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16. Abstract

This research was developed to produce usable and meaningful estimates for work zone capacities under a variety of roadway and traffic conditions, work zone configurations, and lane closure scenarios within Texas. Using data collected at eighteen work zone sites, the research presents updated guidance for expected capacities of various freeway work zone lane closure configurations. In addition, models used to evaluate traffic conditions in work zones were evaluated and recommendations for their use were made. Finally, recommendations concerning road user cost analysis for freeway construction projects are included.

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CAPACITY AND ROAD USER COST ANALYSIS OF SELECTED FREEWAY WORK ZONES IN TEXAS

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DISCLAIMER

This research was performed in cooperation with the Texas Department of Transportation (TxDOT) and the Federal Highway Administration (FHWA). The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official view or policies of the FHWA or TxDOT. This report does not constitute a standard, specification, or regulation.

This report is not intended for construction, bidding, or permit purposes. The engineer in charge of the project was Darrell W. Borchardt, P.E. #62074.

The United States Government and the State of Texas do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

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- Ms. Marla M. Jasek, P.E., TxDOT Yoakum District, Project Advisor;
- Mr. Andrew R. Oberlander, P.E., TxDOT Dallas District, Project Advisor;
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- Mr. David Valdez, P.E., TxDOT Traffic Operations Division, Project Advisor; and
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CHAPTER 1. INTRODUCTION

As traffic demand on Texas roadways continues to increase, the state must allocate substantial resources to constructing new roadways as well as maintaining the existing infrastructure. Roadway construction projects are among the most visible activities that the Texas Department of Transportation (TxDOT) completes for the traveling public. Freeway work zones, which typically include closed or narrowed lanes, may cause disruptions to normal traffic flow. These roadway sections with reduced capacities may cause traffic delays resulting in increased road user costs, traffic incidents, and vehicle emissions. The public desires the projects to be completed as quickly as possible with minimal impact on daily travels. In order to assure the quickest project completion minimizes the impacts of freeway work zones, TxDOT constructs most major projects using incentives for early completion and/or liquidated damages for failure to meet the contractual deadlines. Lane assessments or lane rental fees on routine maintenance contracts as well as for standard roadway construction projects are also being used. A critical input into the analysis process for determining the dollar amount of incentive, penalty, or lane rental assessment is the use of accurate roadway capacity for roadway segments impacted by the construction project. In addition to the updated capacity values being used in road user cost studies, TxDOT staff uses these capacity values to quantify the traffic carrying capacity of various work zone configurations using traffic control plan development such that delay to the public will be minimized.

Although there have been previous research studies examining work zone capacity estimation, many of these studies are outdated and may not accurately represent current travel conditions on Texas roadways. This project, which was a joint venture between the Texas Transportation Institute (TTI) and Texas A&M University-Kingsville, was developed to update capacity values in Texas work zones and to evaluate traffic models for estimating road user costs.

DEFINITION OF WORK ZONE CAPACITY

The *Highway Capacity Manual 2000 (HCM 2000)* defines capacity as: "The maximum sustainable flow rate at which vehicles or persons reasonably can be expected to traverse a point or uniform segment of a lane or roadway during a specified time period under given roadway, geometric, traffic, environmental, and control conditions; usually expressed as vehicles per hour, passenger cars per hour, or persons per hour (*1*)."

There are two different approaches to measuring the capacities of freeway work zones. The first considers the work zone capacity as the largest traffic volume as measured through the construction area. In practice, this value is generally accepted as the peak 15-minute traffic flow rate. However, some studies consider this volume as unsustainable for a significant time period. Traffic volume measured in a work zone during congestion is usually the flow rate of the queued vehicles being discharged from the work zone. Thus, the second approach considers the queue-discharge rate of the work zone as the basis for capacity estimation. Some criteria to identify the work zone capacity in previous studies are as follows:

- the flow rate derived from three-minute time intervals during congested conditions (California) (*2*);
- the hourly traffic volume under congested traffic conditions (Texas) (*3*);
- the flow rate at which traffic conditions quickly changed from uncongested to queue conditions (North Carolina) (*4*);
- the maximum recorded five-minute flow rate (Pennsylvania) (*5*);
- the flow rate just before a sharp speed drop (Indiana) (*5*); and
- the highest flow sustained during a 15-minute time period that is either before a rapid speed drop or after a rapid speed increase (Illinois) (*6*).

LITERATURE REVIEW OF WORK ZONE CAPACITY ESTIMATION

The objective of this literature review is to provide a comprehensive examination of work zone capacity estimation methods that may be used to configure lane closures, minimize traffic delay, and manage road user costs. The literature review had three major focus areas:

- estimation of work zone capacities,
- factors impacting work zone capacity,
- delay and road user cost estimation.

ESTIMATION OF WORK ZONE CAPACITIES

Widespread traffic growth has prompted the need for roadway improvements in most sectors of urban roadway systems. This growth combined with the accompanying construction to accommodate the need for expanded roadway capabilities has necessitated the need for an accurate methodology to predict work-zone capacity in areas of construction and maintenance. The impact of work-zones depends not only on the traffic itself, but also the effect of lane closures, construction intensity, and multiple other factors. In order to reduce the negative effects of work-zone activities, careful management, accurate planning and the ability to reliably estimate work-zone capacities are required.

The ability to accurately estimate work-zone capacity is imperative, as it is a key input to queue length, delay, and delay costs estimations. Several factors, such as driver population, vehicle composition (truck percentage), light conditions (day or night), weather conditions, intensity of work activity, lane closure configuration, lane width, roadway terrain, and gradient, must be considered in estimating work zone capacity. Some of these factors are easily measured, whereas others have to be estimated.

Based on research by the Texas Transportation Institute leading to the release of the *Highway Capacity Manual of 1985* (*7*), researchers developed an empirical method of estimating freeway work-zone capacity. This methodology was improved upon so that by the release of the *Highway Capacity Manual 2000* (*1*), this technique had become a standard method used by transportation departments and agencies in estimating the capacity of work zones with lane closures. The *Highway Capacity Manual 2000* (*1*) takes the unrestricted base capacity of 1,600 vehicles per hour per lane (vphpl) used for work zone areas without flow restrictions and modifies it by using multiple reduction factors. This modified value takes into account parameters such as lane width, percentage of heavy vehicles, work intensity and proximity of ramps.

A number of studies have focused on the improvement of work-zone capacity estimation methods. In a recent paper (*8*), research efforts to improve the estimation of the effects of lane closures at freeway maintenance and construction zones were reviewed. In the early 1990s, Krammes and Lopez (*9*) developed new guidelines for estimating capacity for various types of lane closure configurations and introduced updated higher capacity values for short-term work zone lane closures.

Based on field data, Abrams and Wang (*10*) developed a model that combines the *HCM 2000* adjustment factors with a new factor that considers work duration. Dudek et al. (*11, 12*) developed the computer model QUEWZ to estimate capacity by classifying various lane closure configurations and applying a regression analysis. QUEWZ was then improved by integrating additional factors considering work zone intensity, percentage of heavy vehicle presence, and the location of entrance ramps.

Kim, Lovell, and Paracha (*8*) developed a new capacity estimation methodology based on an expanded assessment of a number of factors. These factors included the number of open and closed lanes, location of the closed lanes, heavy vehicle percentage, driver population, entrance ramp volume, width of open lanes, and the length and grade of the work zone. Additional factors included the intensity of the work activity, project duration, weather conditions, and the time of day when work is performed. This new methodology with the newly determined key factors proved more accurate at predicting capacity than the models they reviewed in their study.

In another study by Al-Kaisy and Hall (*13*), two-step guidelines for estimating capacity at freeway reconstruction zones were introduced. In the first step, the effect of heavy vehicles, driver population, weather, site configuration, work activity, and light conditions on capacity was examined. This study suggested that heavy vehicles and driver population were the most significant factors affecting work zone capacity. In the second step, two separate capacity models are offered, one being a generic model and the other a site-specific model.

One of the capacity estimation methods is the multiplicative capacity model. It accounts for several independent factors that may affect work zone capacity and uses appropriate adjustments to reduce an ideal base work zone capacity (*13*). The multiplicative model also used by the HCM 2000 (*1*) uses the following formula and adjustment factors:

$$C = C_b \times f_{HV} \times f_{d1} \times f_{d2} \times f_w \times f_s \times f_r$$

where,

C = the work zone capacity (vphpl);

C_b = ideal base work zone capacity (passenger cars per hour per lane) (pcphpl);

f_{d1} = off-peak weekday driver population (off-peak=f_{d1}, else=1);

f_{d2} = weekend driver population (weekend=f_{d2}, else=1);

f_w = work activity (no work activity=1);

f_s = side of lane closure (left lane closed=f_s, right lane closed=1);

f_r = rain (rain = f_r, no rain=1); and

f_{HV} = heavy vehicle (see formula below).

$$f_{HV} = \frac{1}{\left[1 + P_{HV}(E_{HV} - 1)\right]}$$

P_{HV} = proportion of heavy vehicles in traffic;

E_{HV} = passenger car equivalency for heavy vehicles.

Al-Kaisy and Hall (*13*) collected field data at several work zones to update the adjustment factors. A comparison of the base capacity and capacity reduction factors used by the multiplicative model and those observed in the field are listed below:

Factor	*Multiplicative Capacity Model*	*Site Findings*
Base Capacity	2,050 pcphpl	2,000 pcphpl
Driver Population	4% reduction	7% reduction
Weekend Drivers	17.5% reduction	16% reduction
Work Activity	3.5% reduction	1.85-12.5% reduction
Lane Closure	5.7% reduction	6% reduction
Rain	2.5% reduction	4.4-7.8% reduction

A majority of the values used by the multiplicative capacity model are close to those observed at the field sites.

Another class of capacity estimation methods, the additive capacity models are based on multivariate linear regression and incorporate variables similar to those used in the multiplicative model. In addition to looking at the variables as independent factors, the additive capacity model examines the interaction between variables. Only the factors showing a significant interaction effect are included in the additive capacity model. Many widely utilized models belong to this category, which include the following:

- From Memmott and Dudek (*12*)

  $C = a - b(CERF)$

  where,

  C = estimated work zone capacity;

  CERF = capacity estimate risk factor suggested in the research; and

  a, b = coefficients given in the research.

- From Al-Kaisy and Hall (*13*)

  $C = 1964 - 20.9P_{HV} - 82D_1 - 352D_2 - 172W - 121S - 71R + 55SD_1 + 185WD_2 + 58SD_2 + 107RD_2$

  where,

C = capacity in vphpl;

P_{HV} = percentage of heavy vehicles in the traffic stream;

D_1 = off-peak weekday driver population;

D_2 = weekend driver population;

W = work activity at site;

S = side of lane closure;

R = rain (rain=1, else=0);

SD_1 = side of lane closure and off-peak weekday driver population;

WD_2 = work activity and weekend driver population;

SD_2 = side of lane closure and weekend driver population; and

RD_2 = rain and weekend driver population.

Researchers concluded that pure multiplicative models or pure additive models could not predict the capacity accurately, and efforts were made to combine the two kinds of models. The proposed, so-called "generic" capacity model is a combination of multiplicative and additive models. The multiplicative model was improved by including the following two factors:

- f_l=light condition; and
- f_i = nonadditive interactive effects.

Al-Kaisy and Hall first proposed this concept in 2003 (*13*). Their model had a multiplicative format, but it also accounted for the interaction between variables just as the additive models. Other generic capacity models include the following:

- From Krammes and Lopez (*9*)

  $$C = (1600 + I - R) * H * N$$

  where,

  C = estimated work zone capacity;

  I = adjustment for type and intensity of work activity suggested in the research;

  R = adjustment for presence of ramps suggested in the research;

  H = heavy vehicle adjustment factor given in the *HCM*; and

  N= number of lanes open through the work zone.

- From Abrams and Wang (*10*)

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

  where,

C= estimated work zone capacity;

TF = truck adjustment factor given in the *HCM*;

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

WZF = work zone capacity adjustment factor determined in the research.

- From Kim et al. (*8*)

$$C = 1857 – 168.1\mathit{NUMCL} – 37.0\mathit{LOCCL} – 9.0\mathit{HV} + 92.7\mathit{LD} – 34.3\mathit{WL} – 106.1\mathit{WI}_H – 2.3\mathit{WG}*\mathit{HV}$$

where,

C = estimated work zone capacity;

NUMCL = number of closed lanes;

LOCCL = location of closed lanes;

HV = proportion of heavy vehicles;

LD = lateral distance to the open travel lanes;

WL = work zone length;

WI_H = intensity of work zone activity;

WG = work zone grade; and

HV = proportion of heavy vehicles.

- From W. Virgil Ping and Kangyuan Zhu (with interaction effects of two factors) (*14*)

$$C = 1619 + \mathit{lane} + \mathit{value(ffs)}*\mathit{wffs} + 10.2*\mathit{grade} – 12.0*\mathit{truck} + \mathit{truck}*\mathit{lane} + \mathit{grade}*\mathit{lane} – 1.97*\mathit{truck}*\mathit{grade}$$

where,

ffs: free flow speed;

truck: percentage of heavy vehicles;

	Lane configuration [number of all lanes, closed lanes]		
	[2,1]	[3,2]	[3,1]
Lane	-3.6	177.0	0.0
*truck*lane*	-0.17	-3.95	0.0
*grade*lane*	-0.93	-19.7	0.0

value (ffs) = 0.48 when ffs = 55 mph;

value (ffs) = 0.50 when ffs = 60 mph; and

value (ffs) = 0.55 when ffs = 70 mph.

Because of the many interacting variables affecting work zone capacity, it is difficult to estimate capacity by a simple mathematical formula. Recently, more and more computational intelligence methods and commercial software have been introduced to help solve this capacity problem. Jiang and Adeli (*15*) used a neuro-fuzzy method to quantify factors and develop new software to estimate the capacity (*16*). The Neuro-Fuzzy Logic Model introduces a neural network of interacting variables that are quantified using a fuzzy inference method. This method accounts for seventeen different variables affecting work zone capacity. A comparison of the Neuro-Fuzzy Logic Model against two other well known work zone capacity equations, the Krammes and Lopez's (1994) empirical method (*9*) and the multiple-variable regression equation by Kim et al. (*8*), the Neuro-Fuzzy Logic Method was found to be more accurate in most cases than the other two. Also, the Neuro-Fuzzy Logic Model incorporates more factors than the other models.

