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16. Abstract

Recommendations on estimating the capacity of short-term freeway work zone lane closures are presented. The recommendations are based upon 45 hours of capacity counts at 33 different work zones between 1987 and 1991. These new data indicate average capacities for short-term freeway work zone lane closures from 3 to 1 lanes and from 2 to 1 lanes that are significantly higher than older values reported in the 1985 *Highway Capacity Manual*.

A base capacity value of 1,600 pcphpl is recommended for all short-term freeway work zone lane closure configurations. Adjustments are recommended for the effects of the intensity of work activity, percentage of heavy vehicles in the traffic stream, and presence of entrance ramps near the beginning of the lane closure. It is recommended that the new base capacity value and adjustments be used in lieu of the current procedures in the 1985 *Highway Capacity Manual*.

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UPDATED SHORT-TERM FREEWAY WORK ZONE LANE CLOSURE CAPACITY VALUES

by

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and

Gustavo O. Lopez

Research Report 1108-5
Research Study Number 2-8-87/1-1108

Sponsored by

Texas Department of Transportation
in cooperation with
U. S. Department of Transportation, Federal Highway Administration

TEXAS TRANSPORTATION INSTITUTE
The Texas A&M University System
College Station, TX 77843

September 1992

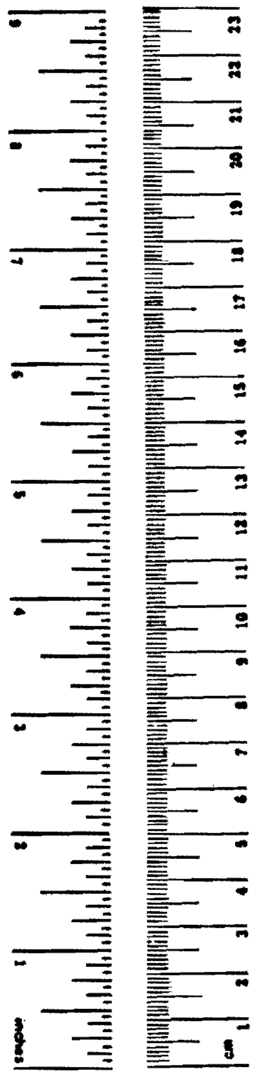
METRIC (SI*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
	LENGTH			
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			
in²	square inches	645.2	centimetres squared	cm ²
ft²	square feet	0.0929	metres squared	m²
yd²	square yards	0.836	metres squared	m²
mi²	square miles	2.59	kilometres squared	km²
ac	acres	0.395	hectares	ha
	MASS (weight)			
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
	VOLUME			
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft³	cubic feet	0.0328	metres cubed	m³
yd³	cubic yards	0.0765	metres cubed	m³

NOTE: Volumes greater than 1000 L shall be shown in m³.

	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C



APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
	LENGTH			
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			
mm²	millimetres squared	0.0016	square inches	in²
m²	metres squared	10.764	square feet	ft²
km²	kilometres squared	0.39	square miles	mi²
ha	hectores (10 000 m²)	2.53	acres	ac
	MASS (weight)			
g	grams	0.0353	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams (1 000 kg)	1.103	short tons	T
	VOLUME			
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m³	metres cubed	35.315	cubic feet	ft³
m³	metres cubed	1.308	cubic yards	yd³

	TEMPERATURE (exact)			
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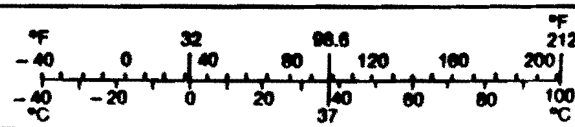

These factors conform to the requirement of FHWA Order 5190.1A.

* SI is the symbol for the International System of Measurements

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The authors gratefully acknowledge the cooperation and assistance of many Texas Department of Transportation personnel during the conduct of this study. Mark A. Marek (D-8) served as Technical Panel Chairperson. Lewis R. Rhodes, Jr. (D-18STO) and Steven Z. Levine (District 12) served as a Technical Panel Members. Numerous district and residency personnel in the Austin, Dallas, Fort Worth, Houston, and San Antonio districts assisted in identifying potential work zone capacity study sites.

