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16. Abstract

This report documents the results of eleven field studies at temporary work zone lane closures on urban freeways in Texas. Traffic volume and travel time data were collected at each site on days when the lane closures were implemented at each site, and compared to data collected during the same time periods on similar days without a closure present. Study results indicated a large amount of natural diversion occurred at those sites where normal freeway traffic demands far exceeded the available capacity through the work zone. Entrance ramp volumes were lower a considerable distance upstream of the beginning of the queue, and were even lower at ramps located within the actual freeway queuing. Exit ramps upstream of the queue displayed very small changes in volumes. In contrast, the first exit ramp motorists encountered after reaching the freeway queue consistently experienced significant increases in volumes. As a result of the significant diversion occurring at each site, freeway queuing and delays tended to reach a threshold soon after the lane closure was enacted. The queue and delay then remained at approximately that threshold level throughout the duration of the closure. Also discussed in this report is the application of the findings from these studies to the QUEWZ computer model for estimating queuing and road user costs at freeway lane closures.

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NATURAL DIVERSION AT TEMPORARY WORK ZONE LANE CLOSURES ON URBAN FREEWAYS IN TEXAS

by

Gerald L. Ullman

Research Report 1108-6
Research Study 2-8-87/1-1108
"Traffic Pattern Assessment and Road User Delay Costs
Resulting From Roadway Construction Options"

Sponsored by

Texas Department of Transportation
in cooperation with
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Texas A&M University System
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November 1992

METRIC (SI*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

LENGTH

Symbol	When You Know	Multiply By	To Find	Symbol
in	inches	2.54	centimetres	cm
ft	feet	0.3048	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km

AREA

Symbol	When You Know	Multiply By	To Find	Symbol
in^2	square inches	645.2	centimetres squared	cm^2
ft^2	square feet	0.0929	metres squared	m^2
yd^2	square yards	0.836	metres squared	m^2
mi^2	square miles	2.59	kilometres squared	km^2
ac	acres	0.395	hectares	ha

MASS (weight)

Symbol	When You Know	Multiply By	To Find	Symbol
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg

VOLUME

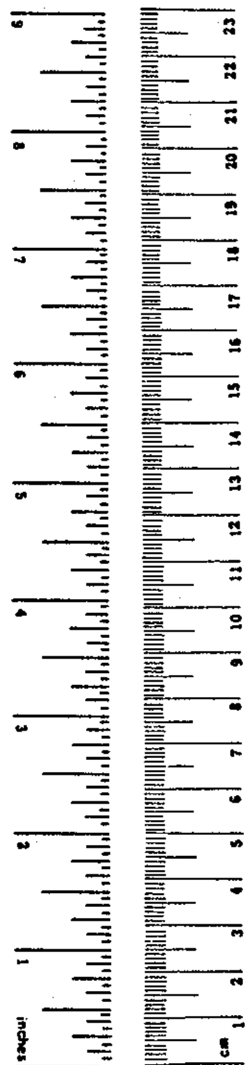
Symbol	When You Know	Multiply By	To Find	Symbol
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft^3	cubic feet	0.0328	metres cubed	m^3
yd^3	cubic yards	0.0765	metres cubed	m^3

NOTE: Volumes greater than 1000 L shall be shown in m^3.

TEMPERATURE (exact)

Symbol	When You Know	Multiply By	To Find	Symbol
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

* SI is the symbol for the International System of Measurements



APPROXIMATE CONVERSIONS TO SI UNITS

LENGTH

Symbol	When You Know	Multiply By	To Find	Symbol
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi

AREA

Symbol	When You Know	Multiply By	To Find	Symbol
mm^2	millimetres squared	0.0016	square inches	in^2
m^2	metres squared	10.764	square feet	ft^2
km^2	kilometres squared	0.39	square miles	mi^2
ha	hectores (10 000 m^2)	2.53	acres	ac

MASS (weight)

Symbol	When You Know	Multiply By	To Find	Symbol
g	grams	0.0353	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams (1 000 kg)	1.103	short tons	T

VOLUME

Symbol	When You Know	Multiply By	To Find	Symbol
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m^3	metres cubed	35.315	cubic feet	ft^3
m^3	metres cubed	1.308	cubic yards	yd^3

TEMPERATURE (exact)

Symbol	When You Know	Multiply By	To Find	Symbol
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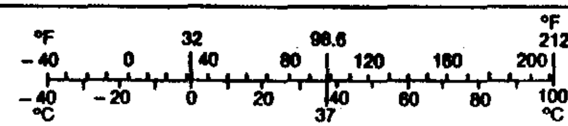

These factors conform to the requirement of FHWA Order 5190.1A.

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DISCLAIMER

The contents of this report do not necessarily reflect the official views of the Texas Department of Transportation or the Federal Highway Administration. This report does not constitute a standard, specification, or regulation, and is not intended for construction, bidding, or permit purposes. The report was prepared by Mr. Gerald L. Ullman, Texas P.E. registration #66786.

SUMMARY

Field studies were performed at eleven temporary work zone lane closures on urban freeways in Texas. Ten of the sites included continuous frontage roads adjacent to the freeway; a discontinuous frontage road existed at the eleventh site. Travel times and volumes recorded on the freeways and frontage roads during the closures were compared to data collected on similar days without closures. Eight of the studies were conducted at sites where the normal demand volumes on the freeway were two to four times greater than the estimated capacity through the work zone; at three other sites, normal demands were only 10 to 20 percent greater than the estimated work zone capacity.

The studies indicate that a considerable amount of diversion from the freeway occurred at sites where significant traffic queuing developed on the freeway, both in terms of motorists choosing not to enter the freeway and in terms of motorists already on the freeway exiting early. This first type of diversion was evident even a substantial distance away from the area of congestion, based on lower entrance ramp volumes recorded upstream of congestion. Within the region of congestion, proportional reductions in entrance ramp volumes were even greater and were relatively consistent from site to site and from ramp to ramp within a given site. Meanwhile, exit ramps upstream of congestion were not affected to any appreciable degree. Within congestion, the first exit ramp tended to experience significant increases in volume. It appeared that changes in exit ramp volumes farther into the queue depended on the degree to which the first ramp could accommodate those motorists wishing to exit the freeway early. If most motorists wishing to exit could do so at the first exit ramp in the queue, subsequent exit ramps experienced lower volumes. If not, those motorists presumably wishing to exit but unable to (probably due to the capacity limitations of the first ramp) appeared to proceed to the second ramp and exit.

Data from the three sites where significant queuing and delay did not develop also suggested that diversion occurred at those sites. Freeway volumes past the work zone when no queue was present were approximately 5 percent less than volumes at the same location and time on a similar day without a lane closure. It is not known whether this small reduction is due to the available media traffic information sources (newspapers, radio traffic reports) or direct motorist observations, however. Coupled with capacities that were slightly greater than expected, these sites remained right at the threshold between queued and non-queued conditions.

The studies also indicated that freeway queuing tended to reach a threshold level at most sites and remain at approximately those levels for the remainder of the closure. Although the point at which this threshold was reached (in terms of the actual queue length) varied by site, it was fairly consistent in the number of ramps engulfed in the queue prior to attaining that threshold. At the sites examined in this research, which represent travel patterns and conditions on circumferential urban freeways in Texas, the queue stabilized after encompassing a total of four to five entrance and exit ramps combined.

IMPLEMENTATION STATEMENT

Based on the results from these studies, the diversion algorithm implemented in QUEWZ3 was retained. It is recommended that queue length be used as the default diversion threshold variable in the algorithm, and that adjustments to this default be estimated based on average ramp spacings upstream of the proposed lane closure. Although not directly programmed into the QUEWZ model, the data also indicate that traffic volumes at lane closure sites will be slightly lower than normal historical counts would indicate. The user may wish to reduce historical freeway demand volumes by five percent prior to analyzing a work zone using the QUEWZ model.

It should be noted that all data where significant queuing occurred on the freeway were from sites having continuous frontage roads adjacent to the freeway. The reader is cautioned when applying these results to locations where frontage roads are not present. Diversion may be less significant at these sites, leading to slightly greater queue length threshold values.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. INTRODUCTION

Problem Statement

Temporary work zone lane closures on high-volume urban freeways typically generate significant amounts of congestion, as traffic demands approaching the work zone exceed the reduced capacity of the roadway. These lane closures affect both the normal operating conditions and the normal motorist travel patterns on the freeway. Drivers already on the freeway may choose to exit upstream of the ramp they had originally intended to use, whereas drivers approaching their intended entrance ramps may decide to remain on the frontage road or seek an alternative route to their destination. Some drivers may avoid the freeway corridor altogether, relying entirely on alternative routes to their destinations or even altering the destinations of their trips. For purposes of this report, these changes in travel behavior in response to non-recurrent congestion are termed "natural diversion." This diversion is not required by law enforcement nor encouraged by highway agency personnel at the work zone through advance signing. Natural diversion is not restricted to work zone capacity reductions; it can occur at incident locations as well.

Natural diversion is the result of a complex decision-making process, a phenomenon not well understood at this time, although previous research has identified some of the major factors that may influence a driver's decision to divert (1-6). Without a good understanding of how natural diversion affects normal travel patterns, the impacts of work zone lane closures upon freeway operating conditions cannot be accurately estimated. As a result, it is difficult to predict:

- The amount of freeway delay that will be generated (important in the calculation of excess road user costs),
- The extent of the traffic queue that will develop on the freeway upstream of the work zone (important in the design of traffic control plans), and
- The amount of traffic normally using the freeway that will divert to the frontage road or to other routes in the corridor (important in the mitigation of work-zone-induced traffic impacts away from the freeway).

Although laboratory studies and motorist surveys provide insight into what factors influence natural diversion, they can not be used to predict just how much natural diversion will actually occur at a lane closure at a given site. A strong need exists for traffic operation and travel pattern data from actual work zone lane closures on high-volume urban freeways. Such data would improve the understanding of natural diversion at these closures as well as allow better estimates of natural diversion and traffic impacts of future lane closures. In response to these needs, a series of field studies were conducted at urban freeway work zone lane closures as part of Texas HPR Study 1108, "Traffic Pattern Assessment and Road User Costs Resulting from Roadway Construction Options," sponsored by the Texas Department of Transportation (TxDOT).

Study Objectives

The specific objectives of this phase of the study were as follows:

1. Determine the magnitude of delays and queuing that develop upstream of work zone lane closures on urban freeways in Texas,

2. Quantify the changes in normal freeway travel patterns due to natural diversion,

3. Investigate the relationships between the amount of natural diversion and the operating conditions that result upstream of the lane closure, and

4. Recommend how these relationships can be incorporated into the existing computer model QUEWZ for estimating traffic queuing and excess road user costs at freeway work zone lane closures.

Study Approach

A series of field studies were conducted at temporary work zone lane closures on freeways in Houston, San Antonio, and Dallas, TX. These studies included volume counts on all entrance and exit ramps in the vicinity of the lane closures; travel time measurements on the freeway and adjacent frontage road; and hourly measurements of the queue length upstream of the lane closures. Studies were conducted at each site prior to the day of the lane closure, and then during the closure itself. In this way, changes in the traffic conditions and volumes (relative to "normal" travel conditions) could be assessed.

The data from these studies were consolidated and potential relationships were explored between the changes in travel patterns and select roadway, work zone, and traffic characteristics. These results were then considered in terms of their potential application to the QUEWZ model for estimating traffic queuing and additional road user costs due at freeway lane closures similar to those studied.

Organization of this Report

The main body of this report is divided into four chapters. Chapter 2 provides a discussion of the field study methodology utilized and summarizes the roadway, work zone, and traffic characteristics of each study site. Chapter 3 presents the results of the field studies, documenting the effect of the lane closures upon mainlane and frontage road travel times; traffic queues upstream of the closures; and mainlane, frontage road, and ramp volumes. Chapter 4 describes the application of the study results to the prediction of diversion and traffic conditions at future freeway work zone lane closures. The report concludes with an overall summary of the study findings in Chapter 5.

