3.49
I 74 WB 79	44.04	42.56	-1.48
I 80 WB 39	53.84	53.72	-0.12
I 80 EB 44	48.31	53.67	5.36
I 70 EB 145	49.85	51.93	2.08

Figure 7.10 compares the average speed of the 10 simulation runs to the field data. It can be seen that only for I 55 NB 224 case the speed difference is greater than 10 mph. As has been mentioned earlier, in I 55 NB 224 a flagger was present for one and a half-hour out of the two hours the data was collected. So two cases were considered I 55 NB 224A when flagger was present and I 55 NB 224B when flagger was absent. Table 7.12 compares the average speed returned by FRESIM with the average speed observed in the field and also shows the difference. The average speed returned by FRESIM is very close to the

average speed in the field. The difference in the average speed returned by FRESIM and the average speed in the field ranges from –3.49 to 5.36 mph and the average difference is 0.65 mph.

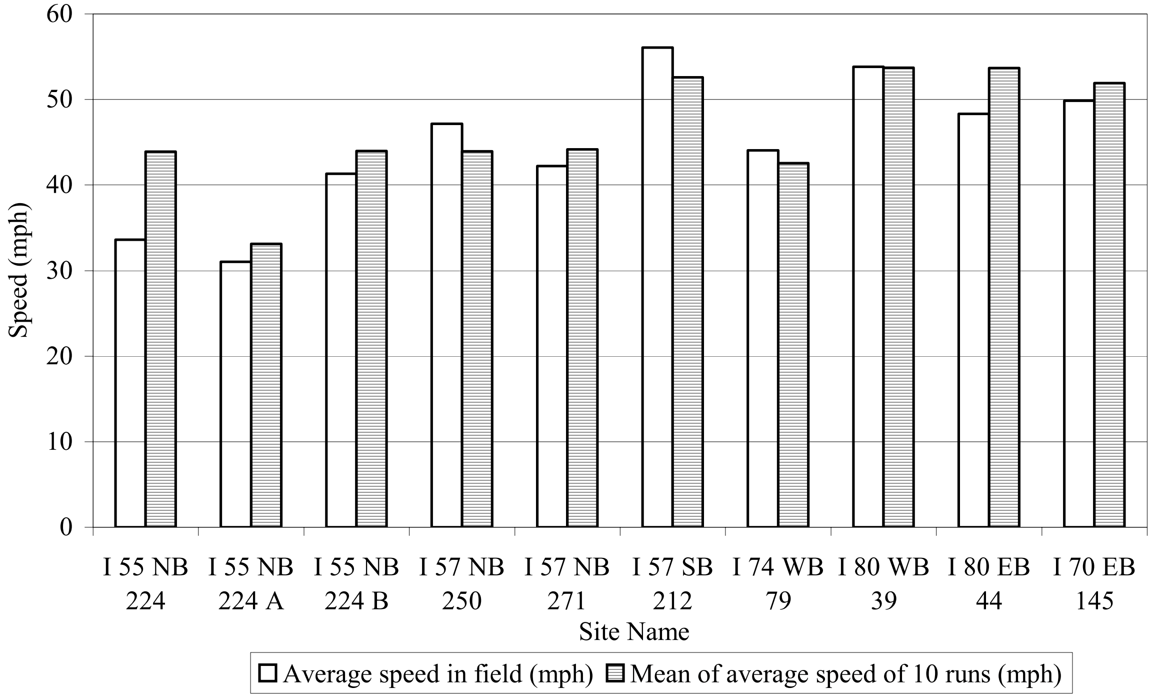


Figure 7.10 Average Speed in Field Vs Mean of Average speed given by 10 runs of FRESIM for sites without queuing

To find if it can be concluded that the average speed returned by FRESIM is not different from average speed observed in the field, the paired t-test was performed. It can be stated that the two values are the same at the 97 % confidence level. Therefore we can conclude that in low volume conditions when there is no queuing, FRESIM's estimate of average speed in the work zones is same as the speed observed in the field.

7.6.3 Sites with queuing

Three sites had queuing during the time the data was collected. Each of the sites was modeled in FRESIM as a series of links representing roadway before the lane closure taper, the reduced-lane section and after work zone section. Twenty-five links for upstream of the work zone, one link for the work zone and one link after the work zone were used. In the case of queuing sites upstream links were modeled while they were not modeled in non-queuing sites because we need to estimate the extent of queuing upstream of the taper. Ten simulation runs were performed for each of the sites.

From the data collected at I 55 SB 55 and I 74 EB 5 sites, queuing was observed for one full hour while at I 55 NB 55 queuing was observed for 2 full hours. In I 55 SB 55 and I 74 EB 5 at the beginning of the hour considered for the simulation no queue was present. Therefore the number of arrivals was considered as the hourly demand for these two sites. But at I 55 NB 55 queuing was present to begin with. This condition cannot be simulated in FRESIM. FRESIM cannot be initialized to have a queue on the link. Therefore the hourly demand was taken to be the sum of the number of vehicles in queue and the arrivals during the hour at the end of the queue. Table 7.13 shows the number of arrivals, vehicles in queue at the beginning of the hour and the demand values used in FRESIM.

Table 7.13 Results from FRESIM for sites without queuing

Site	# of arrivals at the end of the queue	# of vehs in queue at the beginning of the hour	Hourly demand used in FRESIM (vph)	Average speed in field (mph)	Mean of average speed of 10 runs (mph)	Difference between FRESIM speed and field speed (mph)
I 74 EB 5	1860	0	1860	20.88	41.85	20.97
I 55 SB 55	1320	0	1320	19.18	39.46	20.28
I 55 NB 55 hour 1	1568	297	1865	24.04	45.50	21.46
I 55 NB 55 hour 2	975	332	1307	26.44	45.55	19.11

Table 7.14 shows the average speeds returned by ten simulation runs of FRESIM for each of the sites. It also shows the mean of the average speeds in the ten runs along with the associated estimate of error based on a 95% confidence level. The maximum error is 0.12 mph, and therefore more simulation runs were not performed.

Table 7.14 Average speeds returned by 10 runs of FRESIM

Site	Mean of average speed of 10 runs (mph)	Error based on 95% confidence level (mph)	Average speed from Run #									
			1	2	3	4	5	6	7	8	9	10
I 74 EB 5	41.85	0.12	41.98	41.44	42.24	41.96	41.95	42.04	41.75	41.45	41.86	41.82
I 55 SB 55	39.46	0.03	39.47	39.39	39.55	39.37	39.50	39.49	39.51	39.43	39.46	39.46
I 55 NB 55 hour 1	45.50	0.05	45.24	45.46	45.54	45.48	45.58	45.56	45.46	45.56	45.57	45.56
I 55 NB 55 hour 2	45.55	0.06	45.68	45.74	45.52	45.53	45.55	45.39	45.73	45.50	45.34	45.54

Table 7.13 compares the mean of the average speeds returned by FRESIM with the average speed observed in the field. The difference in the average speed returned by FRESIM and the average speed in the field ranges from 19.11 to 21.46 mph and the average difference is 20.46 mph. Figure 7.11 compares the mean speed returned by FRESIM to the field data. From the figure it is clear that FRESIM overestimates the speed for sites with queuing.

FRESIM does not return an estimate of the queue length as a part of its output. However, FRESIM does return the number of vehicles on each link at the end of the simulation time period and the average speed observed on each link over the simulation time period. Under queuing conditions it is expected that the average speeds on links with queues would be much lower than the average speeds on a regular link and the vehicular densities would be much higher. Therefore, it would be expected that in the zone immediately upstream of the work zone, there would be high densities and lower speeds and a long distance upstream of the work zone where the effect of queuing has not reached, there would be high speeds and low densities. In between these two zones there would be a transition area where the densities

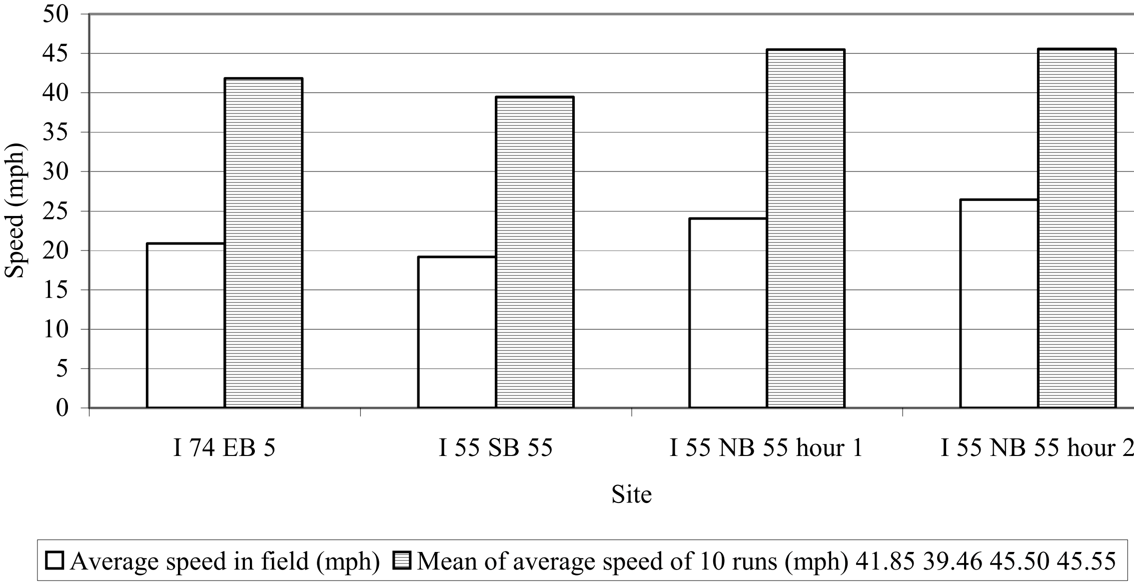


Figure 7.11 Average Speed in Field Vs Mean of Average speed given by 10 runs of FRESIM for work zone link with queuing

and speeds would vary significantly over a short distance. It has been assumed that the length of the queue would correspond to that distance over which consistently high densities and lower speeds would be observed. In absence of any estimate of queue length from FRESIM, this reasonable approach has been adopted to get an estimate of the queue length at the end of the hour using the output provided by FRESIM. At each of the sites, 25 links upstream of the work zone link have been modeled. At I 55 SB 55 each upstream link was 500 ft in length while they were 1000 ft each at the other two sites. Figures 3 through 6 show the spatial profiles of the mean of the average speeds and vehicular densities returned by 10 runs of FRESIM.

In Figure 7.12 it can be observed that from links 18 through 25 the density is around 9 vehicles per 1000 ft and the speeds are over 60 mph. From links 1 through 12, the density is around 30 vehicles per 1000 ft and the speeds are varying from 7.14 to 22.59 mph and on the rest of the links the transition between queuing and free-flow condition can be observed. The speed of 22.59 mph on link 12 is very close to 20 mph, the approximate speed at which the end of the queue was moving. Clearly links 1 through 12 are crowded. Therefore for I 74 EB 5 the queue length at the end of the hour has been taken to be 12000 ft.

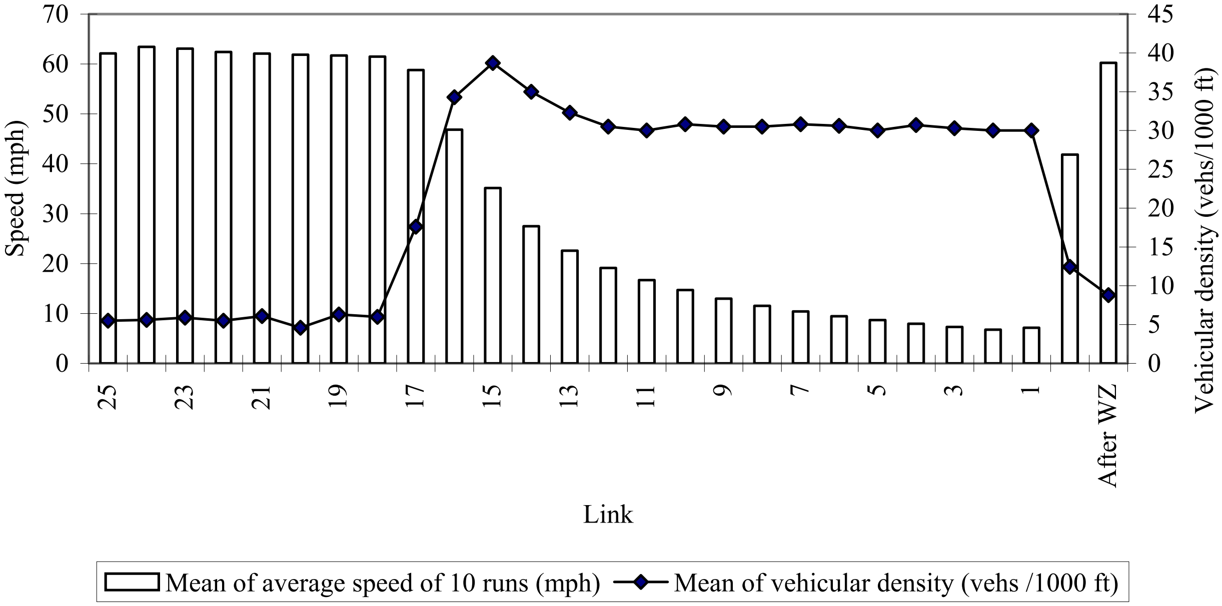


Figure 7.12 Spatial variation of average speed and vehicular density for I 74 EB 5

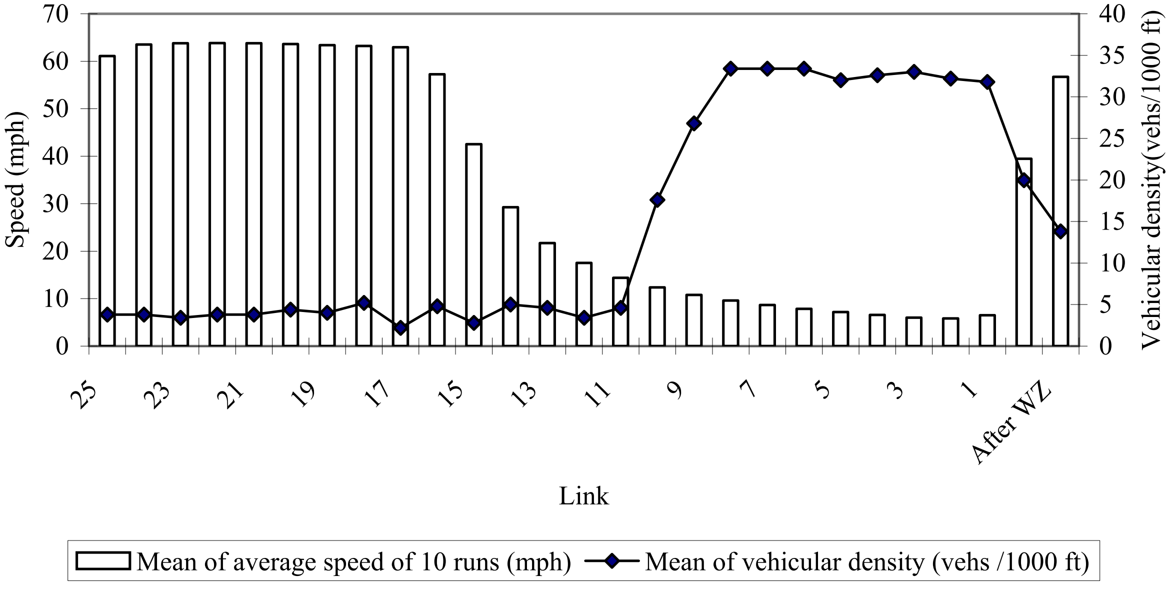


Figure 7.13 Spatial variation of average speed and vehicular density for I55 SB 55

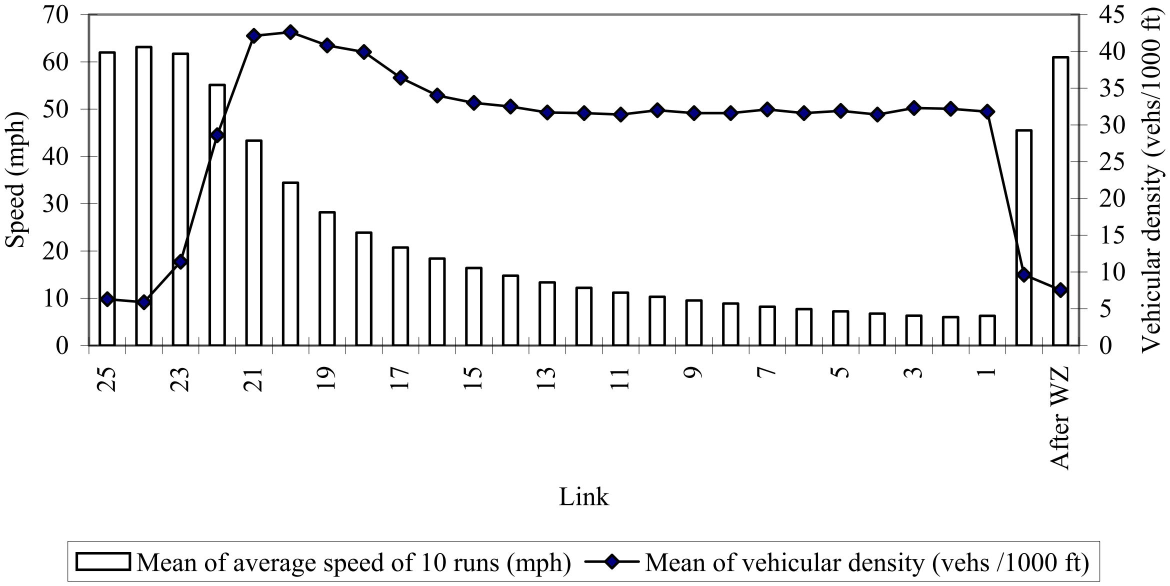


Figure 7.14 Spatial variation of average speed and vehicular density for I 55 NB 55 Hr 1

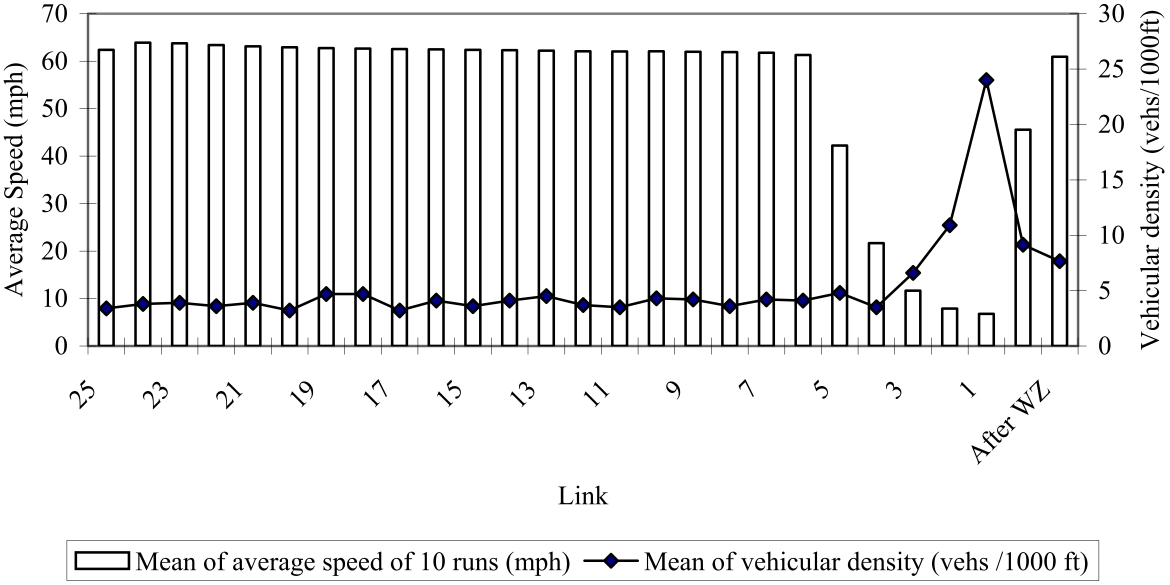


Figure 7.15 Spatial variation of average speed and vehicular density for I 55 NB 55 Hr 2

By similar examination of Figure 7.13 it can be concluded that links 1 through 9 are with queue at I 55 SB 55. For this site, the queue length at the end of the hour has been taken to be 4500 ft (Note: at this site each link has been modeled as a link of 500 ft). From figure 5 it can be concluded that links 1 through 15 are with queue at I 55 NB 55. For this site, the queue length at the end of the first hour has been taken to be 15000 ft. At I 55 NB 55, toward the end of the second hour the queue was depleting due to a lower demand. From Figure 7.15 it can be observed that there is no extended stretch of the highway, other than link 1, where high densities and low speeds occurred. Therefore, the queue length at the end of the second hour for this site has been taken to be 1000 ft.

Table 7.15 and Figure 7.16 compare the queue length returned by FRESIM to the queue length in the field. The difference in the queue length estimate of FRESIM and the field queue length varies from -6000 ft to 7260 ft. From Figure 7.16 we can conclude that the queue lengths returned by FRESIM do not match the queue lengths observed in the field.

Table 7.15 Comparison of queue length returned by FRESIM to the queue length in the field

Site	Queue length at the end of the hour (ft) from	
	FRESIM	Field
I 74 EB 5	12000	7380
I 55 SB 55	4500	10500
I 55 NB 55 hour 1	15000	7740
I 55 NB 55 hour 2	1000	5740

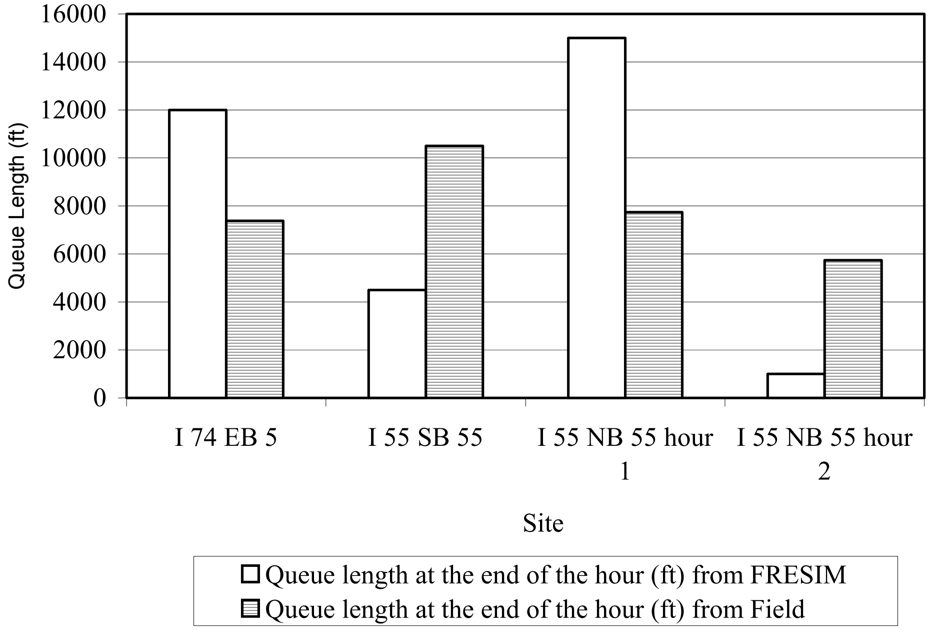


Figure 7.16 Comparison of queue length returned by FRESIM to the queue length in the field

7.6.4 Findings for FRESIM

When there is no queuing at work zones, there is no statistical difference between the average speeds returned by FRESIM and the speeds observed in the field. When there is queuing, FRESIM overestimates the speed in the work zone. The queue lengths obtained from the FRESIM results did not match the observed queue lengths in the field. In half of the cases the queue lengths were lower and in the other half the queue lengths were higher than the corresponding lengths in the field. In FRESIM, specifying the capacity is an issue. In this study the speed-flow relationship was used to get an estimate of the car following sensitivity factor (CFSF) that resulted in the capacity values that were observed in the field. This is a necessary step. However, it did not help to match the FRESIM results with the field data. Using FRESIM when there is queuing must be done with great caution.

7.7 Comparison of field data with QuickZone

QuickZone requires as input the demand for every link on the network for all the 168 hours of a week and it returns the total delay, maximum queue length, and total queue length for the week. The minimum duration of a project in QuickZone is one week. Therefore the sites were modeled in QuickZone as projects that were one week long. Since the data was collected only for a few hours at each site, except for the hours the data was collected, the demand values for all the links were inputted as zero. Each of the sites was modeled in QuickZone with the following data observed in the field

- Hourly volume
- Percentage Heavy vehicles
- Lane closure data
  - length
  - configuration (i.e., number of lanes closed)
- Free-flow speed
- Jam density
- Service capacity

For each of the sites the jam density was obtained from the average vehicle length and jam spacing of 10 ft. QuickZone needs the decrease in capacity of the links as a user input. The service capacities observed in the field were used as the reduced capacities of the links.

7.7.1 Sites without queuing

QuickZone returns the estimates of queue length and user delay for each phase of the construction project. QuickZone algorithm essentially applies Input-Output analysis to every link on the mainline to compute the resultant number of vehicles in queue and the delay experienced by the users. QuickZone does not take into account the effect of slower speeds experienced within the work zones on the user delay. Thus for undersaturated conditions when the demand is less than capacity, QuickZone does not return any values for user delay or for queue lengths. Therefore, for undersaturated conditions, QuickZone cannot be used to estimate the delay experienced by the users.

7.7.2 Sites with queuing

Three sites had queuing during the time the data was collected. From the data collected at I 55 SB 55 and I 74 EB 5 sites, queuing was observed for one full hour while at I 55 NB 55 queuing was observed for 2 full hours. In I 55 SB 55 and I 74 EB 5 at the beginning of the hour considered for the simulation no queue was present. Therefore the number of arrivals was considered as the hourly demand for these two sites. At I 55 NB 55, queuing was present to begin with. Therefore the demand for the first hour was taken to be the sum of the number of vehicles in queue and the arrivals during the hour at the end of the queue. Table 7.16 shows the number of arrivals, vehicles in queue at the beginning of the data collection and the demand values used in QuickZone.

Table 7.16 Comparison of QuickZone with Field data

Site	Hourly demand (vph)	Service Capacity (vph)	Queue length returned by QuickZone (mi)		Queue length returned by QuickZone (mi)	Queue length in field (mi)
			Weekly Max	Weekly Total		
I 74 EB 5	1860	1459	1.19	1.2	1.19	1.40
I 55 SB 55	1320	1220	1.2	1.2	1.2	1.99
I 55 NB 55 Hr 1	1865	1341	1.72	2.2	1.72	1.47
I 55 NB 55 Hr 2	975	1341			0.48	1.09

QuickZone returns the value of the maximum of queue lengths observed at the end of the hour and the total queue length over the week. These values are shown in Table 7.16. For I74 EB 5 and I 55 SB 55, since queuing was observed only for one hour, the maximum queue over the week and total queue length actually correspond to the queue length at the end of the hour. For I 55 NB 55, the maximum queue length would correspond to the queue length at the end of the first hour. Therefore the queue length at the end of the second hour would be the difference between the total queue length and the maximum queue length.