The work zone capacity estimator software system called IntelliZone® developed by Jiang and Adeli (*16*) is based on pattern recognition and neural network models. IntelliZone uses seventeen interacting factors in estimating work zone capacity, delay, and queue length. The main benefit of this model compared to previous models is its ability to examine a variety of work zone scenarios, multiple roadway segments and various traffic flow strategies. Also beneficial are its interactive user interface and effective, user-friendly help features.

FACTORS IMPACTING WORK ZONE CAPACITY

There are many factors affecting work zone capacity. Some of them weigh more heavily than others in their significance, and some are combined and measured by their joint influence within the capacity analysis. Most factors can be grouped into one of five major categories:

- Work Zone Configuration
  - Number of Lanes Closed: The ratio of closed to total number of lanes is an important input in work zone capacity analysis.
  - Work Zone Layout: The positioning of closed lanes versus open lanes as well as entry/exit ramp closures; a more effective layout will result in a greater work zone capacity.

  - Length of Work Zone: A longer work zone indicates a greater likelihood of more intense work activity and the increased presence of warning signs; these combined items may reduce capacity.
- Roadway Conditions
  - Roadway Grade: Steep grades may reduce driver visibility and the ability to maintain constant speed and vehicle spacing.
  - Pavement Conditions: A lower quality pavement riding surface will affect vehicle speeds.
  - Lane Width: Width of the travel lanes, lack of shoulders, and distance to lateral obstructions will impact capacity.
- Work Activity
  - Intensity of Work Activity: High intensity work activity with a large number of workers will reduce capacity.
  - Work Time: Capacity is impacted by the time-of-day of work activity.
  - Type of Work: Various types of work will affect work zone capacity in different ways.
  - Duration of Work: Project duration is a contributing factor to traffic flow through a work area.
- Environmental Conditions
  - Significant Rain Shower: A significant rain shower can reduce roadway capacity by 10 to 20 percent.
  - Significant Snow: While not common for most parts of Texas, snowfall can impact traffic flow within work zones.

Although the significance of the combined impact of multiple factors can be ranked according to its individual effect on the work zone capacity, researchers suggest evaluating each factor on an individual basis.

ROAD USER COST ESTIMATION IN WORK ZONES

The estimation of work zone user costs is a more complex effort compared to work zone capacity estimation. Capacities and delays are required input to user cost calculations. There are many variables affecting work zone capacities and delays, and therefore road user cost cannot be simply estimated using simple calculations. Road user cost calculations are often performed using various software packages.

The general definition of road user costs (RUC) of a work zone is the total incremental cost to the traveling public resulting from work zone activity. Road user cost usually includes several components, such as user delay costs (i.e., value of time), vehicle operating costs (VOC), and accident/crash costs (*17, 18*).

Delay is one of the major concerns in work zones. Estimated delay is not only used for planning work zones, but it is a critical input to road user cost estimation. Most researchers focus on deterministic queuing delay. A queue may form where traffic demand exceeds the capacity of a work zone. The *Highway Capacity Manual (1994)* adopted this approach to estimate delay at work zones (*19*).

Memmott and Dudek (*12*) considered splitting delays into two components; one being the queue delay, and the other is delay through the lane closure section. Unlike queuing delay, delay through the lane closure section seldom changes during a day. The following formulas have been developed to calculate these two components.

Delay through the lane closure section:

$CLL = 0.1 + (WZD + 0.1)(V / C_{WZ})$,

If $WZD <= 0.1$ or $V / C_{WZ} > 1$,

Then $CLL = WZD + 0.2$ and $DWZ = CLL(1 / SP_{WZ} - 1 / SP_{AP})(VLL)$

where,

CLL: the effective length of closure;

WZD: length of restricted capacity around the work zone in miles;

V / C_{WZ}: ratio of demand volume to capacity of work zone;

DWZ: delay going through work zone at reduced speed;

SP_{WZ}: speed through work zone;

SP_{AP}: approach speed; and

VLL: hourly vehicle volume.

Delay due to queue formation:

$DQUE_i = (ACUM_{i-1} + ACUM_i) / 2$,

where,

$DQUE_i =$ the average delay for each hour a queue;

$ACUM_i = ACUM_{i-1} + VL_i - CAPW_i$: the accumulated vehicles in the queue at the hour i;

$CAPW$: restricted capacity through work zone (vehicles per hour) (vph) for hour i; and

VL_i: vehicle demand during hour i.

Then, total delay is calculated as:

$$TD = DQUE + DWZ$$

Although VOC is defined by AASHTO Red Book (*20*) as total vehicle operating costs, there is the added costs each vehicle incurs by making speed changes and stops (*21*) that is also used in estimating road user costs (*17, 22*). The cost factors reflecting 1970 prices are available. To make these costs applicable to present day economics, these data are adjusted to current cost by using an escalation factor derived from the Consumer Price Index. Some of the contributing factors to VOC are stopping/speed changes, idling, and detour costs.

Costs due to crashes consist of two parts. One is a direct cost, which is the economic loss incurred from an accident or crash site. These losses can include medical expenses, administration costs, and repairing expenses. The second part is an indirect cost, which can be measured through the lost quality of life associated with injuries and even deaths, and the negative impacts this inflicts upon society. Although crash costs are typically not included in road user costs studies, agencies should be aware of the monetary impact of crashes in work zones.

The State of Texas has been in the forefront of using road user costs in determining values for incentive/disincentive for almost two decades. One of the early studies in estimating construction related user costs for a freeway project in Houston was in 1988. The estimation of road user costs was completed for three adjacent segments of the US 59 Southwest Freeway with the intent of using the RUC values to aid in determining appropriate values for incentive/ disincentive monetary costs for the freeway construction project (*23*). As TxDOT became more active in applying road user cost based liquidated damages in construction projects, it became apparent that it would be beneficial for TxDOT employees to be trained in RUC study techniques. In 1998, the Construction Division funded an effort to develop a training course and manual to be used by TxDOT so department employees could complete RUC studies for various types of projects (*24*). This effort resulted in the completion of the training of TxDOT personnel statewide. As a follow up to the successful training, a research project was awarded to further expand the use of RUC studies for construction projects in Texas. This effort resulted in the development of tables for estimating RUC values for typical added-capacity and highway rehabilitation projects as well as providing further guidance in completing these studies (*25*).

CHAPTER 2. SURVEY OF CURRENT PRACTICES IN TEXAS

A survey was conducted to determine the current state of practice of estimating work zone capacity in Texas. Prior to conducting the survey, the research team met with the project director and project advisors to discuss the main focus, the structure, content, and format of the survey. The project monitoring committee recommended that the survey as well as the research should primarily focus on freeway work zone capacity. The research team determined that the most effective format of conducting a survey would be an email questionnaire sent to the Directors of Transportation Operations in all TxDOT districts. Figure 1 shows the survey structure that was presented at the project meeting and approved by the project monitoring committee.

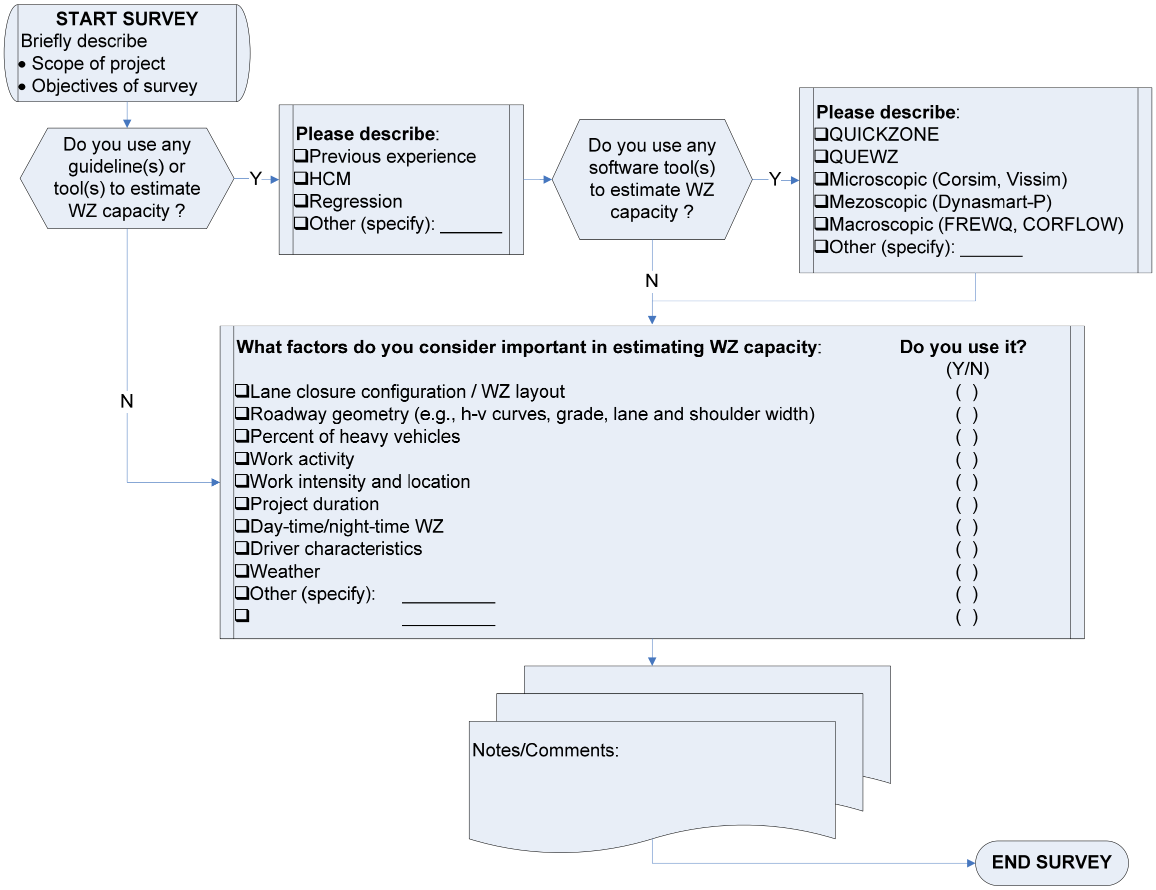

Figure 1. Survey Structure.

The survey was composed of three question areas:

- guidelines used,
- software tools used; and
- factors considered important for estimating work zone capacity.

The survey structure was further refined and then sent via email to TxDOT Directors of Transportation Operations. Figure 2 shows the content of this email survey.

Greetings!
The Texas Transportation Institute is conducting a TxDOT research project to determine Updated Work Zone Capacities (Project No 0-5619). As part of this research we are conducting a brief survey to gather input from TxDOT districts about their current practices in determining roadway capacity for various road construction and maintenance projects. We are particularly interested in the capacity of freeway work zones.

The following brief questionnaire is intended to TxDOT personnel with experience in estimating roadway capacities and road user costs for construction and maintenance projects. We would appreciate if you could forward it to the appropriate person in your district.

QUESTIONNAIRE:
What guideline(s) or method(s) do you use to estimate work zone capacity?
( ) None
( ) HCM
( ) Field experience, engineering judgment
( ) Regression model(s)
( ) Other (specify):

What software tool(s) do you use to estimate work zone capacity?
( ) None
( ) QUICKZONE
( ) QUEWZ
( ) FREWQ
( ) Microscopic simulation (Corsim, Vissim)
( ) Other (specify):

What factors do you consider important in estimating work zone capacity?
( ) Lane treatment (e.g., lane closure, lane shift, narrow lanes)
( ) Roadway geometry
( ) Horizontal/vertical curves
( ) Grade
( ) Lane width
( ) Shoulder width
( ) Percent of heavy vehicles
( ) Work activity
( ) Work intensity and location
( ) Project duration
( ) Day-time/night-time WZ
( ) Weather
( ) Other (specify):

***Please list any major freeway construction(s) in your district for the first half of 2008**:*

We would appreciate receiving the completed questionnaire by January 7, 2008. If you have any questions, please contact the Research Supervisor, Darrell Borchardt (Tel: 713-686-2971, e-mail: d-borchardt@tamu.edu), or Geza Pesti (Tel: 979-845-9878, e-mail: g-pesti@tamu.edu). The survey results along with other research findings will be documented in the final report of TxDOT research project 0-5619.

Thank you in advance for your cooperation.

Figure 2. Email Survey.

The response rate was slightly over 50 percent. A total of 13 surveys were returned and completed in sufficient detail. This section presents the questions and the distribution of answers. All distributions are based on a set of 13 responses unless otherwise specified. Note that the distributions of answers, in most cases, do not add up to 100 percent because respondents may have given multiple answers for a single question.

Question: What guideline(s) or method(s) do you use to estimate work zone capacity?

Answers: Figure 3 summarizes the responses. Nine of the TxDOT districts use previous field experience and engineering judgment to estimate work zone capacity. The *HCM* is used by three of the responding districts and two do not use any guidelines for work zone capacity estimation.