2. DESCRIPTION OF THE FREEWAY LANE CLOSURE FIELD STUDIES

Data Collection

The data collection effort for the field studies consisted of travel time measurements performed at hour or one-half hour intervals on both the freeway and the adjacent frontage road; measurements of the queue length on the freeway due to the lane closure during each travel time run; and traffic volume counts made on the freeway mainlanes, frontage road, and entrance and exit ramps in the vicinity of the lane closure.

Travel time data were collected using the floating-vehicle technique, whereby the driver attempts to travel at the speed of an average vehicle in the traffic stream. At each site, a study section was identified beginning 3 or 4 miles upstream of the anticipated location of the lane closure and extending beyond the point where the work zone was expected to end. Travel time runs were initiated at the same time on the freeway and frontage road so as to provide a consistent basis for comparison. Times were recorded at the start of each run, at several intermediate points (usually cross-street centerlines), and at the end of the study section.

Traffic queue data were collected during the travel time runs conducted on the day of the lane closure at each site, using an in-vehicle distance measuring instrument (DMI). The instrument was used to record the instantaneous speed, time, and cumulative distance from the start of the run to selected locations along each route. These locations included the centerline of major cross-streets, advance warning signs for the work zone, the beginning and ending points of each lane closure cone taper, and the beginning of the traffic queue. The beginning of the traffic queue was defined as the location where the instantaneous speed (as shown on the DMI) dropped to below 30 mph.

Traffic volume data were collected continuously on the freeway mainlanes, frontage roads, and all entrance and exit ramps (to the extent possible) in the study section. The frontage road and ramp counts were collected using mechanical counters connected to pneumatic tubes placed across the ramp or travel lanes. Because of the high traffic volumes and wide cross-sections, counts on the freeway mainlanes were recorded either by loop detectors already imbedded in the pavement or by manual counts made by data collection personnel. Freeway mainlane counts were made upstream of the work zone close to the beginning of the study section. In San Antonio, an automatic traffic recording (ATR) station operated by the TxDOT was used to collect mainlane data. Because of this, volumes at the upstream end of the section had to be estimated by adding and subtracting entrance and exit ramp volumes between the ATR station and the upstream location. At the other sites, traffic was counted manually at the desired upstream location.

Study Site Descriptions

An attempt was made to select study sites that encompassed a range of demand volumes and work zone lane closure configurations. This was to be done in order to observe sites with different anticipated levels of diversion and congestion patterns. However, it was extremely difficult to locate suitable temporary lane closure sites, as closures occur primarily as part of ordinary maintenance activities by TxDOT. Typically, TxDOT personnel could only provide one to two days notice of an upcoming lane closure. This made it difficult for study personnel to react in time to collect data at a given site. Nevertheless, enough sites were eventually identified to fulfill the contractual requirements of the study, although not over the range of site conditions originally desired.

Table 2-1 summarizes the characteristics of each work zone lane closure site studied. The first eight sites were located on the I-410 North Loop in San Antonio. These lane closures were performed as part of a seal-coat operation in both directions of travel. At each of those sites, two of the three mainlanes were closed. The ninth and tenth sites were located in Houston. Site nine involved the closure of one of the four inbound travel lanes on the Katy (I-10) freeway (the right lane). The tenth site was located on the Gulf (I-45) freeway, where the left lane of three inbound lanes was closed to make guardrail repairs. The final site was located in south Dallas on the East R.L. Thorton (I-35E) freeway, where two of the four outbound lanes were closed to install inductive loops for an automatic traffic counting station. Maps of the respective study site locations are provided in Figures 2-1 through 2-3.

Table 2-1 also presents the range of normal demand volumes recorded throughout the day at each location, the range of work zone capacities that would be expected for each site (based on data reported by (7)), and the estimated excess demand at each location (computed as the difference between the normal demand volumes and expected capacities). This excess demand must either queue upstream of the lane closure or divert and find another route to travel. Based on the estimates provided in the table, normal traffic demands at the first eight sites were from 2000 to 5000 vph higher than the expected traffic flow capacity past the work zones. In contrast, excess demands at the latter three sites were generally less than 1000 vph. Expressing the relationship between

TABLE 2-1. SUMMARY OF STUDY SITE CHARACTERISTICS

Site	Location	Lane Closure Configuration	Normal Volumes At Work Zone, vph	Expected Work Zone Capacity, vph[a]	Excess Demand, Vph	Volume-to-WZ Capacity Ratio
1	I-410 WB, San Antonio	2 of 3 lanes closed	4150-4900	1600	2550-3300	2.6-3.1
2	I-410 WB, San Antonio	2 of 3 lanes closed	3600-4500	1600	2400-2900	2.3-2.8
3	I-410 WB, San Antonio	2 of 3 lanes closed	3750-4500	1600	2150-2900	2.3-2.8
4	I-410 WB, San Antonio	2 of 3 lanes closed	4150-4900	1600	2550-3300	2.6-3.1
5	I-410 EB, San Antonio	2 of 3 lanes closed	5100-6250	1600	3500-4650	3.2-3.9
6	I-410 EB, San Antonio	2 of 3 lanes closed	4950-6200	1600	3350-4600	3.1-3.9
7	I-410 EB, San Antonio	2 of 3 lanes closed	5300-6450	1600	3700-4850	3.3-4.0
8	I-410 EB, San Antonio	2 of 3 lanes closed	3300-4000	1600	1700-2400	2.1-2.5
9	I-10 Katy Fwy WB, Houston	1 of 4 lanes closed	5300-5600	4500	800-1100	1.2
10	I-45 Gulf Fwy NB, Houston	1 of 3 lanes closed	3300-3800	3200	100-600	1.0-1.2
11	I-35E Fwy SB, Dallas	2 of 4 lanes closed	2000-3650	3200	0-450	0.6-1.1

[a] Capacity values as reported in (7)

WB, EB, NB, SB = westbound, eastbound, northbound, southbound

WZ = work zone

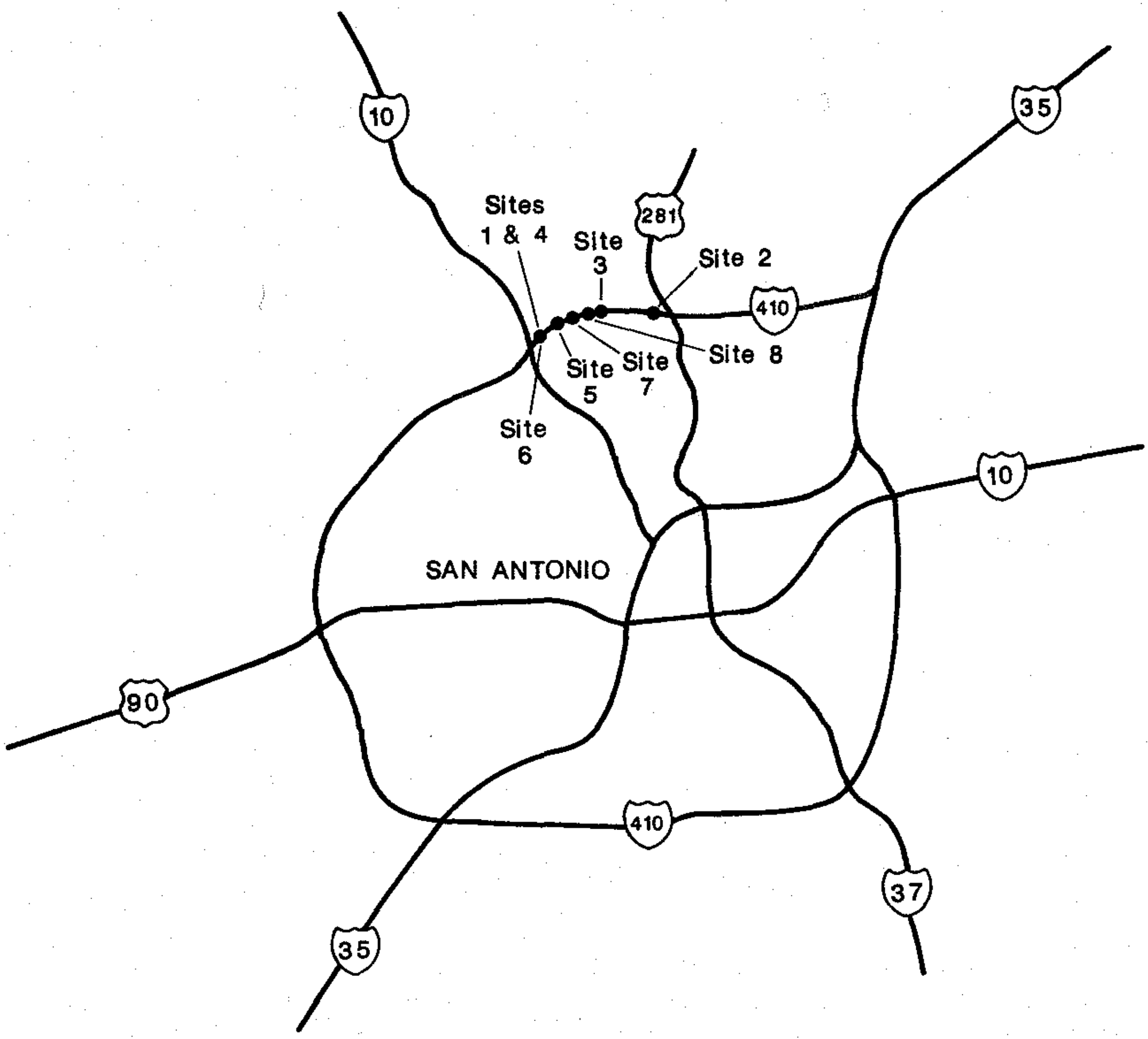

Figure 2-1. Study Sites 1 through 8 (I-410, San Antonio).

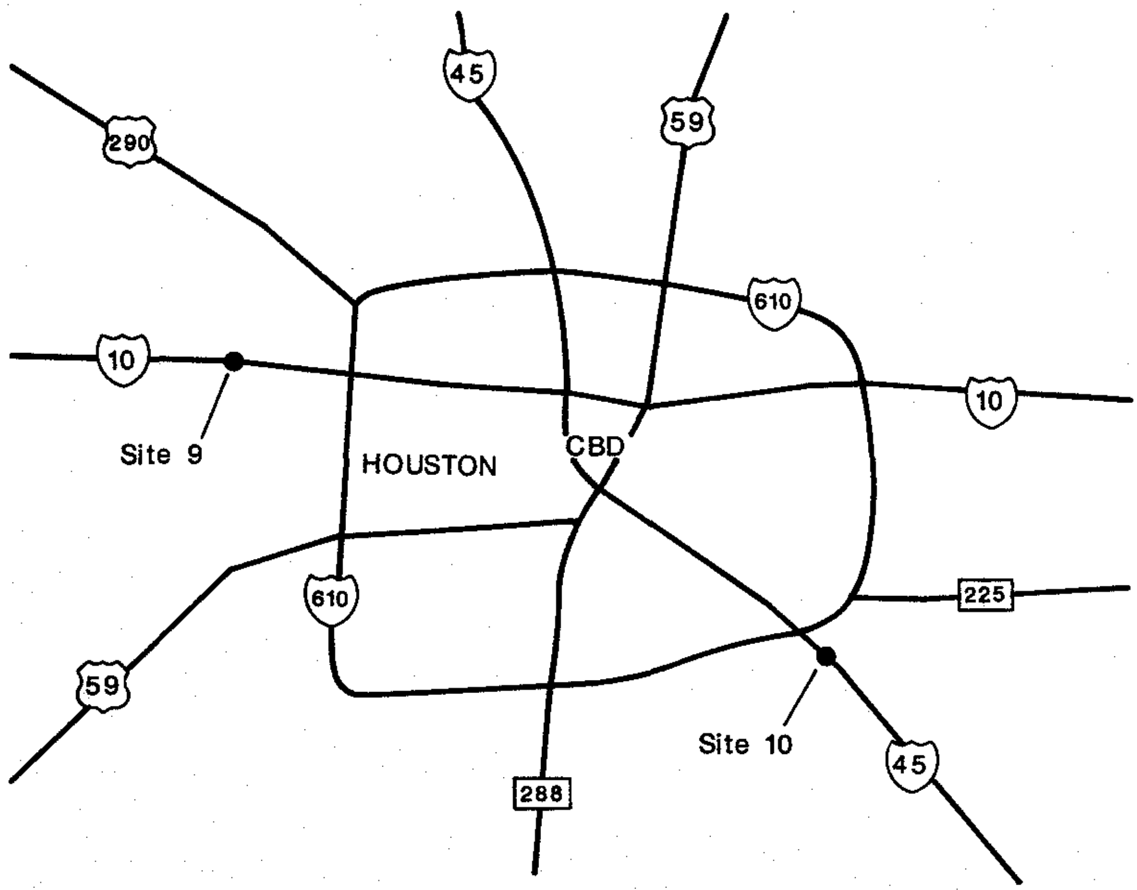

Figure 2-2. Study Sites 9 and 10 (I-10 and I-45, Houston).