SUMMARY OF FINDINGS

This report is the fifth interim report prepared under Study No. 2-8-87/1-1108 "Traffic Pattern Assessment and Road User Delay Costs Resulting from Roadway Construction Options." Previous reports were:

- o Report 1108-1 "Travel Impacts of Freeway Reconstruction: Synthesis of Previous Experience"
- o Report 1108-2 "Analysis of Accidents at Long-Term Construction Projects in Texas"
- o Report 1108-3 "Travel Impacts of Urban Freeway Reconstruction Projects in Texas"
- o Report 1108-4 "Travel Impacts of the US-59 Southwest Freeway Reconstruction Project in Houston"

This report reviews previous studies of work zone capacity, summarizes the analysis of new capacity data collected as part of Study 1108, and presents recommendations for estimating the capacity of short-term freeway work zone lane closures. The new data indicate significantly higher average capacities for closures from 3 to 1 lanes and from 2 to 1 lanes than older values reported in the 1985 *Highway Capacity Manual*. Therefore, it is important that these more current values be incorporated into the Department's lane closure planning and scheduling activities. The recommendations for estimating capacity include a base capacity value of 1,600 passenger cars per hour per lane and adjustments for the intensity of work activity, the percentage of heavy vehicles in the traffic stream, and the presence of entrance ramps near the beginning of the lane closure.

IMPLEMENTATION STATEMENT

It is recommended that the new base capacity value and adjustments be used in lieu of the current procedures in the 1985 *Highway Capacity Manual* for estimating the capacity of short-term freeway work zone lane closures. It is also recommended that these values be incorporated into the revised version of QUEWZ that is also being developed as part of Study 1108.

DISCLAIMER

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1. INTRODUCTION

This report presents new data on the traffic-handling capacity of short-term freeway work zone lane closures. The data were collected between 1987 and 1991 as part of Study 1108 "Traffic Pattern Assessment and Road User Delay Costs Resulting from Roadway Construction Options." It is recommended that the new capacity values presented herein be used in lieu of the older values in Chapter 6 of the 1985 *Highway Capacity Manual* (*1*), which were based upon data collected in Texas during the late 1970s and early 1980s (*2*, *3*). The new values are higher than the older values, which has important implications for planning and scheduling work zone lane closures.

The remainder of this chapter discusses the uses of work zone capacity values and synthesizes previous research on work zone capacity. Chapter 2 presents the new capacity values and compares them with the older values. Chapter 3 provides recommendations for estimating work zone capacity.

USES OF WORK ZONE CAPACITY VALUES

Maintenance and construction projects should be conducted in a manner and at a time that minimizes the total cost of the project. The two principal components of the total cost of a project are: (1) the costs of administering and performing the required work, and (2) the increased vehicle operating and delay costs associated with decreased levels of service through the work zone.

In the past, the first component may have been of primary concern. More recently, however, minimizing the impacts of freeway work zone lane closures on the motoring public has been an important goal of the Texas Department of Transportation. Examples of efforts toward achieving this goal include the procedures used in Houston for scheduling lane closures and the provisions in most urban freeway reconstruction projects throughout the state limiting lane closures to off-peak periods only. Several research efforts have also been funded to monitor the traffic impacts of maintenance and construction activities, develop corridor traffic management planning guidelines for freeway reconstruction projects, and evaluate contract bidding strategies that incorporate motorist cost considerations.

The traffic-handling capacity of a work zone is the principal determinant of the magnitude of the traffic impacts of a work zone on a given section of freeway during a given time period and given prevailing traffic demands. If the capacity exceeds prevailing demand, then delays are likely to be minimal. When demand exceeds capacity, however, queues form and delays may be significant.

Demand-capacity analysis is an important step in planning and scheduling freeway work zone lane closures. The analysis may be performed manually or by computer. QUEWZ is a computer program developed under TxDOT sponsorship for performing Queue and User Cost Evaluations of Work Zones. The new capacity values presented herein will be incorporated into the revised version of QUEWZ that is also being developed as part of Study 1108.