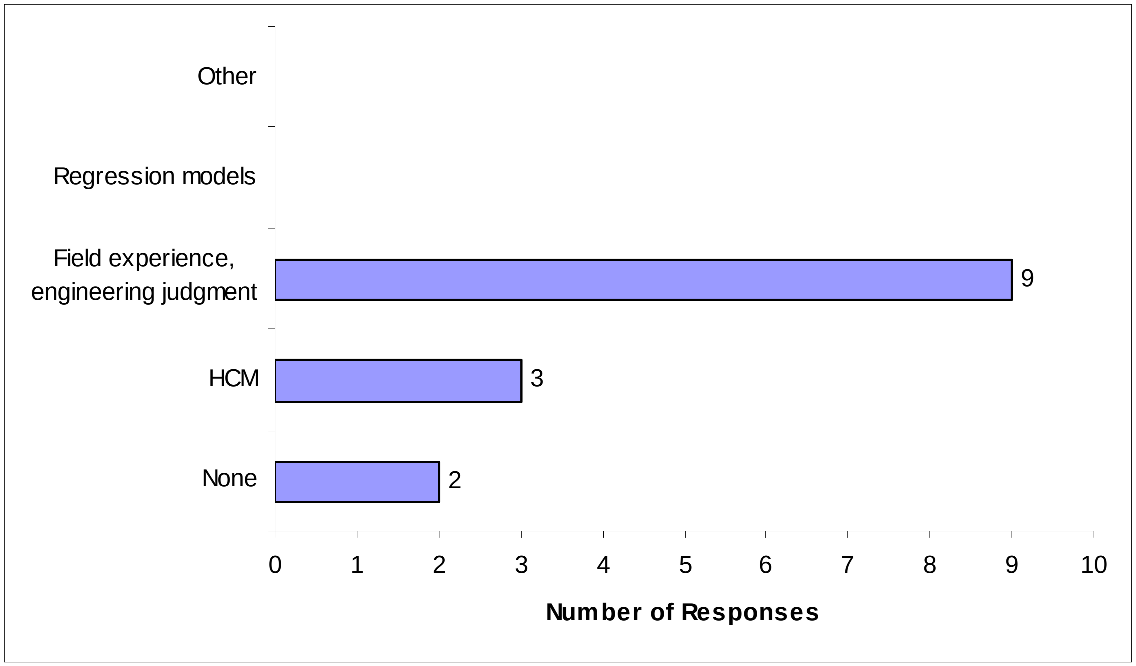

Figure 3. Survey Results: Guidelines to Estimate Work Zone Capacity.

Question: What software tool(s) do you use to estimate work zone capacity?

Answers: Figure 4 summarizes the responses. Ten districts do not use any software to estimate work zone capacity. Three of the respondents indicated that they use either QUEWZ, FREQ, or some microscopic traffic simulation model.

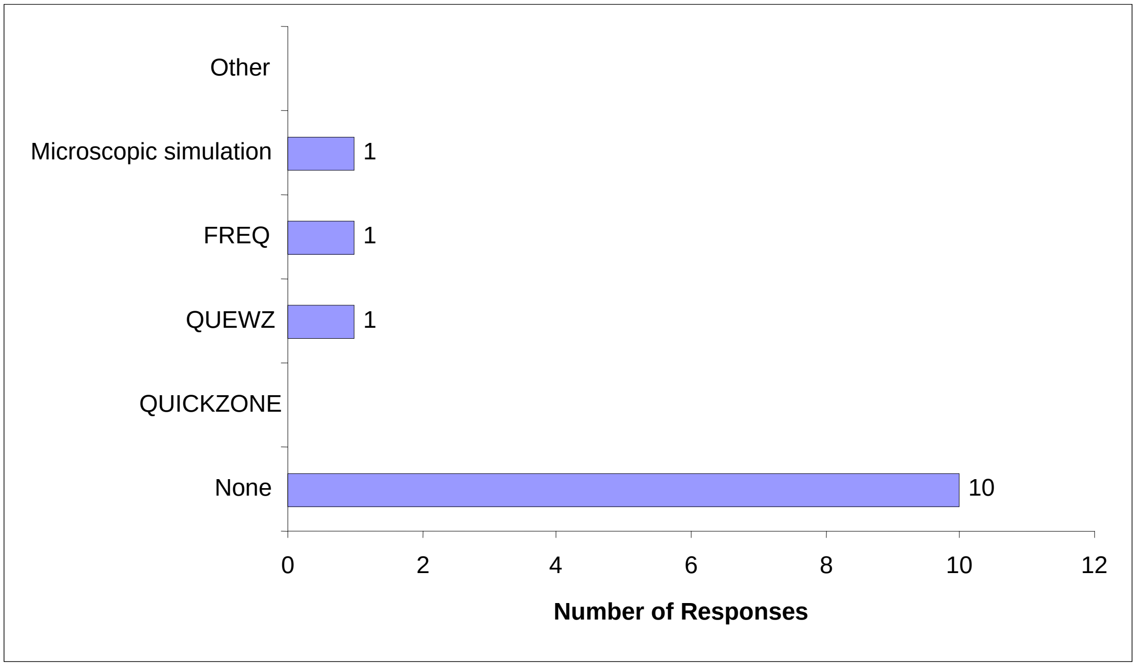

Figure 4. Surveys Results: Software to Estimate Work Zone Capacity.

Question: What factors do you consider important in estimating work zone capacity?

Answers: Figure 5 summarizes the responses. The three factors that were considered important by most districts are roadway geometry, lane width, and lane treatment. Project duration and truck percentage were also considered important by more than half of the respondents. Slightly fewer than one-half of the responding districts indicated that shoulder width was an important factor. According to more than one third of the districts, work activity, grade level, horizontal and vertical curves also significantly affect work zone capacity. Somewhat less than one third of the respondents indicated that the intensity and location of work zone activities are important factors. Smaller percentages of the respondents considered the effect of weather, night-time/day-time work, and other factors important.

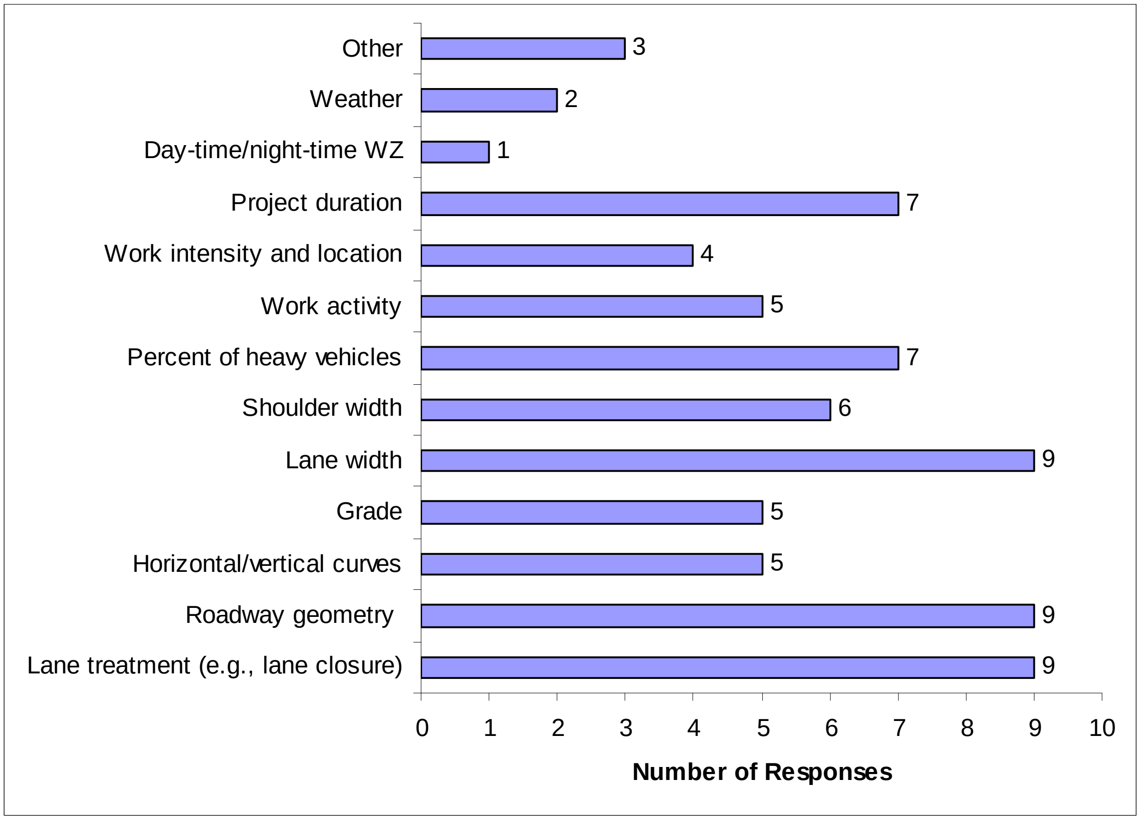

Figure 5. Survey Results: Factors Affecting Work Zone Capacity.

Request: Please list any major freeway construction(s) in your district for the first half of 2008.

Answers: Five of the 13 responding districts could provide a list of major expected freeway construction locations for the first six months of 2008. Table 1 summarizes major freeway construction projects in the returned surveys. Researchers used the IH 10 project in Orange as a study site.

Table 1. Major Freeway Constructions Listed by Districts.

District	**Freeway Constructions**
Beaumont	IH 10 at the Trinity River Bridge in Chambers County IH 10 between FM 105 and SH 62 in Orange (Two separate but back to back projects.)
Corpus Christi	SH 358 (SPID) in Corpus Christi US 59 in Goliad US 59 in George West US 77 in Sinton US 181 in Sinton
Abilene	IH 20/US 277,US 83 Interchange, Taylor Co.
Brownwood	IH 20 - reconstruct existing pavement (Tentative letting: May 2008)
Pharr	US 83 in Hidalgo County (From: Spur 31 to Hidalgo/Cameron County Line) in Mercedes US 83 in Cameron County (From: Cameron/Hidalgo County Line to Lewis Lane) in La Feria and Harlingen US 77 in Willacy County (Raymondville Area)

CHAPTER 3. FIELD MEASUREMENT OF WORK ZONE CAPACITY

One goal of this project was to produce usable and meaningful estimates for work zone capacities under a variety of roadway and traffic conditions, work zone configurations, and lane closure scenarios within Texas. To accomplish this task, data were collected at a limited number of work zones through the state.

STRATEGY FOR SITE SELECTION

A strategy for field site selection was developed based upon a prioritized list of criteria in order to select a representative sample of work zone sites for field studies. In recent years, TxDOT has become more sensitive to the impacts of construction activities on the traveling public; consequently a large portion of work activities requiring major lane closures are being conducted at nighttime when traffic volumes are lower to minimize traffic impacts. This reduces the likelihood that traffic demands will exceed the work zone capacity, hence more difficult to estimate the capacity of the work zone. Nighttime work zones typically only have capacity flow conditions for a short time (one to two hours) immediately after any lane closures are deployed. Initially, a matrix of work zone configurations was developed as a guide for the researchers to identify the quantity of work zones needed to satisfy the project objectives. Figure 6 presents the resulting matrix.

					Urban												Rural							
					Interstate				State Hwy				Arterial				Interstate				State Hwy			
					Temporary		Long-term		Temporary		Long-term		Temporary		Long-term		Temporary		Long-term		Temporary		Long-term	
Lane configuration		Trafic control	Weather	Shoulder	Day	Night	Day	Night	Day	Night	Day	Night	Day	Night	Day	Night	Day	Night	Day	Night	Day	Night	Day	Night
Lane closure	2-to-1	Early merge	Dry	Wide																				
				Narrow																				
			Rain	Wide																				
				Narrow																				
		Late merge	Dry	Wide																				
				Narrow																				
			Rain	Wide																				
				Narrow																				
		Dynamic merge	Dry	Wide																				
				Narrow																				
			Rain	Wide																				
				Narrow																				
	3-to-2	Early merge	Dry	Wide																				
				Narrow																				
			Rain	Wide																				
				Narrow																				
	3-to-1	Early merge	Dry	Wide																				
				Narrow																				
			Rain	Wide																				
				Narrow																				

Figure 6. Initial Matrix of Study Site Design.

Satisfying all of the configurations in the matrix would require finding approximately 400 work zones specific to the criteria as listed. It would be very unlikely to find those work zones and would be beyond the budget of the project as well. Discussions at the October 2007 project committee meeting in Corpus Christi resulted in a decision to concentrate on lane closures on major freeways in urban areas. While this reduced the number of work zone configurations studies to a more reasonable number, it also allowed researchers to concentrate on work zones typical for construction activities on Texas roadways. It was decided that a mix of long-term and short-term closures would also be studied. For the purpose of this research project, a short-term closure is defined as one where the work activity is present for only a short time; workers are separated from traffic only by barrels and/or cones. These types of activities typically last from a few hours to less than a week. Long-term closures exist for months at a time and the workers are separated from traffic by concrete barriers. In some cases, the number of lanes has not been reduced, but the roadway capacity is impacted by narrow lanes and the removal of shoulders.

It is also desirable to locate study sites with different levels of work intensity. Examples of different types of work intensity are:

- low – barrier/guardrail installation/repair and pavement repair;
- medium – resurfacing/asphalt removal and striping removal; and
- heavy – pavement marker and bridge repair.

A second alternative is to classify the work intensity into two groups according to whether the work activity is present or not. While the researchers strove to obtain field sites of each type of work intensity, it was considered as secondary in terms of finding adequate field sites. The types of activity were recorded and special observations as to any impact it may have were made as needed. Work zones were not eliminated from consideration for field data collection based upon the presence or lack of work intensity levels.

The selection of field study sites for use in this research project proved to be a dynamic process. Identifying the appropriate study sites, determining if traffic data can be safely collected without impacting traffic and/or work activity, and if there is sufficient traffic to be able to measure the capacity of the work zone, has been quite challenging. In some cases, no information was available on existing traffic demands, therefore data collection had to be completed as the work activity may have been present for a limited number of days. This strategy has proven to be very successful in being able to collect some data at more work zones rather than employing a strategy of only studying work zones where it was known that volume would exceed capacity.

Researchers completed a weekly review of the TxDOT Road Conditions web site (http://apps.dot.state.tx.us/travel /road_conditons2.htm) to aid in identifying long-term construction projects with lane closures. A list of the scheduled closures had been updated each Tuesday beginning in October 2007 and provided to each member of the research team for review. Locations which looked promising for further study were then followed up with a field visit. The majority of the closures listed tended to be for non-freeway roadways, therefore not usable for this research project. One example of a site identified as promising is as follows: IH 20 in Palo Pinto County – US 281 to Parker County – roadway reduced to one lane, speed limit lowered to 60 mph. In conjunction with another scheduled trip, a field visit to this site was completed. While the work zone configuration was ideal for study, the traffic volumes in this rural area were not sufficient to allow for estimation of the capacity in the work zone.