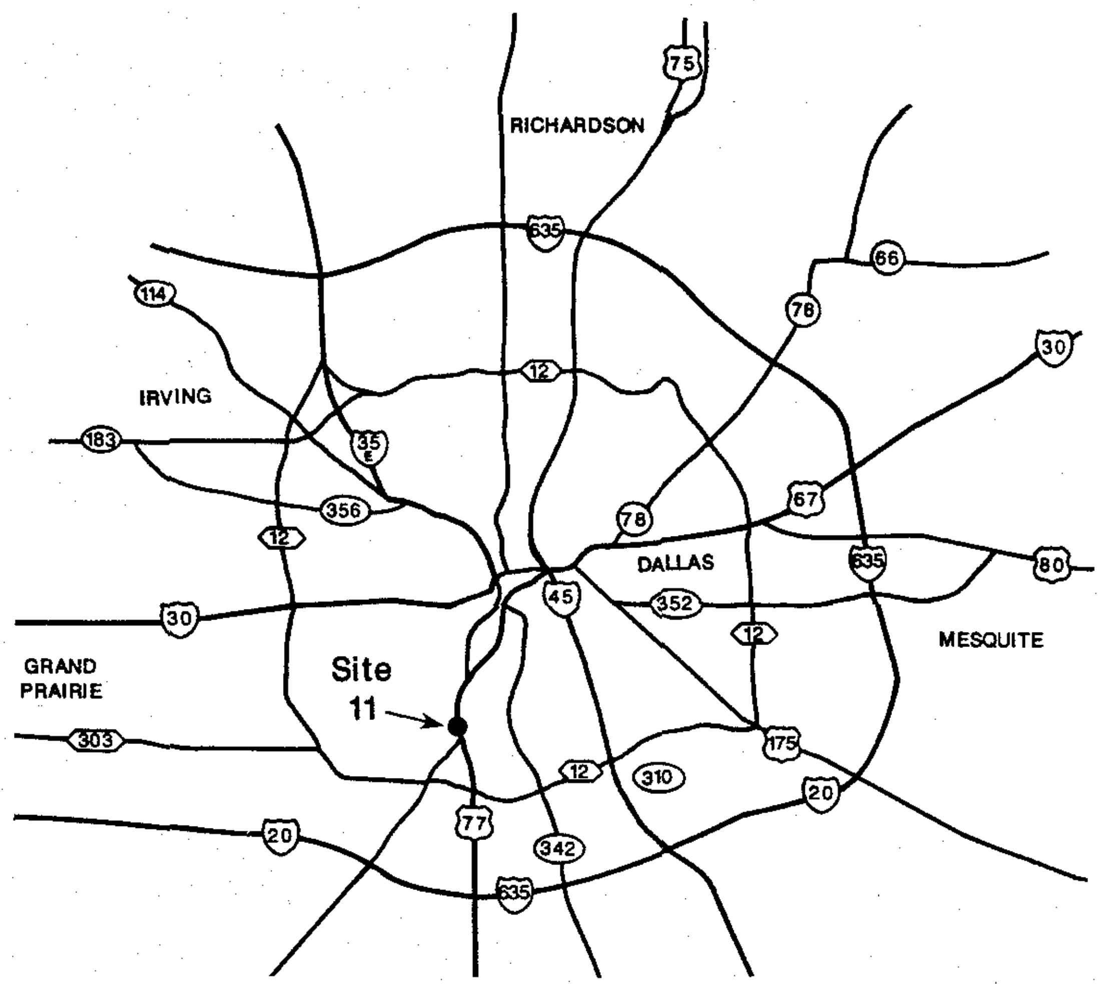

Figure 2-3. Study Site 11 (I-35E, Dallas).

normal traffic demands and expected work zone capacity as a ratio (shown in the last column of Table 2-1), it can be seen that normal demand volumes at the first eight sites were two to four times the expected capacity of the work zone, whereas normal demands were about 1.2 times the estimated work zone capacity at the last three sites.

In addition to the overall work zone and traffic characteristics at each site, the characteristics of the entrance and exit ramps immediately upstream of the lane closures were also of interest in this study. Ramps represent the discrete locations where changes in freeway travel patterns can be measured. Consequently, differences in ramp configuration, spacing, and normal traffic demands were expected to influence both the natural diversion process as well as the traffic conditions which developed upstream of the lane closures.

Average ramp spacings at each site immediately upstream of the lane closure are documented in Table 2-2. Average spacings between successive entrance ramps range from a low of 2700 ft (0.5 mile) at Site 5 to a high of 6250 ft (1.2 miles) at Site 9. In comparison, average spacings between exit ramps vary between 2450 ft (0.5 mile) and 4825 ft (0.9 mile) at Sites 6 and 7, respectively. Considering all ramps together (regardless of type), spacings were between 1600 ft (0.3 mile) and 2525 ft (0.5 mile).

Also shown in Table 2-2 are the average ratios of the ramp volumes to mainlane volumes at each site. These ratios are presented to illustrate the relative significance of the ramp volumes entering and exiting the freeway to the mainlane volumes. Low ratios indicate that a ramp has a minimal impact upon normal freeway volumes, whereas higher ratios indicate that the ramps contribute significantly to the mainlane traffic volumes. Indirectly, these ratios suggest the degree by which changes in individual ramp volumes can then affect freeway conditions.

Generally speaking, the ratios indicate that the ramp volumes represented 5 to 20 percent of the mainlane volumes at each site. When the ramps were major freeway-to-freeway interchanges, however, the volumes made up between 30 and 40 percent of the mainlane volumes. Comparing entrance and exit ramp ratios for each site, it can be seen that they are very similar Sites 1 through 8, indicative of the non-directional flows typical of circumferential freeways. Meanwhile, Sites 9 and 10 located in the inbound direction of a radial freeway, display entrance ramp ratios which are slightly larger than the ratios for the exit ramps. Finally, this trend is reversed at site 11, located in the outbound direction of a radial freeway.

TABLE 2-2. RAMP CHARACTERISTICS AT EACH SITE

Site	Average Ramp Spacing, Ft			Ratios of Ramp Volume to Mainlane Volume	
	Entrance-to-Entrance	Exit-to-Exit	Overall	Entrance	Exit
1	3900	4525	2150	0.06-0.18	0.03-0.26
2	3675	3975	2150	0.10-0.29	0.10-0.40
3	3400	3700	1975	0.06-0.30	0.10-0.40
4	3900	4525	2150	0.06-0.18	0.03-0.18
5	2700	4500	2025	0.03-0.18	0.04-0.16
6	3200	2450	1600	0.11-0.25	0.03-0.21
7	3950	4875	2075	0.03-0.11	0.04-0.16
8	5400	3900	2325	0.07-0.38	0.04-0.30
9	6250	4050	2500	0.08-0.17	0.03-0.13
10	5825	3900	2525	0.13-0.19	0.02-0.13
11	5000	3325	2000	0.05-0.16	0.04-0.22

3. FIELD STUDY RESULTS

This chapter documents the impacts of the work zone lane closures at each of the eleven study sites. Two types of impacts are described: (1) changes in the operating conditions on the freeway and frontage road (defined in terms of travel time delays on the freeway and frontage road), and the length of queue extending upstream from the lane closure), and (2) changes in traffic volumes using the entrance and exit ramps upstream of the lane closure.

Effect of Lane Closures upon Traffic Operations

Comparisons of Queuing, Freeway Delay, and Frontage Road Delay by Site

The impacts of the lane closures upon traffic operations are illustrated in graphs of freeway delays, frontage road delays, and freeway queue lengths by time of day at each of the study sites. The freeway delays shown are due solely to the traffic queue present when the travel time measurements were taken (recorded from the beginning of the queue to the end of the lane closure taper). The frontage road delays reflect the changes in travel time over that same distance. Additional delays incurred at some of the sites due to slower speeds through the actual work zone were not included in these figures. Delays through the actual work zone are more a function of the length of the work zone than of the queuing or diversion upstream of the lane closure bottleneck. Because the work zones at these study sites varied dramatically in length, it was decided to focus solely on the delays due to the freeway queuing to allow more direct comparison across sites.

It was noted in Chapter 2 that the lane closures at Sites 1 through 8 were similar, with two of three lanes closed to traffic and normal demands two to four times the reduced capacity through the work zone. Review of Figures 3-1 through 3-8, though, show considerable variation in the magnitude of queuing at each site. Queuing patterns at all eight sites are consistent, however, in that the majority of queue growth occurred during the first hour or two of the closure. After that time, the queue tended to either oscillate slightly forward and back or even decrease slightly as the day progressed. Given the large estimated V/C ratios computed for these sites, the fact that the queues stabilized to some extent is indicative of a large amount of diversion at these sites.

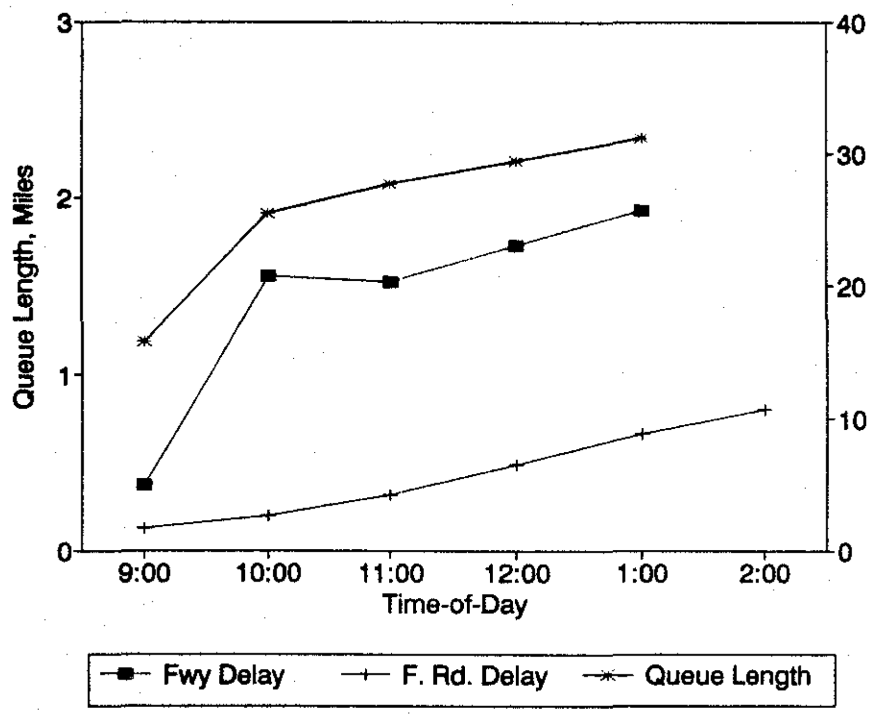

Figure 3-1. Queue Length and Delay Profiles from Site 1.