PREVIOUS RESEARCH ON WORK ZONE CAPACITY

Chapter 6 of the 1985 *Highway Capacity Manual* presents the best available work zone capacity values and outlines manual procedures for demand-capacity analysis of work zones. Most of the values presented are drawn from capacity studies conducted during the late 1970s and early 1980s by the Texas Transportation Institute under TxDOT (then State Department of Highways and Public Transportation) sponsorship. In fact, the tables and figures presented in the *Highway Capacity Manual* are identical to those presented in Research Reports 228-6 (*2*) and 292-6F (*3*). Capacity data are presented for both short-term maintenance work zones and long-term construction sites.

Short-Term Maintenance Work Zones

The results from the previous capacity studies in Texas suggest that the capacity of a short-term maintenance work zone with a work crew at the site is most significantly influenced by the lane closure configuration. The configuration is designated [A,B], where A represents the normal number of lanes in one direction, and B represents the number of lanes open through the work zone.

Figure 1 illustrates the observed work zone capacities for each lane closure configuration. Considerable variability is observed in the capacities for a given lane closure configuration. This variability may be explained by differences in the type and intensity of work activity, the proximity of the work activity to traffic, traffic composition (percentage of heavy vehicles), the cross section of the traveled way (lane width and lateral clearance to obstructions), and the alignment (percent grade and degree of horizontal curvature). There were not sufficient data to quantify the effect of these factors, and, therefore, the capacity values presented represent averages for a given configuration over a range of work, traffic, and geometric conditions.

Table 1 summarizes the average capacities in vehicles per hour (vph) observed in Texas during the late 1970s and early 1980s for each configuration (*1-3*). The capacities represent full-hour volume counts in a work zone lane closure while traffic was queued upstream of the lane closure.

Table 1 also includes the average percentage of heavy vehicles (i.e., trucks, buses, and recreational vehicles) and the calculated average capacity in passenger cars per hour per lane (pcphpl) for those configurations for which traffic composition data were available. The average capacities in pcphpl were computed using a passenger car equivalent of 1.7 passenger cars per heavy vehicle, as recommended in the 1985 *Highway Capacity Manual* for trucks on freeway segments in level terrain. Adjusting for the percentage of heavy vehicles narrows the range of average capacities among the lane closure configurations.