The Houston and San Antonio regions appeared to be the most ideal places to find suitable work zones for the field studies. Each of these regions has roadway construction activities in the urban area as well as on freeways outside the cities. While not in the urban areas, these freeways have traffic volumes high enough that congestion can develop, queues form, and the capacity of the work zone can be measured. The basis for work zone identification in these regions was the traffic management center web sites of Houston TranStar and San Antonio TransGuide. Each has a specific section of the web site dedicated to real-time construction information; this has proven to be very effective in identifying short-term lane closures. The closed circuit television (CCTV) camera system and roadside sensors of Houston TranStar proves to be a good tool to not only identify active road closures, but as a source of traffic data in some instances where the work zone was in a detection zone for the radar sensors. The Houston District installed Wavetronix™ and EIS RTMS radar sensors at some freeway locations primarily for traffic monitoring during hurricane evacuation scenarios.

RESULTS OF FIELD STUDIES

As the field study sites were selected, the methodology for collecting the data at each site was refined. If permanently installed ITS devices were available at the study site, the data collected by the devices were utilized. In cases where no ITS devices were present, either portable data collection devices or manual counts were completed at each study site to estimate the capacity of each work zone. While the technique for collecting the data at each site is important from a research project management viewpoint, the work zone configuration is of primary importance. Table 2 identifies the field sites in terms of the configuration of the work zone as related to the number of closed lanes to total number of freeway lanes. Table 2 also presents the estimated capacity of each study site based upon the field data collection and the maximum observed volume throughput of the work zone. Only data collected when congestion (i.e., presence of queued vehicles) was observed within or on the approach to the closure were considered as "valid data" for capacity estimation. Appendix A provides details on the location and specific characteristics of each field study. In addition to the traffic studies, the characteristics of each work zone in terms of the type of closure, length of closures, and other observational data were documented. This information was needed for use in modeling selected field sites.

Table 2. Summary of Maximum Work Zone Volumes.

Work Zone Configuration (total lanes - open lanes)	City	Description of Site Location	Maximum Observed Volume (vph/hr)
3 – 1	Houston	1) IH 610 North Loop Eastbound near Liberty Road–two inside lanes closed in "moving" work zone	1,160
2 – 1	Orange	2) IH 10 near US 90–left lane closed	1,650
2 – 1	Orange	3) IH 10 near US 90–right lane closed	1,690
2 – 1	San Antonio	4) IH 37 near IH 410–left lane closed	1,620
2 – 1	San Antonio	5) IH 37 near IH 410–right lane closed	1,680
3 – 2	Pearland	6) SH 288–at Sims Bayou–one lane closed	1,510
3 – 2	Pearland	7) SH 288–at Sims Bayou–one lane closed	1,670
3 – 2	Pearland	8) SH 288–at Sims Bayou–one lane closed	1,740
3 – 2	San Antonio	9) IH 35 North of George Beach–left lane closed	1,700
3 – 2	San Antonio	10) IH 35 North of George Beach–left lane closed	1,740
3 – 2	San Antonio	11) IH 35 near Zarzamora Street–right lane closed	1,680
3 – 2	San Antonio	12) IH 410 near IH 10–right lane closed	1,640
4 – 3	Houston	13) IH 45 Southbound at West Little York–right lane closed for CCTV maintenance	1,750
3 – 1	Houston	14) US 290 Eastbound at Gessner–nighttime only short-term closure – two lanes closed	1,380
3 – 1	Houston	15) US 290 Westbound at Jones Road–nighttime only short-term closure – two lanes closed	1,340
3 – 2	San Antonio	16) IH 35 Southbound at Splashtown–one left lane closed	1,270
5 – 1	San Antonio	17) IH 410 at San Pedro–only right lane remaining open	1,200
3 – 3	San Antonio	18) IH 410 at Rolling Ridge–three narrow lanes, no shoulders	1,800

The initial concept of the research project was to collect data in work zones at a variety of roadway types such as freeways, multilane highways, and urban streets. However, it was determined that this project should concentrate on work zones with lane closures on freeways. While these were a large number of active work zones with lane closures, many of the scheduled closures would not result in sufficient traffic to generate a congested work zone. The presence of congestion is a necessary element to be able to estimate the traffic handling capabilities of each work zone.

Traffic data were collected downstream of the bottleneck caused by the lane closure or any other capacity reduction associated with the work zone and were used as the basis for the estimation of the work zone capacity. At selected study sites, traffic demand data upstream of the work zone were also collected to aid in estimating the road user cost impacts of the closure. In addition to traffic volume data, the travel speeds within the work zones of some locations were also collected.

The traffic volume information used for this study was collected using various methods. If the work zone was in an area monitored by TxDOT ITS devices, the data were obtained from any devices located in the work zone. Radar data from the Houston TranStar system were utilized for selected sites in the Houston urban area and the study site in Orange. The advantages of using the existing devices are that the data collection costs are minimized, there is no need to deploy personnel to the field to complete counts or deploy equipment, and the data are high quality. These sites provided volume and speed measures on a per lane basis in 30-second intervals. For selected study sites in San Antonio, similar data summarized in five-minute intervals were obtained from the TxDOT TransGuide facility.

In locations where ITS devices were not available, traffic volume data were collected by manually counting traffic through the work zone. This was completed by either sending personnel to the work zones and counting onsite, using the TTI portable data collection video trailer, or using video recorded from the Houston TranStar CCTV. The ability to access the Houston TranStar cameras was important in that this allowed TTI to collect data remotely without any impacts to roadway traffic as well as the flexibility to collect data for 24 hours per day with minimal expenses. The video was recorded within the TTI offices without any impacts to operations at Houston TranStar. The CCTV cameras were used by control room operators at Houston TranStar per a normal basis as needed. TTI reviewed the recorded work zone video and completed manual counts as needed if appropriate to the study.

CHAPTER 4. VALIDATION OF SIMULATION MODELS

There are numerous simulation models available for analyzing traffic operations within a freeway work zone. These models can be used to evaluate the impacts of the proposed lane closure as well as estimate road user costs. Although there are many models to consider, this effort concentrated on a detailed evaluation of a selected few models. The "straight-line" models studied were QUEWZ-92, HCS, MicroBENCOST, and Kim's regression model. Each of these models is classified as "linear" models as each essentially evaluates the work area as a simple straight line. "Network" models, such as QuickZone and VISSIM, are more detail oriented and can complete detailed evaluations of the work area and the lane closure impact on adjacent roadways including any designated alternate routes.

"LINEAR" MODELS

QUEWZ-92

TTI developed QUEWZ-92 for TxDOT to evaluate the impacts of freeway work zone lane closures in the early 1990s (*26*). QUEWZ-92 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. The software is a computerized version of commonly used manual techniques for estimating the queue lengths and additional road user costs resulting from work zone lane closures. It simulates traffic flows through freeway segments both with and without a work zone lane closure in place, and it estimates the changes in traffic flow characteristics and additional road user costs resulting from a lane closure whose time schedule and lane configuration are described by the model user. The road user cost which could be calculated by the package includes vehicle operating costs and travel time costs. QUEWZ-92 can also identify time schedules without causing excessive queuing under a given number of closed lanes. 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.

The input data required by QUEWZ-92 could be classified into 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:

- number of directional roadways in which lanes are closed (one or two);
- 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 could be described as: 1) the hours the lane closure begins and ends, and 2) the hours the work activity begins and ends. The hours of work activity may be the same as or different from the hours of lane closure but must be totally contained within the hours of lane closure.

QUEWZ-92 requires directional hourly traffic volumes for the traffic flow analysis. The user can provide directional hourly volumes for the period of interest or the AADT of the roadway. The most accurate form of input data would be the first one (i.e., directional hourly volumes obtained from traffic counts). QUEWZ-92 estimates the directional hourly volume from the AADT using the two sets of adjustment factors (one for urban and the other for rural), which are based on data collected in rural and urban interstates in Texas in 1985. Therefore, the estimated directional hourly volumes from the AADT reflect only the average distribution in Texas based upon 20-year old information and not the unique traffic patterns in any particular location.

QUEWZ-92 uses several default values for the model constants unless the user specifies otherwise. These default values include cost update factor, percentage of trucks, speed-volume relationship work zone capacity, and definition of excessive queuing.

The cost update factor adjusts the road user costs for the effect of inflation. All the costs computed in QUEWZ-92 are expressed in 1990 dollars. To adjust the cost to another time period, the user can modify the Cost Update Factor using the Consumer Price Index for that period. The cost update factor is calculated by the following equation:

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

The default value of cost update factor in QUEWZ-92 is 1.00. Updates of the Consumer Price Index can be found on the U.S. Department of Labor Bureau of Labor Statistics web site (*27*).

While the user is allowed to input site-specific values in the speed-volume relationship, QUEWZ-92 uses a default value of eight percent trucks.

QUEWZ-92 estimates the capacity of the work zone when work activity is present using the following equation to compute the capacity of the work zone with work activity.

$$C = (1600 + I - R) * H * N$$

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; and

N = number of open lanes through the work zone.

The output from QUEWZ-92 includes:

1) input data summary, including lane closure configuration, traffic parameters, and schedule of work activity;
2) summary of user costs, including additional road user costs for each hour of the day and for each direction;
3) summary of traffic conditions, including approach volume, capacity, approach speed, work zone speed, and average queue length during each hour of the closure; and
4) the summary of traffic volumes, including estimated volume remaining on the freeway and the volume diverting from the freeway.

The lane closure schedule indicates the hours under certain lane closure conditions in which work activity can continue without resulting in excessive queues.

Highway Capacity Software (HCS+)

The McTrans Center at the University of Florida developed the HCS+ Release 5 of the Highway Capacity Software for Windows 98/Me/NT/2000/XP. This version of the HCS implements the procedures defined in the *HCM 2000* (*1*). While HCS+ does not provide specific functions to estimate the work zone capacity, it estimates the capacity of a general freeway segment with the considerations of effects of lane width, lateral obstructions, and interchanges.

Input requirements include general freeway characteristics and traffic characteristics. Generally, freeway characteristics are used to estimate capacities, and traffic characteristics are used to estimate the travel speeds and delays.

HCS+ provides for a level-of-service (LOS) measure and service volume table The LOS result consists of estimates of traffic conditions (i.e., volumes, capacities, speeds, density, and LOS for each target segment). Regarding the service volume table, the output includes three summary sections: 1) peak hour volume peak direction; 2) peak hour volume both directions; and 3) AADT summary.

Kim's Multiple Regression Model

Kim et al. (*8*) developed a multiple regression model as a simple method for establishing a functional relationship between work zone capacity and several key independent factors such as the number of closed lanes, the proportion of heavy vehicles, and intensity of work activity. This model was developed using data collected at 12 work zone sites with lane closures on four normal lanes in one direction, mainly after the peak-hour during the daylight and night.

Kim's model evaluated a lot of factors affecting the work zone capacities, including:

- number of closed lanes,
- location of closed lanes,
- number of open lanes,
- percentage of heavy vehicle,
- driver population,
- on ramp at work,
- lateral distance,
- work zone length,
- grade,
- work zone intensity,
- work duration,
- weather,
- work time, and
- average speed.

Seven of these were identified as the independent factors and are included in the Kim's model for estimating the work zone capacity as follows:

$$CAPACITY = 1857 - 168.1NUMCL - 37.0LOCCL - 9.0HV + 92.7LD$$
$$- 34.3WL - 106.1WI_H - 2.3WG * HV$$

where,

$NUMCL$: number of closed lanes;

$LOCCL$: location of closed lanes (right = 1, otherwise = 0);

HV: percentage of heavy vehicles;

LD: lateral distance to the open lanes;

WL: work zone length;

WI_H: work zone intensity; and

WG: work zone grade.

MicroBENCOST

MicroBENCOST was developed in the early 1990s through the National Cooperative Highway Research Program as a comprehensive and convenient framework for doing highway user benefit-cost analysis on personal computers.

This DOS-based computer program can be used to analyze work zones and incidents in conjunction with seven different project types. MicroBENCOST allows up to a total of three work zones on any route to evaluate the impact of lane closings and reduced capacity at the route segment.

The required inputs for work zone analysis include:

- area type (rural or urban);
- total lanes;
- open lanes;
- work zone length;
- lane closure begins;
- lane closure ends;
- heavy vehicle;
- access control (full, partial, none);
- hourly volume/AADT;

- grade;
- curvature;
- lane width;
- shoulder width;
- design speed; and
- normal roadway capacity.

MicroBENCOST calculates discomfort costs resulting from three sources: vehicle stopping, congestion, and rough pavement. The program uses speed and volume-capacity-ratio relationships for rural highways and incident and work zone delays based on simple queuing concepts. Model outputs include speed, service volume values, and operating costs based upon time, vehicle operation, and crash costs.

“NETWORK” MODELS

QuickZone

QuickZone, jointly developed by the Office of Research, Development, and Technology in the FHWA and Mitretek Systems, is a software that estimates user delays in work zones. This software package can evaluate the traffic impacts for work zone mitigation strategies and estimates the costs, traffic delays, and potential backups associated with these impacts.

The software provides information in a spreadsheet form and can accommodate networks with up to 100 nodes and 200 links. The user would enter data on the planned work zone such as location, projected detour routes, anticipated traffic volumes, and construction dates and times. The program then displays the amount of delay in vehicle hours, the maximum length of the project traffic queue, and the costs associated with the work zone activity.

While the software is easy to use and is in spreadsheet form, it does require a significant amount of data to accurately model the roadway system. As QuickZone is a network flow model that analyzes individual segments in specified time steps, the software relies on a network composed of links and nodes. Hourly and daily demand patterns are needed to populate the links with traffic flow. If hourly volumes are not available, QuickZone can estimate these values using HCM procedures. QuickZone is very flexible in terms of input parameters and the open-source software product allows users to modify and customize to fit local conditions as desired.