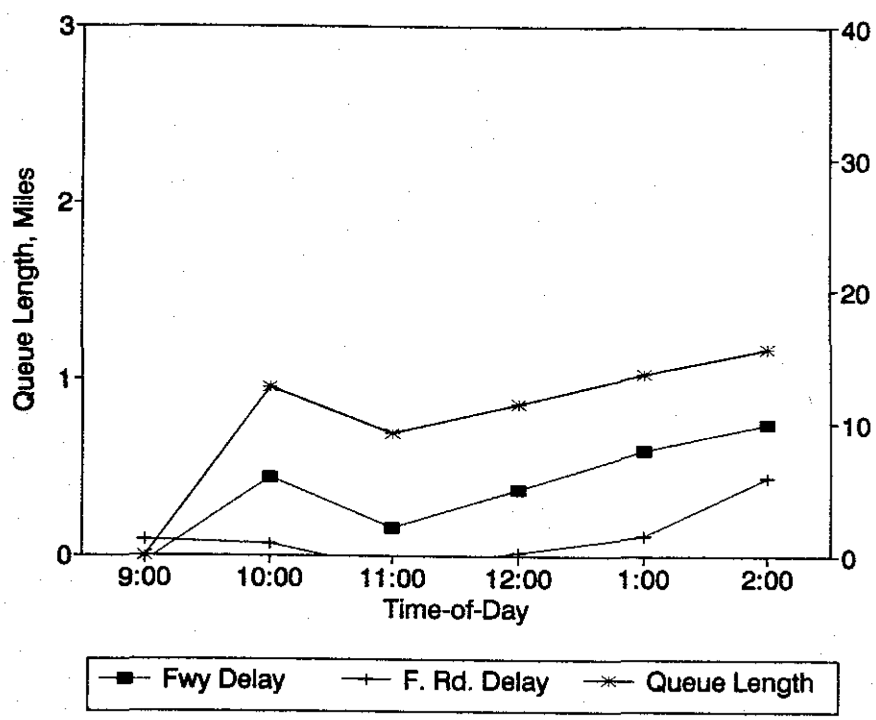

Figure 3-2. Queue Length and Delay Profiles from Site 2.

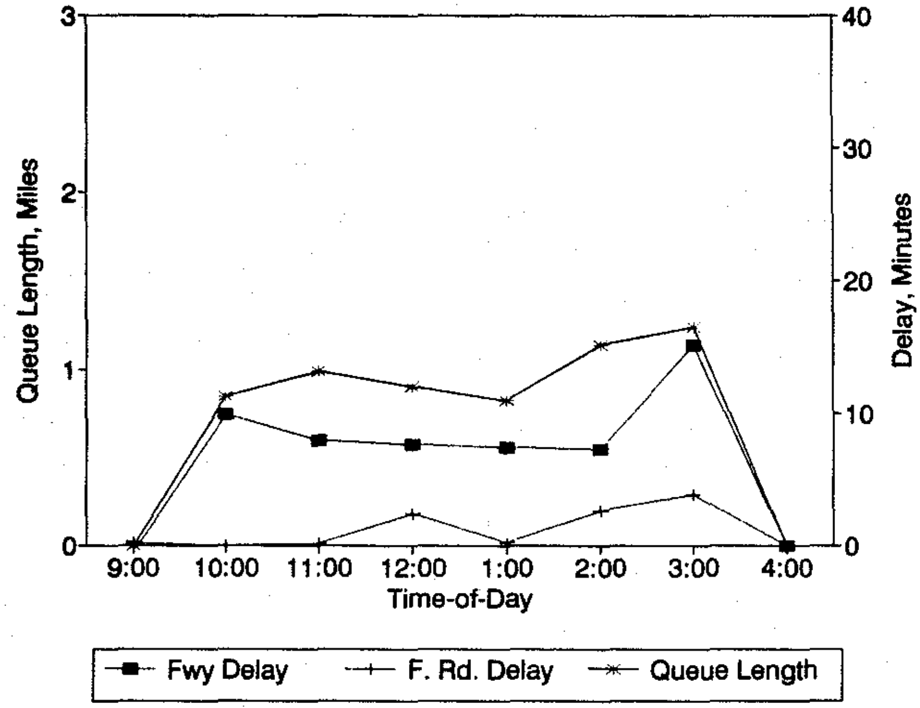

Figure 3-3. Queue Length and Delay Profiles from Site 3.

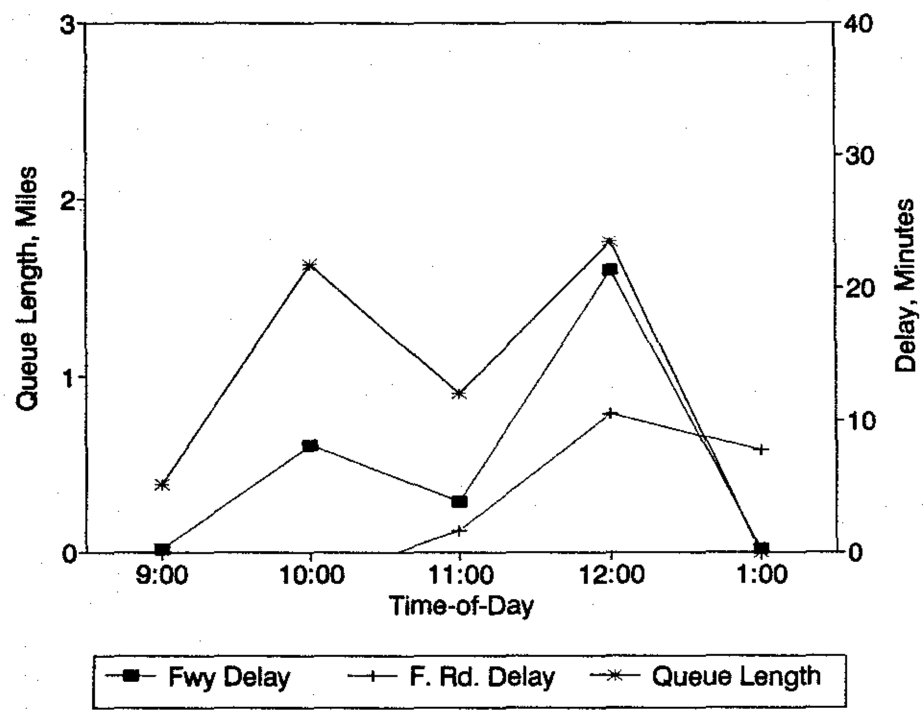

Figure 3-4. Queue Length and Delay Profiles from Site 4.

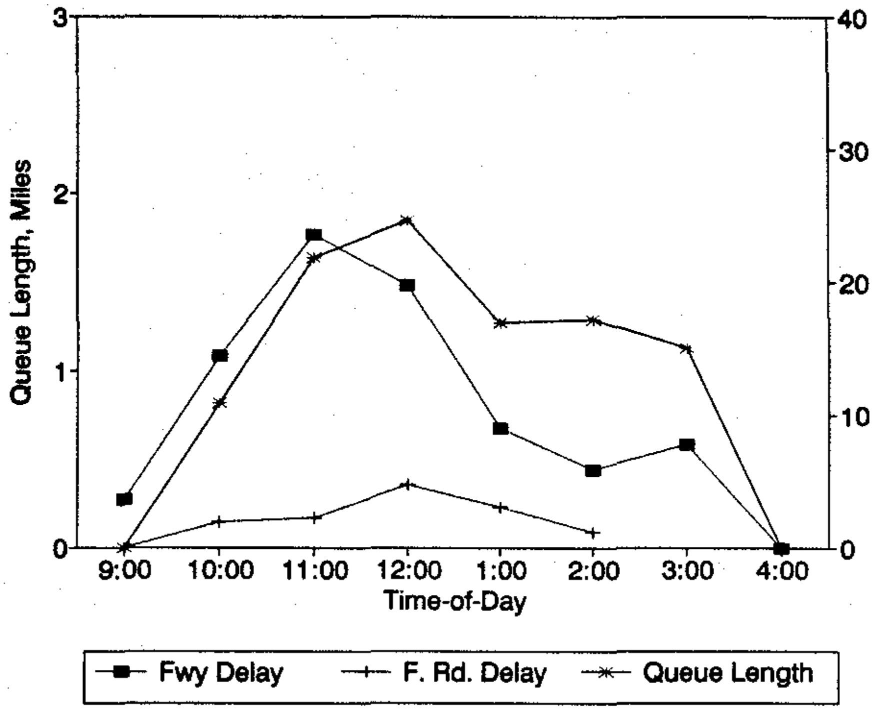

Figure 3-5. Queue Length and Delay Profiles from Site 5.

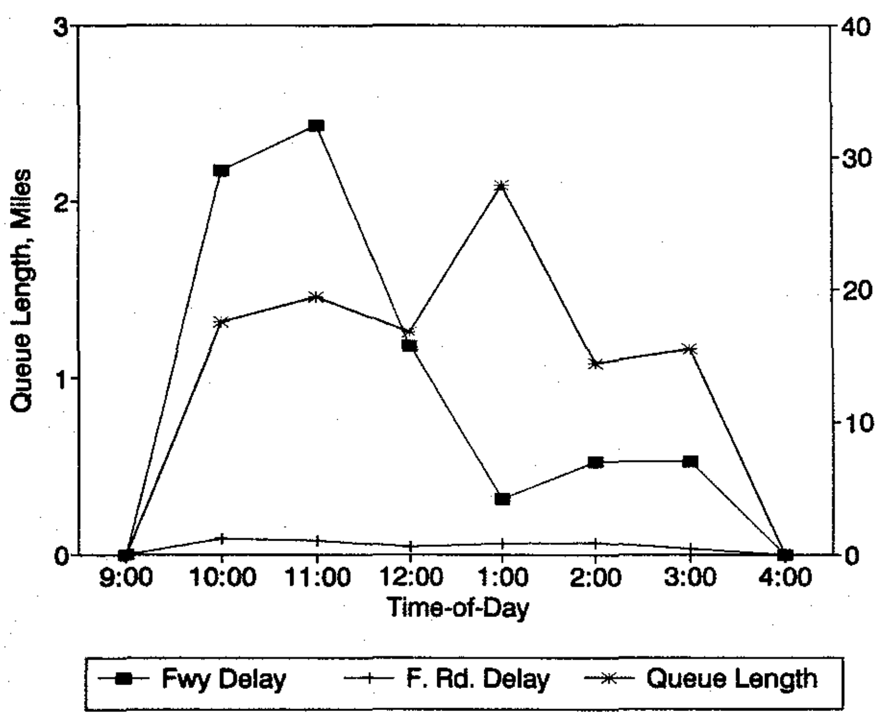

Figure 3-6. Queue Length and Delay Profiles from Site 6.

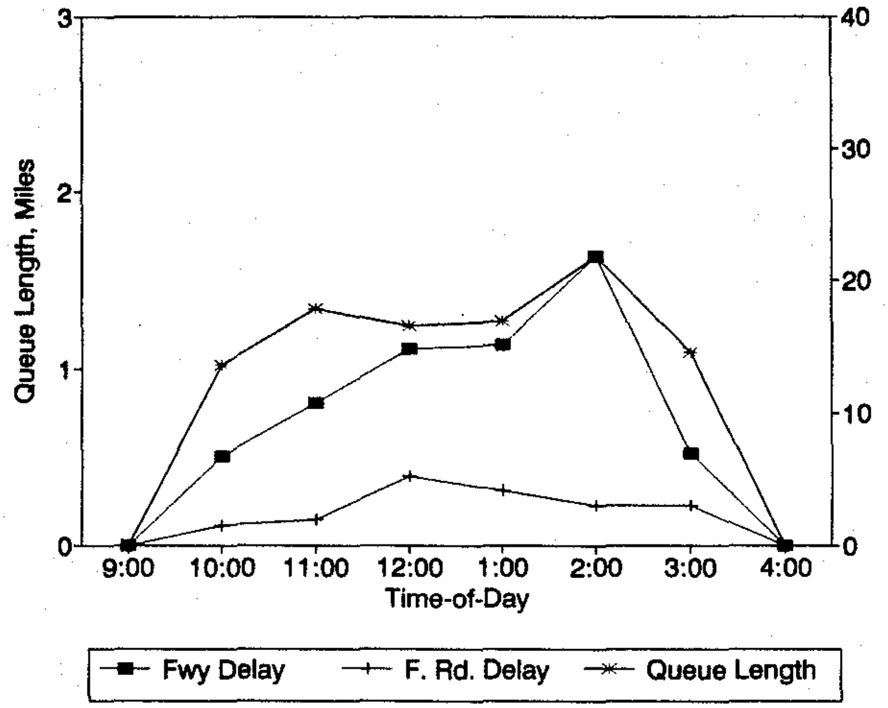

Figure 3-7. Queue Length and Delay Profiles from Site 7.