Table 7.16 and Figure 7.17 compare the queue lengths returned by QuickZone and the queue lengths observed in the field. The difference between the queue length observed in the field and the queue length returned by QuickZone ranged from –0.25 to 0.79 miles. From Figure 7.17, it can be seen that the estimates of queue length by QuickZone do not match the field data and generally QuickZone underestimated the queue lengths. On the average QuickZone underestimated the queue length by 0.33 miles.

QuickZone also returns the estimate for the total delay experienced by the users. Table 7.17 and Figure 7.18 compare the total delay returned by QuickZone with the total delays in the field. QuickZone consistently underestimates the total delay observed in the field. The difference ranges from 63 to 374 veh hours and the average difference is 217 veh-hrs. This is expected because QuickZone does not take into account the delay due to the slower speed in work zones. Table 7.17 also shows the delay due to slower speeds and delay due to queuing separately.

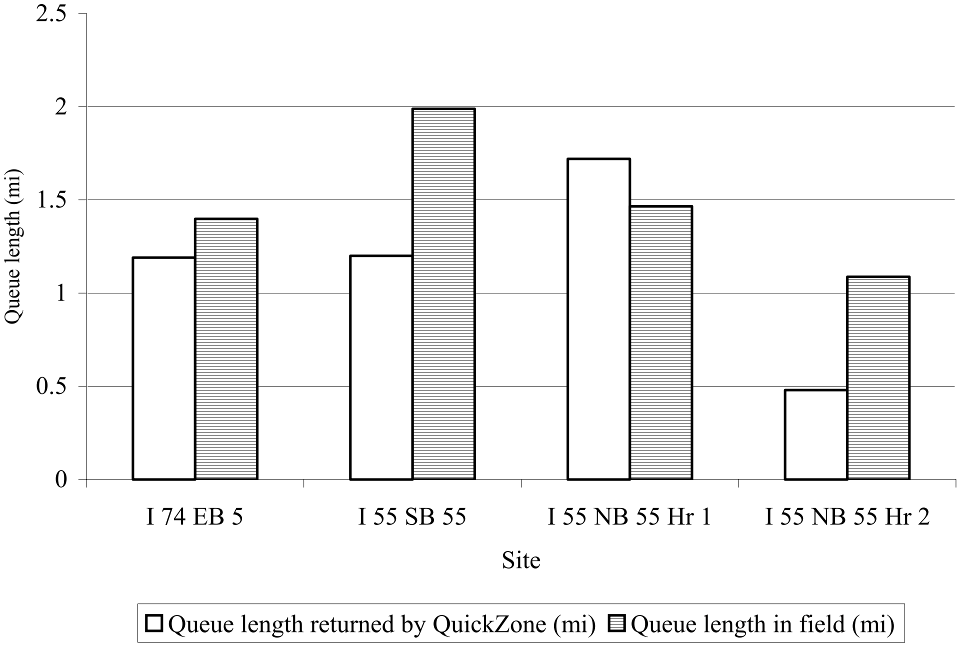


Figure 7.17 Queue length returned by QuickZone Vs queue length observed in the field

Table 7.17 Comparison of Total delay returned by QuickZone to the delays in the field

Site	Delay in Field			Total delay returned by QuickZone (veh hrs)
	Delay due to slower speed (veh hrs)	Delay due to waiting in queue (veh hrs)	Total delay (veh hrs)	
I 74 EB 5	78	386	464	401
I 55 SB 55	197	364	561	348
I 55 NB 55	99	958	1056	682

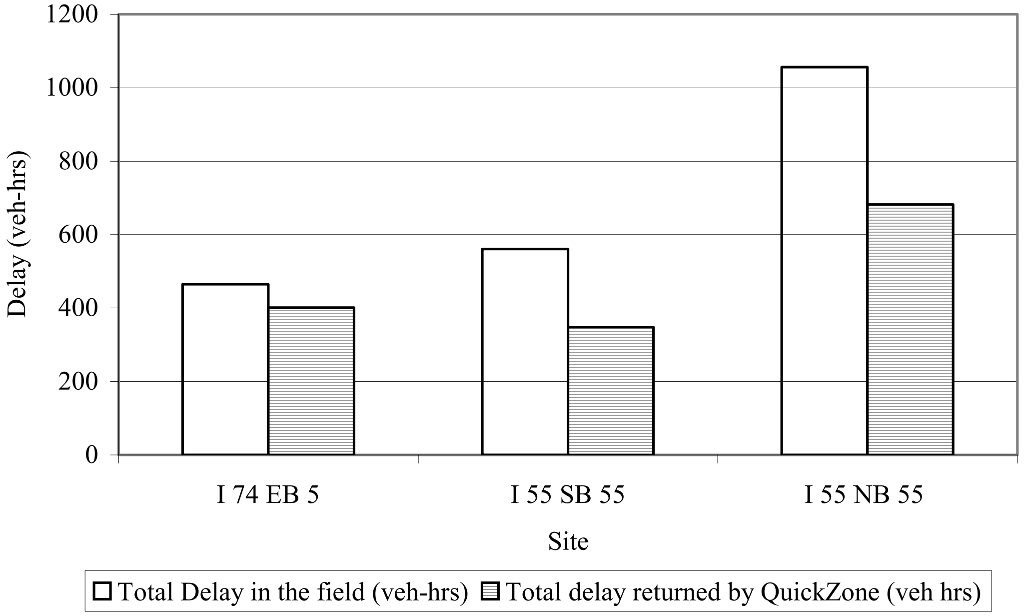


Figure 7.18 Total delay returned by QuickZone Vs Total delay in the field

Figure 7.19 compares the total delay returned by QuickZone to the queuing delay in the field. Even if the delay due to queuing only is compared to the total delay returned by QuickZone it can be seen that the estimates returned by QuickZone do not match the field data. The difference ranges from –276 to +15 hours and on the average QuickZone underestimated the queuing delay by 92 hrs. Therefore QuickZone cannot be used to estimate the delay due to queuing.

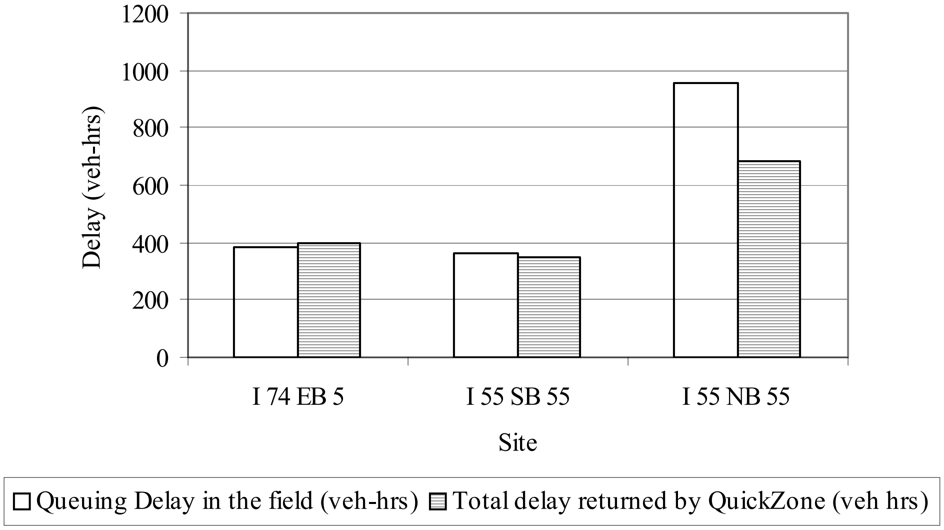


Figure 7.19 Total delay returned by QuickZone Vs Queuing delay in the field

7.7.3 Findings for QuickZone

QuickZone uses Input-Output analysis for estimating the queue lengths and user delays due to work zones. QuickZone does not consider the delay due to slower speed experienced in the work zones. Thus for undersaturated conditions, when the demand is less than capacity QuickZone does not return any values for user delay. Therefore, for undersaturated conditions, QuickZone cannot be used to estimate the delay experienced by the users. The estimates of queue length by QuickZone did not match the field data and generally QuickZone underestimated the queue lengths. QuickZone also returns the estimate for the total delay experienced by the users. QuickZone consistently underestimated the total delay observed in the field. This could be attributed to the fact that QuickZone does not take into account the delay due to the slower speed in work zones. Even when the Total delay returned by QuickZone was compared with the queuing delay in the field, the results did not match. QuickZone underestimated the waiting delay. Therefore, even for sites with queuing QuickZone cannot be used to estimate the queue lengths or total delay.

7.8 Findings from comparisons of Softwares

Capacity of the work zone, speed and queue length in the work zone are required inputs to estimate the road user costs. In this chapter the comparison of the three software packages with the field data has been discussed. Table 7.18 summarizes the findings.

Table 7.18 Summary of Findings

Software Package	With/without Queue	Capacity	Speed	Queue length
Default QUEWZ	Without queue	Underestimated	Overestimated	n/a
	With queue	Overestimated	Overestimated	Underestimated
Modified QUEWZ	Without queue	Modified parameters to get field capacity	Overestimated	n/a

Table 7.18: Continued

	With queue	Modified parameters to get field capacity	Overestimated	Underestimated
FRESIM	Without queue	Does not estimate	Statistically same	n/a
	With queue	Does not estimate	Overestimated	No consistent trend *
QuickZone	Without queue	Does not estimate	Does not estimate	n/a
	With queue	Does not estimate	Does not estimate	Underestimated

*: Estimated queue length using the spatial variation of average speed and vehicular density.

Capacity

Capacity of the work zone is the most critical input to the calculations of road user costs because estimates of speed and queue length are dependent on the capacity. Error in estimating the capacity would propagate through the rest of the calculations. FRESIM and QuickZone do not estimate the capacity of a work zone. They require the user to input this value. QUEWZ, however, has an in-built capacity estimation model. In this study, it was found that QUEWZ underestimated the capacity of the work zone when there was no queuing. When there was queuing, it was observed that QUEWZ overestimated the capacity.

Speed

Motorists may experience delay due to a slower speed (in addition to the delay due to queuing) while traveling in the work zone. The delay due to slower speed becomes significant especially when there is queuing and the work zone is long. In the default case it was found that QUEWZ overestimated the speed regardless of the presence of queue. Values of the default parameters were modified to get the observed capacity as the capacity estimated by QUEWZ. However, QUEWZ still overestimated the speed. It was found that when there was no queuing, there is no statistically significant difference between the average speed returned by FRESIM and the speed observed in the field. Under queuing conditions FRESIM overestimated the speed in the work zone. QuickZone does not estimate the speed of the drivers in the work zone.

Queue Length

Delay caused due to queuing is a major component of the delay to the motorists. It was found that QUEWZ underestimated the queue length in both the default case and in the modified case. FRESIM does not return an estimate for queue length. Queue length was estimated using the spatial variation of average speed and vehicular density. There was no consistent trend. In half of the cases the queue length was lower and in the other half higher than the observed queue length. QuickZone generally underestimated the queue length observed in the field.

7.9 References

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CHAPTER 8 - MODEL FOR CAPACITY IN WORK ZONES

This chapter is divided into two major parts, a thorough analysis of the data, and the development of a model for capacity in work zones based on the results of the analysis. The model for the estimation of queue and delay are discussed in chapter 7.

8.1 Analysis of Data

Eleven sites, where speed of individual vehicle was computed from the videotapes, were chosen for detailed data analysis. Out of the eleven sites, three were short-term and eight were long-term construction sites. Three of the long-term construction sites had queuing. Data was collected for about 4 hours at these three sites and in one of the short-term sites. The data was grouped for two-hour time intervals in each site. As a result, there were fifteen two-hour data sets. Most of the analyses were done using Excel spreadsheet and Statistical Analysis System (SAS).

8.1.1 Platooning Criteria

Vehicles were classified into platoon or non-platoon based on speed and spacing. Spacing is the distance between the front bumper of leading vehicle and the front bumper of following vehicle. The spacing for a vehicle was computed by multiplying its headway by its speed. During the data reduction, a vehicle was initially considered to be a part of a group of vehicle if it was spatially close to other vehicles. This determination was only based on the judgments of the persons reducing the data. After analyzing the headway, speed and spacing of the vehicles in the field data, the criteria for platooning were established. A vehicle is consider being in platoon if its headway is less than or equal to four seconds or its spacing is less than or equal to 250 ft.

8.1.2 Time Series Plots

After establishing the condition for platooning vehicles, the time series plots of flow and speed were studied to find how the presence of non-platoon vehicles affects the flow. Three groups of plots were studied, platoon, non-platoon and both platoon and non-platoon vehicles combined. The time series was plotted for an interval of 5 minutes. The time series plots for the platoon, non-platoon and all vehicles Is given in Appendix C.

Comparison of the time series plots for platoon, non-platoon and all vehicles shows that the plot for platoon vehicles is smoother plots than non-platoon vehicles. The time series plots for non-platoon vehicles show significant fluctuations in speed and flow. Similar fluctuations are also reflected in the plots for all the vehicles. The fluctuations indicate that non-platoon vehicles should not be used in determining the capacity of work zones. Capacity should be determined when a continuous flow of traffic exists and vehicles are in platoon. In a queuing condition, almost all the vehicles will be in a platoon, but in undersaturated conditions not all the vehicles will be in platoon. In order to measure the capacity of work zone, only the vehicles that are in platoon are considered.

8.1.3 Maximum Flow or Ideal Capacity

Using the time series plots for platooning vehicles, a 15-minute time period is found, that is either before a rapid speed drop or after a rapid speed increase, that sustained the highest flow level with little or no fluctuation in flow. Such a time period would represent the ideal capacity of the site. When there was no significant change in speed, a 15-minute time period that had highest sustained flow was used. The maximum 15 minute sustained flow for each site was calculated. The values are given in Table 8.1. The max 15-minute mixed flow observed in the field (in unit of vehicle per hour (vph)) was converted to all passenger car equivalents (in unit of passenger car per hour (pcph)) using the conversion factor given in HCM 2000. The passenger car equivalency factor is 1.5 for level terrain, which was used for all sites.

Table 8.1 Maximum 15-minute sustained flows

site no	Sites	Maximum 15-min flow	% truck in 15-min	Maximum 15-min flow	Average Speed in 15-min
		vph	%	pcph	mph
1	I57_NB_271_0718	1832	28.40	2092	43
2	I55_NB_224_0723	1697	37.19	2013	44
3	I57_NB_250_0724	1798	31.30	2079	50
4	I74_WB_79_0723	2062	29.40	2365	45
5	I80_EB_43-44_0725	1710	34.70	2007	42
6	I80_WB_39-40_0725	2088	38.20	2487	53
7	I74_EB_5_0725	1981	6.05	2041	43
8	I70_EB_145-146_0801	1615	42.60	1959	50
9	I57_SB_212_0801	2167	16.90	2350	57
10	I55_SB_56-55_0802	2033	18.90	2225	45
11	I55_NB_55-56_0802	2004	14.50	2149	60

The maximum 15-min sustained flow indicates that under ideal conditions during that particular 15-min period, this is the maximum flow that can be processed (assuming all vehicles are in platoon). As the conditions changes these flows will also change. Therefore to determine the maximum flow that can be processed in a work zone, a more detailed study of the work zone conditions have to be done.

The values in Table 8.1 indicate that there is variation in ideal flow, but also that there is consistency. For the three short-term construction sites, the ideal capacity values are 2092, 2013, and 2079. These capacity values are practically the same and indicate the consistency in finding the ideal capacity values. Similarly for long term construction sites there was consistency when similar conditions were compared. The highest ideal capacity value was for I 80 WB where the speed limit was 55 and there were no workers present. The drivers in platoon in that 15-minute time period were traveling at a speed of 53 mph. The ideal capacity value is comparable to the 2400 pcph that HCM recommends for a single lane of such a freeway. Since there were only 8 long-term construction sites with detailed data, the field data rather than statistical analysis was used to understand the relationship between different variables and capacity and in developing the capacity model for work zones.

8.2 Estimating Work Zone Capacity

To estimate work zone capacity, speed-flow curves for work zones were needed. Then, the adverse effects of work zone conditions on speed needed to be determined in terms of speed reduction.

8.2.1 Speed Flow Curves

Based on the 5-minute flow and speed data, the relationship between the speed and flow in work zone under maximum flow conditions (continuous discharge flow which means that all vehicles are in platoon) was established. Figure 8.1 gives the speed flow curve for the maximum flow conditions. A relationship in the form of a power function was found to represent the data points in Figure 8.1 very well. The equation for the power function was obtained using regression analysis and it is expressed as:

$$q = 145.68 \times U^{0.6857} \tag{8.1}$$

Where,

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

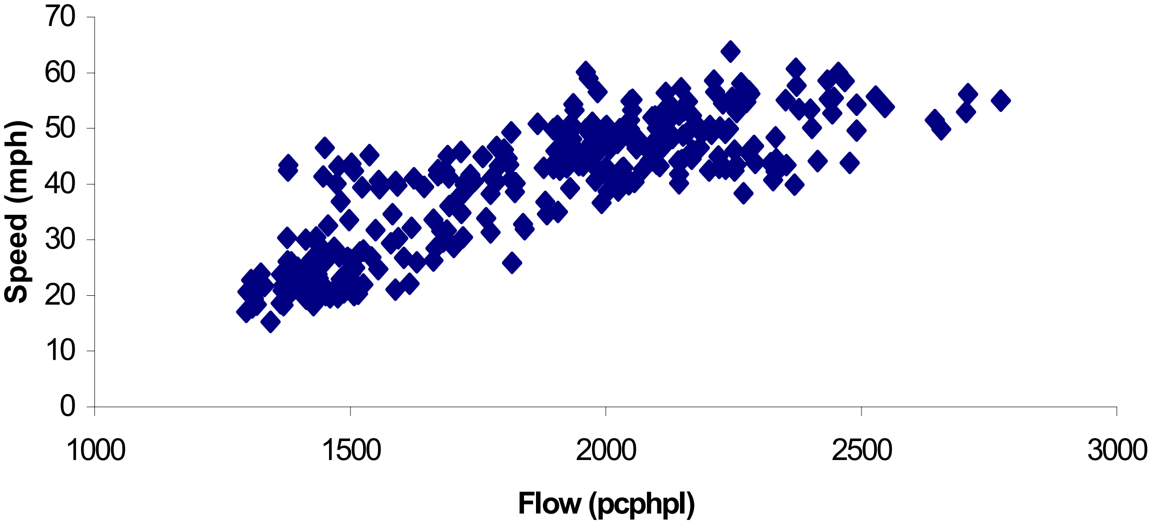

Figure 8.1 Flow Vs Speed for Maximum Flow Conditions

This equation was used to establish the lower part (congested part) of the speed-flow curve. Thus, it is used in determining capacity values and flow rates when speed is below the optimal speed (speed at capacity). The free flow part of the curve (when speed is higher than the optimal speed) is based on information from HCM 2000, ideal capacity values from the field data as shown in Table 8.1, and knowledge of the authors. A speed range of 65 mph to 40 mph was used to establish the speed-flow curves. The capacity for each speed level was decided considering all of the above mentioned factors. It was also decided that the flow at which the free flow speed begins to drops is at 1300 pcphpl. This value is based on the information in HCM2000 and knowledge of the authors. The speed drop between 1300 pcphpl and the capacity value is based on the following equation which is obtained from the above discussion:

$$Speed = FFS - (FFS - U_c) * \left[\frac{flow - 1300}{capacity - 1300} \right]^{2.6} \qquad (8.2)$$

Where,

FFS = free flow speed (mph)

U_c = Speed at Capacity (optimal speed) in mph obtained from equation 8.1

The exponent of 2.6 used in Equation 8.2 is used in HCM 2000 for comparable equations (Chapter 23 – Basic Freeway Sections). Putting the upper and lower parts of the speed-flow curves resulted in a series of speed-flow curve as shown in Figure 8.2. Figure 8.2 is developed in this study and there is no specific reference for this curve in the literature. It is based on the findings from the field data, knowledge of authors about capacity and traffic flow and information that is available in HCM.

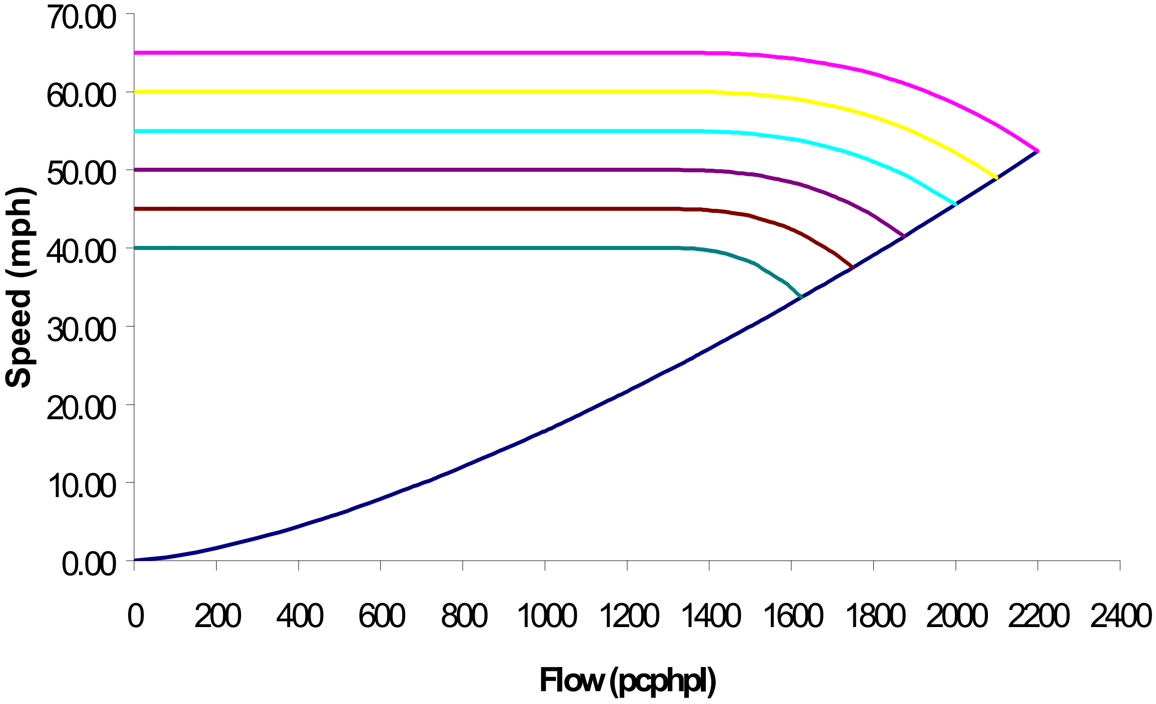

Figure 8.2 Speed-Flow Curves for Work Zones

8.2.2 Operating Speed

Operating speed in a work zone is defined as the speed at which the vehicles would travel through the work activity area after reducing their speed due to work intensity, lane width and lateral clearance. The equation for operating speed is given as:

$$U_o = FFS - R_{WI} - R_{LW} - R_{LC} - R_o \tag{8.3}$$

Where,

U_o = Operating Speed (mph)

FFS = free flow speed (It is assumed that FFS= Speed limit + 5 mph)

R_{WI} = Reduction in speed due to work intensity (mph)

R_{LW} = Reduction in speed due to lane width (mph), see Table 8.2

R_{LC} = Reduction in speed due to lateral clearance (mph), see Table 8.2

R_o = Reduction in speed due to all other factors that may reduce speed (mph) (including those that may cause a flow breakdown)

Table 8.2 Adjustments due to lane width and lateral clearance

Adjustment for lane width				
Lane width (ft)	**Reduction in speed (mph)**			
12 ft or more	0.0			
11	1.9			
10	6.6			
9	15.0*			
8	25.0*			
Adjustment for left shoulder				
Left shoulder (ft) width	**Reduction in speed (mph)**			
2 ft or more	0			
1	1			
0	2			
Adjustment for right shoulder				
Right shoulder width (ft)	**Reduction in speed (mph)**			
	No of Lanes in one direction (without work zone)			
	2	**3**	**4**	**>= 5**
6 ft or more	0	0.0	0.0	0.0
5	0.6	0.4	0.2	0.1
4	1.2	0.8	0.4	0.2
3	1.8	1.2	0.6	0.3
2	2.4	1.6	0.8	0.4
1	3.6	2.0	1.0	0.5
0	3.9	2.4	1.2	0.6

(*: Based on author's best estimate)

8.2.3 Work Intensity

The work intensity in a work zone is characterized by two main factors. The factors are:

1) Number of workers and construction equipment in the closed lane that is adjacent to the open lanes
2) Proximity of the workers and equipment to the nearest open lane (how far the crew/equipment is from the traveled lane)

To quantify the reduction in speed due to the work activity, a ratio called the work intensity ratio is developed. Work intensity ratio is obtained by dividing the sum of the number of workers and equipment in the active work area in the closed lane by the distance between the active work area and the open lane. It is expressed as:

$$WI_r = \frac{w + e}{p} \tag{8.4}$$

Where,

WI_r = work intensity ratio
w = number of workers in the active work area (w varies from 0 to a maximum of 10)
e = number of equipment in active work area (e varies from 0 to a maximum of 5)
p = distance between the active work area and the open lane (feet) (p varies from 1 to a maximum of 9 ft)

The speed reduction due to work intensity in long term work zone (e.g. using concrete barriers) will be different from the reduction for short term work zones (e.g. using barrels), because of the different types of traffic control devices used.

8.2.4 Speed Reduction in Short Term Work Zones

For short-term work zones, the relationship between work intensity ratio and speed reduction was developed based on a survey conducted among the drivers at a rest area. A sample of the survey sheet is given in Appendix D. The total number of observations was 120. The collected data was examined and any inconsistent and inaccurate responses that did not reflect valid speed reductions were deleted. After this reduction 90 observations were plotted against the different work intensity conditions. Different models were examined and the one, which had the best fit, was chosen. The relationship was further verified with the field data. The relationship is given as

$$SR_S = 11.918 + 2.6766 \ ln(W.I) \tag{8.5}$$
$$R^2 = 0.1213$$

Where,

SRs = speed reduction in short term work zones (mph)

WI_r = Work intensity ratio

Figure 8.7 gives the relationship for this equation. The values obtained from this graph are very close to those observed in field.

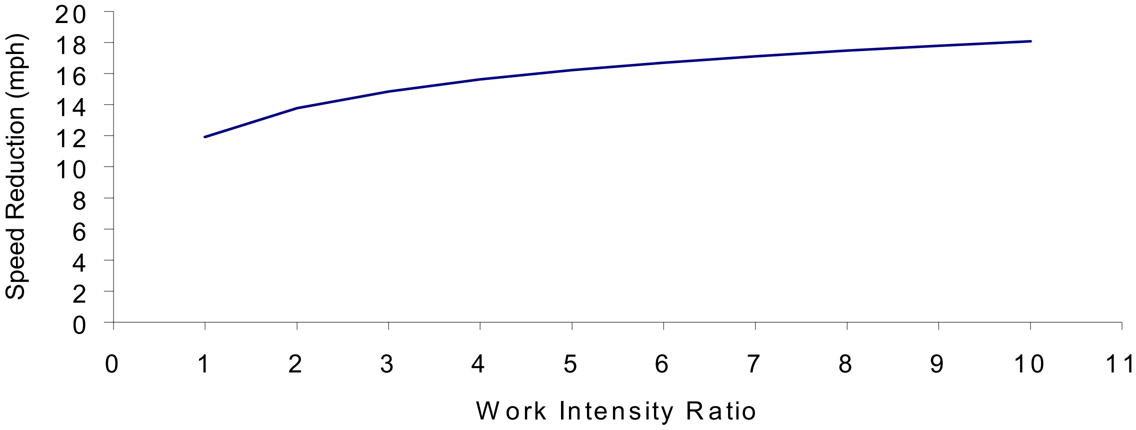

Figure 8.3 Work Intensity Ratio Vs Speed reduction- Short Term

The data used for arriving at this relationship had wide variation in speed reduction because different drivers react differently. We could average the data and could get higher R^2 values but that will conceal the variation in data that will give a wrong impression. So we took the actual values.