VISSIM

VISSIM is a microscopic, behavior-based, multi-modal traffic simulation model. It was developed by PTV AG in Karlsruhe, Germany and has also been widely used in the United States. It is capable of modeling traffic and public transport operations in a network integrating street and freeway systems. The program can analyze traffic operations under constraints such as different lane configurations, traffic compositions, and traffic signals, thus making it a useful tool for the evaluation of various traffic control alternatives based on measures of effectiveness such as delay, queue length, and throughput.

One of the unique features of VISSIM is the Vehicle Actuated Programming (VAP) Language Module. It allows the user to externally control vehicle detection, traffic control, and driver behavior logic. The VAP Language Module makes it possible to model and evaluate the effectiveness of various ITS applications, such as variable message signs, traffic diversion, and various work zone traffic control strategies.

With its Dynamic Assignment model, VISSIM can also answer route choice dependent questions such as the impacts of work zone or incident related congestions. This feature may be useful to study the regional impact of a single or multiple road construction projects on a complex freeway arterial network.

VISSIM has an optional vehicle emission module that can be used to estimate vehicle emissions produced as a function of the vehicle's operating mode. The model can predict second by second emissions for HC, CO, NOx, and CO2 and fuel consumption for a range of vehicle categories. Thus, it can be used to estimate the environmental impact of work zones under various traffic conditions.

VISSIM requires very detailed information on network geometry, traffic demand, vehicle composition, and traffic control. Setup of the simulation network and calibration of the model is a fairly complex task that requires personnel with significant experience of the system. Therefore, this model may be more applicable as a planning tool to estimate the regional impact of some very complex road construction projects on a large freeway-arterial network.

Also, there are several features of VISSIM that limit its ability to faithfully and easily model traffic operations through work zones. For example, it is possible to define different lane width for each lane within a link, but the narrower lanes do not automatically influence vehicle free flow speeds. Therefore they do not have an effect on lane capacity.

CA4PRS

One of the more recent innovations developed in California is the Construction Analysis for Pavement Rehabilitation Strategies (CA4PRS) software. This is a schedule and traffic analysis decision-support tool to help transportation agencies select more efficient and economical rehabilitation strategies. CA4PRS is beneficial when utilized during the planning and design stages to evaluate different scenarios to balance construction scheduling, traffic delay costs, and project costs. While the software was not available for extensive evaluation in this research project, the FHWA endorsed the product in 2008 for nationwide deployment. The most appropriate use of this product, which was developed specifically for rehabilitation projects, begins during the initial stages of project development. CA4PRS can aid agencies in estimating working days and CPM schedules, developing construction staging plans, traffic control plan design, and identifying incentive and cost (A) + time (B) contracts.

COMPARISON OF MODEL OUTPUTS

Each of the four "linear" models were compared in terms of capacity estimation output validation. Using the inputs for the typical work zones where field data were collected for this research study, each model (QUEWZ-92, HCS+, MicroBENCOST, and Kim's model) was evaluated for 12 sites.

Appendix B includes the inputs as used for each model and their default values. Although users can modify the default values according to individual work zone needs, the default values in each model were not changed for this comparison. After reviewing the input requirements of each of the four models, some unique characteristics are summarized as follows.

- Only Kim's model distinguished the difference between left and right lane closure.
- HCS+ and MicroBENCOST distinguished differences of rural and urban work zones. Although QUEWZ-92 has the same input requirement, it is used to transfer the AADT to hourly volume and then to estimate the road user cost, not the capacity.
- Only Kim's model and MicroBENCOST considered the impacts of lateral distance on work zone capacity.
- Kim's model and QUEWZ-92 considered the work activity as a factor affecting the work zone capacity, while MicroBENCOST does not include work activity schedule as inputs.

- While HCS+ does not have a direct function to estimate work zone capacity, it was used to estimate work zone capacity in this study by assigning the posted speed to match the observed speed at which the maximum traffic volume was found.

The capacities estimated by each model were compared with the observed maximum volume from the field studies. Table 3 presents the comparison summary among the four models. According to the comparison results, the capacity values estimated by HCS+ are generally larger than those estimated by QUEWZ, Kim's, and MicroBENCOST model. The performance of each model is summarized as follows.

- For a work zone located in rural area, QUEWZ-92 is likely to overestimate the work zone capacity, while more likely to underestimate the capacity in an urban setting.
- The HCS+ model is more likely to overestimate work zone capacity. It is based upon the observation that HCS+ overestimated the capacity of 11 of the 12 work zone sites reviewed.
- Kim's model is expected to underestimate the capacity of urban work zones.
- MicroBENCOST (MB) is more likely to underestimate the work zone capacity in both rural or urban areas; it underestimated 11 of the 12 work zone sites.

Table 3. Capacity Comparison.

Work Zone	Type	Configuration	Observed	QUEWZ	Diff	HCS+	Diff	Kim's	Diff	MB	Diff
1	R	2-1	1652	1800	8.96%	1710	3.51%	1627	-1.51%	1554	-5.93%
2	U	3-1	1694	1545	-8.80%	1862	9.92%	1461	-13.75%	1556	-8.15%
3	R	3-1	1742	1800	3.33%	1719	-1.32%	1722	-1.15%	1563	-10.28%
4	R	3-1	1519	1556	2.44%	1719	13.17%	1694	11.52%	1563	2.90%
5	R	3-1	1678	1800	7.27%	1719	2.44%	1615	-3.75%	1563	-6.85%
6	U	2-1	1625	1447	-10.95%	1776	9.29%	1453	-10.58%	1470	-9.54%
7	U	2-1	1683	1447	-14.02%	1776	5.53%	1416	-15.86%	1470	-12.66%
8	U	3-1	1704	1485	-12.85%	1809	6.16%	1486	-12.79%	1526	-10.45%
9	U	3-1	1741	1485	-14.70%	1809	3.91%	1465	-15.85%	1503	-13.67%
10	U	4-1	1686	1567	-7.06%	1941	15.12%	1467	-12.99%	1586	-5.93%
11	U	4-1	1755	1535	-12.54%	1913	9.00%	1574	-10.31%	1565	-10.83%
12	U	3-1	1640	1545	-5.79%	1862	13.54%	1467	-10.55%	1556	-5.12%

In summary, it is noted that for the work zone located in urban area, QUEWZ-92, Kim's model, and MicroBENCOST are all likely to underestimate the field-measured capacity. The mean of the estimation of the three models are: -10.8% (SD=3.29%); -12.8% (SD=2.26%); and -9.5% (SD=3.02%). Kim's model has the least standard deviation. To compare the estimation errors of different models, an analysis of variance (ANOVA) was conducted. The ANOVA tests whether or not the mean estimation error are the same among the three models:

$$H_0: \quad \mu_1 = \mu_2 = \mu_3$$

$$H_a: \quad \text{not all } \mu_i \text{ are equal}$$

where,

μ_i are the mean estimation errors of each model. The ANOVA had a P-value of 0.13 indicating that the differences in mean estimation errors of the three models are not statistically significant at the 95% confidence level.

Regarding the work zones located in rural areas, the mean of the estimation of the three models are 5.5%, 1.3%, and -5.0%. Similarly, an ANOVA was performed to test whether or not the mean estimation error are the same among the three models. The P-value of ANOVA was 0.046 indicating that the differences in the mean estimation errors of the three models are statistically significant at the 95% confidence level.

In comparing the field study sites by area type, Kim’s model generates the least RMS error for rural areas. Considering the urban area sites, the HCS+ model has the least RMS error of the eight work zone sites.

CHAPTER 5. ROAD USER COST ANALYSIS

Additional travel time and delays in work zones can be expressed as time costs and additional fuel expenses incurred on the traveling public. This study also served to evaluate road user costs as outputs from model simulation. Software packages evaluated in this study are classified as planning level (high level) and operation level. The planning level packages include Jiang's model, QUEWZ-92, and MicroBENCOST, while the operation level package refers to VISSIM. Generally speaking, the operation level package could more accurately simulate the drivers' behaviors such as merge, vehicle stop, acceleration, and deceleration, and therefore may generate a more accurate estimation of construction-related user costs. For contrast, the planning packages are easier to use than its operation counterpart. For this purpose, VISSIM was selected as the baseline to estimate the road user cost based on the field data and then compared with the results yielded from each of the three planning level packages using the same input for traffic demands and work zone configurations.

Four of the field study sites in San Antonio, two on IH 35 and two on IH 37, were modeled in VISSIM with the appropriate model configuration based on the real-world data. The four sites selected for the RUC analysis each had the additional data needed to complete a detailed analysis for the RUC comparison among the models. Each of the work zones will be depicted by the VISSIM model to establish the base condition to provide a valid comparison for Jiang's model, QUEWZ-92, and MicroBENCOST.

Jiang (*5*) concluded that the traffic delays in a work zone should include the delays caused by vehicle deceleration when approaching the work zone, reduced vehicle speed through the work zone, time needed for vehicles to resume freeway speed after exiting the work zone, and any vehicle queues encountered within the work zone. Vehicle queues occur when traffic flow is higher than the traffic capacity of the work zone. Because of the randomness of traffic flow, vehicle queues may also form even when traffic flow is below the work zone capacity. Based on the above theory, Jiang developed an analytical method to estimate the road user delay cost for Indiana DOT, which is briefly introduced in the following.

When approaching a work zone on a freeway, a vehicle gradually reduces speed from the freeway speed v_f to the work zone speed v_z over a deceleration distance (s). The equation for deceleration delay was obtained as:

$$d_d = \frac{s}{v_f + v_z} - \frac{s}{v_f}$$

The deceleration delay cost of hour i can then be calculated by multiplying d_d with related traffic flow rates and unit costs of time for given types of vehicles.

$$C_{di} = d_d \cdot F_{ai}(P_c \cdot U_c + P_t \cdot U_t)$$

where,

C_{di} = deceleration cost of hour I;

d_d = deceleration delay per vehicle (hr);

F_{ai} = approach traffic flow rate of hour i;

P_c = percentage of cars;

U_c = unit cost of time for cars;

P_t = percentage of trucks; and

U_t = unit cost of time for trucks.

Due to the existence of work zone and work activities, vehicles in the work zone area are usually traveling at a reduced speed. The traffic delay due to reduced speed at a work zone of length L is defined as following:

$$d_z = L(\frac{1}{v_z} - \frac{1}{v_f})$$

Similarly, the delay cost of hour i due to reduced speed at a work zone is:

$$C_{zi} = d_z \cdot F_{ai}(P_c \cdot U_c + P_t \cdot U_t)$$

After exiting a work zone, a vehicle typically accelerates from the work zone speed to the freeway speed. Assuming a constant acceleration rate a, the delay for the vehicle to accelerate to the freeway speed is:

$$d_a = \frac{(v_f - v_z)^2}{2av_f}$$

The delay cost of hour i due to reduced speed at a work zone is:

$$C_{ai} = d_a \cdot F_{ai}(P_c \cdot U_c + P_t \cdot U_t)$$

Calculations of vehicle queues are different for traffic flow rate below the capacity and for traffic flow rate above the capacity. Therefore, the calculations of the corresponding delay costs are also different. When traffic rate is less than the work zone capacity, vehicle queues may form because of the stochastic nature of traffic flows. Using the hourly flow rates, F_{ai} for the arrival traffic flow rate of hour i and F_d for the departure traffic flow rate, the average waiting time can be written as:

$$d_w = \frac{F_{ai}}{F_d(F_d - F_{ai})}$$

$$C_{wi} = d_w \cdot F_{ai}(P_c \cdot U_c + P_t \cdot U_t)$$

Traffic congestion occurs with the formation of vehicle queues when the traffic flow rate exceeds the work zone capacity. If traffic congestion started at hour 1 and ended during hour I, then the equation of traffic delay for hour i = 1, 2, 3,…I-1 is:

$$D_i = Q_{i-1} + \frac{1}{2}(F_{ai} - F_d)$$

The traffic delay for hour i=I is:

$$D_I = \frac{Q_{I-1}^2}{2(F_d - F_{aI})}$$

The corresponding cost is:

$$C_{qi} = D_i(P_c \cdot U_c + P_t \cdot U_t)$$

The total hourly excess user cost at the work zone for each direction is the sum of these individual user costs. Consequently, the equation for total hourly road user cost associated with work zone is thus:

$$C_{total} = C_{di} + C_{zi} + C_{ai} + C_{wi} + C_{qi}$$

Although MicroBENCOST can estimate road user cost in terms of travel time delay, it was designed to evaluate the long term roadway project and not short-term work zones. The cost estimation output from MicroBENCOST represents an annual total. Compared with the other three models which provide hourly road user cost, MicroBENCOST may not be suitable for estimating RUC in individual work zones. However, it could offer insight into long-term impacts of extended time period work zone deployment.

As MicroBENCOST may not provide for a similar comparison, the road user cost generated from VISSIM, Jiang's model, and QUEWZ-92 only were compared. The VISSIM model output was used as the baseline to compare the performance of the other two models. It should be noted that the output of VISSIM and Jiang's model are travel time cost in terms of hour, while the output of QUEWZ-92 are in terms of dollars. Therefore, the output of VISSIM and Jiang's model were converted into a dollar value for comparison purposes. In QUEWZ-92, the dollar value of time is \$12.64 per vehicle hour for passenger cars and \$23.09 per vehicle hour for trucks in 1990 dollars. In this study, the dollar value of time was updated to 2007 dollars using the Consumer Price Index (CPI) index. In 1990, the CPI value was 130.70; while in 2007, it was 207.24. Therefore, an update factor of 1.59 was used to convert the QUEWZ-92 user costs to 2007 values.

Table 4 provides for a comparison of these models in regards to RUC estimations for four work zones in San Antonio. Appendix C includes the details of these results. Comparing a 24-hour analysis of the IH 35 northbound study site, the RUC as estimated by VISSIM and Jiang's model is almost twice as high as the RUC provided by QUEWZ-92. In all instances, QUEWZ-92 estimates the RUC value more than the VISSIM base model. In each of these four instances, a statistical review indicates that the Jiang's model generates much less RMS error and therefore performs better than QUEWZ-92.