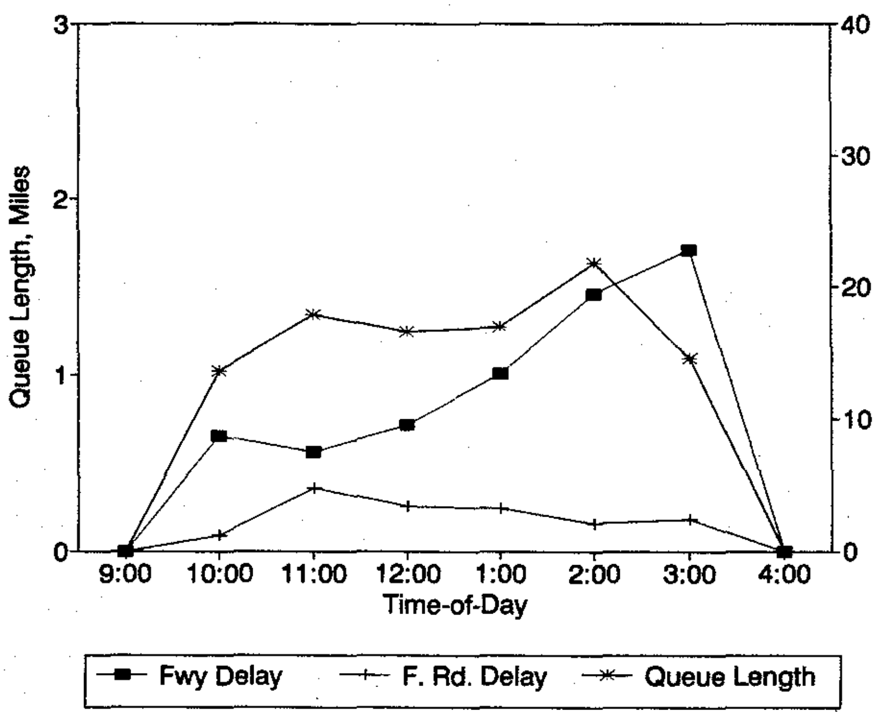

Figure 3-8. Queue Length and Delay Profiles from Site 8.

Without this magnitude of diversion, queues would have grown at a tremendous rate throughout the duration of the closure.

In general, the freeway delays shown in Figures 3-1 through 3-8 correlate with the queuing patterns at each site, with larger delays during the day occurring when queues were greater. However, the amount of delay associated with a given queue length differed from site to site. In other words, traffic flow conditions within the queues (i.e., average speeds) differed from site to site.

Frontage road delays were relatively minor at the first eight sites. Sites 1 and 4 did see delays approach 10 minutes for part of the day, but were around 5 minutes or so at the other sites. From these results, it would appear that most of the traffic which diverted from the freeway at each site did not choose to remain on the frontage road and reenter the freeway downstream of the lane closure. Rather, drivers seemed to have left the freeway/frontage road corridor entirely and searched for other routes to their destinations.

Figures 3-9 through 3-11 summarize the queuing and delay characteristics at Sites 9 through 11. Unlike the first eight sites, the lane closure configurations and normal demands at these locations resulted in expected V/C ratios only slightly above 1.0. As a result, the traffic impacts were relatively minor at these sites. In fact, traffic queuing that was anticipated at these sites materialized only for short periods of time, and then dissipated quickly. Meanwhile, little or no delay developed on either the freeway or frontage road. Overall, traffic conditions appeared to hover near capacity conditions throughout the duration of the lane closures, only occasionally (and temporarily) drifting beyond oversaturated conditions as a result of the stochasticity of traffic demands.

Freeway and Frontage Road Travel Times through Congestion

The common urban freeway design in Texas includes adjacent parallel continuous frontage roads located within the freeway's right-of-way. Given its proximity to the freeway, the frontage road is a logical candidate for traffic diverting from the freeway during short-term work zone lane closures. Furthermore, this design allows motorists to see conditions on the frontage road and compare them with travel on the freeway. Under normal travel conditions, freeway speeds are expected to be much higher than on the frontage road. However, when a lane closure on the freeway results in significant queuing, the freeway may or may not provide quicker travel. Theoretically, motorist

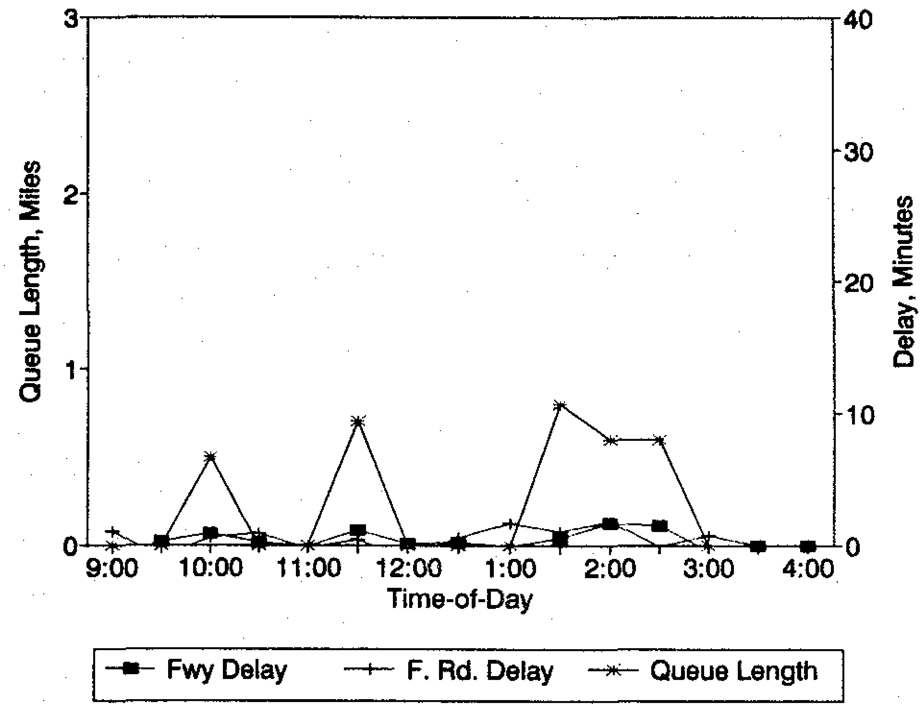

Figure 3-9. Queue Length and Delay Profiles from Site 9.

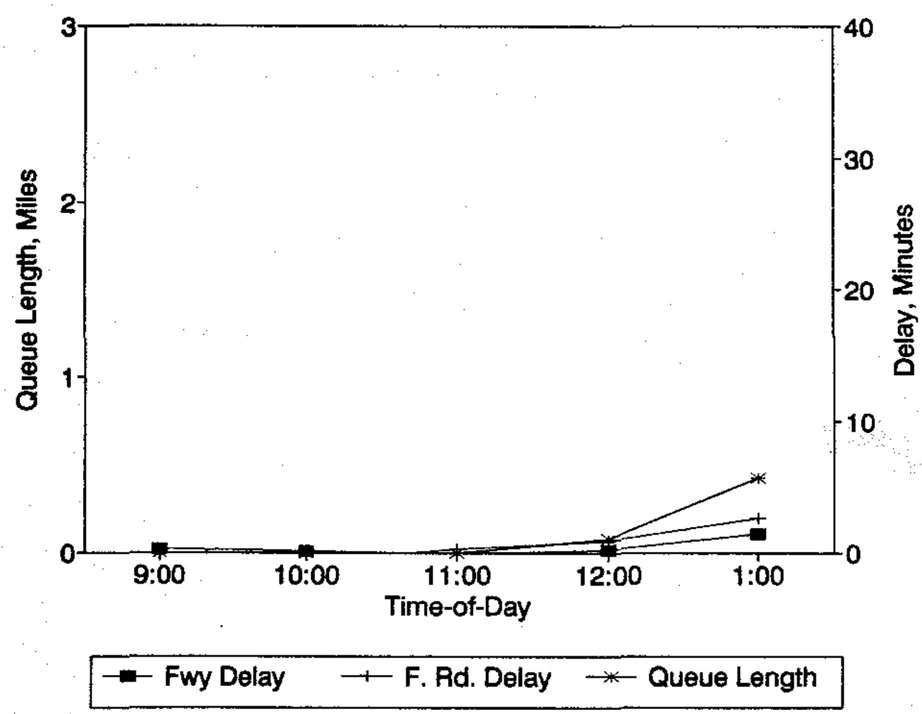

Figure 3-10. Queue Length and Delay Profiles from Site 10.

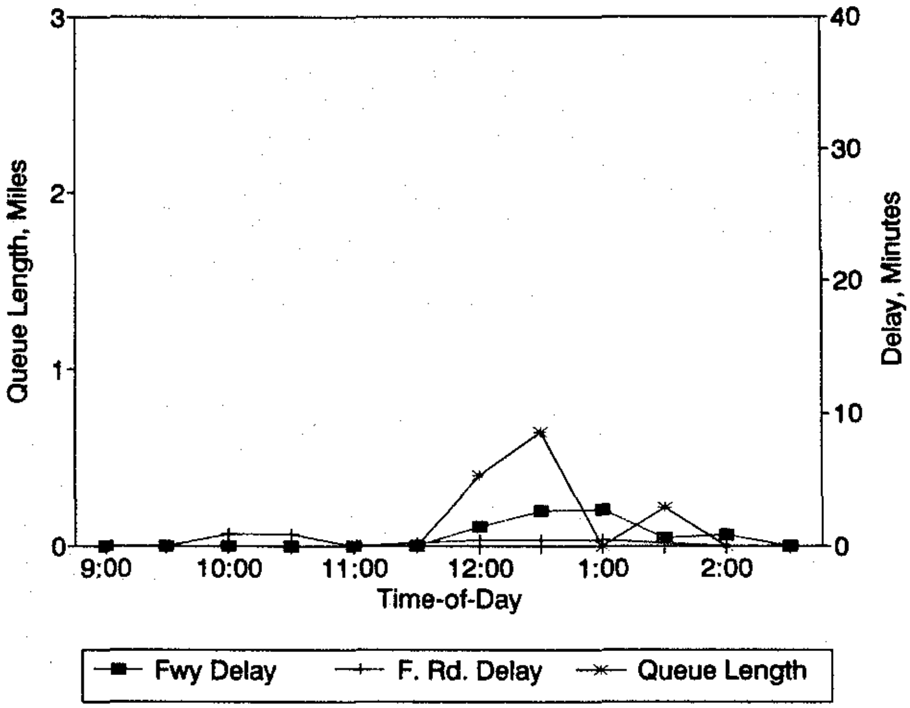

Figure 3-11. Queue Length and Delay Profiles from Site 11.

decisions on whether or not to divert might be influenced significantly by their perceptions of the comparative travel conditions on the freeway and frontage road.

A quantitative comparison of the influence of the lane closure upon freeway and frontage road travel times is shown in Table 3-1. Here, the travel time on the freeway at each site is presented from the last exit ramp before the start of the queue to the end of the lane closure taper, consolidated over all travel time runs during the lane closure. The average frontage road travel times over this same distance at each site are also provided in the table.

TABLE 3-1. COMPARISON OF FREEWAY AND FRONTAGE TRAVEL TIMES OVER THE LENGTH OF FREEWAY QUEUING

Site	Average Freeway Travel Time (min.)	Average Frontage Road Travel Time (min.)	Average Travel Time Difference (min.)
1	20.4	11.5	8.9
2	8.6	7.1	1.5
3	11.0	4.9	6.1
4	13.1	8.3	4.8
5	13.5	6.8	6.7
6	18.5	5.1	13.4
7	14.4	7.5	6.9
8	14.9	6.3	8.6
9	2.8	3.3	-0.5
10	1.5	4.1	-2.6
11	2.8	2.2	0.6

Data from the first eight sites indicate freeway travel times through the queue to be 1.5 to 13.4 minutes higher than over the same distance on the frontage road. In other words, once the average freeway driver encountered the back of the traffic queue, it would have been quicker to divert to the frontage road and bypass the congestion than to remain on the freeway. Site 11 displayed a similar trend with freeway travel times being larger than on the frontage road. However, the actual difference was extremely small, less than one minute on the average. Certainly, it is unreasonable to expect motorists to be able to accurately estimate relative delays on either the freeway or the frontage road under these congested condition. Nevertheless, the consistency by which freeway travel times exceed frontage road travel times over a comparable distance suggests a tendency for motorists to prefer to remain on the freeway (due to an aversion to diverting, confidence in freeway travel, etc.) rather than divert. This correlates well with related laboratory research suggesting that motorists view diverting from the freeway less desirable than diverting prior to entering the freeway (8).