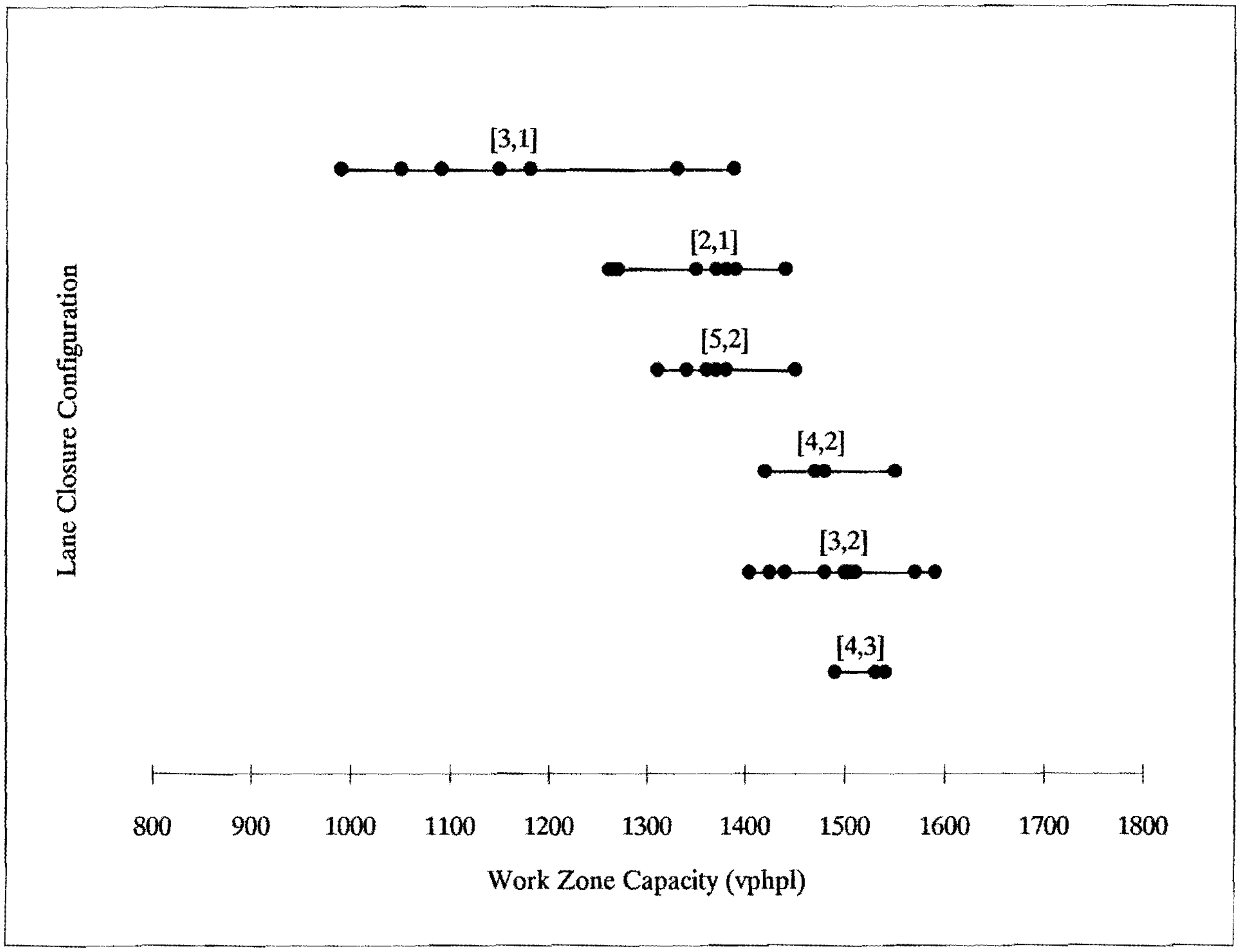

Figure 1. Previously Observed Short-Term Freeway Work Zone Lane Closure Capacities (*1*)

TABLE 1. SHORT-TERM FREEWAY WORK ZONE AVERAGE PER-LANE CAPACITY BY LANE CLOSURE CONFIGURATION

Lane Closure Configuration [Normal, Open]	Number of Studies	Average Capacity (vphpl)	Average Percentage of Heavy Vehicles	Average Capacity (pcphpl)
[3,1]	7	1170	18.7	1320
[2,1]	8	1340	7.8	1410
[5,2]	8	1370	7.8	1450
[4,2]	4	1480	--	--
[3,2]	9	1490	6.6	1560
[4,3]	4	1520	--	--

Table 2, which is derived from Table 6-3 in the 1985 *Highway Capacity Manual*, combines California data collected during the late 1960s with the Texas data collected during the late 1970s and early 1980s (in parentheses). The California data were stratified by lane closure configuration and type of work. The California data "are only a guide since they were determined from a very limited amount of data ... by taking several 3-minute counts after lanes are closed (under congested conditions)" (*4*).

TABLE 2. SHORT-TERM FREEWAY WORK ZONE AVERAGE PER-LANE CAPACITY (VPH) BY LANE CLOSURE CONFIGURATION AND TYPE OF WORK

Type of Work	Lane Closure Configuration (Normal, Open)				
	[3,1]	[2,1]	[5,2]	[4 or 3,2]	[4,3]
Median Barrier/Guardrail Installation/Repair	--	1500[1]	--	1600 (1470)[2]	1600 (1523)
Pavement Repair	1050	1400	--	1500 (1450)	1500
Resurfacing, Asphalt Removal	1050	1200 (1300)	-- (1375)	1300 (1450)	1333
Striping, Slide Removal	--	1200	--	1300	1333
Pavement Markers	--	1100	--	1200	1200
Bridge Repair	-- (1350)	-- (1350)	--	1100	1133

[1] California data reported by Kermode and Myyra (*4*)
[2] Texas data reported by Dudek and Richards (*3*)

The data in Table 2 suggest that the type of work affects the work zone capacity. For example, capacities are lower for pavement marker placement and striping, which occur close to the open travel lanes, and for resurfacing and bridge repair, which typically involve more equipment and workers; whereas, capacities are higher for median barrier/guardrail installation/repair, which occur further from the open travel lanes, and for pavement repairs, which typically involve less equipment. Unfortunately, the available data are not sufficient to quantify the relationship between the intensity of work activity and the adjustment to the base capacity value.