8.2.5 Speed Reduction in Long Term Work Zones

The relationship between work intensity ratio and speed reduction for long term work zones was developed based on the field data. For computing the proximity of the long-term work zone, a distance of 2 feet is added to the distance from the travel lane to account for the width of the concrete barrier. The relationship is given by the equation

$$SR_L = 2.6625 + 1.2056 \ln(WI_r) \qquad (8.6)$$
$$R^2 = 0.1472$$

Where,

SR_L = speed reduction (mph)

WI_r = work intensity ratio

Figure 8.8 gives the relationship for this equation.

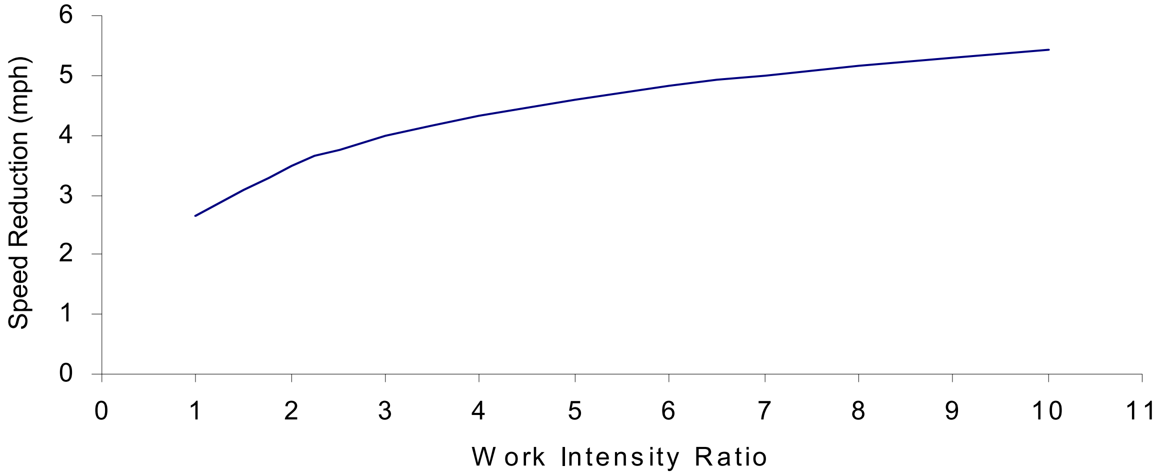

Figure 8.4 Work Intensity Vs Speed Reduction - Long Term

8.2.6 Lane Width and Lateral Clearance

Speed reduction due to lane width and lateral clearance are based on the values given by HCM 2000. Exhibit 23-4 in HCM 2000 gives the reduction speed for lane width and Exhibit 23-5 gives the reduction in speed for lateral clearance for 2 lane freeways.

8.2.7 Work Zone Capacity

The capacity model given in this section is based on the principle that the work zone factors (intensity, lane width, and lateral clearance) cause a reduction in the speed of the vehicles, which will again affect the work zone capacity. So, by establishing a relationship between speed reduction and the work zone factors, the capacity of the work zone can be estimated. The basic capacity model is given in equation 8.7.

$$C_{adj} = C_{U_o} * f_{HV} \tag{8.7}$$

Where,

C_{adj} = adjusted capacity (vphpl)
Cu_o = capacity at operating speed U_o (pcphpl)
f_{HV} = Heavy vehicle factor

The heavy vehicle factor is calculated from the following equation:

$$f_{HV} = \frac{1}{1 + P_T(PCE - 1)} \tag{8.8}$$

The heavy vehicle adjustment factor is the same one used in HCM. The passenger car equivalent (PCE) factors change with terrain of the roadway environment. For example, for large trucks PCE is 1.5, 2.5, and 4.5 for level, rolling, and mountainous terrains, respectively. It should be mentioned that when the length of an upgrade or its steepness causes a significant speed reduction in trucks, the procedure uses different PCE values to account for the adverse effects. The HCM factors are not developed based on work zone data, but they can be used for work zone without significant concerns until more data becomes available.

8.2.8 Step-by-Step Approach to Estimate Work Zone Capacity

The steps involved in finding the adjusted work zone capacity is given below:

1. Find speeds reduction due to narrow lane width (R_{LW}) and lateral clearance (R_{LC}) from Table 8.2.
2. Compute the work intensity ratio (WI_r) using equation 8.4.
3. Compute the speed reduction (R_{WI}) due to work intensity from equation 8.5 for short term work zones and equation 8.6 for long term work zones.
4. Calculate the Operating speed (Uo) based on the equation 8.3
5. Find the capacity (Cu_0) corresponding to the operating speed from the speed flow curve given in Figure 8.2.
6. Compute the heavy vehicle factor (f_{HV}) using the equation 8.8
7. Calculate the adjusted capacity (C_{adj}) from Equation 8.7

8.3 Calibration of the Capacity Model

The capacity model was based on three data sites, which were not used in the development of the model. The three data sets used are, I-270 EB MP9, I-290/IL-53 EB MP4 and I-57 SB MP355. The observed values and the estimated models are given in table 8.3.

Table 8.3 Observed Flows Vs Estimated Flows

Site	Hour	Average speed (mph)	Observed flow (vph)	# of trucks	% trucks	Observed flow (pcphpl)	Estimated flow (pcphpl)
I-290/IL-53 EB MP9	1	19.96	1321	44	3.33	1343	1135
	2	20.6	1321	36	2.73	1361	1160
I-57 SB MP 355	1	21.88	1418	154	10.86	1495	1209
	2	23.69	1518	122	8.04	1579	1276
I-270 EB MP9	1	49.85	938	267	28.46	1072	1072

The sites I-290/IL-53 and I-57 were 3 lane sites reduced to 2 lanes. The data was collected on the left lane. There was very low percentage of trucks in the left lane. The observed flows were higher than the estimated flows because the estimated flows were based on a 2 lane to 1 lane reduction. So, This difference between the observed flow and the estimated flow is expected. The site I-270 had 2 lanes reduced to 1 lane. In this site, due to the local condition there was a queue before the location of data collection and the queue length remained around 0.6 miles. At the location where speed and flow data was collected, the traffic flow was not influenced by queue. Average speeds based on a systematic sampling of vehicles were found out to be 49 mph. This represents a free flow condition at the location. Based on our field observation and video taping of the site, we determined that the traffic operation at the location of the site was not under the influence of the stationary queue. In fact, there were large gaps between the vehicles and they were mostly free flowing traffic. This represented an undersaturated condition. As a result we should compare the data point with the flow speed curve for the undersaturated condition.

Five data points provided the data that supports the validity of this model. There was a good agreement between the 5 data points; further validation of this model under a variety of roadway conditions would be helpful in gaining the confidence of model users.

CHAPTER 9 - APPLICATION OF METHODOLOGY

9.1 Concept behind the UIUC methodology for capacity, delay and queue length

The proposed methodology is referred as UIUC methodology in this chapter to distinguish it from other methodologies. Work zone operating factors such as work intensity, lane width, lateral clearance, and others would cause reductions in the speed of the vehicles. The reductions in speed may affect the number of vehicles that go through the work zone. In other words, the flow, particularly at moderate and high volume conditions, will depend on the speed at which vehicles travel through the work zone.

Also speed and consequently flow through a work zone would depend on queue presence (slow-moving or stopped queue) in the work zone. When traffic flow breakdown occurs, the average speed drops below the optimal speed and flow becomes less than the normal capacity of the work zone in normal conditions. Queue presence and low speeds are indications of flow breakdown. Under the flow breakdown conditions, the work zone operates less efficiently and the number of vehicles processed is less than the number processed under normal operating conditions in the work zone.

The flow breakdown may be due to work zone operating conditions or extraneous factors that could cause flow breakdown. There are known factors such as demand exceeding capacity or an incident partially blocking the work zone that would cause the flow to breakdown in work zones. However, in general it is not easy to predict if flow breakdown will occur in a work zone, mainly because it depends on the operating conditions. We will discuss flow breakdown and potential causes for it later in this chapter. Regardless of the cause of flow breakdown, the effect is manifested as low speeds in the work zone.

In the UIUC methodology, first the speed reductions due to the work zone factors are determined. Then, the work zone operating speed is computed. Knowing the operating speed, the number of vehicles that can be processed (flow) is determined using the speed flow curves developed in this study. Once the flow is determined, it is adjusted to account for the adverse effects of heavy vehicles. This flow represents the capacity at which the work zone will operate. After the capacity is determined, queue length at the end of every hour is computed. Finally delays due to slower speed in work zone and stopped queue, if present, are computed.

9.2 Step-by-Step Approach to Estimate Work Zone Capacity, Queue Length and Delay

1. Find speed reductions due to narrow lane width (R_{LW}) and less than ideal lateral clearance (R_{LC}) from Table 8.2.

Table 8.2 Adjustments due to lane width and lateral clearance

<table>
<tr><th colspan="5">Adjustment for lane width</th></tr>
<tr><th>Lane width (ft)</th><th colspan="4">Reduction in speed (mph)</th></tr>
<tr><td>12 ft or more</td><td colspan="4">0.0</td></tr>
<tr><td>11</td><td colspan="4">1.9</td></tr>
<tr><td>10</td><td colspan="4">6.6</td></tr>
<tr><td>9</td><td colspan="4">15.0*</td></tr>
<tr><td>8</td><td colspan="4">25.0*</td></tr>
<tr><th colspan="5">Adjustment for left shoulder</th></tr>
<tr><th>Left shoulder (ft) width</th><th colspan="4">Reduction in speed (mph)</th></tr>
<tr><td>2 ft or more</td><td colspan="4">0</td></tr>
<tr><td>1</td><td colspan="4">1</td></tr>
<tr><td>0</td><td colspan="4">2</td></tr>
<tr><th colspan="5">Adjustment for right shoulder</th></tr>
<tr><th rowspan="3">Right shoulder width (ft)</th><th colspan="4">Reduction in speed (mph)</th></tr>
<tr><th colspan="4">No of Lanes in one direction (without work zone)</th></tr>
<tr><th>2</th><th>3</th><th>4</th><th>>= 5</th></tr>
<tr><td>6 ft or more</td><td>0</td><td>0.0</td><td>0.0</td><td>0.0</td></tr>
<tr><td>5</td><td>0.6</td><td>0.4</td><td>0.2</td><td>0.1</td></tr>
<tr><td>4</td><td>1.2</td><td>0.8</td><td>0.4</td><td>0.2</td></tr>
<tr><td>3</td><td>1.8</td><td>1.2</td><td>0.6</td><td>0.3</td></tr>
<tr><td>2</td><td>2.4</td><td>1.6</td><td>0.8</td><td>0.4</td></tr>
<tr><td>1</td><td>3.6</td><td>2.0</td><td>1.0</td><td>0.5</td></tr>
<tr><td>0</td><td>3.9</td><td>2.4</td><td>1.2</td><td>0.6</td></tr>
</table>

(*: Based on author's best estimate)

2. Compute the work intensity ratio (WI_r) using Equation 8.4.

$$WI_r = \frac{w + e}{p} \tag{8.4}$$

Where,

WI_r = Work intensity ratio

w = Number of workers working together as a group in the work activity area (w varies from 0 to a maximum of 10)

e = Number of large construction equipment in work activity area near the workers group (e varies from 0 to a maximum of 5)

p = Lateral distance between the work area and the open lane (feet) (p varies from 1 to a maximum of 9 ft)

3. Using the work intensity ratio (WI_r) computed in step 2, compute the speed reduction (R_{WI}) due to work intensity from Equation 8.5 for short-term work zones and Equation 8.6 for long-term work zones. In these two equations "ln" stands for natural logarithm.

$$R_{WI} = \begin{cases} SR_S \ in \quad short - term WZ \\ SR_L \ in \quad long - term WZ \end{cases}$$

$$SR_S = 11.918 + 2.676 \ ln(WI_r) \tag{8.5}$$

Where,

SR_S = Speed reduction in short term work zones (mph)

WI_r = Work intensity ratio

Speed reduction for long term work zones is computed from Equation 8.6.

$$SR_L = 2.6625 + 1.2056 \ ln(WI_r) \tag{8.6}$$

Where,

SR_L = Speed reduction in long term work zones (mph)

WI_r = Work intensity ratio

4. Calculate the Operating speed (U_O) based on Equation 8.3.

$$U_O = FFS - R_{LW} - R_{LC} - R_{WI} - R_O \tag{8.3}$$

Where,

U_o = Operating Speed (mph)

FFS = Free flow speed (It is assumed that FFS= Speed limit + 5 mph)

R_{LW} = Reduction in speed due to lane width (mph), see Table 8.2

R_{LC} = Reduction in speed due to lateral clearance (mph), see Table 8.2

R_{WI} = Reduction in speed due to work intensity (mph)

R_O = Reduction in speed due to all other factors that may reduce speed (mph) (including those that may cause a flow breakdown)

5. Find the capacity (Cu_0) corresponding to the operating speed by entering the operating speed on the vertical axis of Figure 8.2

Alternative procedures for finding C_{Uo} instead of reading from the speed –flow curve

To reduce the error caused by reading from the curve, the operating speed can be rounded to the nearest integer and the capacity corresponding to this approximate operating speed can be obtained from Table 9.1. To use Table, 9.1, first select the column corresponding to the free flow speed, second select the row corresponding to the operating speed, then, read the capacity value shown in the intersecting cell. For operating speeds below 25-mph equation 8.1 should be used to obtain the capacity.

To reduce the error caused by reading from the curve estimate the capacity precisely, equation 8.1 or 9.1, as appropriate can be used:

From Table 9.2, for a given free flow speed, find the maximum capacity and the speed at maximum capacity.

If the operating speed (U_O) is less than the speed at capacity, substitute the value of Uo for U in Equation 8.1 and compute q, which is the same as C_{Uo}.

$$q = 145.68 \times U^{0.6857} \tag{8.1}$$

Where,

q = C_{Uo} = Capacity corresponding to operating speed (pcphpl)

U = U_o = Operating Speed (mph)

Figure 8.2 Speed Flow curve for work zones

Table 9.1 Capacity corresponding to operating speeds*

Operating Speed (mph)	FFS (mph)					
	65	60	55	50	45	40
65	1300	-	-	-	-	-
64	1640	-	-	-	-	-
63	1743	-	-	-	-	-
62	1818	-	-	-	-	-
61	1879	-	-	-	-	-
60	1931	1300	-	-	-	-
59	1977	1618	-	-	-	-
58	2018	1715	-	-	-	-
57	2056	1785	-	-	-	-
56	2091	1842	-	-	-	-
55	2123	1890	1300	-	-	-
54	2154	1933	1596	-	-	-
53	2183	1972	1686	-	-	-
52	2200	1993	1727			
52	2188	2007	1751	-	-	-
51	2159	2040	1804	-	-	-
50	2130	2070	1849	1300	-	-
49	2101	2099	1889	1553	-	-
48	2071	2071	1925	1630	-	-
47	2042	2042	1958	1685	-	-
46	2012	2012	1988	1730	-	-
45	1982	1982	1982	1769	1300	-
44	1951	1951	1951	1803	1508	-
43	1921	1921	1921	1834	1571	-
42	1890	1890	1890	1862	1617	-
41	1859	1859	1859	1859	1654	-

Table 9.1: Continued

40	1828	1828	1828	1828	1686	1300
39	1796	1796	1796	1796	1714	1460
38	1765	1765	1765	1765	1739	1509
37	1733	1733	1733	1733	1733	1544
36	1700	1700	1700	1700	1700	1573
35	1668	1668	1668	1668	1668	1597
34	1635	1635	1635	1635	1635	1619
33	1602	1602	1602	1602	1602	1602
32	1568	1568	1568	1568	1568	1568
31	1535	1535	1535	1535	1535	1535
30	1501	1501	1501	1501	1501	1501
29	1466	1466	1466	1466	1466	1466
28	1431	1431	1431	1431	1431	1431
27	1396	1396	1396	1396	1396	1396
26	1360	1360	1360	1360	1360	1360
25	1324	1324	1324	1324	1324	1324

***: For speeds below 25-mph use equation 8.1.**

Table 9.2 Free flow speed, max capacity and speed at max capacity

FFS = speed limit+5 (mph)	Max Capacity (pcphpl)	Speed at max Capacity (mph)
65	2200	52.4
60	2100	48.97
55	2000	45.6
50	1875	41.51
45	1750	37.53
40	1625	33.69

If the operating speed (U_O) is greater than speed at capacity, use Equation 9.1. This equation is obtained by rearranging the terms in Equation 8.2.

$$C_{Uo} = 1300 + (C - 1300)\left(\frac{FFS - U_O}{FFS - U_C}\right)^{0.3846} \tag{9.1}$$

Where

C_{Uo} = Capacity corresponding to operating speed (pcphpl)

FFS = Free flow speed

U_o = Operating Speed (mph)

U_C = Speed at max capacity (mph)

C = Max capacity of the work zone (pcphpl) (from Table 9.2 or from speed-flow curve)

6. Compute the heavy vehicle factor (f_{HV}) using Equation 8.8.

$$f_{HV} = \frac{1}{1 + P_T(PCE - 1)} \tag{8.8}$$

Where

f_{HV} = Heavy vehicle factor

P_T = Percentage of heavy vehicles (entered as decimal)

PCE = Passenger car equivalents from Table 9.3 when no grade is long enough or steep enough to cause a significant speed reduction on trucks (when no one grade of 3% or greater is longer than 0.25 miles or where no one grade of less than 3% is greater than 0.5 miles). Otherwise, PCE should be obtained from Exhibit 23-9 of the Highway Capacity Manual.

Table 9.3 Passenger Car Equivalence

Passenger Car Equivalence	Type of Terrain		
	Level	Rolling	Mountainous
Trucks and Buses	1.5	2.5	4.5

7. Calculate the adjusted capacity (C_{adj}) from Equation 8.7.

$$C_{adj} = C_{U_o} * f_{HV} \tag{8.7}$$

Where,

C_{adj} = Adjusted capacity (vphpl)

C_{Uo} = Capacity at operating speed U_o (pcphpl)

f_{HV} = Heavy vehicle factor

8. If demand is greater than capacity do step 8. Otherwise, skip steps 8 and 9 and proceed to step 10.

Estimate the queue length at the end of every hour using the following procedure

Compute number of vehicles in queue (n_{i+1}) at the end of (i+1)th hour using Equation 9.2.

$$n_{i+1} = n_i + V_{i+1} - C_{adj} * N_{op} \tag{9.2}$$

Where,

n_i = Number of vehicles in queue at the end of ith hour

n_{i+1} = Number of vehicles in queue at the end of (i+1)th hour

V_{i+1} = Total demand in (i+1)th hour (vph)

C_{adj} = Adjusted capacity (vphpl)

N_{op} = Number of lanes open in the work zone

Compute l_{eff} (effective spacing between vehicles) using Equation 9.3.

$$l_{eff} = (P_T * l_T + P_C * l_C) + buffer\ space \tag{9.3}$$

Where,

l_{eff} = Effective spacing between vehicles (feet)

P_T = Percentage of heavy vehicles (entered as a fraction)

l_T = Length of heavy vehicles (feet)

P_C = Percentage of passenger cars (entered as a fraction)

l_C = Length of passenger cars (feet)

Buffer space = Distance between vehicles when both are stopped (10 feet)

Calculate stacked queue length (Q_{Si}) using Equation 9.4.

$$Q_{Si} = n_i * l_{eff} \tag{9.4}$$

Where,

Q_{Si} = Stacked queue length at the end of i^{th} hour (ft)

n_i = Number of vehicles in queue at the end of i^{th} hour

l_{eff} = Effective spacing between vehicles (feet)

Determine the distance from the work activity area to the beginning of the transition taper (D)

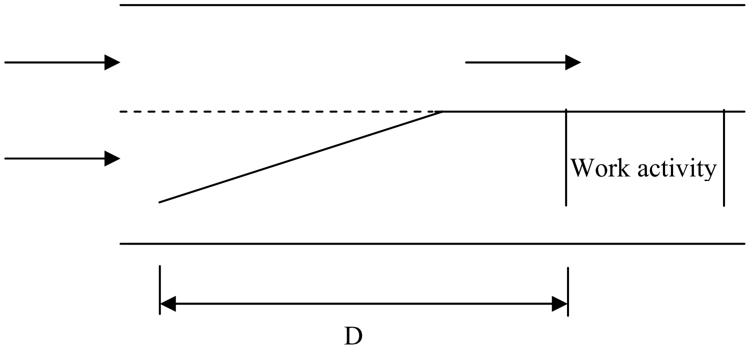

Figure 9.1 Determining D in a work zone

If D > Q_{Si} / N_{op}, queue will not extend outside of the work zone. Then queue length at the end of the i^{th} hour is computed using Equation 9.5.

$$Q_i = Q_{Si} / N_{op} \tag{9.5}$$

Where

Q_i = Queue length at the end of the i^{th} hour (ft)

Q_{Si} = Stacked queue length at the end of i^{th} hour (ft)

N_{op} = Number of lanes open in the work zone

If D < Q_{Si} / N_{op}, queue will extend outside of the work zone. Then queue length at the end of the i^{th} hour is computed using Equation 9.6.

$$Q_i = D + (Q_{Si} - D*N_{op})/ N_{nr} \tag{9.6}$$

Where,

Q_i = Queue length at the end of the i^{th} hour (ft)

D = Distance from the work activity area to the beginning of the taper (ft)

Q_{Si} = Stacked queue length at the end of i^{th} hour (ft)

N_{op} = Number of lanes open in the work zone

N_{nr} = Number of lanes open before the work zone

It should be noted that the queue length is measured from the beginning of the work activity area.

9. Estimate the delay due to queuing using the Equation 9.7.

$$d_q = \sum_{i=0}^{t-1} \left(\frac{n_i + n_{i+1}}{2} \right) \tag{9.7}$$

Where,

d_q = Delay due to queuing (in veh-hours)

t = Number of hours of queuing

n_i = Number of vehicles in queue at the end of i^{th} hour

n_{i+1} = Number of vehicles in queue at the end of $(i+1)^{th}$ hour

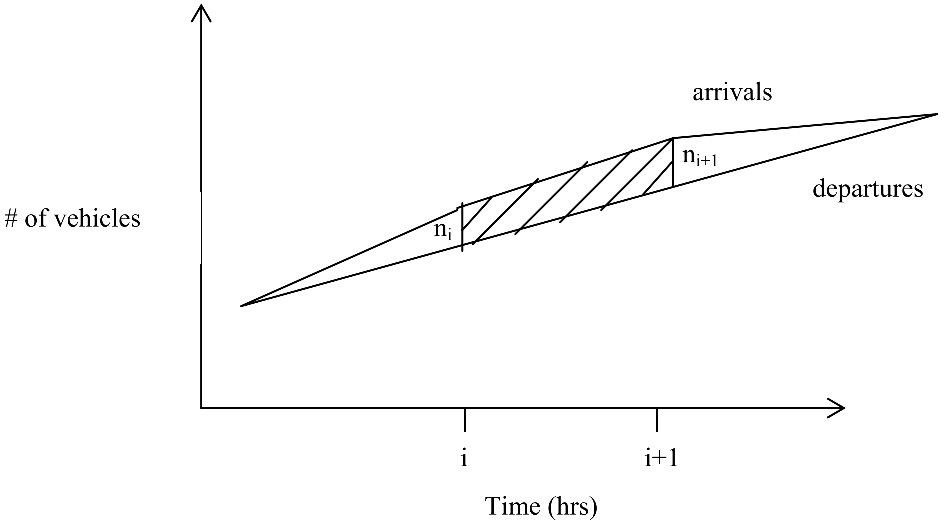

Figure 9.2 Average delay due to queuing

The shaded area is a trapezoid and the average delay experienced by the vehicles during hour i+1 is given by $d_{i+1} = (n_i + n_{i+1})/2$

If we had "t" hours of queuing, the total queuing delay summed over the hours is given by the following Equation

$$d_q = \sum_{i=0}^{t-1} \left(\frac{n_i + n_{i+1}}{2} \right)$$

10. Estimate the delay due to slower speed in the work zone using Equation 9.8.

$$d_{spd} = \sum_i V_i * \left(\frac{L}{U_o} - \frac{L}{U_{\lim}} \right) \tag{9.8}$$

Where,

d_{spd} = Delay due to slower speed (veh-hours)

L = Length of the work zone (miles)

V_i = Demand in hour i (vph)

U_o = Operating Speed (mph)

U_{lim} = Posted speed limit inside the work zone (mph)

11. Estimate the total delay using Equation 9.9.

$$d_{total} = d_{spd} + d_q \tag{9.9}$$

Where,

d_{total} = Total delay experienced by the users (veh-hours)

d_{spd} = Delay due to slower speed (veh-hours)

d_q = Delay due to queuing (veh-hours)

12. Compute users cost

$$UC = d_{total}\ ((P_T * C_T) + (P_C * C_C * N_{occ})) \tag{9.10}$$

Where,

UC = Total user costs ($)

d_{total} = Total delay experienced by the users (in veh-hours)

P_T = Percentage of heavy vehicles

C_T = Hourly delay costs for trucks ($/hr)

P_C = Percentage of passenger cars

C_C = Hourly delay costs for each passenger in a car ($/hr/passenger)

N_{occ} = Average number of occupants in cars (passengers/car)

9.3 Examples

In this study the work zones were classified into long-term and short-term work zones. Of the eleven work zones at which detailed data was collected eight were long-term and three were short-term sites. During the data collection period three sites experienced queuing. All the three sites were long-term sites.

In this section three examples that are based on the field data are presented

- Short-term site without queuing
- Long-term site without queuing
- Long-term site with queuing

The procedure for short-term sites is almost same as the procedure for long-term sites. The only difference is in Step 3 where the speed reduction due to work intensity is estimated.

9.3.1 Example 1 (Short-term Non-queuing site)

I 57 NB Mile Post 271

The site was near Buckley. It was a short-term work zone (cones/ barrels were used in the site) with one lane closed and one lane open. The left lane was closed. The work zone length was 0.6 miles. The speed limit inside the work zone was 45 mph. The open lane was 12 ft wide, with 8-ft wide right shoulder and left shoulder was closed within the lane closure section. Four workers were present with one piece of heavy equipment and the work activity was 6 ft away from the open lane. The demand was 446 vph in the first hour and 465 vph in the second hour. There were 27.22% heavy vehicles. Figure 9.3 shows the schematic of the work zone. Please note that the sketch is not drawn to scale.