Conversely, freeway travel times in the queues at Sites 9 and 10 were slightly shorter than travelling the corresponding distances on the frontage roads. Presumably, the extremely small queues generated at these sites did not increase travel times on the freeway enough to offset the longer frontage road travel times which existed normally.

Effect of Lane Closures Upon Traffic Volumes

The introduction of a work zone lane closure into the freeway driving environment restricts the available roadway capacity and directly impacts the traffic flows on the freeway upstream and through the lane closure. Traffic volumes past the closure are throttled down to the restricted capacity, with excess traffic demands forced to either queue on the freeway upstream of the closure or to divert to alternative routes. To date, study of the impacts of lane closures on traffic volumes have been limited to the analysis of their effect on roadway capacity. This section of the report is devoted to the analysis of other impacts the lane closures have upon traffic volumes. In particular, the effects of the lane closures and subsequent congestion upon entrance ramp volumes, exit ramp volumes, and frontage road volumes are discussed herein.

From the perspective of individual motorists, natural diversion can occur at a multitude of locations along their normal route, or even prior to beginning their trip. Research efforts to date have examined diversion primarily from this driver perspective, identifying factors assessing diversion decisions, assessing the probability of an individual diverting in response to these different factors, and attempting to model the actual decision-making process of individual drivers (1-6,9). By necessity, these models are complex because they must attempt to relate roadway network attributes, traffic flow dynamics, and individual motorist characteristics to driving behavior.

Although the specifics of the individual diversion decisions and resulting behavior are quite complex, the aggregate effect of these decisions upon freeway conditions can be measured directly in the changes in ramp volumes upstream and within the work zone lane closure. These changes occur at both entrance and exit ramps. Those motorists who choose not to use the freeway, regardless of exactly where along their trip they decide not to enter or what alternative route they use, cause a reduction in volumes at those entrance ramps they normally use (measured relative to the volumes normally existing at those ramps). This reduction also manifests itself in lower volumes at the downstream exit ramps normally used. Exit ramp volumes may also be reduced within and just downstream of freeway traffic queuing because of the slower rate at which freeway traffic destined for that ramp can reach it. Exit ramp volumes can also be higher, though, if other motorists destined for exit ramps farther downstream decide to leave the freeway early (although this change would further reduce traffic volumes at those downstream exit ramps or through the lane closure).

Changes in Entrance Ramp Volumes

Changes in entrance ramp volumes (measured relative to "normal" traffic demands) over the duration of the lane closure at each study site are shown in Table 3-2. The ramps at each site were categorized according to their relationship to the freeway queue that developed upstream of the lane closure. Ramps that were almost immediately engulfed by the queue once the closure was established were labelled with an "I" (inside the queue), whereas ramps which were always upstream of the beginning of the queue were labelled with a "U" (upstream of queue). If the ramp was initially upstream of the queue, but was eventually engulfed as the queue lengthened over time, it was labelled with a "U/I" (first upstream, then in, the queue). Also shown in Table 3-2 is the average change in ramp volume, measured over the duration of the lane closure at that site, and the percentage that change represents relative to the normal volumes at the ramp.

Considering the average changes in hourly volumes at the various ramps, one sees significant variation in the magnitude of changes which were observed. At the first eight sites where extensive congestion developed, reductions in ramp volumes ranged from 6 vehicles per hour (vph) to more than 700 vph. At the latter three sites, ramp volume changes were much more minor. In fact, one ramp at site 10 actually experienced a small increase in traffic (measured relative to normal conditions).

TABLE 3-2. ENTRANCE RAMP VOLUMES

Site	Ramp Number Upstream of Lane Closure	Location Relative to Queue	Average Volume Change (vph)	Average Volume Change (%)
1	1	I	-584	-79.0
	2	I	-203	-72.5
	3	U	-178	-16.2
	4	U	-143	-28.5
2	1	I	NA	NA
	2	U	NA	NA
	3	U	NA	NA
3	1	I	NA	NA
	2	I	NA	NA
	3	U	-165	-31.2
	4	U	-194	-25.3
4	1	I	NA	NA
	2	U	-93	-32.7
	3	U	NA	NA
	4	U	-197	-38.1
5	1	I	-536	-94.3
	2	I	-168	-80.5
	3	U/I	-438	-51.9
	4	U	NA	NA
6	1	I	-509	-59.2
	2	I	NA	NA
	3	I	NA	NA
	4	U	NA	NA
7	1	I	-356	-82.0
	2	U/I	-385	-65.4
	3	U	NA	NA
	4	U	-529	-60.5
8	1	I	-711	-82.6
	2	U/I	-218	-49.3
	3	U	-187	-31.3
	4	U	-6	-2.7
9	1	U/I	-7	-1.8
	2	U	-116	-17.2
10	1	U/I	-62	-10.9
	2	U	+31	+4.6
11	1	U/I	-74	-17.1
	2	U	-17	-3.3

I = in queue, U = upstream of queue, U/I = initially upstream but eventually within queue

NA = data not available

Although no clear trends are evident in terms of the changes in absolute volumes at each ramp, certain ramps displayed more consistency when the changes were converted to percentages. Overall, the percentage change at entrance ramps display two distinct patterns, depending upon whether the ramp is situated within the limits of freeway queuing or is located upstream of congestion. Those ramps located within the queue (labelled with an "I") experienced between a 59.2 and a 94.3 percent reduction in volume. If the ramp at Site 6 with the lower value is ignored, the range in volume changes among those ramps within the queue was narrowed to between 72.5 and 94.3 percent. The ramp at Site 6 is a freeway-to-freeway interchange, rather than a regular entrance ramp from the adjacent frontage road. Consequently, motorists could not see the congestion that existed on the freeway being entered, nor did they have an easily accessible alternative route if they decided not to use that ramp. Meanwhile, those ramps upstream of the queue experienced between 2.7 and 60.5 percent less traffic during the lane closures, with the change being less than 38.1 percent at eight of the nine upstream ramps for which data were available. At the latter three sites, the changes at upstream ramps were 17.2 percent or less.

The changes in the ramp volumes upstream of congestion are presumed to reflect the proportion of motorists who (1) know of or have an expectation of the congestion (and the lane closure) downstream, (2) intend to travel on the freeway to, or beyond, the region of congestion, and (3) who then choose to use a route other than the freeway. These changes in volume are likely due to a number of different factors, including newspaper and radio traffic reports warning some of the motorists of the downstream lane closure, previous motorist experiences with the lane closure (and congestion) earlier in the day, or visual observations made by some motorists as they travelled in the opposite direction on the freeway on the way to their destination (who then utilize a different route on their return trip).

This same type of diversion would also be expected at ramps located within the limits of the freeway queue immediately upstream of the lane closure. In addition, however, those motorists who come to the entrance ramp, find that it is queued, and then choose another route would further reduce volumes at these ramps. The greater reductions in volumes observed at those ramps in queue support this contention.

At some of the ramps, the throttling effect of the freeway queue may actually limit how many vehicles can use the ramp, with the added vehicles queuing on the ramp itself. In turn, these ramp queues may stimulate more motorists originally intending to use that ramp to divert as well. However, given the consistency of the percentage reductions in volumes at the various ramps in queue in most cases, the entrance ramp diversion appears to be in response to the perceived severity of freeway congestion rather than throttling of the entrance ramp volume and subsequent ramp queuing.

Changes in Exit Ramp Volumes

Changes in exit ramp volumes are even more complex to assess than those for the entrance ramps. First of all, exit ramp volumes are dependent upon upstream entrance ramp volumes, such that any volume reductions at entrances upstream also manifest themselves as lower exit ramp volumes downstream. Second, freeway queuing reduces the rate at which vehicles can reach the exit ramps in the queue or beyond the lane closure, further reducing volumes at those downstream ramps. Third, motorists already on the freeway may decide to exit prior to the ramp originally intended, increasing the volume at the exit ramp actually used and decreasing the volume at the original downstream exit ramp.

A summary of the changes in exit ramp volumes at each study site is provided in Table 3-3. Again, the ramps are categorized by site and by whether the ramp was located in or upstream of the freeway queue. The average hourly volume at each ramp measured during the lane closure is shown, along with the absolute change in hourly volumes at those ramps (relative to the "normal" ramp volumes at each). Changes in exit ramp volumes are not easily interpreted on a percentage basis. Unlike entrance ramps where diversion always results in a decreased ramp volume, diversion at exit ramps can result in increased volume at one or more ramps. Depending on the volume normally using the exit ramp, this increase can result in percentages much greater than 100.

The data in Table 3-3 suggest that exit ramps upstream of the freeway queuing tend to be only slightly affected by the lane closures. In general, there appears to be a slight reduction in exit ramp volumes at these upstream ramps, although ramps at a few of the sites actually showed slight increases in volumes. This is in contrast to the volumes observed at upstream entrance ramps, which were considerably lower than normal. Taken together, these data support a hypothesis that the motorists destined for exit ramps in the freeway queue or beyond are those not using the upstream entrance ramps, whereas those motorists with exits upstream of the freeway queue continue to use the upstream entrance ramps as normal.

TABLE 3-3. EXIT RAMP VOLUMES

Site	Ramp Number Upstream of Lane Closure	Location Relative to Queue	Average Volume During Lane Closure (vph)	Average Volume Change (vph)
1	1	I	412	-881
	2	I	409	+263
	3	I	1172	+719
	4	U	603	-11
2	1	I	1225	+671
	2	U/I	1522	+386
	3	U	514	-25
	4	U	433	-1
3	1	I	1646	+971
	2	U	1286	-434
	3	U	541	-19
	4	U	1144	-22
4	1	I	248	+110
	2	I	1141	+706
	3	U	572	-70
5	1	I	1668	+946
	2	U	764	-87
	3	U	999	+50
	4	U	564	NA
6	1	I	555	-240
	2	I	1603	+646
	3	U	841	NA
	4	U	620	NA
7	1	I	439	-416
	2	I	1482	+1234
	3	U	632	-93
	4	U	777	-30
8	1	I	1164	-281
	2	U/I	1203	+314
	3	U	222	-30
	4	U	690	-47
9	1	U	296	+85
10	1	U/I	540	+76
	2	U	285	0
11	1	U/I	643	-31
	2	U	153	+21

I = in queue, U = upstream of queue, U/I = initially upstream but eventually within queue

NA = data not available

Within the freeway queue, a fairly consistent pattern was evident in the exit ramp volumes. The ramp first encountered (the highest ramp number in queue) experienced an increase in volume, to near the estimated capacity of the ramp (i.e., 1500 to 1800 vph (10)). Meanwhile, those exit ramps farther into the queue (where there were some) did not display any particular trend on a ramp-by-ramp basis. However, the sum of the volume changes at all exit ramps within the queue at a given site always yielded a positive change (i.e., the total volumes exiting at the ramps in queue were always greater than normal). Given the fact that entrance ramp volumes upstream and within the queue were lower during the lane closure, the increased volumes at exit ramps in queue indicate that a portion of the freeway traffic destined for exits beyond the lane closure chose to leave the freeway early. The actual number of motorists choosing to do this, however, varied widely from site to site.

It appears that drivers approaching a freeway lane closure make a decision whether or not to attempt to exit at the first opportunity once they encounter congestion. Undoubtedly, this decision depends on several factors at the site as well as characteristics of the individual and the trip being made. Observations made at each site suggest that the volume at the first exit ramp encountered in the queue increases to the point of capacity. If, after saturating the first exit ramp, there are still some motorists on the freeway who desire to exit, they must then proceed to the next exit ramp. Whether or not all motorists desiring to exit at the first ramp can do so depends on how much additional traffic (above that intending to use that ramp anyway) the ramp can accommodate. In other words, exit ramps normally serving a high traffic demand will not be able to accommodate as many additional motorists desiring to exit as will a ramp which normally handles only a small amount of traffic.