A study of traffic characteristics at four [2,1] lane closures in Illinois also evaluated the effect of the intensity and location of work activity on mean speeds through a work zone (*5*). The results suggest that mean speeds decrease as the intensity of work activity increases. Work intensity was quantified using an index based upon the number of workers, size of equipment, presence of flaggers, and noise and dust levels at the site. Mean speeds also decreased as the work activity moved closer to the travel lanes. A 2 mph drop in mean speeds was observed for every 3 ft shift of work activity closer to the travel lanes.

Further evidence of the effect of the intensity of work activity is the reported capacity data in the 1985 *Highway Capacity Manual* for one [4,2] work zone in Texas at which no work was underway in the lane adjacent to the open travel lanes, providing a buffer lane between the work activity and traffic. The capacity of this work zone was estimated at 1,800 vphpl, which is considerably larger than the average value for [4,2] lane closures.

Other previously published data on short-term work zone lane closure capacity are limited. The only other known data are from a Federal Highway Administration study for which capacities were measured at two [2,1] lane closures (*6*). Capacities of 1,060 and 950 vph were observed; these values correspond to approximately 1,160 and 1,060 pcph (using a passenger car equivalent for trucks of 1.7). These values were deemed unusually low due to "the very unusual equipment and construction operation in combination with the narrow travelway" at the site.

Long-Term Construction Zones

The 1985 *Highway Capacity Manual* includes data on 10 long-term construction zones at which the work activity area is separated from traffic by portable concrete barriers. Table 3 summarizes these data. As with the short-term work zone capacities reported in the *Manual*, the data for long-term construction zones were collected in Texas. Average capacities are reported in vphpl; the percentage of trucks was not reported and, therefore, capacities in pcphpl could not be computed.

TABLE 3. CAPACITY OF LONG-TERM CONSTRUCTION SITES WITH PORTABLE CONCRETE BARRIERS

Lane Closure Configuration	Number of Studies	Average Capacity (vphpl)
[3,2]	7	1,860
[2,1]	3	1,550

Data for one long-term [2,1] construction zone in Pennsylvania indicates a capacity of 1,200 vphpl (with 9 percent trucks) or approximately 1,275 pcphpl (*7*). This observation falls within the range of capacities observed in Texas for short-term maintenance work zones and reported in the 1985 *Highway Capacity Manual.*

Capacity data were also reported in two FHWA studies for a limited number of long-term construction zones in which a crossover configuration was employed. One study reported capacities for two work zones at which the capacities were 1,450 and 1,550 vph in the crossover direction and 1,720 and 1,800 vph in the opposite direction (*8*). The other study reported capacities for five work zones with capacities ranging from 1,030-1,600 pcph in the crossover direction and 1,520-1,910 pcph in the opposite direction (*6*).

2. NEW SHORT-TERM WORK ZONE CAPACITY VALUES

This chapter summarizes the new data on short-term freeway work zone lane closure capacity that were collected as part of Study 1108. First, the data collection methodology is described. Next, the new data are presented and then compared with the older values reported in the 1985 *Highway Capacity Manual*. Finally, a study of the effect of lane closure placement relative to entrance ramps is discussed.

DATA COLLECTION METHODOLOGY

The data reported herein represent more than 45 hours of capacity counts at 33 different freeway work zones with short-term lane closures. Data were collected for 5 different lane closure configurations: [3,1], [2,1], [4,2], [5,3], and [4,3]. More than 15 hours of data collected at 8 additional sites were excluded from the analysis because they violated requirements described below. Attempts to collect data at a number of additional sites were unsuccessful due to problems with work zone and/or traffic conditions or inclement weather.

All sites at which data were collected were short-term lane closures. Most were maintenance work zones, although several were short-term, off-peak lane closures at long-term reconstruction projects. All of the work zones were in general compliance with the Texas *Manual on Uniform Traffic Control Devices* (*9*). Standard channelizing devices were used at the lane closures (i.e., traffic cones, drums, or vertical panels).