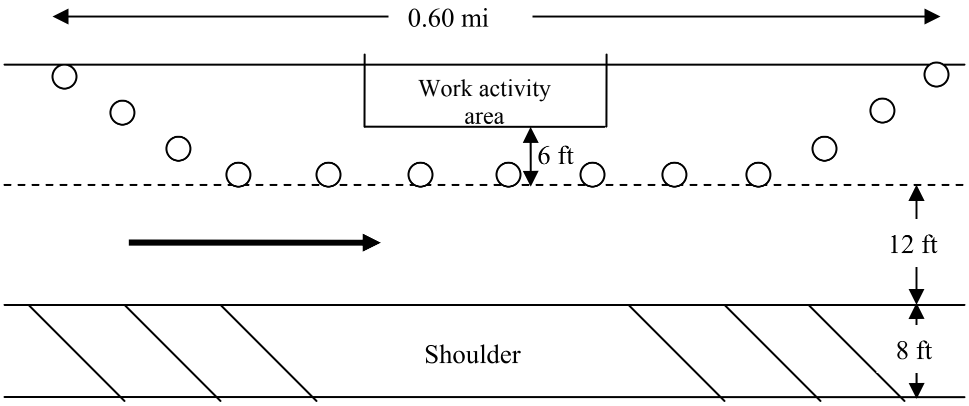

Figure 9.3 Schematic of Work zone at I 57 NB MilePost 271(Not to scale).

1. Find speed reductions due to narrow lane width (R_{LW}) and lateral clearance (R_{LC}) from Table 8.2.

Lane Width: 12 ft

From Table 8.2 Reduction in speed for 12 ft wide lanes = 0 mph.

So R_{LW} = 0 mph

Right shoulder: 8 ft

From Table 8.2 Reduction in speed for 8 ft wide right shoulder with two lanes without work zone = 0 mph.

Left shoulder: 0 ft

From Table 8.2 Reduction in speed for 0 ft wide left shoulder = 2 mph.

So reductions due to lateral clearance = R_{LC} = 0 + 2 = 2 mph

2. Compute the work intensity ratio (WI_r) using Equation 8.4.

$$WI_r = \frac{w + e}{p} \tag{8.4}$$

Number of workers working together as a group in work activity area (w) = 4

Number of large construction equipment in work activity area near the workers group (e) = 1

Lateral distance between the workers group and the open lane (p) = 6 feet

So work intensity ratio (WI_r) = (4+1)/6 = 0.83

3. Compute the speed reduction due to work intensity (R_{WI}) from Equation 8.5 because this is a short-term work zone.

$$SR_S = 2.676\ln(WI_r) + 11.918 \tag{8.5}$$

Substituting 0.83 for WI_r in the above Equation yields R_{WI} = 11.42 mph

4. Calculate the Operating speed (Uo) based on Equation 8.3.

$$U_O = FFS - R_{LW} - R_{LC} - R_{WI} - R_O \tag{8.3}$$

Speed Limit = 45 mph

FFS = Speed Limit + 5 = 50 mph

R_{LW} = 0 mph

R_{LC} = 2 mph

R_{WI} = 11.42 mph

$R_O = 0$ mph

So $U_o = 36.58$ mph

[This should be compared to speed observed in the field, which was 42.22 mph. This showed a reasonable match.]

5. Find the capacity (Cu_0) corresponding to the operating speed from the speed flow curve given in Figure 8.2 or using the Equations 8.1 or 9.1 as appropriate.

Since U_O (36.58 mph) lesser than U_C (Speed at capacity = 41.51 mph, from Tables 9.2) use Equation 8.1.

$$q = 145.68 \times U^{0.6857} \tag{8.1}$$

$U = Uo = 36.58$ mph

Therefore

$C_{Uo} = q = 1719$ pcphpl

The capacity corresponding to operating speed (Cu_0) can be obtained by entering the operating speed on the vertical axis of Figure 8.2. This is illustrated in Figure 9.4 and it shows that Cu_0 is approximately 1720 pcphpl. Since the number obtained from the equations is precise, 1719 pcphpl shall be used in the following calculations. But the user can use the approximate number obtained from the graph.

6. Compute the heavy vehicle factor (f_{HV}) using Equation 8.8.

$$f_{HV} = \frac{1}{1 + P_T\,(PCE - 1)} \tag{8.8}$$

$P_T = 27.22\% = 0.2722$

PCE = 1.5 (For level terrain) from Table 9.3

So $f_{HV} = 0.8802$

7. Calculate the adjusted capacity (C_{adj}) from Equation 8.7.

$$C_{adj} = C_{U_O} * f_{HV} \tag{8.7}$$

$C_{Uo} = 1719$ pcphpl

$f_{HV} = 0.8802$

$C_{adj} = 1513$ vphpl

[This number should be compared to the observed service capacity in the field (from section 7.4.1 in report) which was 1600 vphpl. There is very good match between the computed capacity and observed one.]

Steps 8 and 9 are not applicable because the demand was lesser than the capacity during both the hours. However, there is delay due to slow moving vehicles.

10. Compute the delay due to slower speed in the work zone using Equation 9.8.

$$d_{spd} = \sum_i V_i * (\frac{L}{U_o} - \frac{L}{U_{\lim}}) \tag{9.8}$$

L = 0.60 miles

V_1 = 446 vph

V2 = 465 vph

U_o = 36.58 mph

U_{lim} = 45 mph

d_{spd} = 446 * (0.60/36.58 – 0.60/45) + 465 * (0.60/36.58 – 0.60/45) = 2.79 veh-hours

Please note that in the field the delay due to slower speed was 0.80 veh-hours.

Figure 9.4 Reading capacity for Example 1

11. Compute the total delay using Equation 9.9.

$$d_{total} = d_{spd} + d_q \qquad (9.9)$$

d_{spd} = 2.79 veh-hours

d_q = 0 veh-hours

Therefore d_{total} = 0 + 2.79 = 2.79 veh-hours

12. Compute users cost using Equation 9.10.

$$UC = d_{total}\,((P_T * C_T) +(P_C * C_C * N_{occ})) \qquad (9.10)$$

d_{total} = 2.79 veh-hours

P_T = 27.22 %

C_T = 22 \$/hr (assumed based on the data from State Survey)

P_C = 72.78 %

C_C = 10 \$/hr (IDOT BDE value)

N_{occ} = 1.25 passengers/car (IDOT BDE value)

Therefore UC = 2.79 ((27.22 * 22) + (72.78 * 10 * 1.25))/100 = $ 42.09

9.3.2 Example 2 (Long-term Non-queuing site)

I 74 WB Mile Post 79

The site was west of Peoria. It was a long-term work zone (concrete barriers were used in the site) with right lane closed and left lane open. The work zone length was 1.26 miles. The speed limit inside the work zone was 55 mph. The open lane was 10.5 ft wide, and both the shoulders were closed within the lane closure section. Three workers were present with no heavy equipment and the work activity was 3 ft away from the open lane. The demand was 771 vph in the first hour and 729 vph in the second hour. There were 21.01% heavy vehicles. Figure 9.5 shows the schematic of the work zone. Please note that the sketch is not drawn to scale.

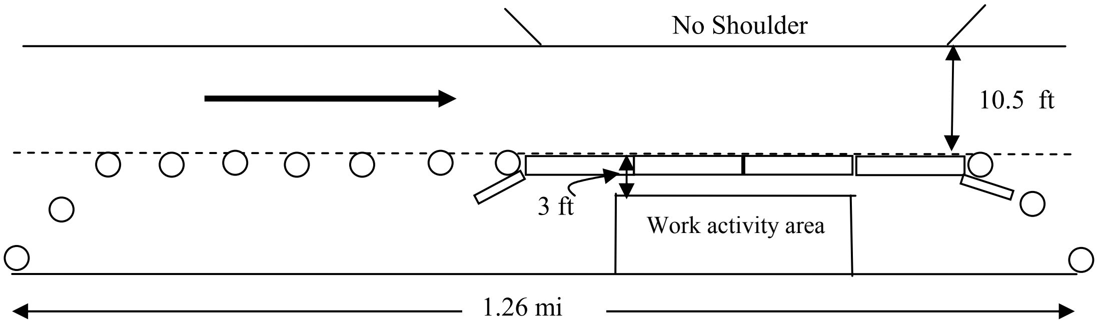

Figure 9.5 Schematic of Work zone at I 74 WB Mile Post 79 (Not to scale)

1. Find speed reductions due to narrow lane width (R_{LW}) and lateral clearance (R_{LC}) from Table 8.2.

Lane Width: 10.5 ft

From Table 8.2 Reduction in speed for 10.5 ft wide lanes = average of the reductions for 10 ft and 11 ft wide lanes = (1.9+6.6)/2 = 4.25 mph.

So R_{LW} = 4.25 mph

Right shoulder: 0 ft

From Table 8.2 Reduction in speed for 0 ft wide right shoulder with two lanes without work zone = 3.9 mph.

Left shoulder: 0 ft

From Table 8.2 Reduction in speed for 0 ft wide left shoulder = 2 mph.

So reductions due to lateral clearance = R_{LC} = 3.9 + 2 = 5.9 mph

2. Compute the work intensity ratio (WI_r) using Equation 8.4.

$$WI_r = \frac{w + e}{p} \tag{8.4}$$

Number of workers working together as a group in work activity area (w) = 3

Number of large construction equipment in work activity area near the workers group (e) = 0

Lateral distance between the workers group and the open lane (p) = 3 feet

So work intensity ratio (WI_r) = (3+0)/3 = 1

3. Compute the speed reduction due to work intensity (R_{WI}) from Equation 8.6 because this is a long-term work zone.

$$SR_L = 1.2056\ln(WI_r) + 2.6625 \tag{8.6}$$

Substituting 1 for WI_r in the above Equation yields R_{WI} = 2.66 mph

4. Calculate the Operating speed (Uo) based on Equation 8.3.

$$U_O = FFS - R_{LW} - R_{LC} - R_{WI} - R_O \tag{8.3}$$

Speed Limit = 55 mph

FFS = Speed Limit + 5 = 60 mph

R_{LW} = 4.25 mph

R_{LC} = 5.9 mph

R_{WI} = 2.66 mph

R_O = 0 mph

So U_o = 47.19 mph

[This should be compared to speed observed in the field, which was 44.04mph. This showed a very good match.]

5. Find the capacity (Cu_0) corresponding to the operating speed from the speed flow curve given in Figure 8.2 or using the Equations 8.1 or 9.1 as appropriate.

Since U_O (47.19 mph) lesser than U_C (Speed at capacity = 48.97 mph, from Table 9.2) use Equation 8.1

$$q = 145.68 \times U^{0.6857} \tag{8.1}$$

$U = U_O$ = 47.19 mph

Therefore

C_{Uo} = q = 2047 pcphpl

The capacity corresponding to operating speed (Cu_0) can be obtained by entering the operating speed on the vertical axis of Figure 8.2. This is illustrated in Figure 9.6 And it shows that Cu_0 is approximately 2040 pcphpl. Since the number obtained from the equations is precise, 2047 pcphpl shall be used in the following calculations. But the user can use the approximate number obtained from the graph.

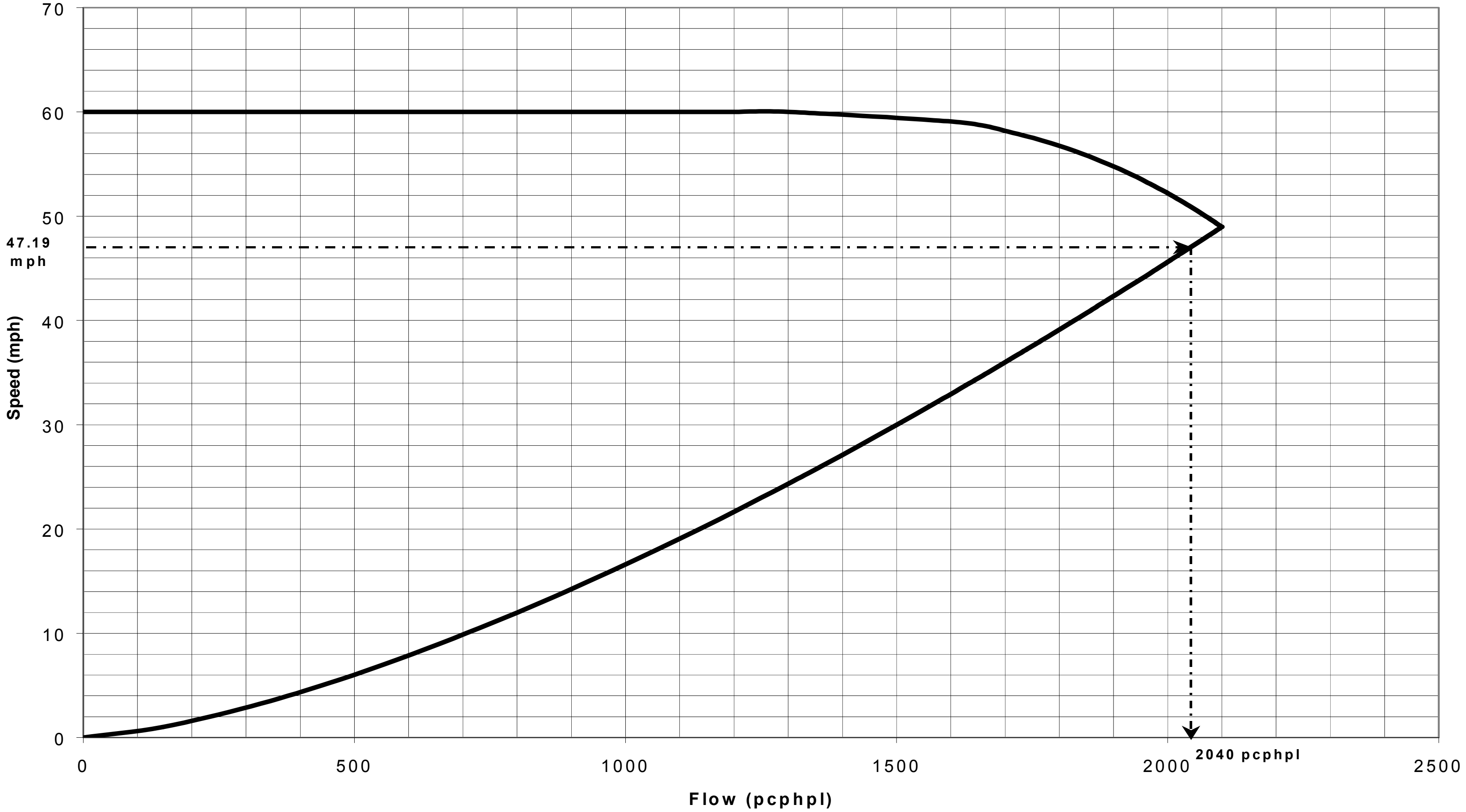

Figure 9.6 Reading capacity for Example 2

6. Compute the heavy vehicle factor (f_{HV}) using Equation 8.8.

$$f_{HV} = \frac{1}{1 + P_T(PCE - 1)} \tag{8.8}$$

$P_T = 21.01\ \% = 0.2101$

PCE = 1.5 (For level terrain) from Table 9.3

So $f_{HV} = 0.9049$

7. Calculate the adjusted capacity (C_{adj}) from Equation 8.7.

$$C_{adj} = C_{U_O} * f_{HV} \tag{8.7}$$

$C_{Uo} = 2047$ pcphpl

$f_{HV} = 0.9049$

$C_{adj} = 1852$ vphpl

[This number should be compared to the observed service capacity in the field (from section 7.4.1 in report) which was 1708 vphpl. There is a reasonably good match between the computed capacity and observed one.]

Steps 8 and 9 are not applicable because the demand was lesser than the capacity during both the hours. However, there is delay due to slow moving vehicles.

10. Compute the delay due to slower speed in the work zone using Equation 9.8.

$$d_{spd} = \sum_i V_i * \left(\frac{L}{U_o} - \frac{L}{U_{\lim}}\right) \tag{9.8}$$

L = 1.26 miles

$V_1 = 771$ vph

V2 = 729 vph

$U_o = 47.19$ mph

$U_{\lim} = 55$ mph

$d_{spd} = 771 * (1.26/47.19 - 1.26/55) + 729 * (1.26/47.19 - 1.26/55) = 5.69$ veh-hours

Please note that in the field the delay due to slower speed was 8.55 veh-hours. This is close to the computed value of 5.69 veh-hours.

11. Compute the total delay using Equation 9.9.

$$d_{total} = d_{spd} + d_q \tag{9.9}$$

$d_{spd} = 5.69$ veh-hours

d_q = 0 veh-hours

Therefore d_{total} = 0 + 5.69 = 5.69 veh-hours

12. Compute users cost using Equation 9.10.

$$UC = d_{total}\,((P_T * C_T)+(P_C * C_C * N_{occ})) \tag{9.10}$$

d_{total} = 5.69 veh-hours

P_T = 21.01 %

C_T = 22 \$/hr (assumed based on the data from State Survey)

P_C = 78.99 %

C_C = 10 \$/hr (IDOT BDE value)

N_{occ} = 1.25 passengers/car (IDOT BDE value)

Therefore UC = 5.69 ((21.01 * 22) + (78.99 * 10 * 1.25))/100 = $ 82.48

9.3.3 Example 3 (Long-term Queuing Site)

I 55 SB Mile Post 55

The site was near Litchfield. It was a long-term work zone (concrete barriers were used in the site) with right lane closed and left lane open. The work zone length was 4.66 miles. The speed limit inside the work zone was 55 mph. The open lane was 12 ft wide, with no shoulder on either side in the work activity area. Seven workers were present with one piece of heavy equipment and the work activity was 2 ft away from the open lane. The distance from the work activity area to the beginning of the transition taper was 23496 ft. The demand during the one hour that had queuing was 1320 vph. There were 18.08% heavy vehicles. At the end of the hour of queuing, the queue length was 10500 ft. The average speed of the vehicles during the hour was 19.18 mph. Figure 9.7 shows the schematic of the work zone. Please note that the sketch is not drawn to scale.

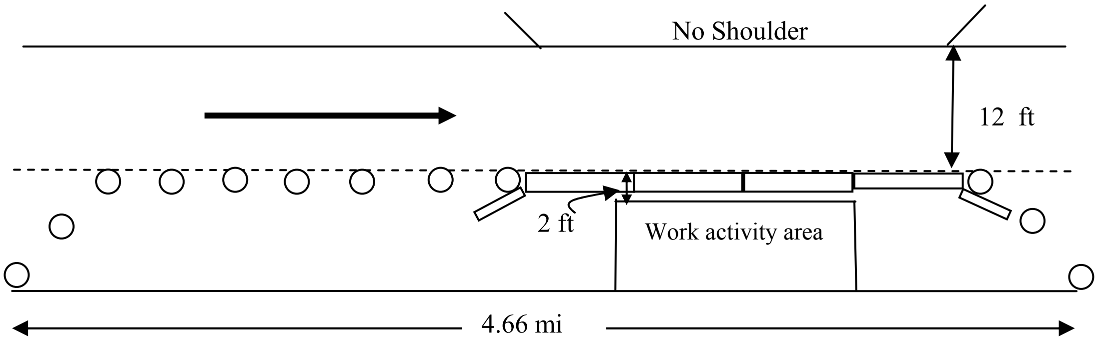

Figure 9.7 Schematic of Work zone at I 55 SB MilePost 55 (Not to scale)

1. Find speed reductions due to narrow lane width (R_{LW}) and lateral clearance (R_{LC}) from Table 8.2.

Lane Width: 12 ft

From Table 8.2 Reduction in speed for 12 ft wide lanes = 0 mph.

So R_{LW} = 0 mph

Right shoulder: 0 ft

From Table 8.2 Reduction in speed for 0 ft wide right shoulder with two lanes in a normal section of the highway = 3.9 mph.

Left shoulder: 0 ft

From Table 8.2 Reduction in speed for 0 ft wide left shoulder = 2 mph.

So reductions due to lateral clearance = R_{LC} = 3.9 + 2 = 5.9 mph

2. Compute the work intensity ratio (WI_r) using Equation 8.4.

$$WI_r = \frac{w + e}{p} \tag{8.4}$$

Number of workers working together as a group in work activity area (w) = 7

Number of large construction equipment in work activity area near the workers group (e) = 1

Lateral distance between the workers group and the open lane (p) = 2 feet

So, work intensity ratio: $WI_r = (7+1)/2 = 4.0$

3. Compute the speed reduction due to work intensity (R_{WI}) from Equation 8.6 because this is a long-term work zone.

$$SR_L = 1.2056\ln(WI_r) + 2.6625 \tag{8.6}$$

Substituting 4.0 for WI_r in the above Equation yields R_{WI} = 4.33 mph

4. Calculate the Operating speed (Uo) based on Equation 8.3.

$$U_O = FFS - R_{LW} - R_{LC} - R_{WI} - R_O \tag{8.3}$$

Speed Limit = 55 mph

FFS = Speed Limit + 5 = 60 mph

R_{LW} = 0 mph

R_{LC} = 5.9 mph

R_{WI} = 4.33 mph

So, U_o = 49.77 mph

In the field there was a breakdown in the flow and the flow did not recover, resulting in a slow moving queue of vehicles. The proposed methodology does not consider the effect of traffic breakdown on speed and hence capacity. Therefore the speed estimated by the methodology does not match the field speed (19.18-mph).

To account for these other factors (for example flow breakdown) that could reduce the speed of the motorists in work zones the factor R_O was introduced in Equation 8.3

$$U_O = FFS - R_{WI} - R_{LW} - R_{LC} - R_O \tag{8.3}$$

With the rapid development of ITS technologies that provide reliable real time information, the speed reduction due to other factors can be obtained from the field.

From the field data we have the actual speed of the vehicles (19.18-mph). Therefore R_o can be computed as the difference between the estimated operating speed (50.41 mph from step 4) and the speed in the field (19.18 mph). Therefore R_o = 50.11 - 19.18 = 30.93 mph.

Using this value of R_o in Equation 8.3, we get U_o = 19.18 mph.

5. Find the capacity (Cu_0) corresponding to the operating speed from the speed flow curve given in Figure 8.2 or using the equations 8.1 or 9.1 as appropriate.

Since U_O (19.18 mph) lesser than U_C (Speed at capacity = 48.97 mph, from Table 9.2) use Equation 8.1

$$q = 145.68 \times U^{0.6857} \tag{8.1}$$

$U = U_O$ = 19.18 mph

Therefore

$C_{Uo} = q = 1104$ pcphpl

The capacity corresponding to operating speed (Cu_0) can also be obtained by entering the operating speed on the vertical axis of Figure 8.2. This is illustrated in Figure 9.8 and it shows that Cu_0 is approximately 1110 pcphpl. Since the number obtained from the equations is precise, 1104 pcphpl shall be used in the following calculations. But the user can use the approximate number obtained from the graph.

6. Compute the heavy vehicle factor (f_{HV}) using Equation 8.8.

$$f_{HV} = \frac{1}{1 + P_T(PCE - 1)} \tag{8.8}$$

$P_T = 18.08\% = 0.1808$

PCE = 1.5 (For level terrain) from Table 9.3

So, $f_{HV} = 0.9170$

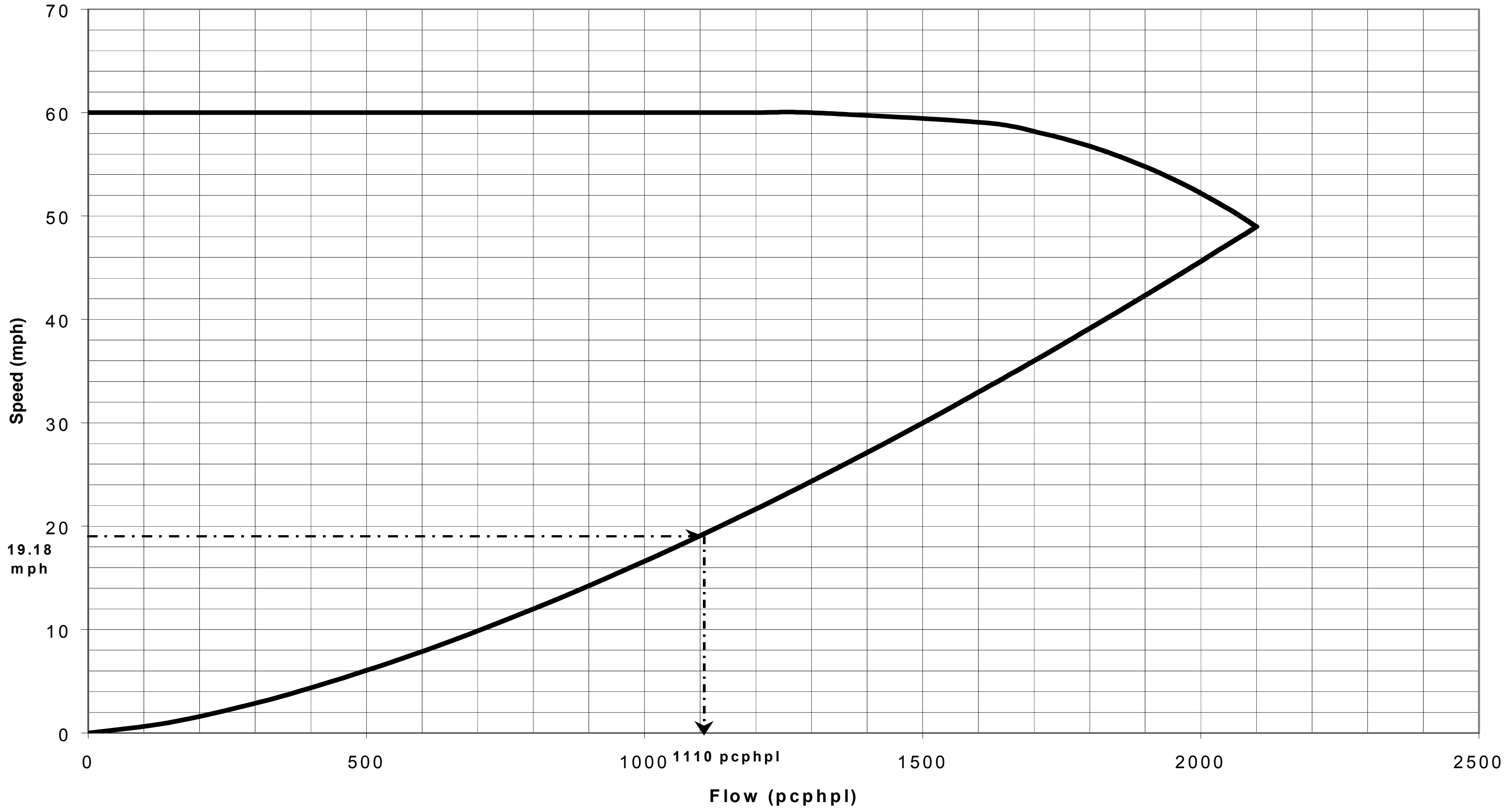

Figure 9.8 Reading capacity for Example 3

7. Calculate the adjusted capacity (C_{adj}) from Equation 8.7.

$$C_{adj} = C_{U_O} * f_{HV} \tag{8.7}$$

C_{Uo} = 1104 pcphpl

f_{HV} = 0.9170

C_{adj} =1012 vphpl

[This number should be compared to the observed service capacity in the field (from section 7.4.1 in report) which was 1220 vphpl. There is a reasonably good match between the computed capacity and observed one.]