Changes in Frontage Road Volumes

A continuous frontage road (a design used extensively in Texas) offers freeway motorists a convenient alternative route around freeway congestion. Furthermore, the motorist is able to directly assess conditions on the frontage road and compare them to those on the freeway (unlike alternative routes away from the freeway for which the motorist has no current information). Of course, as motorists divert to the frontage road, travel conditions on that roadway degrade (especially at the signalized intersections with cross-street traffic), which reduces its desirability as the alternative route.

Frontage road volumes were measured at selected points (usually adjacent to an entrance or exit ramp) at and upstream of the freeway lane closure at each site. Table 3-4 summarizes volumes recorded during the closures, and how these volumes changed from those measured under normal freeway conditions. The data reported was collected both far upstream of the lane closure, and also adjacent to where the lane closure taper ended on the freeway (taken to be the point of the lane closure bottleneck). For those sites where frontage road data upstream of the freeway congestion is available, little change was noted in volumes during the lane closure relative to normal conditions.

Meanwhile, measurements made near the location of the freeway lane closure bottleneck showed that frontage road volumes increased at all sites. Of the first eight sites, six experienced average volume increases on the frontage road at the lane closure bottleneck greater than 700 vph. However, these changes did not totally offset the reduced freeway flow past the lane closure bottleneck (recall from Table 2-1 that normal demands were two to four times the estimated work zone capacity). Frontage road volumes adjacent to the lane closure bottleneck also increased at the last three sites. Although the increases were not as large as observed at the first eight sites, they did account for a higher proportion of the changes in entrance and exit ramp volumes observed at these latter sites.

Summary

Field studies were conducted at eleven temporary work zone lane closures on urban freeways in Texas. Travel time, queue length and traffic volume data were collected during the lane closures and compared to those collected on days when the closures were not present. The analysis of these data yielded the following results:

1. At sites where normal traffic demands were two to four times the estimated work zone capacity, significant queuing and delays quickly developed on the freeway. The majority of queue growth (and delays) occurred in the first hour after the lane closure was initiated. In subsequent hours, the queues and delays remained fairly constant.
2. At sites where normal traffic demands were only 20 percent above the estimated work zone capacity, very little queuing and delay were observed. Any queuing that did develop quickly dissipated. Overall, it appeared that traffic demands were altered just enough to approximately match the work zone capacity over the duration of the closures.

TABLE 3-4. FRONTAGE ROAD VOLUMES

Site	Location	Average Volume During Closure (vph)	Average Change in Volume (vph)
1	Upstream At Bottleneck	405 1311	-50 +993
2	Upstream At Bottleneck	NA 2287	NA +1291
3	Upstream At Bottleneck	1050 2692	+37 +956
4	Upstream At Bottleneck	NA 956	NA +715
5	Upstream At Bottleneck	NA 1312	NA +826
6	Upstream At Bottleneck	NA 473	NA +380
7	Upstream At Bottleneck	128 1900	+33 +303
8	Upstream At Bottleneck	465 1299	-34 +843
9	Upstream At Bottleneck	730 641	-12 +180
10	Upstream At Bottleneck	NA NA	NA NA
11	Upstream At Bottleneck	52 364	-7 +102

NA = data not available

3. Frontage road delays recorded at all sites varied widely, and were not necessarily dependent upon the magnitude of freeway delays or the queue length. However, comparison of freeway and frontage road travel times over the distance of the freeway queue indicated that once the queue had developed, the frontage road provided slightly quicker travel times than did the freeway (measured to the point where the actual work zone began).

4. Entrance ramp volumes upstream of freeway queuing were significantly lower than normal at the first eight sites. However, the reductions were more substantial at entrance ramps located within the actual limits of freeway queuing than upstream. It is hypothesized that motorists travelling past the congestion and the lane closure in the opposite direction of travel and who normally return to their origin via the freeway may alter their travel paths on the return trip, resulting in the lower volumes entering upstream of the lane closure. If the ramp is located within the congestion that develops, additional changes in travel patterns are then made by those motorists who come to the ramp/freeway junction as they begin their trip, see the freeway congestion, and decide then to use another route.

5. Exit ramp volumes were only slightly affected upstream of congestion. Within congestion, the first exit ramp encountered by motorists experienced substantial increases in volume. Meanwhile, exit ramps farther into the queue did not display consistent trends, as volumes at some ramps increased whereas other ramps experienced decreased volumes. It is hypothesized that as motorists on the freeway encounter the upstream end of queue, a certain proportion will choose to leave the freeway early. If the number choosing to leave early is less than the available capacity of the first exit ramp, all these motorists can be accommodated (resulting in lower volumes exiting at downstream ramps in queue and beyond). However, if the number desiring to leave exceeds the available capacity of the first exit ramp, those unable to exit must continue to travel on the freeway until the next exit ramp is reached (increasing the volumes at the next exit ramp in queue). If no second exit ramp exists prior to the end of the queue, those motorists reaching the end of the queue may change their minds again and choose to remain on the freeway and continue their trips as planned.

6. Frontage road volumes upstream of the lane closure and the congestion that resulted were generally unchanged at each of the study sites. Conversely, measured at the point of the freeway lane closure bottleneck, frontage road volumes increased significantly at each site. However, the increases at the first

eight sites did not offset the reduction in freeway volumes past that location, indicating that a significant number of motorists selected other routes to their destinations rather than attempt to bypass the freeway congestion by using the frontage road.

4. ACCOUNTING FOR NATURAL DIVERSION IN THE QUEWZ COMPUTER MODEL

Overview of QUEWZ

In 1982, TTI developed the QUEWZ (Queue and User cost Evaluation of Work Zones) computer model under TxDOT-sponsored research to assist highway agency personnel in estimating the operational and economic impacts of alternative freeway lane closure strategies (11). This model has been updated and enhanced several times through the years in response to changing agency needs. Limited field testing and evaluation indicates that the model is a good analytical tool and provides reasonable estimates of the impacts at lane closure sites where normal traffic demands do not exceed the reduced roadway capacity through the work zone. Although an input-output analysis of traffic queuing characteristics used in the model when traffic demands exceed the reduced capacity is theoretically sound, it requires fairly accurate approach demands in order to provide realistic estimates of traffic queuing.

Since the model's inception, the difficulty has been in estimating the actual approach demands at a lane closure site where queuing is anticipated. Historical traffic volumes are typically used in the model as an estimate of the traffic demands at the work zone. As was shown in the previous chapter, natural diversion at each site can be quite extensive and result in actual traffic demands that are quite different from historical volumes.

An interim version of QUEWZ (12), submitted to TxDOT in 1987, included an empirical algorithm as the first attempt to account for the natural diversion which was being observed at work zones where queuing developed (but had not as yet been quantified). The major assumption of the algorithm was that motorists would tolerate a given amount of delay on the freeway before they would choose to divert rather than continue on the freeway. In other words, once delays reached some "threshold" value, motorists would divert from the freeway at a rate such that the threshold value was never exceeded. A delay value of 20 minutes was suggested as that threshold, based on values of acceptable delays used in previous work analyses (13-15), but the user of the model was given the opportunity to change that value if so desired. Another option provided in the diversion algorithm was the ability to specify a queue length threshold, with enough motorists diverting so that the freeway queue never exceeded the threshold value. Of course, no data were available to assist users in specifying a critical length of queue for urban freeways in Texas.

Recalling the queue length and delay profiles for the eleven study sites in Chapter 3, the first eight sites did appear to reach a threshold during the closures, rather than to continue to grow unbounded as would result if no diversion occurred. It was most noticeable in the queue lengths observed, but was also evident in the delay measurements (as would be expected, given that a direct correlation should exist between queues and freeway delay). These results suggest that a queue length or delay threshold algorithm may be a reasonable representation of the diversion process in QUEWZ. The applicability of this algorithm is assessed more objectively in the next section.

Delay and Queue Length Thresholds in QUEWZ

It was noted in Chapter 3 that the queues at Sites 1 through 8 (where significant queues did develop and continued to remain throughout the duration of the lane closure) grew dramatically during the first hour or two of the closure. In subsequent hours, however, the queue tended to remain fairly stable. Table 4-1 illustrates quantitatively how these queues stabilized, showing the average growth in queue during the first hour of the closure compared to the average growth during the remaining hours of the closure at each site. As can be seen, queue growth essentially stopped at five of the eight sites, and changes in queue length after the first hour were less than 0.1 miles per hour. The queue actually decreased throughout the duration of the closure at two sites. The only consistent queue growth after the first hour occurred at Sites 1 and 8, where queues there grew an average of 0.2 mph during subsequent hours. On a relative scale, however, even these growth rates were only one-fourth to one-tenth of the growth rates observed at these sites during the first hour of the closure.

Although the data indicate that the queues tended to stabilize after the first hour, it is apparent that they did not stabilize at the same length. In addition to the first hour and subsequent hour growth rates at each site, Table 4-1 also presents the maximum queue length observed during each closure. The maximum queue at Site 1, for instance, was more than twice as long as that observed at Site 2. Overall, maximum queues ranged from 1.1 miles to 2.3 miles in length. This wide range occurred despite the fact that all sites were located on the same freeway in the same general area of San Antonio.

TABLE 4-1. QUEUE GROWTH PATTERNS

Site	Queue Growth During First Hour	Average Queue Growth After First Hour	Average Queue Length Observed	Maximum Queue Length Observed
1	1.9 mph	0.2 mph	2.1 mi	2.3 mi
2	1.0 mph	0.1 mph	1.0 mi	1.1 mi
3	0.8 mph	0.1 mph	1.0 mi	1.2 mi
4	1.6 mph	0.1 mph	1.4 mi	1.8 mi
5	NA	-0.1 mph	1.4 mi	1.9 mi
6	1.3 mph	0.0 mph	1.4 mi	2.1 mi
7	1.0 mph	0.0 mph	1.3 mi	1.6 mi
8	0.7 mph	0.2 mph	1.2 mi	1.6 mi

Table 4-2 presents a comparison of freeway delay growth patterns. In general, the trends are similar to those of the queue lengths; namely, that the greatest increases in delay occur during the first hour of the closure, after which average changes in delay were quite small. As with the maximum queue length, maximum delays were extremely variable, ranging from 9.9 minutes to 34.4 minutes. Interestingly, the average of the maximum delays recorded at these sites is 20.3 minutes. Consequently, the data seem to support the 20 minute delay criteria used previously.

Whereas Tables 4-1 and 4-2 support the contention that queuing and delays reach a "threshold" at freeway work zone lane closures, it is also evident that the actual threshold values differ significantly from site to site. Undoubtedly, these differences are dependent upon the location and volumes using (or not using) the entrance and exit ramps upstream of the lane closure. As was shown in Chapter 3, all entrance ramps located within the extent of freeway queuing displayed dramatically lower volumes as motorists sought out alternative routes. To a lesser extent, entrance ramps upstream of the freeway queuing also displayed lower usage, as some motorists aware of the queued conditions downstream sought other routes rather than attempt to use the freeway.

Meanwhile, exit ramps within the queue also experienced changes in volumes. In most cases, the first exit ramp motorists encountered in the queue experienced a significant increase in volume to near the traffic-carrying capacity of the ramp. In some instances, volumes at the next exit into the queue also increased. Taken together, these changes in ramp usage altered the freeway flow characteristics to the point where the queue approached some degree of stability (i.e., a pseudo-equilibrium state).

TABLE 4-2. FREEWAY DELAY PATTERNS

Site	Delay Generated During 1st Hour	Average Delay Increase in Subsequent Hours	Maximum Delay Observed
1	20.7 min/hr	1.7 min/hr	25.7 min
2	5.9 min/hr	1.0 min/hr	9.9 min
3	9.9 min/hr	1.0 min/hr	15.1 min
4	8.1 min/hr	6.6 min/hr	21.3 min
5	14.4 min/hr	-1.3 min/hr	18.4 min
6	31.4 min/hr	-4.9 min/hr	34.4 min
7	6.7 min/hr	0.0 min/hr	15.1 min
8	3.8 min/hr	3.8 min/hr	22.8 min

The QUEWZ model itself does not allow for the direct consideration of ramp location or volumes in the queuing process. It was developed to be user-friendly and to require only a minimum of data. The model output provides a planning level estimate of the operational and road user cost impacts associated with alternative lane closure strategies. The freeway lane closure is treated as a simple bottleneck. The user provides freeway mainlane volumes expected at the lane closure, and an estimate of the reduced roadway capacity through the work zone (or the model selects the value by default).