Table 4. Comparison of Road User Costs for San Antonio Work Zones.

Work Zone – Time Period	Estimated Road User Costs (dollars)		
	VISSIM	Jiang's Model	QUEWZ-92
A. IH 35 Northbound – 24 hours	\$17,150	\$17,050	\$8,710
B. IH 35 Southbound – 5 hours	\$2,840	\$2,830	\$1,370
C. IH 37 Left Lane Closed – 2 hours	\$11,050	\$11,570	\$9,240
D. IH 37 Left Lane Closed – 2 hours	\$7,760	\$6,840	\$6,320

CHAPTER 6. EMISSIONS IN WORK ZONES

As travel speed decreases in a work zone, there may be an impact on emissions when compared to normal operating conditions along the freeway. While none of the simple models used to estimate road user costs can provide predicted emissions values, the VISSIM model is ideal for this purpose as it is a microscopic package and models individual vehicles. While the most time consuming task will be to build the network and scenarios for the work zone, the user only needs to activate the emission function for each desired link in the model.

In order to illustrate how an emission analysis would be completed, the work zone on IH 35 in San Antonio was modeled. The model was designed to compare emission particulates in three segments: approaching the work zone, within the work zone, and after the work zone. Figure 7 illustrates the impacts of the work zone on emissions comparing normal conditions with the same section. This shows the increased levels of particulate emissions throughout the day as traffic volumes increase within the study site. For a typical 24-hour weekday time period, this real-world example results in an approximate 40 percent increase in particulate emissions as predicted by VISSIM.

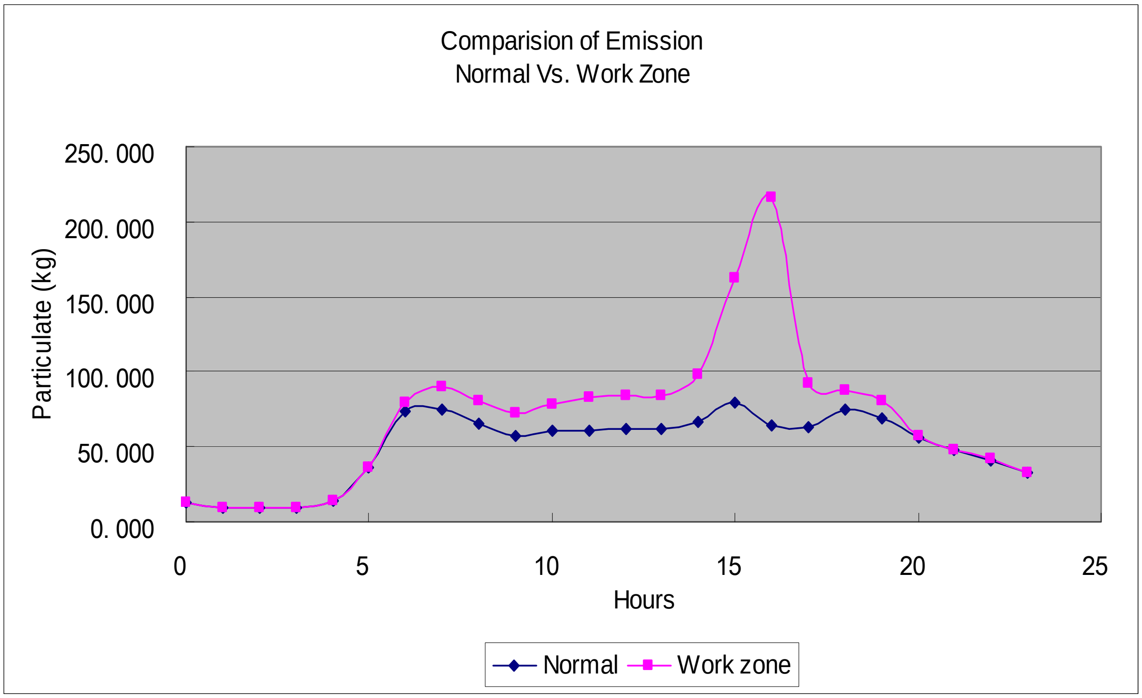

Figure 7. Total Emission for Both Normal and Work Zone Condition.

CHAPTER 7. FINDINGS AND RECOMMENDATIONS

This research project served to address questions concerning capacities in work zones along Texas freeways as well as provide TxDOT with insight regarding available software packages for work zone analysis and road user cost estimation. Project findings and recommendations from the authors are as follows.

- For roadway capacities in work zone:
    - Roadway capacity is reduced by about 20 percent within a work zone.
    - The configuration of the work zone (i.e., number of lanes open versus lanes closed) does not have a significant impact on the per lane capacity in the work zone.
    - As the level of work activity increases, the capacity within work zones can decrease.
    - For work zone planning purposes, the per lane capacity values as presented in Table 2 should be used as guidance in determining impacts of lane closures in work zone traffic.
- For software to model lane closure:
    - While the QUEWZ-92 model tended to underestimate the work zone capacity, its performance was not much worse than the other models reviewed for “linear” modeling. However, should TxDOT decide to use it on a statewide basis, it should be updated to a Windows environment operating system.
    - In cases of a more complex “linear” work zone requiring more robust analysis, Kim’s model should be used. Although it is a series of equations, these could be combined into a more user friendly spreadsheet product for implementation.
    - For projects in which the analysis of adjacent detour routes is necessary, it is recommended that QuickZone be used for a comprehensive network impact analysis.
    - When planning and designing long-term pavement rehabilitation projects, TxDOT should consider using the CA4PRS product as a decision-support tool to reduce highway construction time and the resulting traffic impact.

- For road user cost estimations:
    - As the QUEWZ-92 program does not accurately predict road user costs, Jiang's model should be used for delay cost estimation within the work zone. However, a set of spreadsheet applications need to be developed for ease of use.
    - If TxDOT pursues upgrading the QUEWZ-92 software to the Windows operating system, that effort should include a refinement of the user cost estimation process.
    - For network wide user cost impacts, the outputs of QuickZone and CA4PRS are sufficient.
- For emission measures:
    - Emissions analysis is likely required for a limited number of projects.
    - Only the VISSIM model can provide particulate emission measures.
- For implementation:
    - TxDOT has not provided statewide training in completion of road user costs studies for construction projects since 1999.
    - Because of the federal mandate to reduce work zone delays, TxDOT should consider developing an updated training program for disseminating this information as well as hands-on use of the recommended work zone road user cost estimation packages to assure statewide consistency.

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APPENDIX A. DESCRIPTION OF FIELD STUDY SITES

Site 1 – IH 610 North Loop near Liberty Road in Houston

- Moving work zone of 3–1 closure.
- Data collected on June 6, 2008 – approximately 30-minutes of data collected from reviewing video recorded from TranStar CCTV camera.

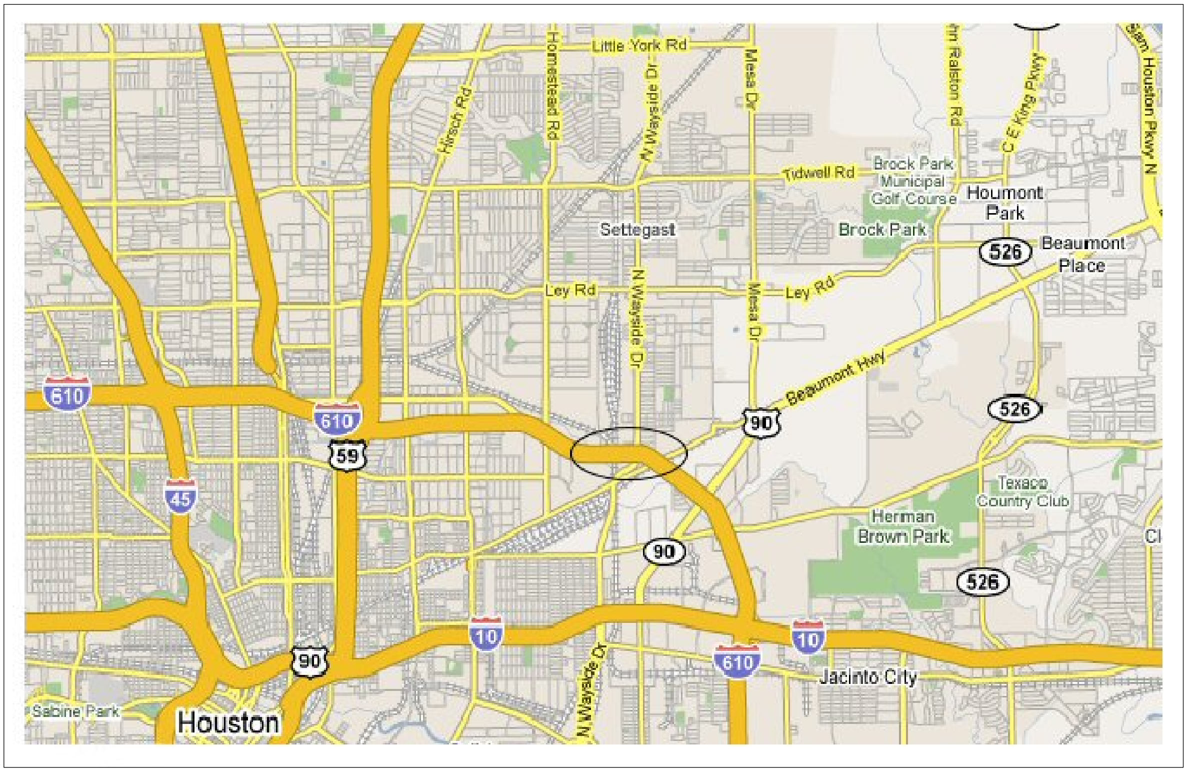

Figure A-1. Site Location for Site 1.

Figure A-2. Site 1 Work Activity.

Figure A-3 Queued Traffic Approaching Site 1.

Sites 2 and 3 – IH 10 East near US 90 in Orange

- Work zone monitored on numerous occasions in August 2007 and January 2008.
- Data collected from Houston TranStar *Wavetronix SmartSensor* located in the work zone (data provided in 30-second intervals).
- Collection of snap-shot images from CCTV used to identify time periods of lane closure and congestion.

Figure A-4. IH 10 East Work Zone near Orange.

Figure A-5. Work Zone Activity as Viewed from Houston TranStar CCTV.

Figure A-6. Drive Through View of Work Activity.

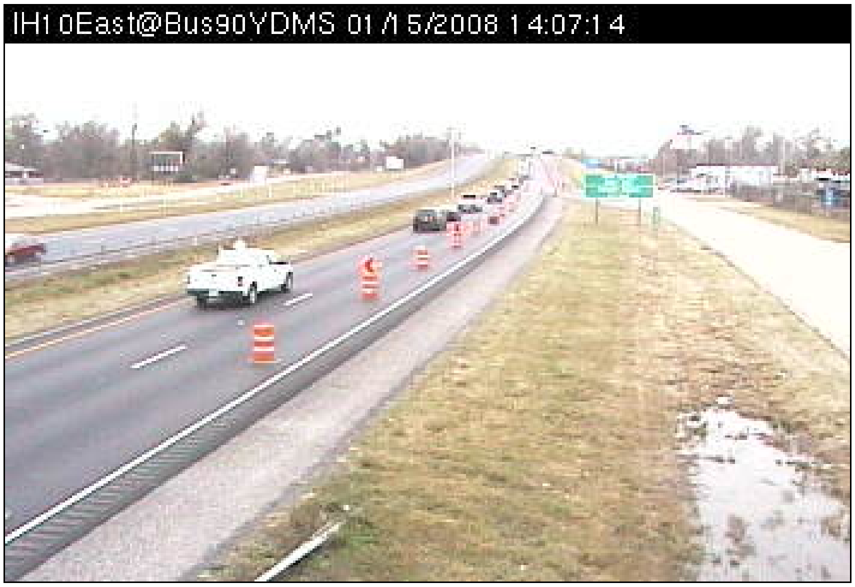

Figure A-7. Work Activity in February 2008.

Sites 4 and 5 – IH 37 near IH 410 in San Antonio

- One lane of two-lane roadway closed.
- Site 4 – left lane closed.
- Site 5 – right lane closed.

Figure A-8. Location of IH 37 Work Zone.

Figure A-9. Left Lane Closure for Site 4.

Sites 6, 7, and 8 – SH 288 at Sims Bayou in Pearland

- Work zone monitored in August 2007.
- One lane of the three-lane roadway closed in both directions to accommodate repairs to bridge structure damaged by flooding.
- Work zone had been deployed for three months prior to data collection.
- CCTV snapshots used to identify periods of congestion.
- Volume data collected using road tube counters and verified by manual counts in closure area.