8. Compute the queue length at the end of 1st hour using the following procedure

Compute n_1 (number of vehicles in queue at the end of 1^{st} hour) using Equation 9.2 with i =0

$$n_{i+1} = n_i + V_{i+1} - C_{adj} * N_{op} \tag{9.2}$$

That is $n_1 = n_0 + V_1 - C_{adj} * N_{op}$

$n_0 = 0$

V_1 = 1320 vph

C_{adj} = 1012 vphpl

$N_{op} = 1$

So, n_1 = 308 vehs

Compute l_{eff} (effective spacing between vehicles) using Equation 9.3.

$$l_{eff} = (P_T * l_T + P_C * l_C) + \text{buffer space} \tag{9.3}$$

P_T = 18.08% = 0.1808

l_T = 55 ft

P_C = 81.92 % = 0.8192

l_C = 15 ft

Buffer space = 10 ft

So, l_{eff} = 32.2ft

Compute stacked Q_{S1} (stacked queue length at the end of 1^{st} hour) using Equation 9.4 with i = 1

$$Q_{Si} = n_i * l_{eff} \tag{9.4}$$

That is $Q_{S1} = n_1 * l_{eff}$

$n_1 = 308$

l_{eff} = 32.2 ft

Therefore, Q_{S1} = 308 * 32.2 = 9917.6 ft = 1.88 miles

In the field the distance from the work activity area to the beginning of the transition taper (D) was 23496 ft.

$D = 23496$ ft

$Q_{S1} = 9917.6$ ft

$N_{op} = 1$

$Q_{S1}/N_{op} = 9917.6$

Since D (23496 ft) > Q_{S1}/N_{op} (9917.6), the queue length at the end of 1st hour (Q_1) is computed using Equation 9.5 with i = 1.

$$Q_i = Q_{Si} / N_{op} \tag{9.5}$$

$Q_1 = Q_{S1}/N_{op} = 9917.6$ ft

From the field the queue length at the end of hour = 10500 ft = 1.99 miles

9. Compute the delay due to queuing using Equation 9.7.

$$d_q = \sum_{i=0}^{t-1} \left(\frac{n_i + n_{i+1}}{2} \right) \tag{9.7}$$

$n_0 = 0$ vehs

$n_1 = 308$ vehs

$t = 1$

Therefore, $d_q = (0+308)/2 = 154$ veh-hours

10. Compute the delay due to slower speed in the work zone using Equation 9.8.

$$d_{spd} = \sum_i V_i * (\frac{L}{U_o} - \frac{L}{U_{\lim}}) \tag{9.8}$$

$L = 4.66$ miles

$V_1 = 1320$ vph

$U_o = 19.18$ mph

$U_{lim} = 55$ mph

$d_{spd} = 1320 * (4.66/19.18 – 4.66/55) = 208.9$ veh-hours

11. Compute the total delay using Equation 9.9.

$$d_{total} = d_{spd} + d_q \tag{9.9}$$

$d_{spd} = 208.9$ veh-hours

$d_q = 147.5$ veh-hours

Therefore $d_{total} = 208.9 + 154 = 362.9$ veh-hours

Total delay from the field data was 416.3 veh-hours.

This is reasonably close to the field data.

12. Compute users cost using Equation 9.10.

$$UC = d_{total} ((P_T * C_T) + (P_C * C_C * N_{occ})) \tag{9.10}$$

d_{total} = 362.9 veh-hours

P_T = 18.08 %

C_T = 22 \$/hr (assumed based on the data from State Survey)

P_C = 81.92 %

C_C = 10 \$/hr (IDOT BDE value)

N_{occ} = 1.25 passengers/car (IDOT BDE value)

Therefore UC = 362.9 ((18.08 * 22) + (81.92 * 10 * 1.25))/100 = \$ 5159.57

In the above example the field speed of 19.18 mph was used for operating speed. However, this speed would not be known a priori. Based on several studies (quoted in section 9.5) 25 mph would be a reasonable assumption for speed under breakdown conditions. So, in Table 9.4, the results of using 25 mph as the operating speed from steps 5 through 12 are presented.

Table 9.4 Steps 5 through 12 using operating speed 25 mph

Step	Computation	Using U_O = 25 mph
5	Unadjusted Capacity (C_{Uo})	1324 pcphpl
6	Heavy vehicle factor (f_{HV})	0.9170
7	Adjusted Capacity (C_{adj})	1214 vphpl

Table 9.4: Continued

8	Queue length $n_0=0, V_1=1320, C_{adj}=1163, N_{op} = 1$	$n_1 = 106$ $l_{eff} = 32.2$ ft $Q_{S1} = 0.65$ mi Since $Q_{S1} < D$ $Q_1 = Q_{S1} = 0.65$ mi
9	Queuing Delay (d_q)	53 veh-hrs
10	Delay due to slower speed (d_{spd})	134.2 veh-hrs
11	Total Delay (d_{total})	187.2 veh-hrs
12	User Costs	$ 2661.54

The assumed speed of 25 mph for flow breakdown condition was higher than the actual speed of 19.1 mph in the field. Thus, the estimated capacity was higher which resulted in a shorter queue length and smaller queue delay. Consequently the user costs were smaller. This comparison illustrates the significance of estimating the speed accurately.

9.4 Some causes of flow breakdown in a work zone

A breakdown in traffic flow occurs when the demand exceeds the capacity of the roadway. Under three conditions demand exceeds capacity: 1) when more vehicles want to use the road (demand is increased), 2) when capacity is reduced, 3) combination of items one and two. Thus, even though the demand might remain at similar levels, there might be a flow breakdown due to the reduction in the capacity of the work zone. In general, the capacity of a work zone would be less than the capacity of the same section of the freeway if there were no work zone. This reduction in capacity can be attributed to many factors such as lane closure, change in roadway geometry, presence of traffic control devices, reduced speed limit, construction workers and equipment, and work activity.

In this study, a UIUC methodology has been developed to estimate the capacity of a work zone given geometric and work activity information. This study did not have enough data to quantify the effect of several other factors on the capacity of the work zone. The effects of most of these factors cannot be easily quantified due to the changes in field operating conditions. They cannot be accounted for as standard factors unless they are clearly defined. For example, an incident reduces capacity, but different incidents reduce capacity differently. One needs to define the incident and its severity and extent before quantifying its effects. Some of the factors that could potentially reduce the capacity and cause the flow to breakdown are:

- Incident: A major incident (crash, vehicle breakdown etc.) could completely choke the flow of traffic especially in the work zones that have only one open lane. On the other hand, a minor incident could have a limited effect on capacity.
- Undue and unnecessary decrease in speed: This could be due to several factors. It was observed in the field that the presence of an aggressive flagger could reduce the speed of the traffic by as much as 20 mph or more even when the traffic was moving at the posted speed limit. Such reductions in speed drastically reduce the capacity of the work zone.
- Drastic reduction in the lane width: This could happen when traffic control devices such as barrels or cones are pushed into the open lane of the work zone.
- Changes in horizontal and vertical alignments: When the horizontal alignment of a road is altered from its normal path by actions such as shifting the lanes, building detour roads, building a crossover, etc, the capacity can be reduced. Similarly, when the vertical profile of a road is altered, capacity often will be less than the normal values. Uneven surface, bumps, rough pavement surface conditions in work zones would reduce work zone capacity particularly when there are a large number of trucks.

- Work activity: In several cases the way the crew works in the work zone caused the traffic to reduce the speed. Examples of these could be stopping of traffic in the open lane by the crew, heavy volume of vehicles moving in and out of the closed lane, dust created by the work activity, uneven condition of the pavement, presence of construction debris on the open lane etc. Although the effect of work activity is considered in the proposed methodology, it was beyond the scope of this study to quantify the effects of all these factors.
- Unusual traffic: Presence of high proportion of heavy vehicles or oversized vehicles combined with the presence of narrow lanes or relatively steep grades drastically reduces the capacity of the work zone.
- Driver behavior: In general presence of overcautious motorists who reduce their speed much below the work zone speed limit reduce capacity. Also drivers who maintain unnecessarily long distance headway reduce work zone capacity, especially if only one lane is open in the work zone.
- Aggressive speed enforcement: When there are police patrol vehicles with lights flashing on the approach to or inside a work zone, it often reduces speed but it may reduce it much below the speed limit of the work zone, thus reducing the capacity.

The above list of factors illustrates the wide range of factors that could affect the capacity of the work zone and that their occurrence cannot be predicted beforehand. Therefore, it is difficult to predict today when the traffic flow would breakdown in a work zone that will be out there in the future, unless real-time information about the operating conditions in the field is available. Without the real-time information, one can only guess which one of these factors could cause capacity reduction, unless there is enough data collected to build a reliable knowledge of frequency and severity of these factors. Then, it will be possible with some certainty to predict the effects of these factors on work zone operating conditions and its capacity. For now, one has to rely on his/her knowledge and understanding of work zone operation to "guestimate" the effects of these factors, until further studies provide more solid basis for such important decisions.

9.5 Speeds observed under flow breakdown conditions

In this study, detailed data was collected at eleven sites. Of the eleven sites, flow broke down at three sites and sustained queuing was observed. The average speeds observed in these sites varied from 19.18 mph to 26.44 mph.

Rouphail et al (1985) collected data at four sites in Illinois. All the sites studied were on four lane interstate highways with single lane closures and no crossovers. Simultaneous 5-min counts of speed and flow rates at the beginning and the end of the lane closure section were conducted. In one of the sites (I-290), heavy congestion resulting in queues was observed during the data collection. The mean speed at the start of the lane closure was 26.75 mph and at the end of the lane closure it was 31.51 mph. In the rest of the sites, during the data collection no flow breakdown occurred.

Jiang (1999) studied eight work zones on interstate highways in Indiana. At each site data was collected for a period of 2 to 4 days. Four of the eight work zones experienced congestion during data collection. Of the four work zones, two were crossover sites, one was a partial lane closure with left lane closed and the other was a partial lane closure with right lane closed. Under congested conditions, the mean speed observed at the site with right lane closed was 31.46 mph and at the site with left lane closed was 38.58 mph.

Polus et al (1999) studied the flow conditions at two suburban freeway work zones in Israel. At both the sites, the construction operations caused congestion, queues and delays. At site 1, two of the three open lanes were closed and the observed median speed was 31.25 mph. Site 2 was a crossover site and the observed median speed was 33.13 mph.

Maze et al. (2000) observed a work zone on rural a rural interstate highway in Iowa. One of the two lanes was closed and the data was collected using videos mounted atop booms. It has been observed in their data that under queuing conditions at the site speeds ranged from 19 to 30mph.

Sarasua et al. (2003) collected data from 22 short-term work zone sites over a period of one year. In four of the sites experienced vehicle queues extending beyond a mile. It has been observed from their data that under congested conditions the speeds on 2 to 1 lane closure projects varied from approximately 12 to 25 mph.

All the studied quoted above had data from 2 to 1 lane closure projects and it can be seen that the speeds observed varied from as low as 12 mph to 38.58 mph. In general the speeds were concentrated between mid 20's and low 30's. In the absence of any data about the prevailing traffic conditions in the field, to be conservative in the estimates of delay and user costs, the authors would recommend the speed range of 20 to 30 mph for speed under flow breakdown conditions.

9.6 Conclusions

In this chapter the methodology for estimating capacity, queue length and delay in work zones and examples illustrating the use of the proposed methodology have been presented. In this study we were limited by the scope of the project to collect data only from work zones on interstate highways with one lane closed and one lane open. Nevertheless, we would expect the concept behind the proposed methodology to be valid for other kinds of work zones such as crossover work zones, three-to-two or three-to-one lane closure work zones etc. However the use of the equations or parameters proposed in this methodology for other configurations of work zones should be done with caution.

The UIUC methodology uses adjustment factors that are not developed specifically for work zones. The passenger car equivalents, speed reductions due to lane width and lateral clearance were directly taken from the HCM for basic freeway sections. The equations proposed for speed reductions due to work intensity in short term and long term work zones were developed based on limited data that was available in this study. It is recommended to collect field data to quantify these values for work zones. As illustrated in section 9.3.3, the speed under flow breakdown conditions significantly affects the delay and user costs computed. Further studies are required to ascertain the factors that cause flow breakdown and the resulting speed under such conditions. In the light of these comments, interim use of the proposed methodology is recommended to verify the proposed parameters and equations.

9.7 References

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Symbols

Below is the list of symbols used in this chapter. The step number (of the Step-by-Step Approach to Estimate Work Zone Capacity, Queue Length and Delay) in which they are used for the first time is shown in parentheses.

Buffer space = Distance between vehicles when both are stopped (10 feet) (Step 8)

C = Max capacity of the work zone (pcphpl) (Step 5)

C_{adj} = Adjusted capacity (vphpl) (Step 7)

C_C = Hourly delay costs for each passenger in a car ($/hr/passenger) (Step 12)

C_T = Hourly delay costs for trucks ($/hr) (Step 12)

C_{Uo} = Capacity corresponding to operating speed (pcphpl) (Step 5)

d_q = Delay due to queuing (in veh-hours) (Step 9)

d_{spd} = Delay due to slower speed (veh-hours) (Step 10)

d_{total} = Total delay experienced by the users (veh-hours) (Step 11)

D = The distance from the work activity area to the beginning of the transition taper (ft) (Step 8)

e = Number of large construction equipment in work activity area near the workers group (e varies from 0 to a maximum of 5) (Step 2)

f_{HV} = Heavy vehicle factor (Step 6)

FFS = Free flow speed (It is assumed that FFS= Speed limit + 5 mph) (Step 4)

l_C = Length of passenger cars (feet) (Step 8)

l_{eff} = Effective spacing between vehicles (feet) (Step 8)

l_T = Length of heavy vehicles (feet) (Step 8)

L = Length of the work zone (miles) (Step 10)

n_i = Number of vehicles in queue at the end of i^{th} hour (Step 8)

n_{i+1} = Number of vehicles in queue at the end of $(i+1)^{th}$ hour (Step 8)

N_{nr} = Number of lanes open before the work zone (Step 8)

N_{occ} = Average number of occupants in cars (passengers/car) (Step 12)

N_{op} = Number of lanes open in the work zone (Step 8)

p = Lateral distance between the workers group and the open lane (feet) (p varies from 1 to a maximum of 9 ft) (Step 2)

P_C = Percentage of passenger cars (Step 8)

P_T = Percentage of heavy vehicles (Step 6)

PCE = Passenger car equivalents (Step 6)

$q = C_{Uo}$ = Capacity corresponding to operating speed (pcphpl) (Step 5)

Q_i = Queue length at the end of the i^{th} hour (ft) (Step 8)

Q_{Si} = Stacked queue length at the end of i^{th} hour (ft) (Step 8)

R_{LC} = Reduction in speed due to lateral clearance (mph) (Step 1)

R_{LW} = Reduction in speed due to lane width (mph) (Step 1)

R_O = Reduction in speed due to all other factors that may reduce speed (mph) (Step 4)

R_{WI} = Reduction in speed due to work intensity (mph) (Step 3)

SR_L = Speed reduction in long term work zones (mph) (Step 3)

SR_S = Speed reduction in short term work zones (mph) (Step 3)

t = Number of hours of queuing (Step 9)

$U = U_o$ = Operating Speed (mph) (Step 5)

U_{lim} = Posted speed limit inside the work zone (mph) (Step 10)

U_o = Operating Speed (mph) (Step 4)

U_C = Speed at max capacity (mph) (Step 5)

UC = Total user costs ($)(Step 12)

V_i = Demand in hour i (vph) (Step 10)

V_{i+1} = Total demand in $(i+1)^{th}$ hour (vph) (Step 8)

w = Number of workers working together as a group in the work activity area (w varies from 0 to a maximum of 10) (Step 2)

WI_r = Work intensity ratio (Step 2)

CHAPTER 10 – ITS and Motorist Signing in Work Zones

10.1 Role of ITS in Work Zones

Technology can help to improve work zone operation and safety. Technologies used in real time traffic control provide information to drivers about WZ delay, travel time, and stopped cars ahead. Delay and travel time information can help drivers to make decisions regarding alternate route choices and diversions. Information related to stopped vehicles ahead, alerts the driver and helps in preventing rear end accidents. The ITS (Intelligent Transportation Systems) techniques used in work zones covers a wide range 0f activities such as incident management, traffic monitoring, traffic management, providing traveler information on dynamic message signs (DMS's) and websites. One good example of ITS in work zones is the using 511 to provide real time information. Certain cellular phone companies in central Florida are now able to dial 511 to obtain real-time traffic information of road conditions. Central Florida is one of six regions in the country to have access to a system of this kind. It incorporates the use of 58 cameras on a 50 mile long section of Interstate 4, located in Osceola County, to relay messages of information about certain road conditions, traffic, special attractions in the area, even emergency situations, such as wildfires and/or developing hurricanes. There is also a work in progress to implement a special emergency service in the central Florida area in the near future. This would involve an E-911 service that tracks cell phone calls to 911 in order to deploy emergency vehicles to the calling source more quickly.

Some ideas recommended by ITS Work Zone Safety Task Force (Source: WSDOT, ***ITS Technology applications for Work Zones*** http://www.wsdot.wa.gov/biz/atb/pdfs/workzone.pdf) include Unilight, Smart Work Zone, Construction Zone Safety System, Speed Violation Detection and Deterrent System (SVDD), and Dual Traffic Warning Light System. The Unilight setup would consist of incorporating the standard green, yellow, red lights at to direct traffic with differing symbols corresponding with each color. The smart Work Zone deals with incorporating video with other signs and technology with hopes of making the traffic conditions safer and getting drivers through in a timely manner. A Construction Zone Safety System would take in a series of information and use specific instruments (such as portable signs, flashing beacons, and SmartSonic sensors) to determine certain decisions on no passing zones. The decisions mainly are based on shortening or lengthening the no pass zone based on the amount of traffic present. The SVDD uses the average speed over a distance, to display on a VMS (Variable Message Sign) so the driver could observe his/her speed. This system would also entail a good accuracy in attaining license plate photos of those who do exceed the speed limit in these Work Zones. The Dual Traffic Warning Light System would perform basically the same function as the Unilight in that it would use flashing light colors to acquire the attention of. There are a variety of ITS technologies employed in work zones. In the next section a brief description of four commercially available systems are presented.

10.2 ITS Systems Used in Work Zones

Several systems are available and have been tested all around the US for providing real time traffic control in work zones. In this section four of them namely ADAPTIR, TIPS, CHIPS, and PTMS are presented.

10.2.1. ADAPTIR

The ADAPTIR (Automated Data Acquisition and Processing of Traffic Information in Real-Time) is developed by the Scientex Corporation with support from the FHWA and the Maryland State Highway Administration. ADAPTIR system was deployed in Peoria, IL on a bridge rehabilitation project to provide traffic control and real time information on speed, delay and diversion/alternate routes. It is a system comprised of several conventional traffic management components, and advises drivers of the slower traffic ahead thus encourages them to slow down by providing speeds downstream of portable changeable message sign (PCMS). Doppler radar sensors deployed at multiple places gather speed data and deliver the average speed over time intervals to the system. The acquired speed data from multiple locations are compared with the ones on the upstream PCMSs. Whenever the acquired average speed is at least ten miles lower than the upstream PCMS's advisory speed value, the PCMSs will display the average downstream speed values. Highway Advisory Radio (HAR) is integrated with the system to provide real time diversion and/or alternative route information. The system sometimes suggests drivers tune in to a HAR station when traffic movement ahead is extremely slow. It also displays the time that the message was started.

The effectiveness of the messages displayed was investigated at a work zone on I-80 between Lincoln and Omaha, Nebraska (McCoy et al., 2000). Speed sensors were placed on the top of three PCMSs located at distances of 1.13, 3.13, and 7.83 miles in advance of the work zone. Advisory speed messages were displayed according to the average speed at downstream PCMS. The two PCMSs farthest upstream of the work zone were blank when the speed difference is not significantly different. It was found that the closer the PCMS was to the work zone, the more messages it displayed. The apparent effectiveness of the speed messages was higher at congested flow conditions than uncongested condition. In case of the two PCMSs located farthest to the work zone, the speed message did not show any effectiveness unlike the closest one, which showed significant effectiveness on speed reduction even when during uncongested flow conditions.

10.2.2. TIPS

Travel Time Prediction System (TIPS) was used for predicting and displaying travel time information for motorists in advance of and through freeway work zones. The system was developed at University of Cincinnati, Ohio and is now available commercially by PDP Associates, Inc. TIPS collects real-time traffic flow data using roadside non-contact sensors, processes the data in an on-site personal computer, calculates estimated travel time between different points on the freeway, and displays travel time information on several portable changeable message signs. Strategically placed microwave radar sensors detect the traffic flow on each lane of highway (up to eight lanes) and transmit the information to the computer. The TIPS software calculates travel time between different points on the freeway and the end of the work zone. The travel time is calculated using speed, which is computed, based on the weighted average lane occupancy. Speed is computed from this equation: $v = v_0 * e^{-k*OCC}$, where v is velocity and OCC is weighted average lane occupancy, and v_0 and, k are parameters that will be determined according to the range of OCC value. The travel time is calculated every 30 seconds and is averaged with the previous three computed travel times. The average computed travel time is transmitted to the CMS. Communication between the computer and CMS, and sensors to computer is conducted through 220 MHz radios.

The TIP system was deployed on north bound of I-75 in the Dayton area and the accuracy of travel time was tested. CMS was placed 14 miles upstream of a 3.9 miles work zone. Three crews conducted floating tests from the CMS to the end of work zone and recorded real travel times. About 119 runs were executed and the results were compared with the computed travel times. Displayed travel times were integer multiples of 4 minutes ranging between 8 minutes and 44 minutes such as 4, 8, 12 etc. A regression model was made based on each pair of actual and predicted travel times. About 88% of predicted times were within ±4 minutes range of actual travel times.

10.2.3. CHIPS

The CHIPS (Computerized Highway Information Processing System) system relies on inputs from a series of queue detectors on the highway, which sends data via radio or hard wire back to the CHIPS system computer. The CHIPS system uses queue detectors and the intrusion alarm both developed under the Strategic Highway Research Program (SHRP). CHIPS system is distributed by ASTI Transportation Systems. The computer sends a signal to activate CMS, VMS or static signboards. CHIPS alerts drivers of stopped traffic, lane blockage, and estimated length of delay. Portable detectors shoot infrared beam across the traffic lanes and measure the time for a vehicle to cross the beam. Once the measured time is longer than preset time, the detectors send this information to the central computer that then enables the VMS to display appropriate messages. A longer measured time than preset time indicates that traffic has either slowed or stopped. In addition to the basic operation, CHIPS can optionally send its information to a traveler advisory radio system, area police and emergency services, and an Internet Web site. The infrared intrusion alarm is a supplement to CHIPS. It sounds a siren when a vehicle inadvertently enters buffer area between the work crews and passing vehicles. CHIPS was used by the Pennsylvania Department of Transportation on U. S. Route 22.

10.2.4. PTMS

The Minnesota Department of Transportation (Mn/DOT) sponsored an operational test of the Portable Traffic Management System (PTMS) in a work zone to provide real-time information to motorists about the traffic conditions as they approach and pass through the work zone. The PTMS was developed through partnership between FHWA, Mn/DOT and Addco, Inc. The technology includes machine vision (video image processing) and wireless communication systems to provide flexibility in obtaining and relaying real-time traffic data. It collects data such as speeds, volumes and incident detection through video cameras, portable machine vision, and magnetic sensor. The collected data is transmitted to the traffic control center through communication subsystem. If speed drops below a threshold the traffic engineer is informed. Appropriate decisions are forwarded to drivers via variable message signs and changeable message signs. Advance warning of delays and traveling time are displayed in advance of work zone to give drivers chance to choose alternative route decisions. Also, driver information can be provided to the public via Internet.

10.3 Benefits of ITS in Work Zones

There has not been a comprehensive objective analysis of benefits of ITS in work zones. Recently FHWA conducted a study on the benefits of using ITS technologies in four Work Zones. A summary of the description of the systems used and their benefits in these sites are given below (Source: http://www.itsdocs.fhwa.dot.gov//JPDOCS/REPTS_TE//13600.html)

I-55 Springfield, Illinois:

The system was called Real Time Traffic Control System (RTTCS). It consisted of seventeen portable dynamic message signs (DMSs), eight portable traffic sensors and four portable closed circuit television (CCTV) cameras. Both the traffic sensors and the CCTVs were connected to a central base station. The arrangement was divided into four sub systems; roadside sensor, RTTCS server, roadway traveler information and personal information access traveler. The roadside sensor system consisted of the queue detectors, which sent the queue data to the RTTCS server. The RTTCS server calculated the volume and the traffic speed and notified the level of congestion to the IDOT staff. Based on the level of congestion, appropriate messages were displayed on the DMS and also the IDOT website gave a congestion graphic of the traffic flow. The benefits of the system were

- No significant traffic backups
- Reduce rate of traffic citations
- Only two crashes-one attributed to fatigue and the other to alcohol

I-496 Lansing, Michigan:

The system used was Temporary Traffic Management system (TTMS). The system consisted of sensors that relayed queue data and data processed using the ITSworkzone™ tool to the Central Traffic Management Center (CTMC). At the CTMC, the traffic was monitored via CCTV imagery, the nature of the queues was verified and any incident clearance needed was initiated. Also the DMS messages were updated and the average roadway speeds were posted on the website www.fix496.com. The system used yielded the following benefits Real-time information on problem areas for travelers

- More effective communications with local agencies
- Helped enable use of full road closure, which reduced construction time (two seasons to one)
- Quicker incident response

I-40/I-25 Albuquerque, New Mexico:

The system used on route I-40/I-25 consisted of CCTV cameras, DMSs, dynamic arrow signs, SmartZone® portable traffic management systems from ADDCO Inc, and Highway Advisory Radios (HAR). The CCTV cameras and the DMS were integrated by the SmartZone® portable traffic management system. The traffic information was also posted on websites. The imageries collected by the CCTV cameras were sent to the incident management, where the NMSHTD staff initiated any action necessary to clear incidents and also information was passed on through several channels like DMS, HAR, websites, fax, e-mail and pager. The benefits of the system were

- 44 percent reduction in incident response and clear time
- Fewer secondary accidents
- Better maintenance of traffic flow

- Praise from travelers and public safety sector
- Better communication with incident management community

I-40 West Memphis, Arkansas:

The system used in this project was called Automated Work Zone Information System (AWIS). The system consisted of CHIPS and HAR. The information was also disseminated through pagers and e-mail. The system offered the following benefits

- Information at strategic locations for alternate routes
- Improved safety through traveler information on traffic backups
- Better relations with the public and neighboring agencies
- Better incident response
- Reduced delay through better construction traffic coordination

10.4 Work Zone Signing and Role of ITS

One of the main issues in work zone traffic management is the credibility and effectiveness of the work zone signs. A contributing factor to this issue is using static signs that do not reflect the work zone operating conditions. Also with the static sign there is very little flexibility to communicate with motorist the unique operating conditions or new signs. Changeable message signs are an integral part of ITS in work zones. They enable us to communicate with motorists on almost real time basis and dynamically change the messages to match the operating situation in work zones. Proper use of ITS technologies can improve credibility and effectiveness of work zone signs as well as the ability to clearly communicate with drivers.