Excess demands are assumed to be stored behind the closure in queue, as though trapped in a pipe.

Integration of the individual ramp features and their effects on the queuing process directly into the QUEWZ model would require a complete reformulation of the model. The simple input-output queuing approach would have to be abandoned for a more detailed (and data-intensive) link-node representation of roadway characteristics. Likewise, traffic volume input volumes for individual ramps would be needed. In general, the model would be forced to take on the features of the several traffic simulation models already in existence.

Although the interactions between ramps and the freeway queuing process are undoubtedly quite complex, it can be argued that it is the location of the ramps (and their frequency upstream of the lane closure) which is the most important. Certainly, as the number of ramps in a given section upstream of the lane closure increases, the more opportunities exist for traffic demands normally destined to pass through the lane closure bottleneck to leave the freeway (or to not enter) and take other routes. Conversely, if no ramps were present upstream of the closure, no diversion could take place and freeway queuing would be well represented using the input-output analysis already in QUEWZ. In actuality, the first eight study sites involving significant queuing were relatively consistent in the number of ramps (entrance or exit) that were engulfed by the queue. Table 4-3 illustrates the average ramp spacing upstream of the closure at each site, the number of ramps encompassed by the average queue and the maximum queues.

Although actual queue lengths were variable from site to site, the number of ramps engulfed by the freeway queue was very stable on a site by site basis. The consistency is even more evident if one considers Sites 1 and 6 separately. These sites were somewhat unique in that they were located immediately upstream or downstream of major freeway-to-freeway interchanges which altered the ability of motorists to change their travel routes on those particular ramps. Considering the remaining six sites together, one sees that the maximum length of queue engulfed between 3 and 5 ramps at each site. Similarly, the average length of queue consistently encompassed 3 ramps (only one site involved less than three ramps in queue).

From this data, a reasonable estimate of the queue length threshold at each site could be obtained by multiplying the average ramp spacing immediately upstream of the lane closure at a site by the number of ramps expected to be engulfed by the queue. As a conservative estimate of the amount of diversion which may occur, it is recommended that the number of ramps engulfed within the maximum queue length at all eight sites (i.e., approximately 5 ramps) be used to estimate the threshold. This would eliminate the need to decide whether the work zone being evaluated is likely to be influenced by nearby freeway-to-freeway interchanges.

TABLE 4-3. RAMPS WITHIN THE FREEWAY QUEUE

Site	Average Ramp Spacing Upstream Of Closure	Number of Ramps Within Average Queue Length	Number of Ramps Within Maximum Queue Length
1	2250	5	6
2	1650	3	3
3	2050	2	3
4	2225	3	5
5	2375	3	5
6	1750	4	6
7	2400	3	4
8	2100	3	4

It is recognized that these data come from only one freeway and represent only a limited database. However, for the purposes for which the QUEWZ model was intended (i.e., a planning-level analysis tool), it is believed that this approach provides a reasonable estimate of the maximum queuing anticipated at sites on urban circumferential freeways in Texas having continuous frontage roads. Intuitively, radial urban freeways may not experience as much diversion if trips are more long-distance in nature (i.e., suburban to CBD). Likewise, diversion may be less significant at sites without continuous parallel frontage roads adjacent to the freeway. Unfortunately, no data was collected on these types of freeway in conjunction with significant queuing to validate or refute this hypothesis. However, if the model user expected less diversion at these types of sites, the queue length threshold could be increased slightly above that estimated from the data reported here.

Traffic Demands At Lane Closures When Queues Are Not Present

Traffic conditions observed at the last three study sites suggest that, even in the absence of significant queuing on the freeway mainlanes, freeway traffic demand volumes at the lane closure tend to be slightly lower during the lane closure than would otherwise be expected based on historical traffic data at that location. Presumably, the traffic information sources available to motorists (newspaper reports, television and radio reports, word of mouth, or seeing the lane closure from the opposite direction of travel) have a small but consistent effect in terms of reducing mainlane traffic demands at the point of the lane closure bottleneck. At sites where historical traffic demands are only slightly above the expected capacity through the work zone, this reduction may be enough to detain or completely eliminate the onset of queuing on the freeway.

Table 4-4 presents mainlane volumes at the lane closure bottleneck at Sites 9 through 11 during the hours when the closure was present but no queuing had developed. These are compared to volumes expected during the same hours on a similar day when a lane closure was not present. Volumes at Sites 9 and 10 were about 5 percent lower than normally expected at those sites, even though no queuing had developed when these counts were taken. In comparison, volumes at Site 11 were actually as high as normal during the lane closure. However, it is possible that the normal data from this site, taken the week following the closure, were unusually low, due to stochastic variations in driver travel patterns. Traffic volumes taken almost two miles upstream of the lane closure at this site were nearly 25 percent higher the day of the closure than they were when the data representing normal travel conditions were taken. If one then compares the relative differences in volumes between the upstream and lane closure locations, volumes at this site would also be considered to be slightly lower during the closure relative to normal conditions.

To a limited extent, the changes in entrance ramp volumes far upstream of the freeway queue at sites 1 through 8 also support the contention that overall freeway demand volumes to the lane closure are lower than historical volumes would indicate. Regression analyses indicate that the magnitude of change in entrance ramp volumes upstream of the queue at these sites was most directly related to the proportion of traffic from that ramp assumed to be destined to pass through the work zone lane closure before exiting (based on previous ramp origin-destination data). Of course, the magnitude of change was much higher than the 5 percent at the latter three sites due to the significant queuing which was present.

TABLE 4-4. COMPARISON OF MAINLANE VOLUMES WITHOUT QUEUING

Site	Traffic Volume During Closure	Traffic Volume Expected	Change
9	15336	16237	-5.6%
10	13514	14087	-4.1%
11	4837	4798	+0.8%

Given that the database from sites without significant queuing is limited, caution must be used when interpreting the results of these studies. However, analysts of future work zone lane closures may wish to reduce historical volumes slightly to account for this type of diversion. At this time, a reduction of five percent appears warranted.

5. SUMMARY AND RECOMMENDATIONS

This report has documented the results of field studies performed at eleven temporary work zone lane closures on urban freeways in Texas. Travel times and volumes recorded on the freeway and frontage road during the closures were compared to data collected on similar days without closures. Eight of the studies were conducted at sites where the normal demand volumes on the freeway were two to four times the reduced capacity through the work zone; at three other sites, normal demands were only 20 percent greater than the reduced work zone capacity.

The studies showed that considerable diversion occurred at those sites where significant traffic queuing developed on the freeway. Some of this diversion occurred a substantial distance away from the area of congestion, as seen by reduced entrance ramp volumes upstream of congestion. Within the region of congestion, reductions in entrance ramp volumes were even greater and were relatively consistent from ramp to ramp and from site to site. Meanwhile, exit ramp volumes upstream of congestion were not affected to any appreciable degree. Within congestion, the first exit ramp tended to experience significant increases in volumes. It appeared that changes in exit ramp volumes farther into queue depended on the degree to which the first ramp could accommodate those motorists wishing to exit the freeway early. If most motorists wishing to exit could do so at the first exit ramp in queue, subsequent exit ramps experienced lower volumes. If not, those motorists wishing to exit but unable to (probably due to the capacity limitations of the first ramp) appeared to proceed to the second ramp and exit. In this case, volumes at the subsequent exit ramp increased.

Data from the three sites where significant queuing and delay did not develop still suggested that some diversion occurred. Freeway volumes past the work zone when no queue was present tended to be about 5 percent less than volumes at the same location and time on a similar day without a lane closure.

The studies also indicated that freeway queuing tended to reach a threshold level at most sites and remain at approximately those levels for the remainder of the closure. Although the point at which this threshold was reached (in terms of the actual queue length) varied by site, it was fairly consistent in the number of ramps engulfed in the queue prior to attaining that threshold. At the sites examined in this research, which represent travel patterns and conditions on circumferential urban freeways in Texas with continuous parallel frontage roads, the queue stabilized after encompassing a total of four to five entrance and exit ramps combined.

Based on the results from these studies, the diversion algorithm implemented in QUEWZ3 was retained. It is recommended that queue length be used as the default threshold value in the algorithm, and that adjustments to this default be estimated based on average ramp spacings upstream of the proposed lane closure. The data also indicate that traffic volumes at lane closure sites will be slightly lower than normal historical counts would indicate. The user may wish to reduce historical freeway demand volumes by five percent prior to analyzing a work zone using the QUEWZ model.

6. REFERENCES

1. Heathington, K.W., R.D Worall, and G.C. Hoff. "Attitudes and Behavior of Drivers Regarding Route Diversion." Highway Research Record No. 363. Highway Research Board, Washington, DC. 1971. pp. 18-23.

2. Huchingson, R., R. McNees, and C. Dudek. "Survey of Motorist Route-Selection Criteria." Transportation Research Record No. 643. Transportation Research Board, Washington, DC. 1977. pp. 45-48.

3. Huchingson, R. and C. Dudek. "Delay, Time Saved, and Travel Time Information For Freeway Traffic Management." Transportation Research Record No. 722. Transportation Research Board, Washington, DC. 1979. pp. 36-40.

4. Shirazi, E., S. Anderson, and J. Stesney. "Commuter's Attitudes Towards Traffic Information Systems and Route Diversion." Transportation Research Record No. 1168. Transportation Research Board, Washington, DC. 1988. pp. 9-15.

5. Stephanedes, Y.J., E. Kwon, and P. Michalopoulos. "Demand Diversion for Vehicle Guidance, Simulation, and Control in Freeway Corridors." Transportation Research Record No. 1120. Transportation Research Board, Washington, DC. 1988. pp. 12-20.

6. Khattak, A.J., J.L. Schofer, and F.S. Koppelman. "Factors Influencing Commuters' En Route Diversion Behavior in Response to Delay." Transportation Research Record No. 1318. Transportation Research Board, Washington, DC. 1991. pp. 125-136.

7. Krammes, R.A. and G.O. Lopez. Updated Short-Term Freeway Work Zone Lane Closure Capacity Values. Research Report FHWA/TX-92/1108-5. Texas Transportation Institute, College Station, TX. September 1992.

8. Dudek, C.L., C.J. Messer, and H.B. Jones "Study of Design Considerations for Real-Time Freeway Information Systems." Highway Research Record No. 363. Highway Research Board, Washington, DC. 1971. pp. 1-17.

9. Mahmassani, H.S. "Dynamic Analysis of Lane Closure Strategies." ASCE Journal of Transportation Engineering, Vol. 114, No. 4, July 1988. pp. 476-496.

10. Highway Capacity Manual. Special Report 209. Transportation Research Board, Washington, DC. 1985.

11. Memmott, J.L. and C.L. Dudek. A Model to Calculate the Road User Costs at Work Zones. Research Report No. FWHA/TX-83/20+292-1. Texas Transportation Institute, College Station, TX. September 1982.

12. Krammes, R. QUEWZ3. Technical Memorandum submitted to the Texas Department of Transportation. Texas Transportation Institute, College Station, TX. September 30, 1987.

13. Denney, R.W., Jr. and S.Z. Levine. "Developing a Scheduling Tool for work Zones on Houston Freeways." Transportation Research Record No. 979. Transportation Research Board, Washington, DC. 1984. pp. 7-11.

14. Levine, S.Z. and R.J. Kabat. "Planning and Operation of Urban Highway Work Zones." Transportation Research Record No. 979. Transportation Research Board, Washington, DC. 1984. pp. 1-6.

15. Roper, D.H., R.F. Zimowski, and A.W. Iwamasa. "Diversion of Freeway Traffic in Los Angeles: It Worked." Transportation Research Record No. 957. Transportation Research Board, Washington, DC. 1984. pp. 1-4.