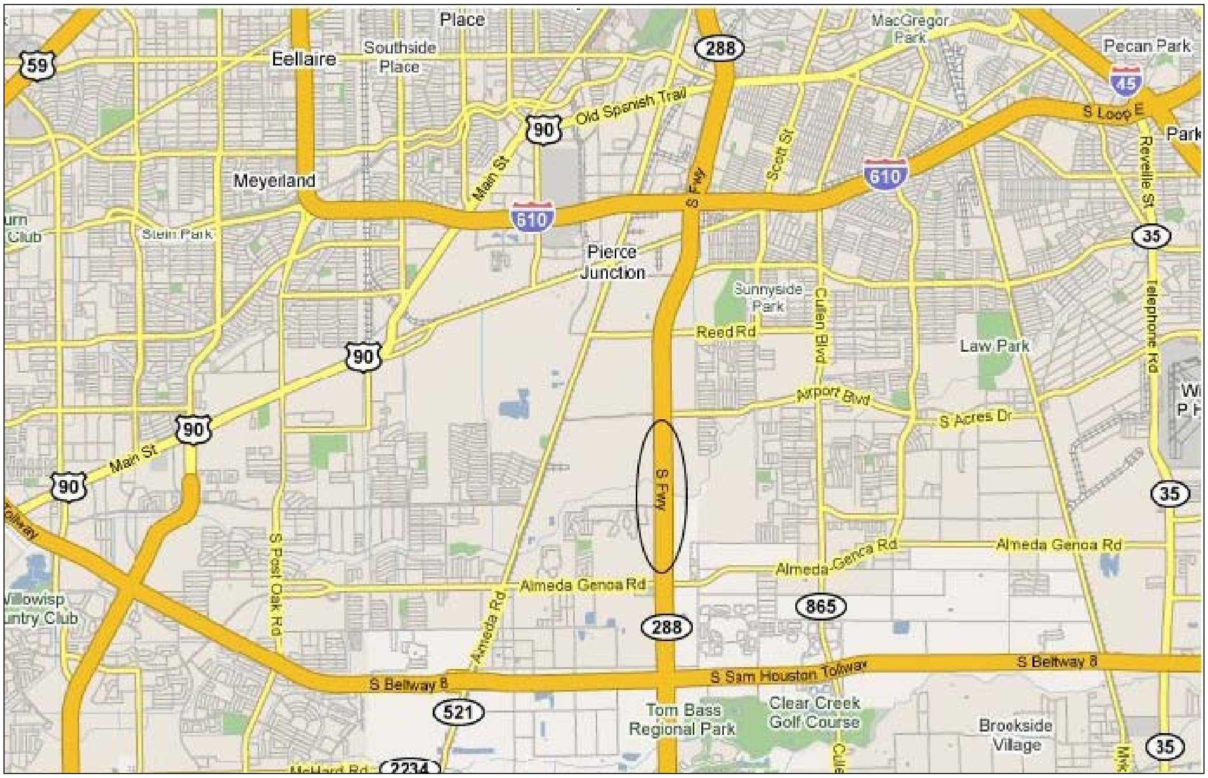

Figure A-10. Location of SH 288 Work Zone.

Figure A-11. Right Lane Closure for SH 288 Southbound; Left Lane for SH 288 Northbound.

Figure A-12. SH 288 Construction in Final Stages.

Figure A-13. Street View of SH 288 Northbound Lane Closure.

Sites 9 and 10 – IH 35 North of George Beach

- One lane of three-lane roadway closed.
- Site 9 for a northbound lane closure.
- Site 10 for a southbound lane closure.

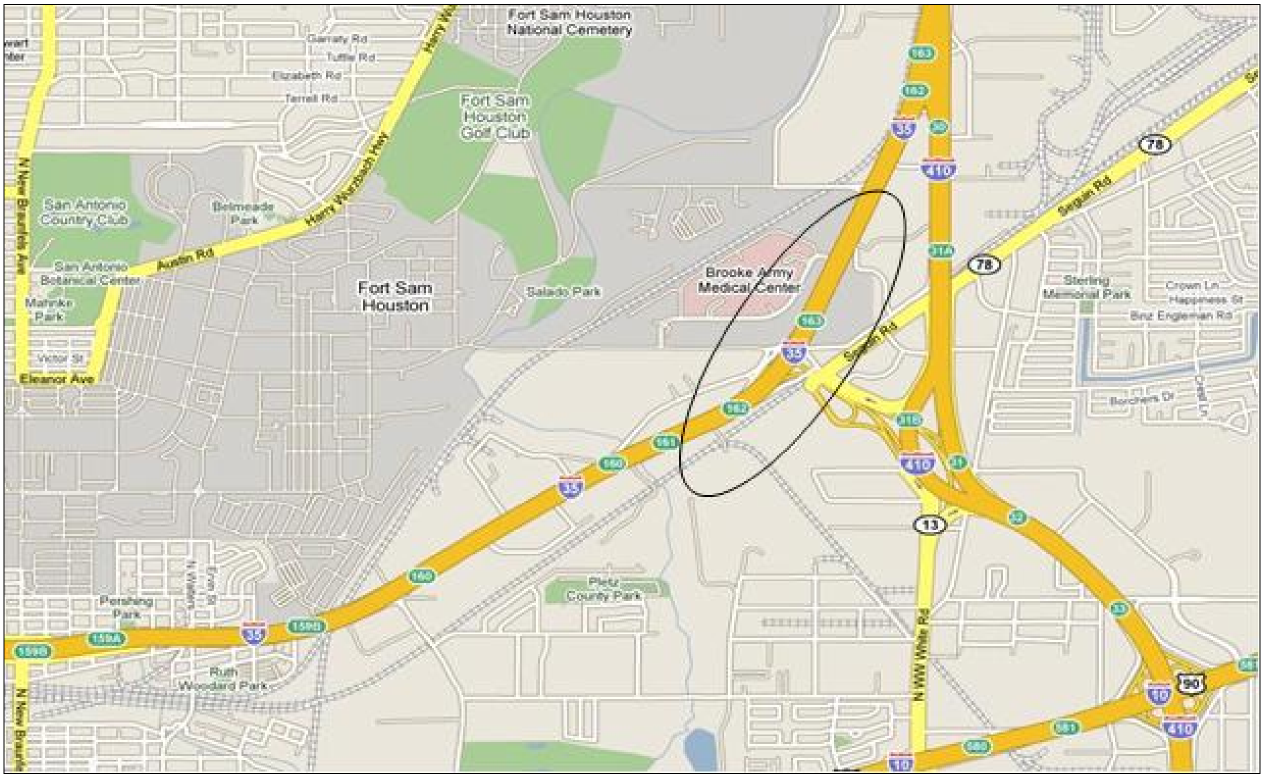

Figure A-14. Location of IH 35 Work Zone for Sites 9 and 10.

Figure A-15. Traffic Congestion in IH 35 Work Zone.

Site 13 – IH 45 North Freeway Southbound at Little York

- Data collected from manual counts of TranStar CCTV video.
- Right lane and shoulder were closed for CCTV camera maintenance.
- This was a short-term daytime only single-day closure.

Figure A-16. Work Zone Layout for Site 13.

Figure A-17. TranStar Camera View of Lane Closure.

Figure A-18. Traffic Flowing through IH 45 Work Zone.

Site 14 – US 290 Eastbound at Gessner

- Night time closure for pavement repair.
- Data collected March 20, 2008 from TranStar radar sensor.

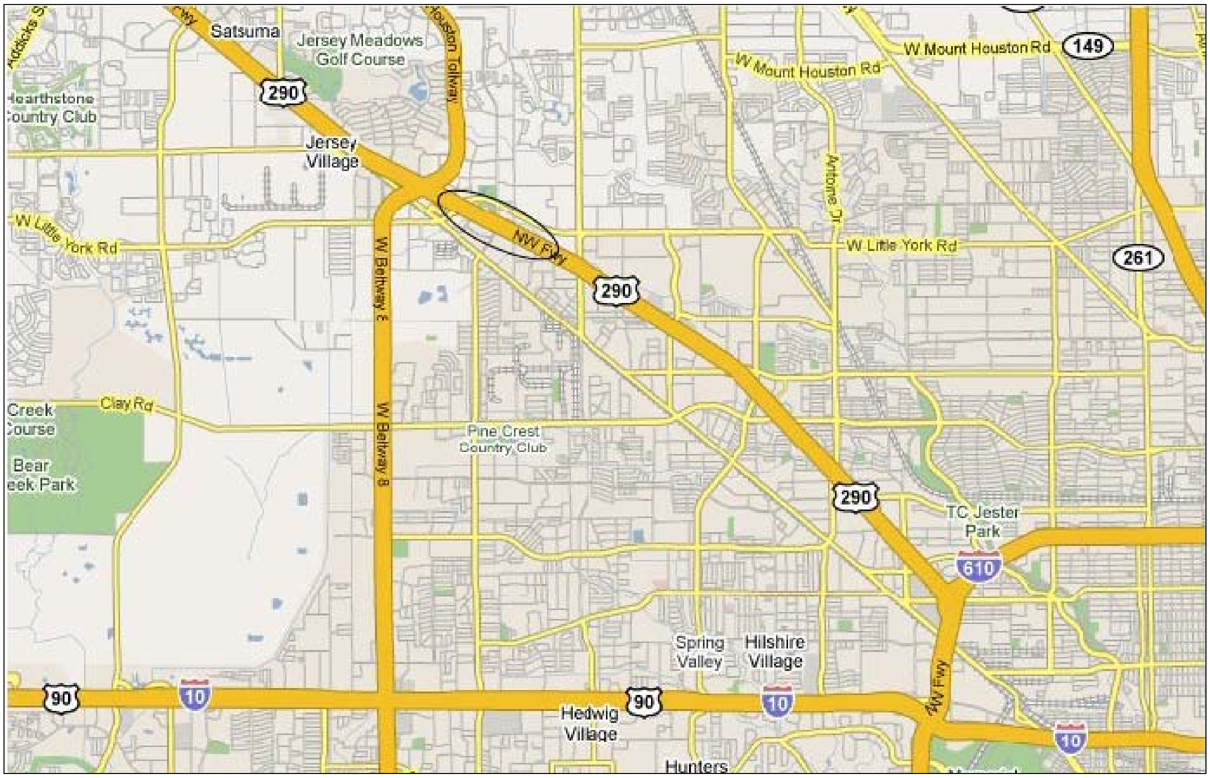

Figure A-19. Location of US 290 Eastbound at Gessner Work Zone.

Site 15 – US 290 Westbound at Jones Road

- Night time closure for pavement repair.
- Data collected May 13 and 14, 2008 by manual field counts.
- Significant portion of traffic observed to detour to freeway frontage road.

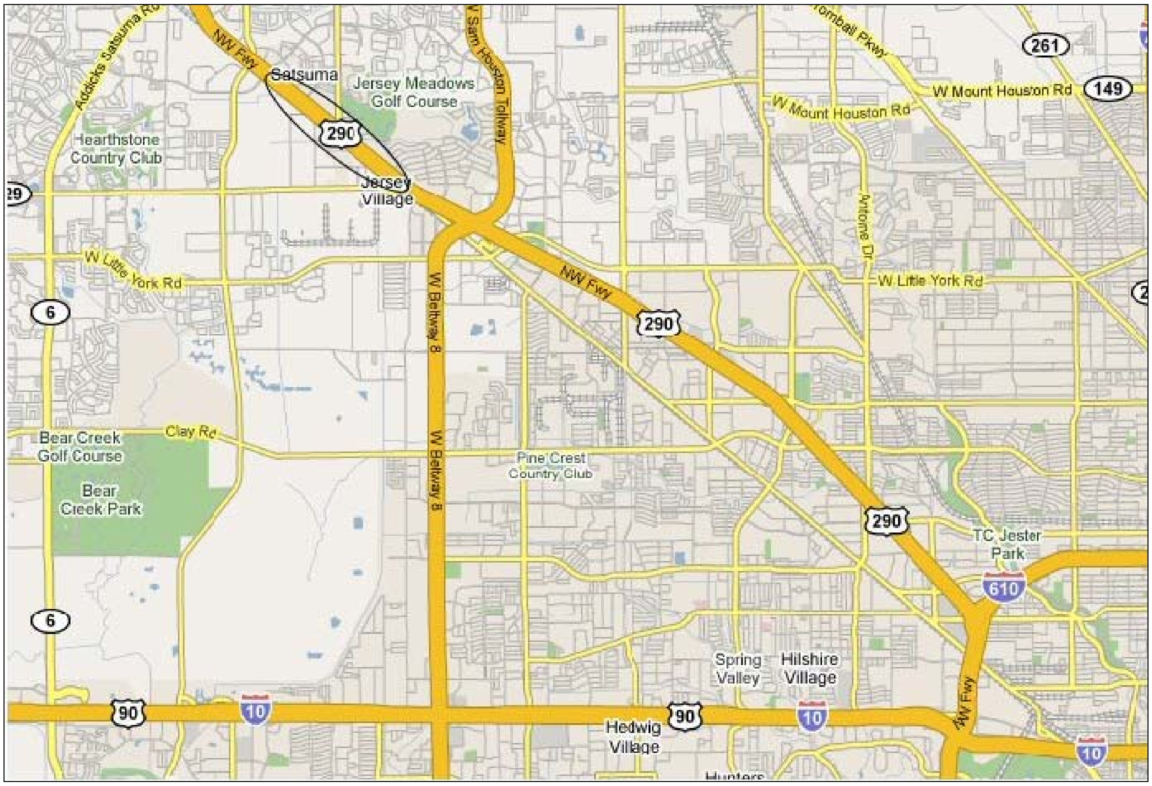

Figure A-20. Location of US 290 Westbound at Jones Road Nighttime Lane Closure.

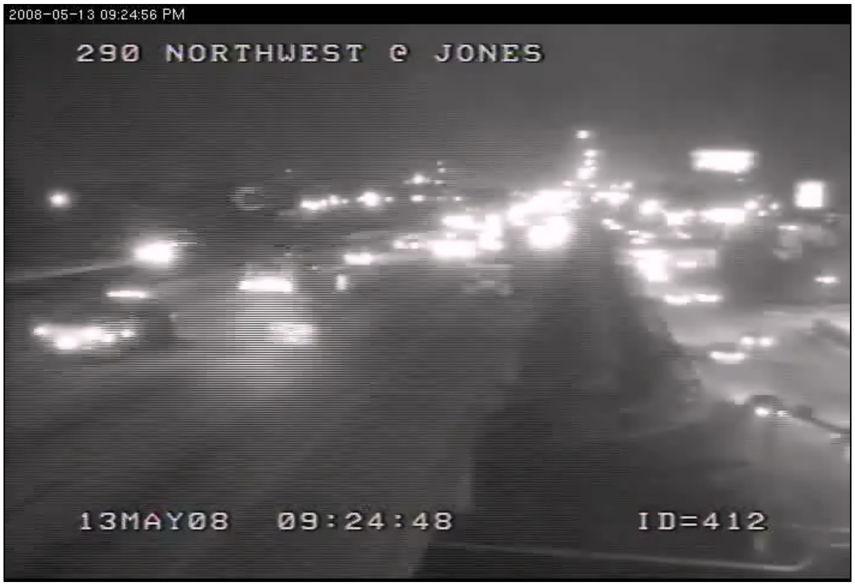

Figure A-21. TranStar CCTV Image of Lane Closure.