Benekohal et al (1993) studied the driver's opinion on the work zone signs. A survey was conducted among 400 drivers. The results of the survey showed that 93.5% of the drivers clearly understood the message of the signs. However, 4.3% of the drivers said that they were confused by some of the work zone signs. The speed limit sign was found to be confusing to several drivers. The drivers said that one of the speed limit signs was a 45-mph speed limit and other one was a 65-mph speed limit. The flagger's slow sign or "Give a break" were confusing to some drivers. One of the suggestions given by the drivers to improve work zone safety was to include more advance warning of work zone signs.

Ogden et al (1991) conducted a study on the driver understanding of work zone signs in Dallas, Texas. The results showed that some of the signs were misinterpreted by a majority of drivers. More than

75% of the drivers misinterpreted the low shoulder symbol sign as uneven pavement. Around 22% of the respondents misinterpreted the advance road construction sign (Road Construction 500 ft), saying that the length of road construction is 500 ft.

10.5 Effectiveness of signs

Dudek (1999) studied alternative messages to display time of day, days of week and month dates in changeable message signs. The study concluded that the drivers had difficulty in reading the calendar dates. Instead it was easier for them to read the days of the week.

Garber et al (1995) studied the effectiveness of Changeable Message Signs (CMS) with radar, in controlling speeds in work zones. The study was conducted at seven sites on interstates in Virginia. The speed characteristics of vehicles that were travelling over a threshold speed, which triggered the CMS with radar, were studied. The speed characteristics with and without the presence of the CMS were then compared. The data was collected at three stations, one station before the CMS and two stations after the CMS. Station 1 was situated at the advance warning area, station 2 at the work activity area and station 3 just before the end of the work zone. The CMS was place between station 1 and station 2. Four different messages were tested at each site:

- EXCESSIVE SPEED SLOW DOWN
- HIGH SPEED SLOW DOWN
- REDUCE SPEED IN WORK ZONE
- YOU ARE SPEEDING SLOW DOWN

The results showed that there is speed reduction between station 2 and station 3 for all the four messages. Also, it was found out the messages HIGH SPEED SLOW DOWN and YOU ARE SPEEDING SLOW DOWN had more impact in reducing speeds than the other two messages.

McCoy, et al (1995) studied the speed reduction effects of speed monitoring displays with radar. The device was tested at a work zone on I-90 in South Dakota. Data was collected both before after installing the device. Speeds were observed at three stations, one station located before the device and other two stations after the device. It was found out that the speed monitoring displays fitted with radar were effective in reducing speeds. For two axle vehicles the reduction in mean speed was 4 mph and for vehicles with more than two axles, the mean speed reduction was 5 mph. The study also indicated that the speed reduction for trucks is more than that for passenger cars.

10.6 Effect of duration of exposure on work zone signs

The effectiveness of signs is also affected by the duration of exposure to the sign. Garber et al (1998) studied the effect of duration of exposure, on the effectiveness of Changeable

Message Signs (CMS). The study was conducted on CMS signs equipped with radar to detect speed. The CMS was tested on two sites in I-81 and one site in route 19 in Lebanon, Virginia. The sites on I-81 had a speed limit of 55 mph and the site on route 19 had a speed limit of 45 mph. The study was conducted for duration of 7 weeks. The study concluded that up to a period of 7 weeks the CMS was found to be effective in controlling the speeds.

Pesti et al (2001) evaluated the long-term effectiveness of Speed Monitoring Devices (SMDs). The study was conducted in a work zone on I-80 near Lincoln, Nebraska. The device was tested for a period of 5-weeks. The study found that the SMDs were effective in reducing the speeds up to 3 mph for the five-week period. Also it was found out that after removing the SMDs, the speeds went up, but were not as high as the speeds observed before the deployment of the SMDs.

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CHAPTER 11 - REVIEW OF BDE MANUAL

This chapter provides a review of the BDE chapters pertaining to the issues related to work zone. Four chapters of the BDE manual are reviewed (chapters 13, 55, 63, and 66). Sections related to incentive/disincentive clauses, road user costs, minimizing road user delays, and the queue delay prediction methods are reviewed to identify how the findings of this study might help to increase the usefulness of the BDE Manual.

11.1 Work Zone Traffic Management Studies

Chapter 13 of the BDE Manual discusses the traffic management studies necessary for the preparation of the Traffic Management Analysis (TMA) for work zones. This chapter gives the definitions for different types time lengths of work zones and also explains the various work zone applications. Five different time length for work zones have been given:

1) long- term stationary work zone
2) Intermediate term stationary work zone
3) Short term stationary work zone
4) Short duration work zone
5) Mobile work zone

Ten different work zone applications have been given in the manual. The manual also explains the conditions under which the different work zone applications have to be used. This chapter 13 of BDE manual also gives the advantages and disadvantages of using different types of construction phases. The use of traffic control devices like changeable message signs is also discussed in this chapter. Several strategies to reduce capacity have also been provided. There are no different classification of capacity strategies for freeways and highways. There are no instructions about the use of real-time ITS technologies other than the changeable message signs. The use of different construction scheduling is also discussed in this chapter. The chapter gives a list of user costs that should be considered while fixing the incentive/disincentive clause. Although the detour costs are clearly explained and the references for cost values are given, the onsite cost evaluation does not given any references to values for right-of-way costs, additional construction costs, environmental costs, delay costs and crash costs.

11.2 Work Zone Traffic Control

Chapter 55 of the BDE manual discusses about the work zone traffic control. This chapter gives detail information required for developing a traffic control plan. The first two sections of this chapter deal with the preparation of traffic control plan and traffic control devices. The use of speed limit signs, guide signs, changeable message signs and arrow boards were presented. It also gives details about the channeling devices, pavement markers, traffic signals and highway lighting with references for detailed design. The third section of this chapter deals with the design criteria like work zone design speed, lane/shoulder widths, taper rates, sight distances, horizontal curvature, vertical curvature, cut and fill slopes, pavement design, temporary bridges and crossovers. Roadside safety is also discussed in this chapter, in which the use of positive protection, temporary concrete barrier, ends treatments, glare screens are discussed.

The next section in this chapter discusses about the highway capacity and the strategies to improve the capacity and also touches upon queuing analysis. Although this sections, emphasis the importance of capacity analysis in work zones, it does not give any procedure or references for capacity analysis. A much more detail explanation of the capacity analysis will be very useful. Similarly queuing analysis is not dealt in a detailed way. No clear procedure for queuing analysis or any reference regarding this has been provided. The next section in this chapter 55 of BDE manual deals with detailed design criteria for various work zone applications which were defined in chapter 13 of the BDE manual. The last section deals with issues related to interstate work zones. In this section, the aspect of disseminating information to public is discussed. It deals with advance signs, construction signs, advance publicity and advisory radio. It does not discuss about online information through the Internet. This section also talks about the strategies to reduce lane closures. It is suggested to use overnight lane closures, time restrictions and early openings to reduce lane closure. Also it is advised that the length of the lane closure should be reduced as much possible. A special provision to reduce the number of days of lane closure is also provided.

11.3 Plan Preparation

Chapter 63 of the BDE manual deals with the different aspects of the traffic control plan preparation like different phases of the plan preparation, details to be provided, guidelines, scales, drawings, standards used etc.

11.4 Contract Processing

Chapter 66 of the BDE manual consists of four basic sections. The second section deals with the plan submission. Part of this section discusses about the Incentive/Disincentive. The project selection for incentive/disincentive clause is based on adverse effects, timing, urban river crossings and nighttime construction. Adverse effects refer to high volume roads, excessive road user cost, and safety hazard economic impact. The manual does not give any measurements to quantify the adverse effects. The application of I/D clauses is also given. I/D clauses can be applied to either to a whole project, or part of a project or multiple projects. The manual includes sample special provisions were given for I/D clause to a whole project and for part of a project. The I/D amount is based on the sum of the road user delay cost and liquidated damages in the case of a whole project and road user delay costs alone in the case of part of a project. The manual also gives the procedure for estimating road user cost delay cost. This road user delay cost is based on the travel time delay cost. However, it does not take into account other costs like queue delay cost, vehicle operating costs and environmental cost. The I/D amount is also limited to maximum of 5% of construction cost. The number of days of incentive is also limited to 30 days.

11.5 How Findings of this study Improves BDE Manual

The BDE Manual uses a procedure for calculating road user cost that relies on knowing speed and capacity of the work zone. However, it does not provide a procedure for determining speed and capacity. Speed and capacity both are very critical in calculating queue, delay and road user cost. The models proposed in Chapters 7 and 8 of this report provide procedures to estimate work zone operating speed and capacity. These models are based on some field data from a small number of work zones in Illinois. The capacity, queue and delay models discussed in Chapters 7 and 8 of this report should further be validated using a large number of work zone sites that covers different roadway and traffic conditions. The proposed models should then be refined, modified, and improved if necessary before they are considered for inclusion in the BDE manual.

CHAPTER-12 CONCLUSIONS AND RECOMMENDATIONS

State and National Surveys:

- Incentive/Disincentive and lane rental procedures were more effective in reducing the delay in work zones. However, there was no consensus on the I/D or lane rental dollar amount to be used.
- HCM techniques to calculate lane capacity, queue length, delay and road user costs were used in five IDOT Districts. Their satisfaction level with the techniques varied from somewhat satisfied to very satisfied. Among the state DOTs, HCM technique for capacity calculation was used more often than other techniques. For estimating queue length and delay, QUEWZ, Quick Zone, and HCM technique were used more often than other techniques. For road users cost calculation, QUEWZ and spreadsheets were used more often than other techniques. States were very satisfied with their spreadsheets for road users cost calculations.
- About 68% of the responding DOTs said they used the vehicle operating costs and 38% said they used motorist delay costs in calculating the road user costs. However not many states use crash costs in such calculations.
- About 57% of the responding DOTs said they use ITS technologies in work zones.
- About 70% of DOTs said that major contributing factors for the loss of credibility of work zone signs are: failure to remove signs when there is no work going on, incorrect information, lack of enforcement, and overuse of signs.

Comparison of Software to Field Data:

The output from QUEWZ and QuickZone and FRESIM were compared to field data.

- QUEWZ overestimated the capacity and average speed, but underestimated the average queue length. This was true with the default-input values as wells as modified capacity values.
- FRESIM requires calibration, which requires knowledge of how the model works. Speeds computed in FRESIM were comparable to the average speeds from the field data, when there is no queuing at work zones. However, when there was queuing, FRESIM overestimated the speed. FRESIM did not return the queue lengths directly. The queue lengths obtained from the suggested procedure were shorter than the field values in half of the cases and longer in the other half of the cases.

- QuickZone requires capacity as an input value. The queue lengths from QuickZone did not match the field data and generally QuickZone underestimated the queue lengths. QuickZone consistently underestimated the total delay observed in the field. When demand is less than capacity QuickZone does not return any user delay because it does not consider the delay due to slower speeds in work zones.
- The results of model comparisons indicated that there is a need for developing a model for estimating capacity, speed and queue length in work zones.

Capacity Estimation:

To determine users cost in work zones one need to know the travel delay and queue delay. Travel delay depends on the operating speed of traffic and queue delay depends on queue length and its duration. The values computed for both speed and queue length depend on capacity of the work zone. Thus, determining the work zone capacity accurately is a critical step in road user cost calculations. This study developed models to estimate capacity and operating speed in work zones. Once operating speed and capacity is known computing queue length and delay is fairly straightforward as discussed in the report. Comparisons of field data with QUEWZ, QuickZone and FRESIM output indicated that the software did not provide reasonable accurate results. The UIUC developed model explained in chapters 8 and 9 of this report provide more accurate results and they match reasonably well with the field data. It is recommended that IDOT consider using the UIUC developed procedures in work zone capacity, delay, and queuing analysis. The UIUC developed procedure should be refined, as more data becomes available.

Also the following recommendations are made for future research and expanding of the findings:

- A spreadsheet or other computer program should be written to make this procedure more user friendly and more efficient.
- The data used in developing the models came from work zones on interstate highways with two lanes per direction. Similar studies or extension of this study is needed for work zones on other types of highways or work zones with differing numbers of lanes.
- Speed reduction models developed in this study were based on a small number of driver reponses and construction sites. It is recommended to study a large number of driver responses and various work zone types and configurations.
- This study is based on data for one lane closure on interstate highway work zones. For work zones with a crossover and/or a different numbers of lane closures, the results may not be directly applicable. It is recommended to do further study for those conditions.

- The operating speed computed using the methodology discussed in this report is for conditions when there is no flow breakdown. A detailed study is needed to determine the causes of flow breakdown and its consequences on work zone speed.
- The speed – flow curve developed in this study did not have enough data to quantify the rapid decrease in capacity during flow breakdown. Further field data is needed to quantify the decrease in capacity for different work zone conditions.
- The adjustment values for lateral clearance, lane width, and PCE for trucks are directly taken form the HCM for basic freeway sections. There is a need to collect field data to determine if these values are applicable for work zones..
- There are other factors such as grade, weather conditions, road surface conditions that may affect capacity and speed in work zones. These effects need to be determined.
- Using ITS technologies may affect work zone capacity. The effect of using ITS technologies on speed-flow curve and capacity needs to be studied.
- A detailed analysis of benefits and costs of using ITS technologies in work zones is needed.
- The BDE Manual provided a procedure for calculating road user cost that relies on knowing speed and capacity of the work zone. However, it does not provide a procedure for determining speed and capacity. The UIUC model proposed in Chapters 8 and 9 of this report provide procedures to estimate work zone operating speed and capacity. The methodology should be used on interim basis to see if it should be refined, modified, and improved before it is considered for inclusion in the BDE manual
- A long-term data collection effort should be initiated to answer many of the issues that need to be addressed about work zone traffic operations.

APPENDIX A - IDOT Districts Survey Questionnaire

SURVEY OF ILLINOIS DISTRICTS

The University of Illinois at Urbana-Champaign is conducting this study (Evaluation of Construction Work Zone Operational Issues) for the Illinois Department of Transportation in accord with BDE 15-00, Procedures to Minimize Motorists' Costs and Inconvenience. . If you have questions or comments, please contact Professor Ray Benekohal at 217-244-6288 (rbenekoh@uiuc.edu) or John Sanford at IDOT at 217-785-2930 (sanfordjl@nt.dot.state.il.us).

1. What types of contract procedures does your District utilize for minimizing delay to motorists in construction work zones?
   a. Incentive/disincentive
   b. Lane rental
   c. A+B
   d. Others (specify_________________):

INCENTIVE/DISINCENTIVE

2. Has your District used incentive/disincentive provisions in construction work zone projects?

   a. No; go to Question 6 b. Yes; please continue

3. Is the use of incentive/disincentive provisions effective in reducing delay to motorists by reducing the construction time?

   a. No; why not? b. Yes; why?

4. What incentive/disincentive dollar amounts does your District use in calculating road user costs?

   $---------------------- per -------------

5. Should the incentive/disincentive dollar amounts be revised?
   a. No b. Yes; what should they be?

LANE RENTAL

6. Has your District used lane rental provisions in highway construction projects?
   a. No; go to Question 10 b. Yes; please continue

7. Is the use of lane rental provisions effective in reducing disruptions to motorists?
   a. No; why not b. Yes; why

8. What lane rental dollar amounts does your District utilize?
   $-------------------- per---------

9. Should the lane rental dollar amounts be revised?
   a. No b. Yes; what should they be?

CAPACITY, QUEUE LENGTH, AND ROAD USER COSTS

10. List up to three software programs or analytical techniques that your District utilizes to estimate the following items in construction work zones with lane closures:
    a. Lane Capacity #1. ____________, #2 _______________, #3_______________, 4. Use none
    b. Queue length #1. ____________, #2 _______________, #3_______________, 4. Use none
    c. Motorist Delay #1. ____________, #2 _______________, #3_______________, 4. Use none
    d. Road user costs #1. ____________, #2 _______________, #3_______________, 4. Use none
    e. Any comments on the above

11. How satisfied are you that the estimated values you get from the software programs or analytical techniques to represent actual field conditions?

	Very Unsatisfied	Somewhat Unsatisfied	Somewhat Satisfied	Very Satisfied	No Opinion
Lane Capacity #1	--------	-------	-------	--------	-------
Lane Capacity #2	--------	-------	-------	--------	-------
Lane Capacity #3	--------	-------	-------	--------	-------
Queue length #1	--------	-------	-------	--------	-------
Queue length #2	--------	-------	-------	--------	-------
Queue length #3	--------	-------	-------	--------	-------
Motorist Delay #1	--------	-------	-------	--------	-------
Motorist Delay #2	--------	-------	-------	--------	-------
Motorist Delay #3	--------	-------	-------	--------	-------
Road user cost #1	--------	-------	-------	--------	-------
Road user cost #2	--------	-------	-------	--------	-------
Road user cost #3	--------	-------	-------	--------	-------

12. Do you have field data available on lane capacity, queue lengths, delay, or road user costs for construction work zones with lane closures?
    a. No b. Yes, please provide the data

13. List the current and programmed construction projects for the 2002 season on interstate highways/freeways with lane reductions, and/or lane rental, and or incentive-disincentive contracts (i.e. project location, length, contract number, approximate beginning and end date, etc)

14. Which existing work zone projects create traffic queues during peak traffic times?

15. List locations of the existing permanent lane drops (no construction) on interstate highways or freeways resulting in traffic queues during peak traffic times

GENERAL QUESTIONS

16. List four specific construction/maintenance operations (i.e. bridge repair, patching, resurfacing, etc) that exhibit the longest queue backups?
    a. --------------------------------------
    b. --------------------------------------
    c. --------------------------------------
    d. --------------------------------------

17. What kind of construction work scheduling (i.e. off peak hour operations, night operations, incentive/disincentive, lane rental, A+B, freeway closure, etc) does your District use to reduce delay and road user costs?

18. Has your District used Intelligent Transportation Systems (ITS) or real time traffic control systems in construction work zones?
    a. No b. Yes; please comment on the system performance

19. Does your District have policies/procedures for determining the construction projects needing real time traffic control?
    a. No b. Yes; please describe

20. In your District in the past three years, have you had construction lane reductions that created queues beyond anticipated/signed lengths?

    a. No b. Yes; what actions were taken for traffic management?

21. In your District in the past three years, have you had traffic accidents in construction zones that created queues beyond anticipated/signed lengths?

    a. No b. Yes; what actions were taken for traffic management?

22. Do you have additional comments/suggestions?

    a. No b. Yes; please describe them

----

23. Please provide the following Information:

Your Name: --
Title: --
Office: --
District: --
Phone/ Fax: --
E-mail: --

THANK YOU VERY MUCH FOR YOUR COOPERATION

APPENDIX B - DOTs Survey Questionnaire

SURVEY OF STATE DOTs ON
ROAD USER COSTS AND DELAY IN CONSTRUCTION WORK ZONES

The University of Illinois at Urbana-Champaign is conducting this study for the Illinois Department of Transportation. If you have questions or comments, please contact Professor Ray Benekohal at 217-244-6288 (rbenekoh@uiuc.edu) or John Sanford at IDOT at 217-785-2930 (sanfordjl@nt.dot.state.il.us). THANK YOU VERY MUCH FOR YOUR PARTICIPATION IN THIS SURVEY.

1. Would you like to get a summary of the results of this survey?

a. Yes b. No

PART I – GENERAL

2. Does your agency utilize any of the following contract procedures to minimize disruption to motorists in construction work zones?

a) Incentive/disincentive (I/D) Yes____ No_____
b) Lane rental Yes____ No_____
c) A+B (Cost-plus-Time) bidding Yes____ No_____
d) Others (specify_________________): Yes____ No_____

3. If YES to question 2, how effective are the procedures in minimizing disruption to motorists?

	Very Effective	Somewhat Effective	Not Effective	No Opinion
I/D	3	2	1	0
Lane Rental	3	2	1	0
A+B	3	2	1	0
Other (specify)	3	2	1	0

4. hat incentive/disincentive dollar amounts does your agency use in calculating road user costs?

$---------------------- per -------------

5. What lane rental dollar amounts does your agency utilize?

$-------------------- per---------

PART II – CAPACITY, QUEUE, DELAY & ROAD USER COSTS

6. List up to three software programs or analytical techniques that your agency utilizes to estimate construction work zones:

a) Lane Capacity #1. _____________, #2 ________________, #3_______________, 4. None
b) Queue length #1. _____________, #2 ________________, #3_______________, 4. None
c) Delay #1. _____________, #2 ________________, #3_______________, 4. None
d) Road user costs #1. _____________, #2 ________________, #3_______________, 4. None

7. How satisfied are you with the accuracy level of the software programs or analytical techniques (listed in the previous question) in representing the actual field conditions?

	Very Satisfied	Somewhat Satisfied	Not Satisfied	No Opinion
a.1. Lane Capacity #1	3	2	1	0
a.2. Lane Capacity #2	3	2	1	0
a.3. Lane Capacity #3	3	2	1	0
b.1. Queue length #1	3	2	1	0
b.2. Queue length #2	3	2	1	0
b.3. Queue length #3	3	2	1	0
c.1. Delay #1	3	2	1	0
c.2. Delay #2	3	2	1	0
c.3. Delay #3	3	2	1	0
d.1. Road user cost #1	3	2	1	0
d.2. Road user cost #2	3	2	1	0
d.3. Road user cost #3	3	2	1	0

8. Does your agency use any of the following factors in calculating road user costs in construction work zones? (If "Yes", please give the dollar figure used)

a. Vehicle Operating costs No____ Yes_____, $_________per______
b. Motorist delay costs No____ Yes_____, $_________per______
c. Crash costs No____ Yes_____, $_________per______
d. Others (specify) _________ No____ Yes_____, $_________per______

9. Do you have field data available on traffic flow and/or queue lengths for construction work zones with lane closures?
a. No b. Yes c. I don't know

10. Do you use any innovative methods to increase traffic capacity in construction work zones?
a. No b. Yes (please briefly describe them)

PART III – INTELLIGENT TRANSPORTATION SYSTEMS (ITS) TECHNOLOGIES IN TRAFFIC CONTROL

11. Have you used any ITS technologies (or real time real-time) for traffic control in construction work zones?
    a. No b. Yes; please provide a description for each

12. If "Yes" to the previous question, please list the technologies used and indicate how effective they were in traffic control.

	Very Effective	Somewhat Effective	Not Effective	No Opinion
a. (specify)___________	3	2	1	0
b. (specify)___________	3	2	1	0
c. (specify)___________	3	2	1	0

13. Are there any benefit-cost analysis done for these technologies?

    a. No b. Yes; please provide any document you have

14. Have you used any other innovative methods for traffic control in construction work zones?

    a. No b. Yes; please briefly describe

PART IV – MOTORIST SIGNING IN CONSTRUCTION WORK ZONES

15. Do you use any motorist signing other than those in the MUTCD?

    a. No b. Yes; please briefly describe them

----

16. Do you know what are the contributing factors to the lack of credibility of the motorist signs?

    a. No b. Yes; please briefly describe them

----

17. Do you have suggestions for improving the effectiveness of motorist signs?

a. No b. Yes; please briefly describe them

PART V – COMMENTS/SUGGESTIONS

18. Do you have additional comments/suggestions?

a. No b. Yes; please describe them

----

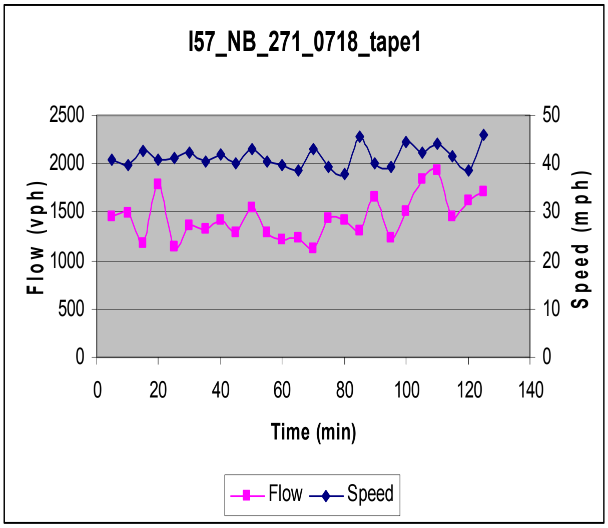
19. Please provide the following Information:

Your Name: --
Title: --
Office: --
District: --
Phone/ Fax: --
E-mail: --

THANK YOU VERY MUCH FOR YOUR COOPERATION

APPENDIX C - Time Series Plots for Speed and Flow

Time Series Plots of Speed and Flow for Platoon Vehicles



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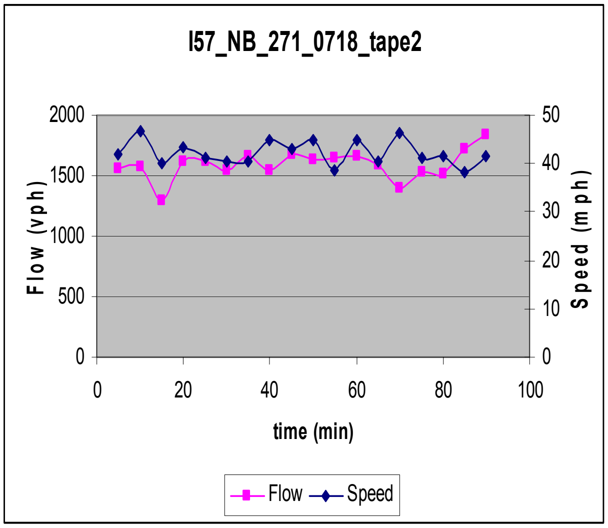

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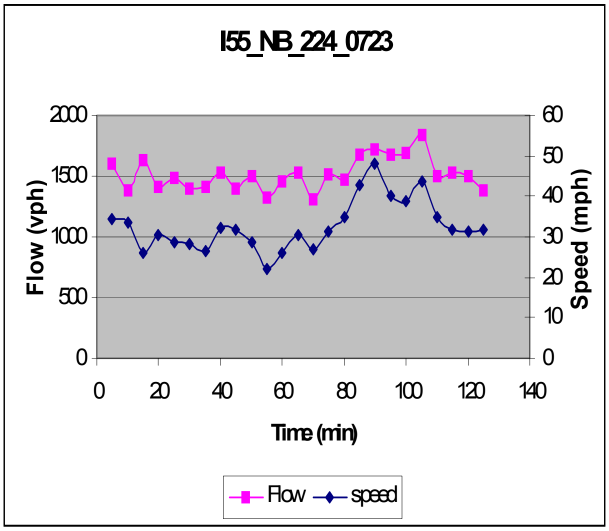

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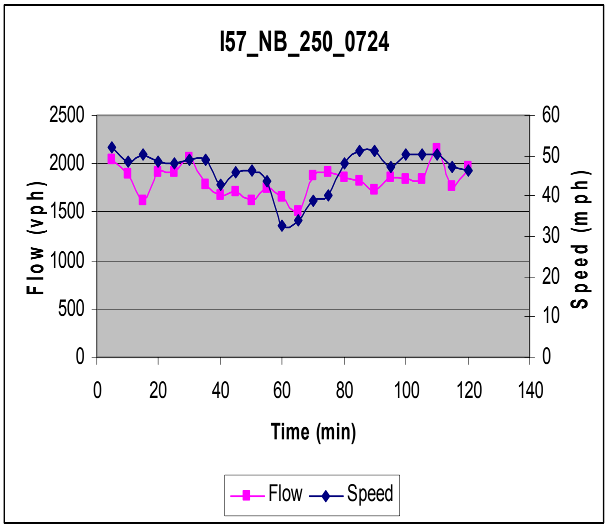