Figure A-22. Traffic Queuing Approaching Lane Closure.

Sites 16, 17, 18, and 19 – San Antonio, Texas

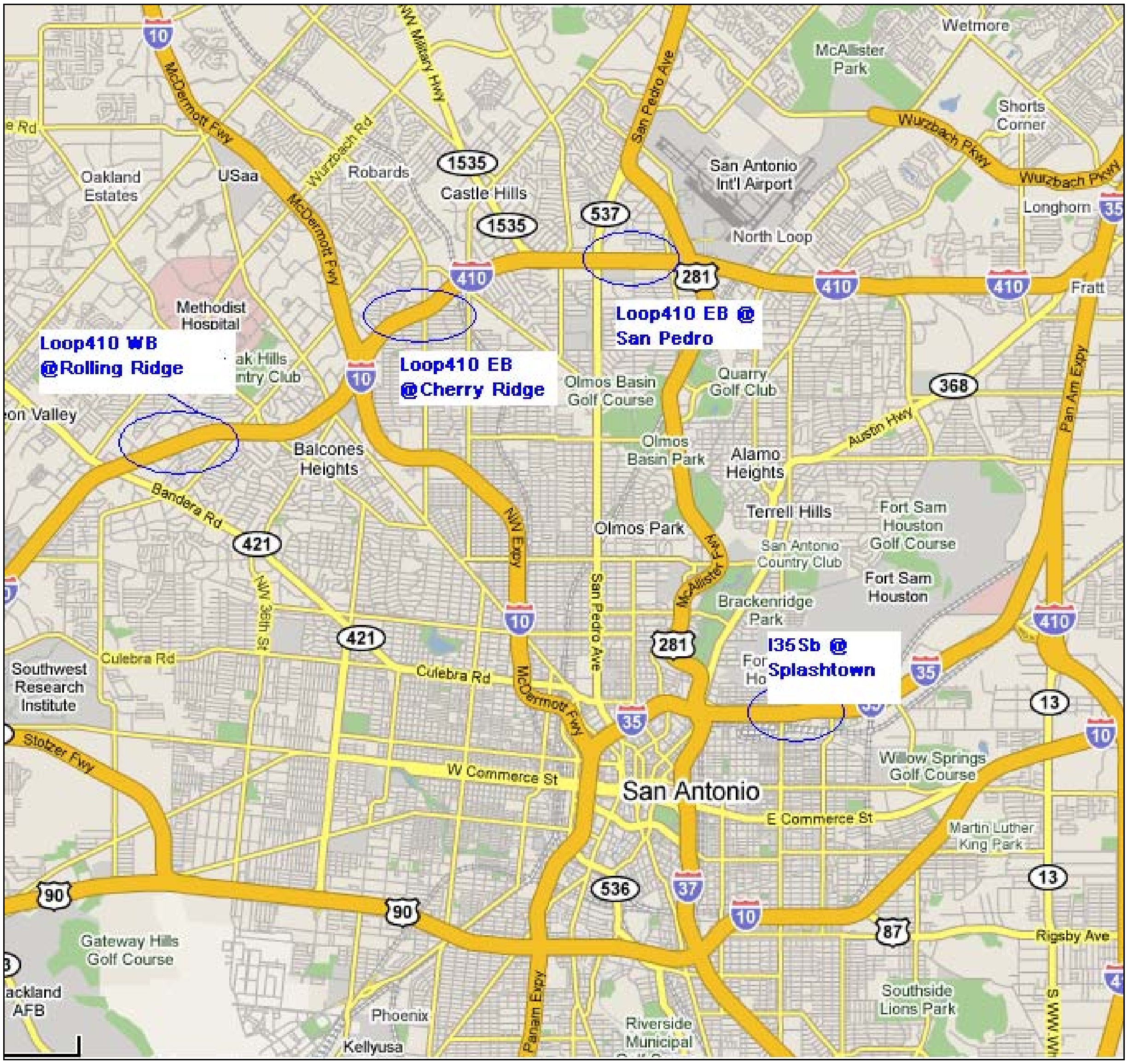

Figure A-23. Location of Study Sites in San Antonio.

Site 16 – IH 35 Southbound at Splashtown

- One left lane of three lanes closed.
- Data collected using TransGuide sensors.
- Closure data for 12:45 pm – 3:00 pm on June 25, 2008.

Site 17 – IH 410 at San Pedro

- Five-lane section narrowed down to one lane over about a mile.
- Data collected over a weekend.

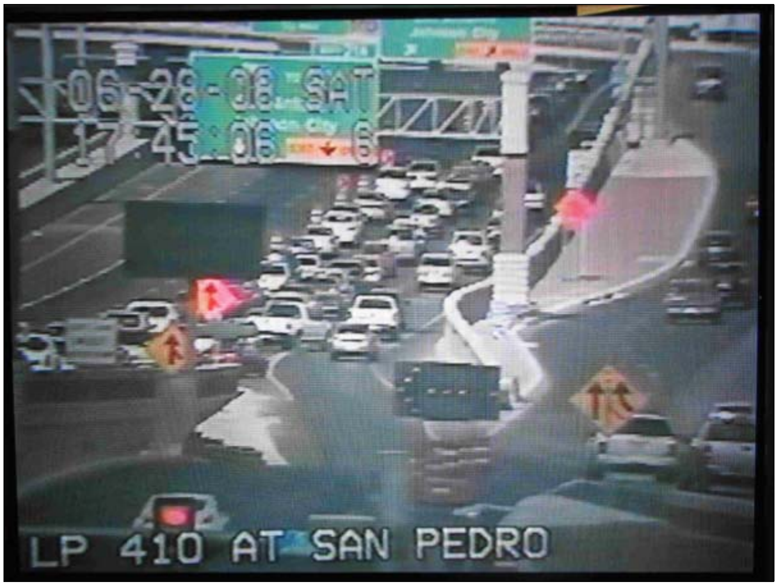

Figure A-24. Traffic Congestion at Site 17.

Site 18 – IH 410 at Rolling Ridge

- No lanes were closed.
- Three-lane section with narrow lanes, CTB adjacent to travel lane, and no shoulders.

Figure A-25. TransGuide View of Traffic at Site 18 in San Antonio.

APPENDIX B. SUMMARY OF DATA INPUT FOR MODEL VALIDATION

Table B-1. Input Values of QUEWZ-92.

QUEWZ-92	**Site**											
Input	1	2	3	4	5	6	7	8	9	10	11	12
Percentage of Truck	5	5	4	4	4	15	15	11	11	3	6	5
Total Lanes	2	3	3	3	3	2	2	3	3	4	4	3
Open Lanes	1	2	2	2	2	1	1	2	2	3	3	2
Length of Lane Closure	0.5	3.0	0.3	0.3	0.3	1.2	1.2	1.3	1.9	1.5	0.3	1.0
Lane Closure Begins	6	0	0	0	6	9	12	0	9	0	9	0
Lane Closure Ends	14	24	24	24	20	11	14	24	14	24	12	24
Work Activity Begins	-	12	-	8	-	9	12	9	9	17	9	7
Work Activity Ends	-	16	-	19	-	11	14	16	14	18	12	8
Hourly Volume/ AADT	AADT	AADT	AADT	AADT	AADT	Volume	Volume	Volume	Volume	AADT	AADT	AADT
Free Flow Speed	60	60	60	60	60	60	60	60	60	60	60	60
Breakpoint Speed	46	46	46	46	46	46	46	46	46	46	46	46
Speed at Capacity	30	30	30	30	30	30	30	30	30	30	30	30
LOS Breakpoint Speed	1850	1850	1850	1850	1850	1850	1850	1850	1850	1850	1850	1850
Volume at Capacity	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000	2000

Table B-2. Input Values of HCS+.

HCS+	**Site**											
Input	1	2	3	4	5	6	7	8	9	10	11	12
Area Type	R	U	R	R	R	U	U	U	U	U	U	U
Class	1	3	1	1	1	3	3	3	3	3	3	3
Posted Speed (mph)	50	50	50	50	50	50	50	50	50	50	50	50
Heavy Vehicle	5	5	4	4	4	15	15	11	11	3	6	5
Number of Lanes	2	2	2	2	2	2	2	2	2	3	3	2
K Factor	0.104	0.097	0.104	0.104	0.104	0.097	0.097	0.097	0.097	0.097	0.097	0.104
D Factor	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55	0.55
Peak Hour Factor	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95	0.95
Local Adjustment Factor	0.9	0.98	0.9	0.9	0.9	0.98	0.98	0.98	0.98	0.98	0.98	0.9

Table B-3. Input Values of MicroBENCOST.

MicroBENCOST	**Site**											
Input	1	2	3	4	5	6	7	8	9	10	11	12
Area Type	R	U	R	R	R	U	U	U	U	U	U	U
Total Lanes	2	3	3	3	3	2	2	3	3	4	4	3
Open Lanes	1	2	2	2	2	1	1	2	2	3	3	2
Work zone Length	0.5	3.0	0.3	0.3	0.3	1.2	1.2	1.3	1.9	1.5	0.3	1.0
Lane Closure Begins	6	0	0	0	6	9	12	0	9	0	9	0
Lane Closure Ends	14	24	24	24	20	11	14	24	14	24	12	24
Heavy Vehicle	5	5	4	4	4	15	15	11	11	3	6	5
Access Control	None	Full	None	None	None	Full	Full	Full	Full	Full	Full	Full
Hourly Volume/ AADT	AADT	AADT	AADT	AADT	AADT	Volume	Volume	Volume	Volume	AADT	AADT	AADT
Curvature	0	0	0	0	0	0	0	0	0	0	0	0
Lane Width	12	12	12	12	12	12	12	12	12	12	12	12
Shoulder Width	10	10	10	10	10	10	10	10	10	10	10	10
Design Speed	70	65	70	70	70	65	65	65	65	65	65	65
Capacity	1953	1936	1942	1942	1942	1838	1838	1878	1878	1968	1956	1936

Table B-4. Input Values of Kim's Model.

Kim's Model	**Site**											
Input	1	2	3	4	5	6	7	8	9	10	11	12
Number of Closed Lanes	1	1	1	1	1	1	1	1	1	1	1	1
Location of Closed Lanes	0	1	0	0	0	0	1	0	0	1	1	1
Percentage of Heavy Vehicles	5	5	4	4	4	15	15	11	11	3	6	5
Lateral Distance	0	0.5	1	1	1	0.5	0.5	0.5	0.5	0	1	0
Work Zone Length	0.5	3.0	0.3	0.3	0.3	1.2	1.2	1.3	1.9	1.5	0.3	1.0
Work Zone Grade	0	0	0	0	0	0	0	0	0	0	0	0
Intensity of Work Activity	0	1	0	1	0	1	1	1	1	1	1	1

APPENDIX C. SUMMARY OF ROAD USER COST MODEL COMPARISON

Table C-1. Updated User Cost Comparison on IH 35 Northbound.

Time	VISSIM Cost		Jiang		QUEWZ-92
	Cost (hour)	Cost ($)	Cost (hour)	Cost ($)	
1	0.043	0.936	0.037	0.811	6.36
2	0.080	1.728	0.050	1.088	4.77
3	0.012	0.251	0.018	0.383	4.77
4	0.032	0.699	0.016	0.346	4.77
5	0.576	12.523	0.544	11.826	12.72
6	0.873	18.955	0.555	12.046	34.98
7	20.089	436.427	20.657	448.759	443.61
8	32.527	706.626	48.090	1044.723	224.19
9	9.605	208.651	9.491	206.189	159
10	9.102	197.731	7.654	166.280	166.95
11	19.628	426.412	18.419	400.149	211.47
12	53.781	1168.349	43.580	946.756	206.7
13	47.158	1024.480	43.086	936.008	213.06
14	49.515	1075.680	35.640	774.251	213.06
15	46.794	1016.559	42.104	914.686	321.18
16	109.624	2381.508	163.800	3558.455	3157.74
17	225.337	4895.300	206.695	4490.305	2593.29
18	95.833	2081.908	89.787	1950.566	143.1
19	50.578	1098.765	42.035	913.176	224.19
20	10.315	224.092	6.213	134.974	149.46
21	3.028	65.772	2.603	56.544	89.04
22	2.741	59.555	2.363	51.328	60.42
23	1.699	36.910	1.273	27.657	44.52
24	0.858	18.643	0.497	10.796	27.03
T-Test			0.944		0.018
RMS Error			280		751

Table C-2. Updated User Cost Comparison on IH 35 Southbound.

Time	VISSIM Cost		Jiang		QUEWZ-92
	Cost (hour)	Cost ($)	Cost (hour)	Cost ($)	
10	18.06	392.33	18.17	394.82	340.260
11	25.79	560.22	25.81	560.74	248.040
12	36.36	789.91	36.30	788.59	168.540
13	26.68	579.67	26.14	567.88	276.660
14	24.17	525.11	24.28	527.54	337.080
T-Test			0.594		0.035
RMS Error			5.53		350.27

Table C-3. Updated Road User Cost for IH 37 with Left Lane Closure.

Time	VISSIM Cost		Jiang		QUEWZ-92
	Cost (hour)	Cost ($)	Cost (hour)	Cost ($)	
10	153.17	3460	170.32	3847	3031
11	336.21	7594	341.86	7723	6217
RMS Error			228		1021

Table C-4. Updated Road User Cost for IH 37 with Left Lane Closure.

Time	VISSIM Cost		Jiang		QUEWZ-92
	Cost (hour)	Cost ($)	Cost (hour)	Cost ($)	
12.5	115.30	2605	94.09	2125	1817
13.5	228.47	5161	208.89	4719	4506
RMS Error			461		724