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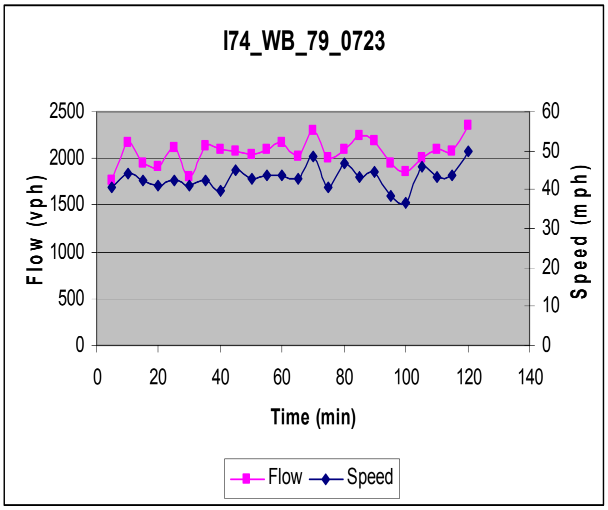
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1500
2000
2500
Speed (mph)
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60
Time (min)
0
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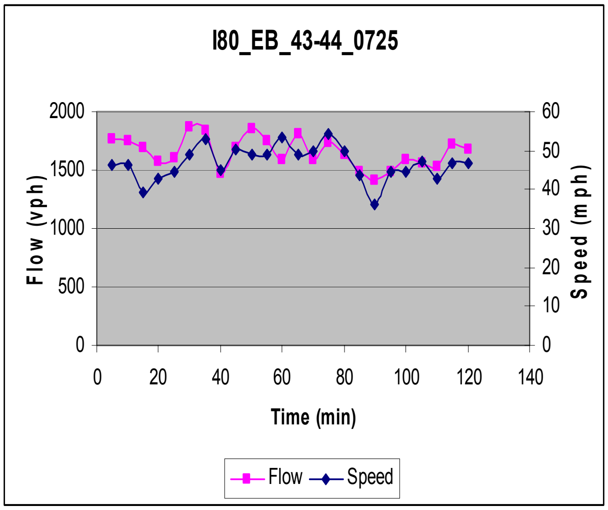
60
80
100
120
140
Flow
Speed

(e)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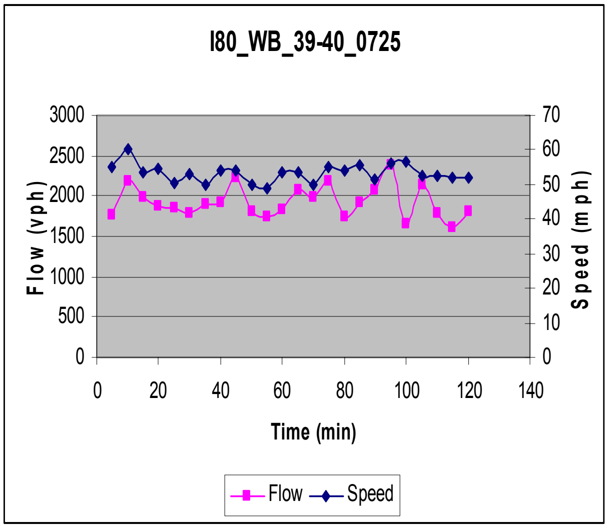
(f)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Speed (mph)
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Time (min)
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Flow
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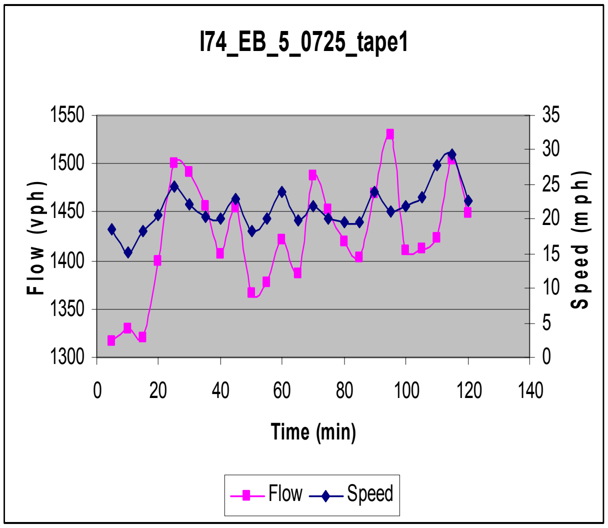
(g)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5
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30
35
Time (min)
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80
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120
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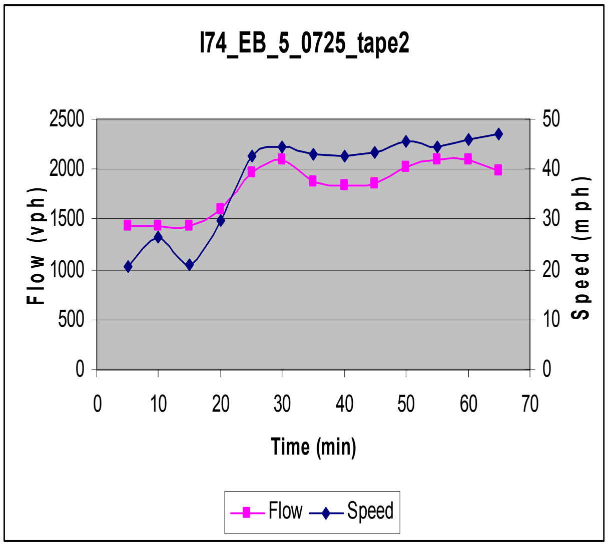
Flow
Speed

(h)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1000
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2000
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Speed (mph)
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Time (min)
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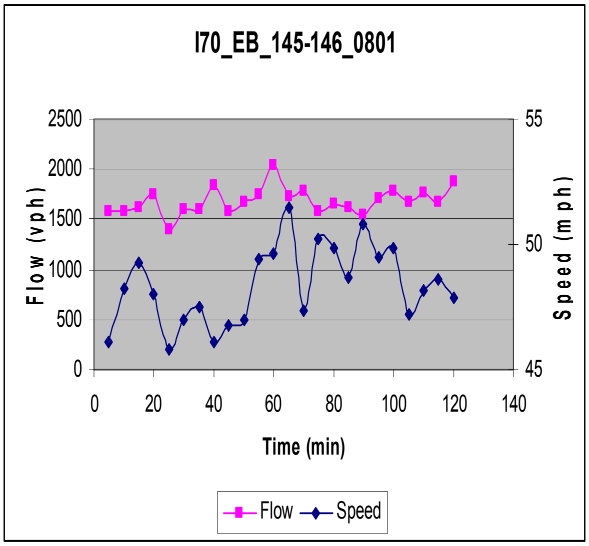
Flow
Speed

(i)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Speed (mph)
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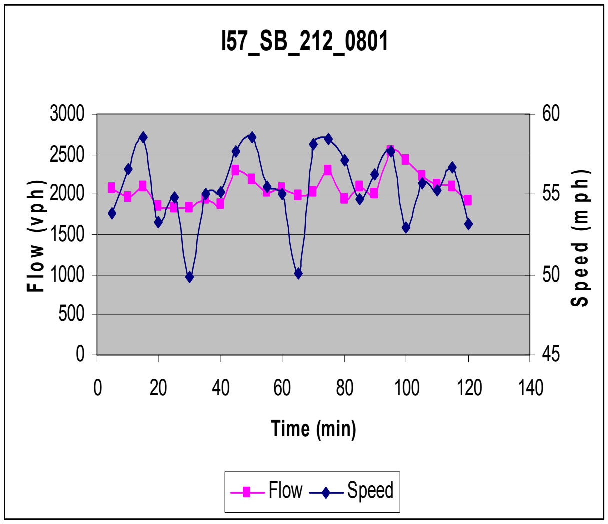
(j)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Speed (mph)
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Flow
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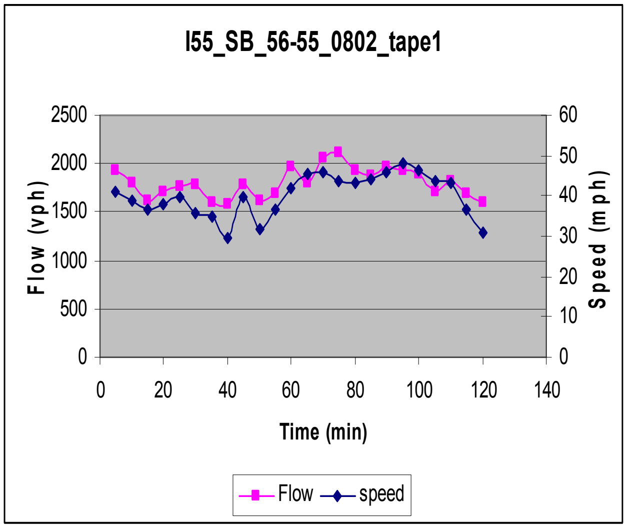
(k)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Speed (mph)
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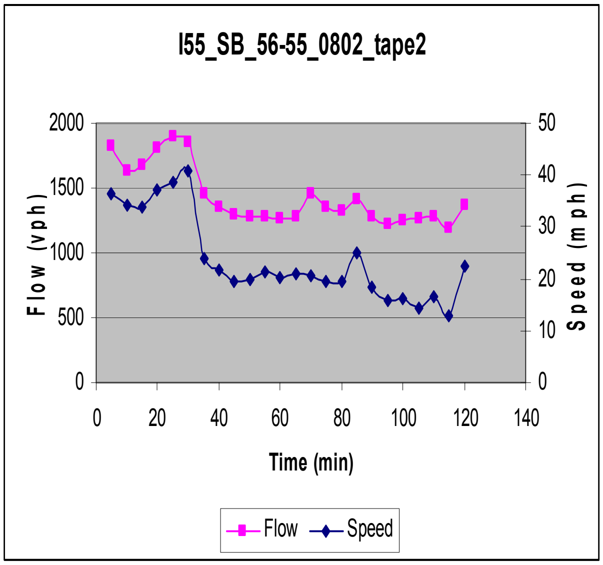
Flow
speed

(l)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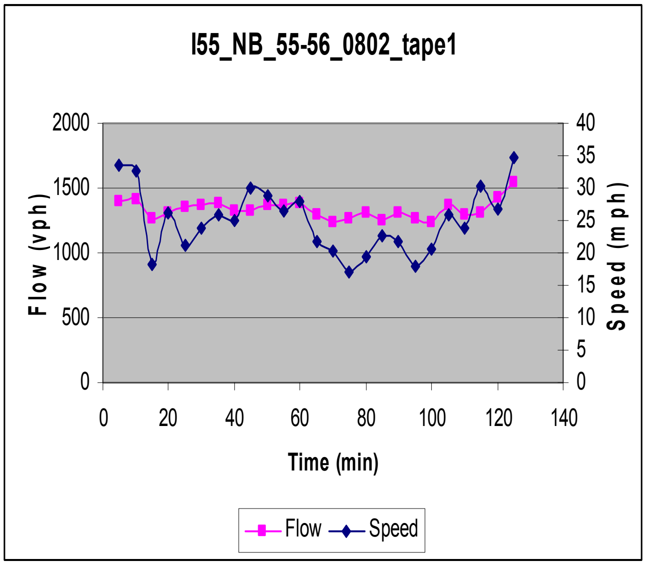
Time (min)
Flow
Speed

(m)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Time (min)
Flow
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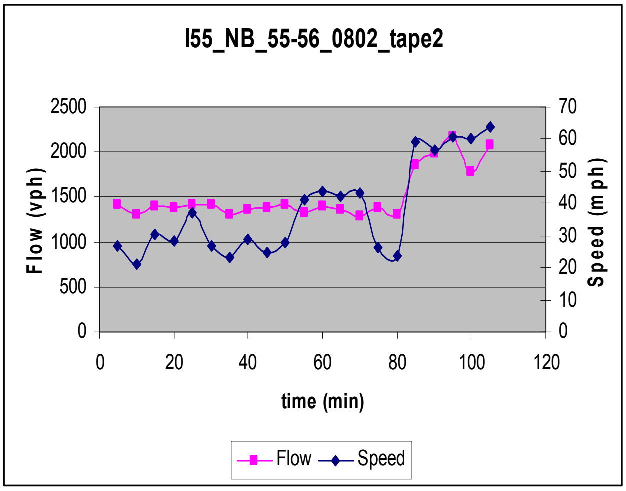
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time (min)
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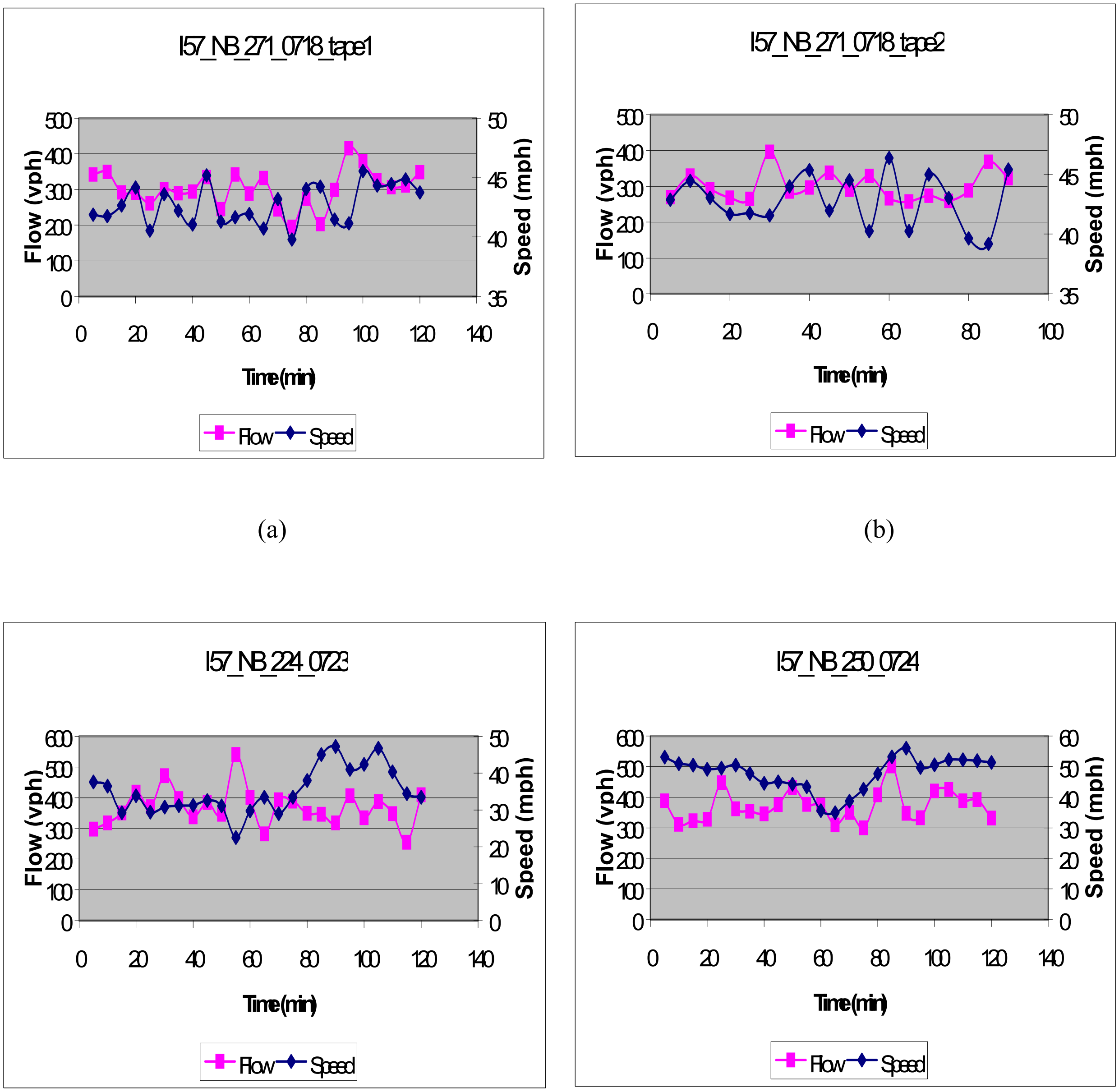
(o)

Time Series Plots for Non-Platoon Vehicles



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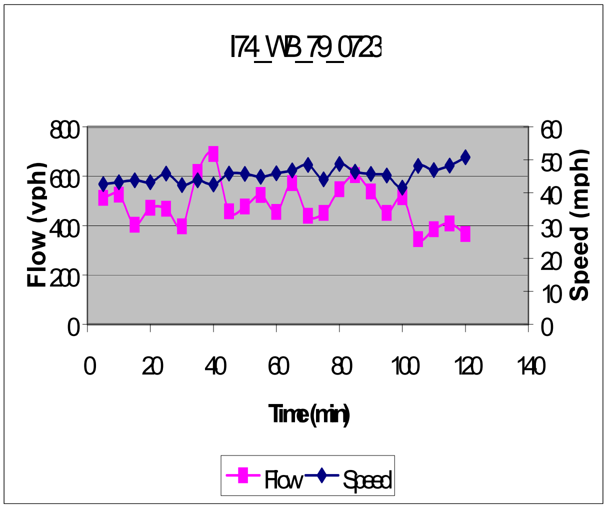
(c) (d)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Time (min)
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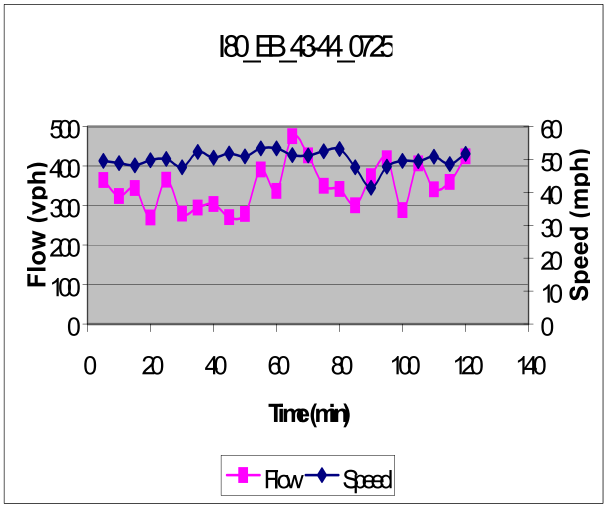
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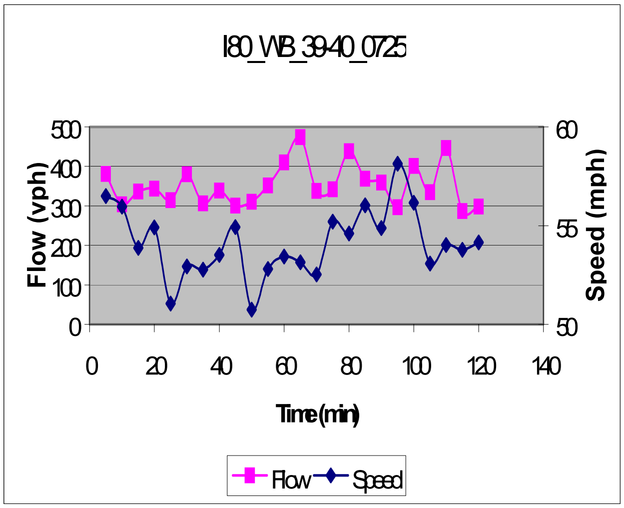
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Time (min)
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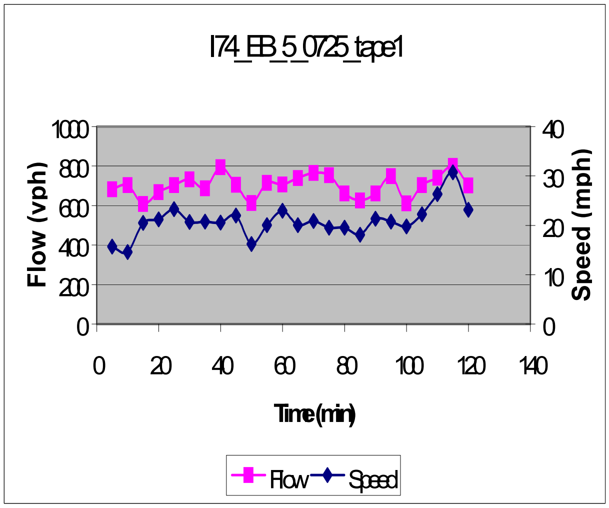
Speed

(g)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Time (min)
Flow
Speed

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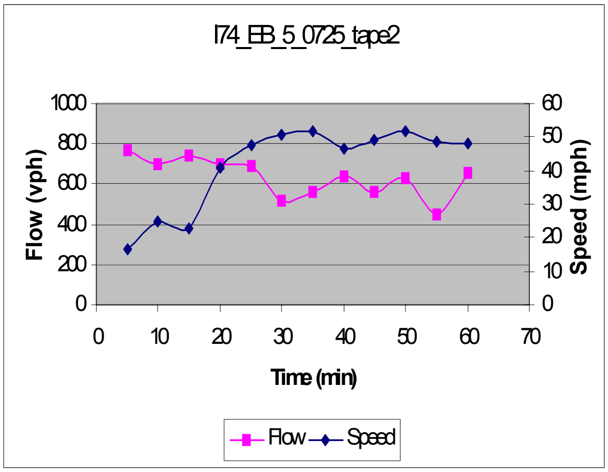
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Flow
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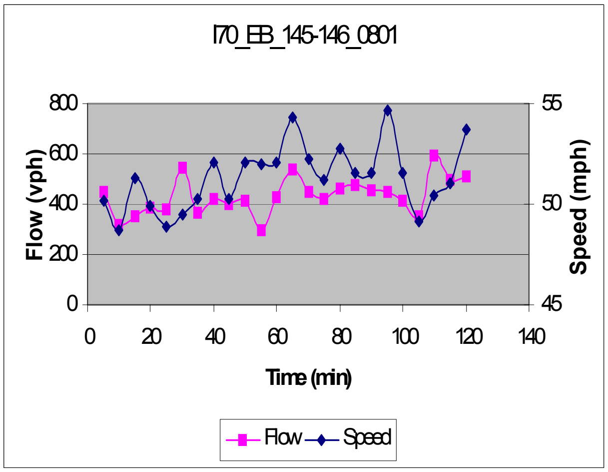
(i)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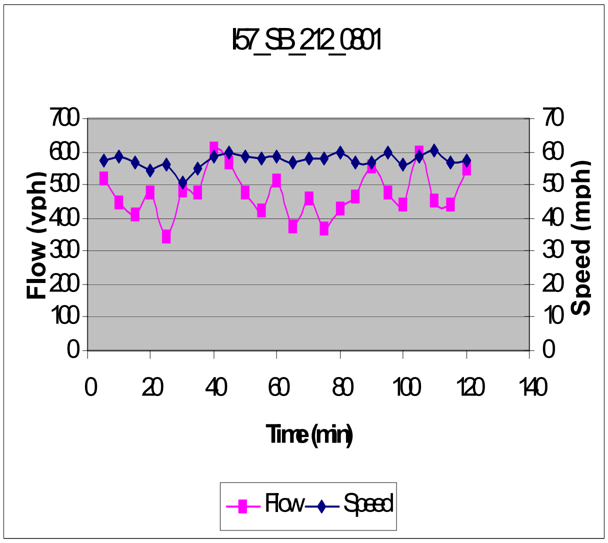
(j)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Speed (mph)
Time (min)
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Flow
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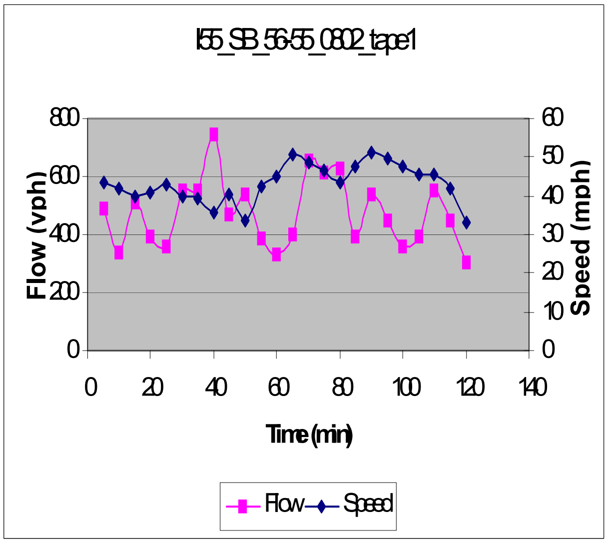
(k)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Flow
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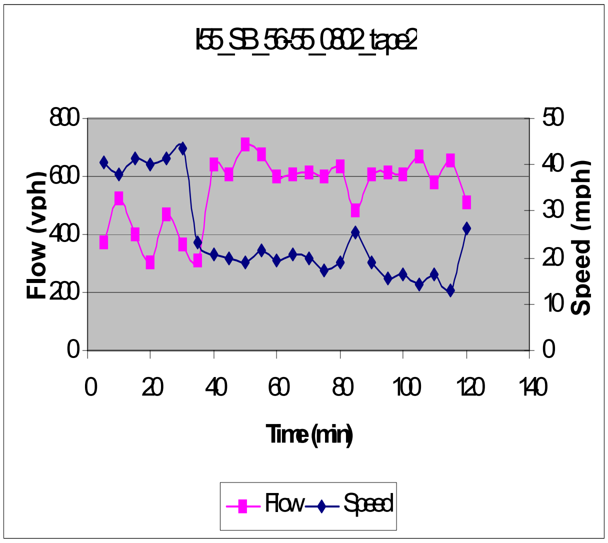
(l)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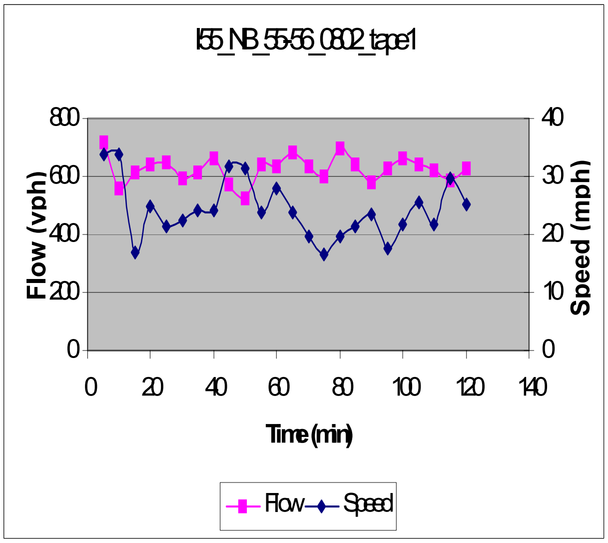
Time (min)
Flow
Speed

(m)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Speed (mph)
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Time (min)
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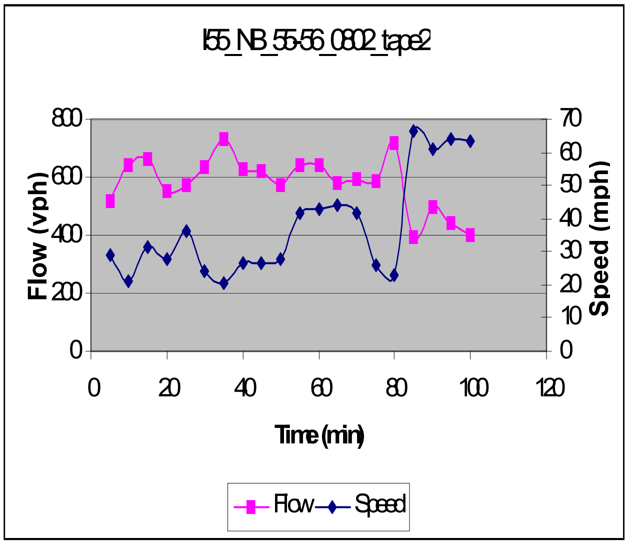
Speed

(n)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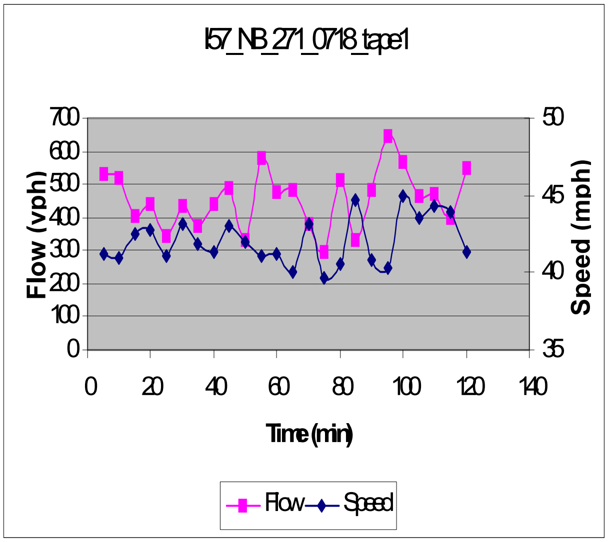
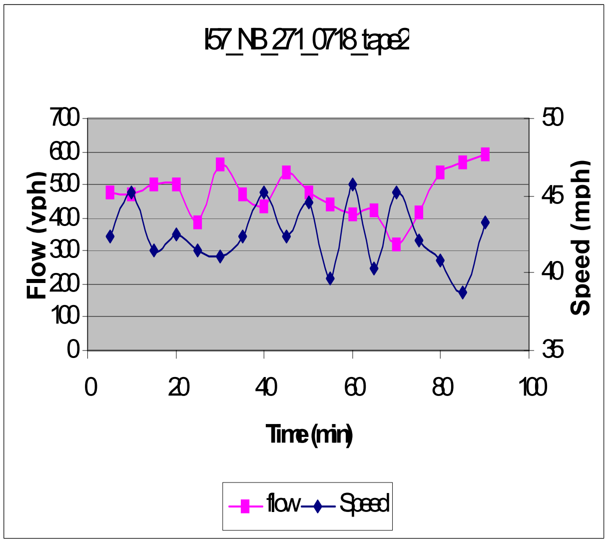
Time (min)
Flow
Speed

(o)

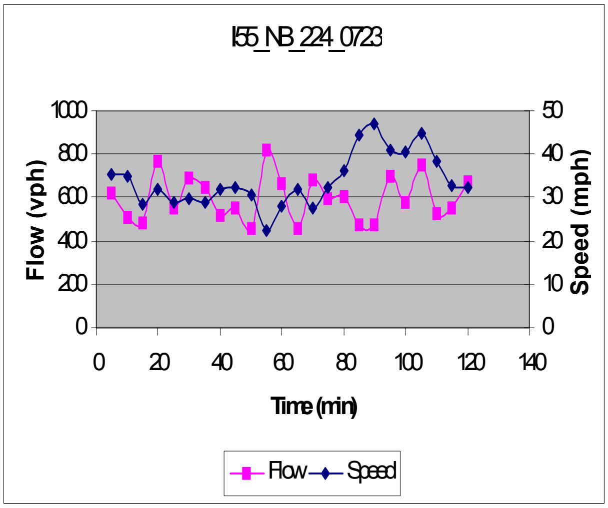
Time Series Plots for All Vehicles

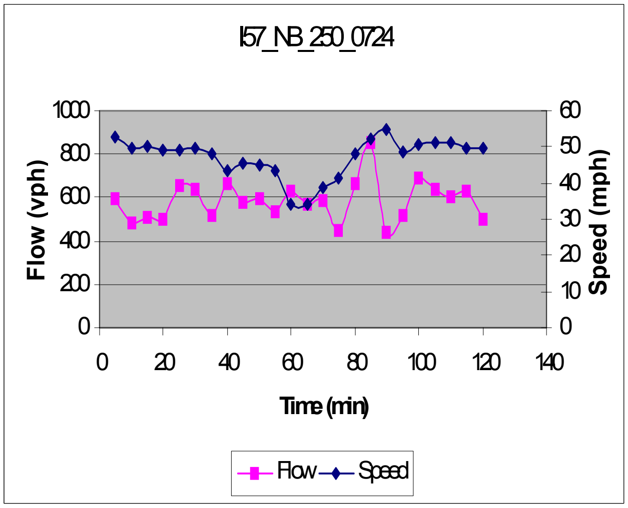




(a)

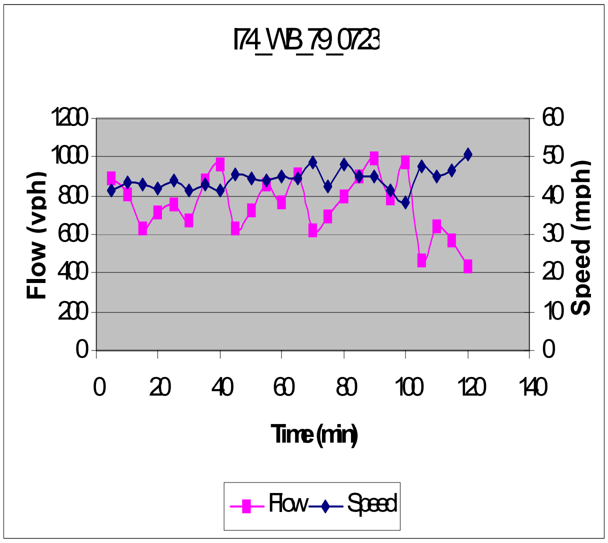
(b)



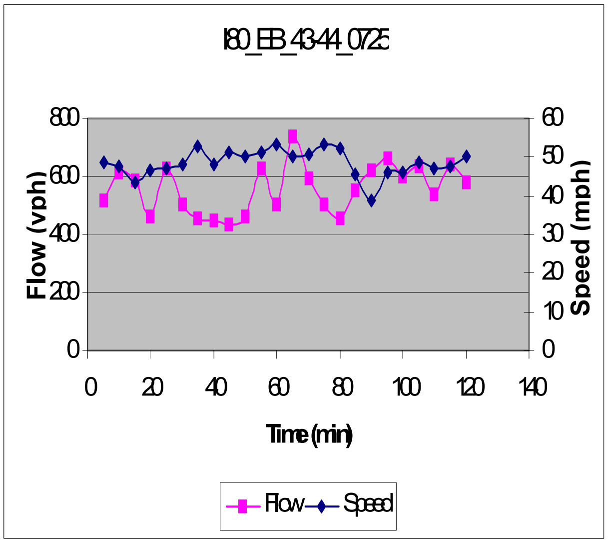


(c)

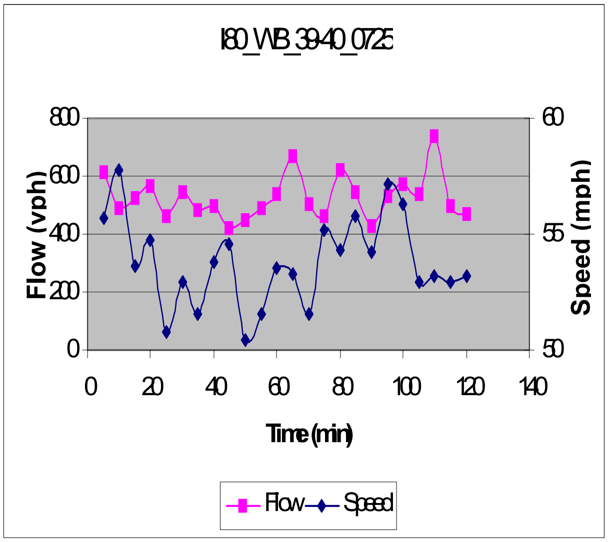
(d)


I74_WB_79_0723
Flow (vph)
Speed (mph)
1200
1000
800
600
400
200
0
60
50
40
30
20
10
0
0
20
40
60
80
100
120
140
Time (min)
Flow
Speed

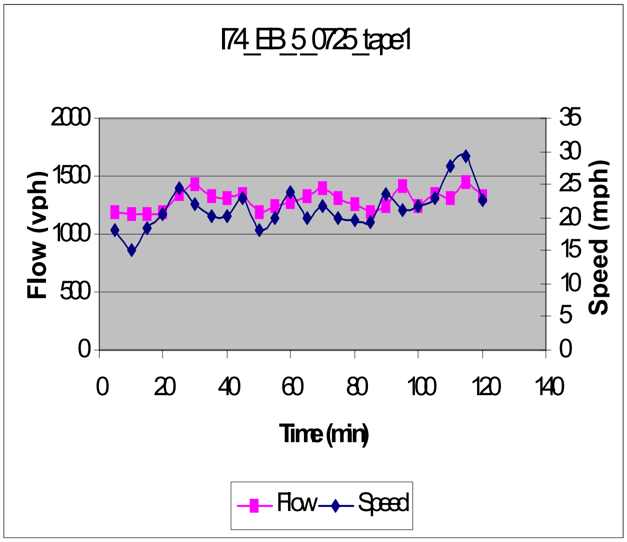
(e)


I80_EB_43-44_0725
Flow (vph)
Speed (mph)
800
600
400
200
0
60
50
40
30
20
10
0
0
20
40
60
80
100
120
140
Time (min)
Flow
Speed

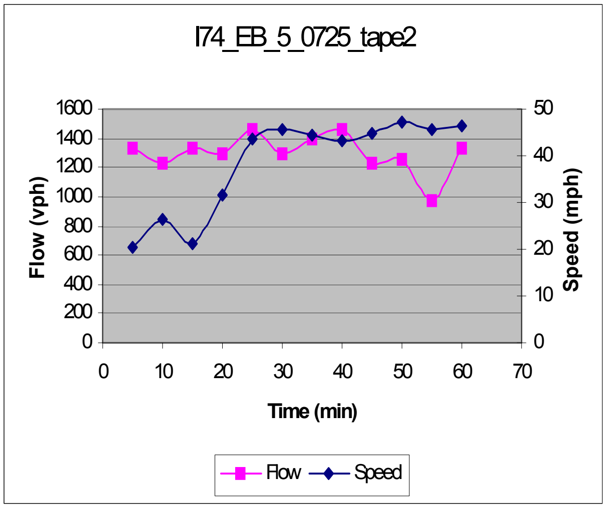
(f)


I80_WB_39-40_0725
Flow (vph)
Speed (mph)
800
600
400
200
0
60
55
50
0
20
40
60
80
100
120
140
Time (min)
Flow
Speed

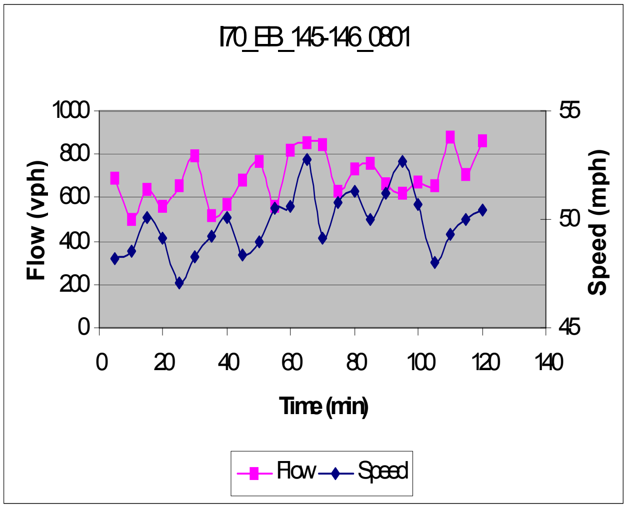
(g)


I74_EB_5_0725_tape1
Flow (vph)
Speed (mph)
2000
1500
1000
500
0
35
30
25
20
15
10
5
0
0
20
40
60
80
100
120
140
Time (min)
Flow
Speed

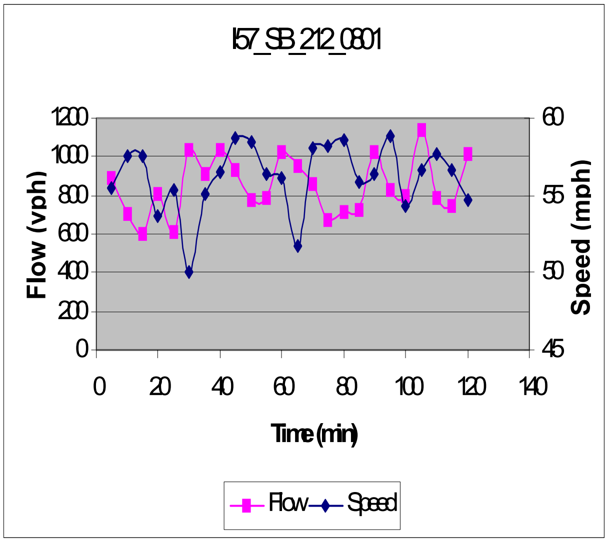
(h)


I74_EB_5_0725_tape2
Flow (vph)
0
200
400
600
800
1000
1200
1400
1600
Speed (mph)
0
10
20
30
40
50
Time (min)
0
10
20
30
40
50
60
70
Flow
Speed

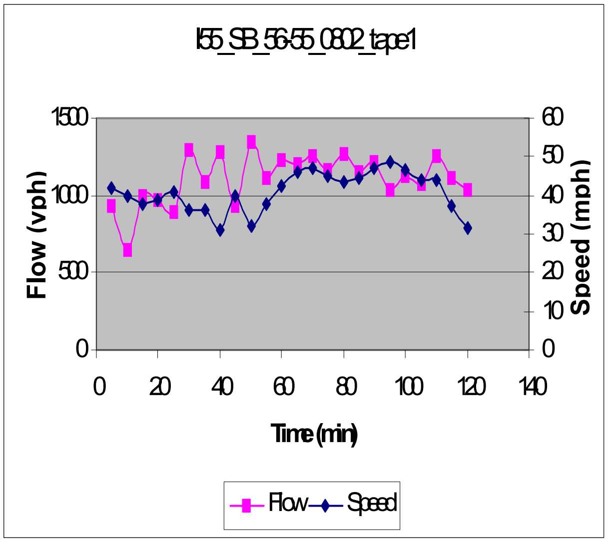
(i)


I70_EB_145-146_0801
Flow (vph)
0
200
400
600
800
1000
Speed (mph)
45
50
55
Time (min)
0
20
40
60
80
100
120
140
Flow
Speed

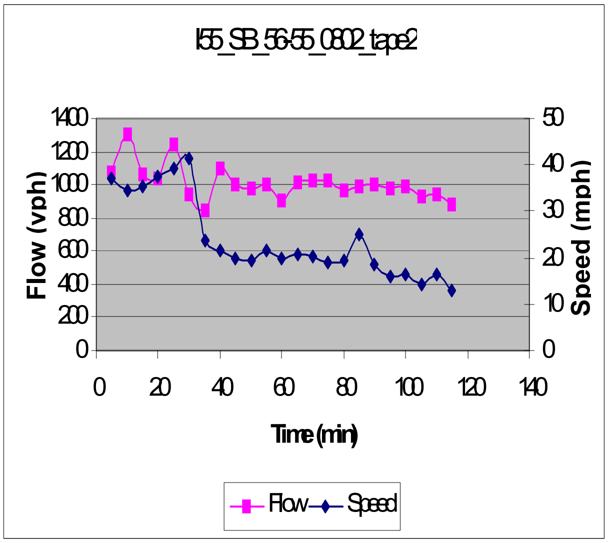
(j)


I57_SB_212_0801
Flow (vph)
0
200
400
600
800
1000
1200
Speed (mph)
45
50
55
60
Time (min)
0
20
40
60
80
100
120
140
Flow
Speed

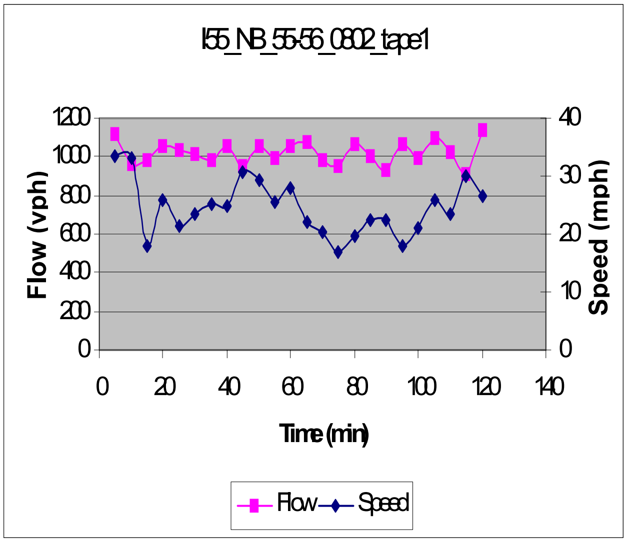
(k)


I55_SB_56-55_0802_tape1
Flow (vph)
0
500
1000
1500
Speed (mph)
0
10
20
30
40
50
60
Time (min)
0
20
40
60
80
100
120
140
Flow
Speed

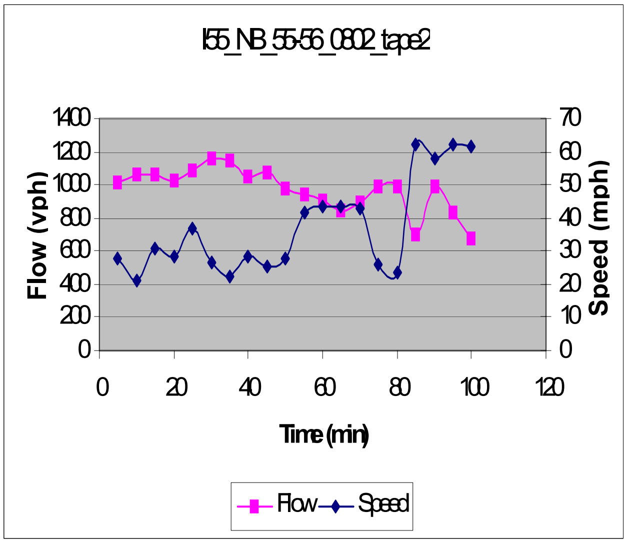
(l)


I55_SB_56-55_0802_tape2
Flow (vph)
1400
1200
1000
800
600
400
200
0
Speed (mph)
50
40
30
20
10
0
0
20
40
60
80
100
120
140
Time (min)
Flow
Speed

(m)


I55_NB_55-56_0802_tape1
Flow (vph)
1200
1000
800
600
400
200
0
Speed (mph)
40
30
20
10
0
0
20
40
60
80
100
120
140
Time (min)
Flow
Speed

(n)


I55_NB_55-56_0802_tape2
Flow (vph)
1400
1200
1000
800
600
400
200
0
Speed (mph)
70
60
50
40
30
20
10
0
0
20
40
60
80
100
120
Time (min)
Flow
Speed

(o)

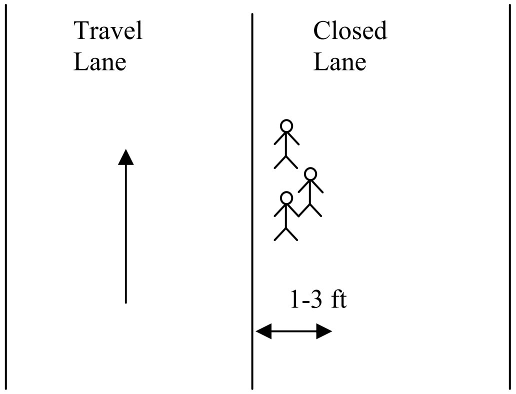
APPENDIX D - Sample Survey Sheet for Driver Survey

You are traveling thru a work zone on interstate highway that has one lane closed using orange barrels/cones. The speed limit inside the work zone is 45 MPH. Please answer questions 1 thru 11.

Thank you for your cooperation

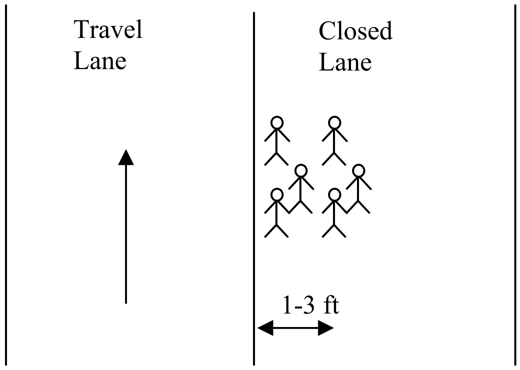
When construction crew is **<u>1-3 feet</u>** away from the travel lane, how much do you reduce your speed?

1-3 WORKERS



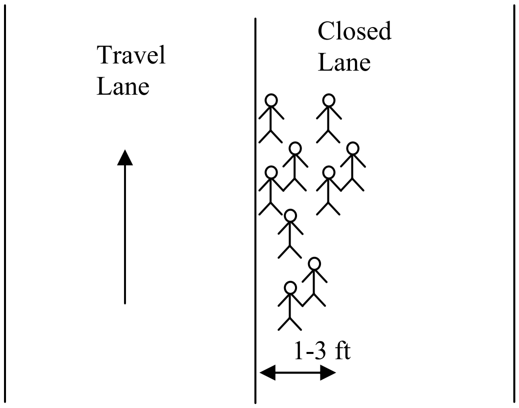
1. I reduce my speed by ____ mph

3-6 WORKERS



2. I reduce my speed by ____ mph

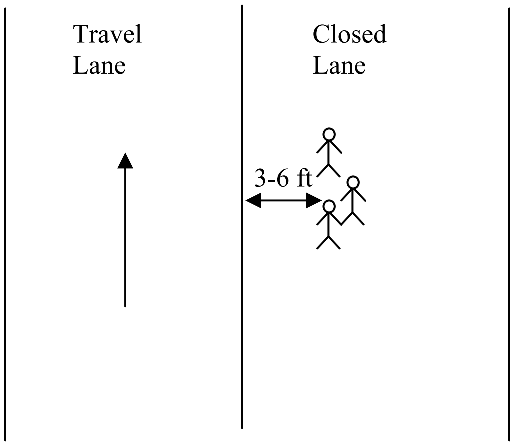
MORE THAN 6 WORKERS



3. I reduce my speed by ____ mph

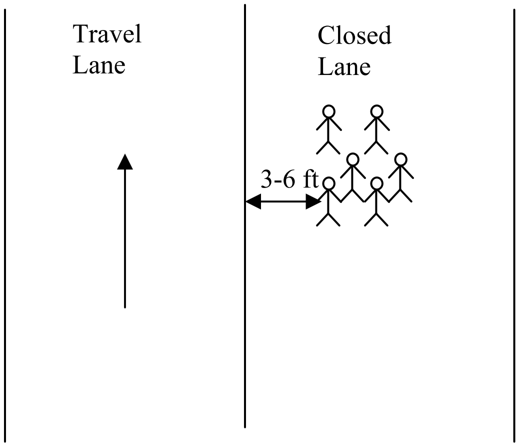
When construction crew is **3-6 feet** away from the travel lane, how much do you reduce your speed?

1-3 WORKERS



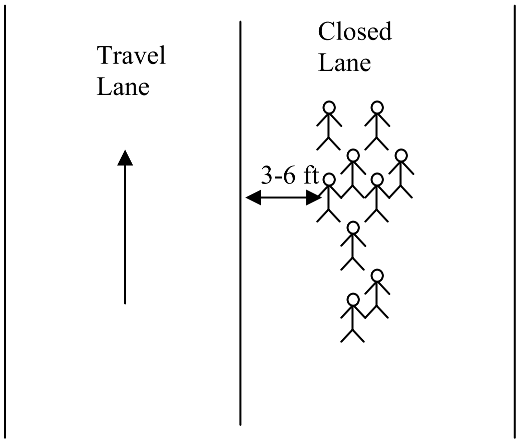
4. I reduce my speed by ____ mph

3-6 WORKERS



5. I reduce my speed by ____ mph

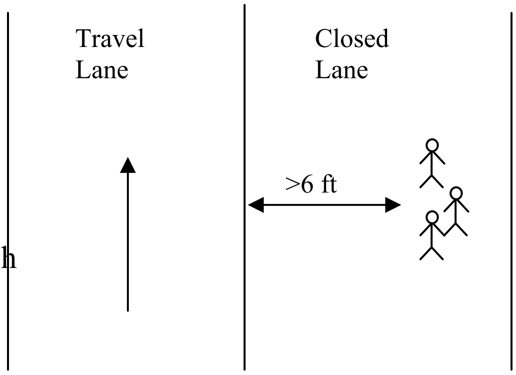
MORE THAN 6 WORKERS



6. I reduce my speed by ____ mph

When construction crew is **more than 6 feet** from the travel lane, how much do you reduce your speed?

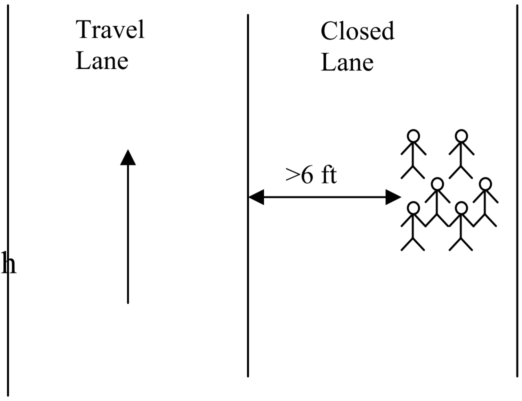
1-3 WORKERS



mph

7. I reduce my speed by ____

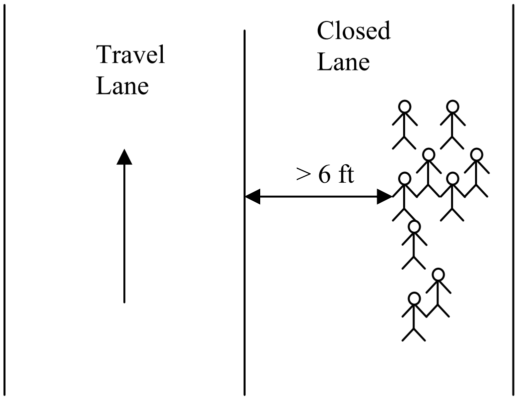
3-6 WORKERS



mph

8. I reduce my speed by ____

MORE THAN 6 WORKERS



mph

9. I reduce my speed by ____

10. I have ________ years of driving experience.

11. I drive (circle one) a) car b) pick up truck c) large truck d) other