All capacity counts were taken as vehicles entered the beginning of the lane closure through the channelizing taper. The count location is illustrated in Figure 2. Data were used only for time periods during which traffic was queued upstream of the lane closure. Therefore, the capacity counts represent the rate at which vehicles, discharge from the upstream queue, merge into the reduced number of lanes through the taper, and enter the lane closure. Sites at which ramps were located within the taper were not analyzed.

In previous work zone capacity studies, some capacity data were collected at points within the work zone (other than the beginning of the lane closure) at which traffic flow appeared to be most constrained. At some such sites, there were intervening ramps between the beginning of the closure and the capacity count location; in these cases, the counts within the work zone would differ from the queue discharge rate entering the beginning of the lane closure by the volume of traffic entering or exiting at the intervening ramps. A number of the capacity counts during the early stages of Study 1108 were collected similarly; these data, however, were excluded from the analysis for reasons discussed below.

In this study, it was determined that capacity counts should be taken only at the beginning of the lane closure for the following reasons:

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

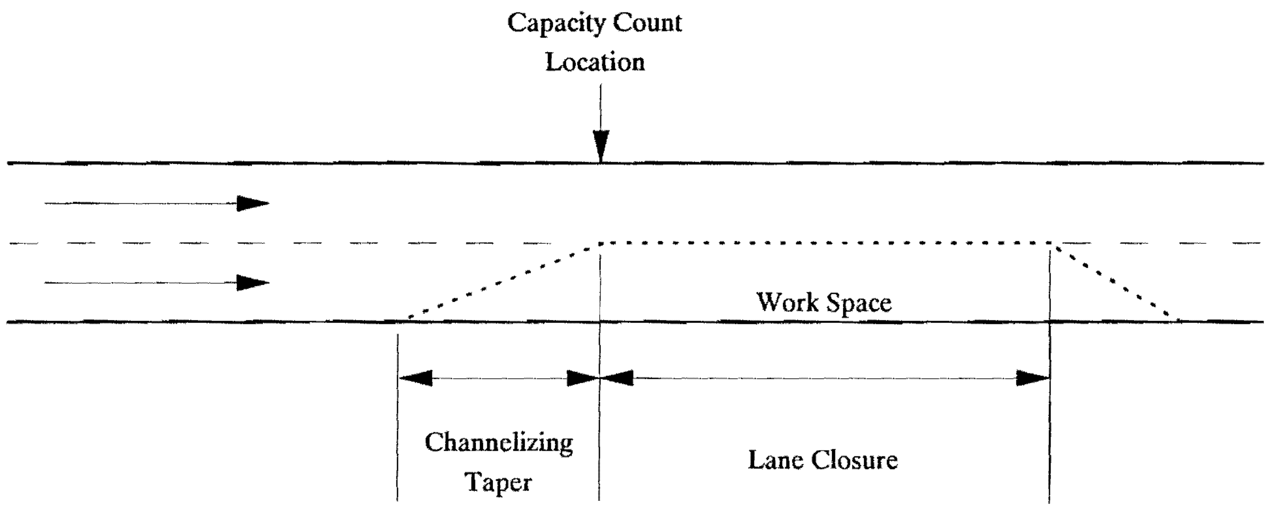

Figure 2. Work Zone Capacity Count Location at the Downstream End of the Channelizing Taper / Beginning of the Lane Closure

Counting capacity only at the beginning of the lane closure eliminates the variability among sites due to differences in the number and traffic volumes of ramps within the work zone. Although sufficient data are not available to test for statistical significance, it appears that entrance ramps within the taper area or immediately downstream of the beginning of a work zone lane closure reduce both the queue discharge rate entering the upstream end of the lane closure and the merging capacity of the entrance ramp. In this report, therefore, it is recommended that the base capacity value represent conditions where the impacts of ramps are negligible, and that the effect of ramps be treated separately.

Debate on the definition, measurement, and value of freeway capacity has heightened in recent years as work progresses toward a new edition of the *Highway Capacity Manual*. Currently, the general concensus appears to be that freeway capacity should be defined and measured as the mean queue discharge rate entering a freeway bottleneck (*10*). The mean queue discharge rate over an extended continuous time period (e.g., one or more hours) or for multiple time intervals over several days is recommended. This definition can be applied directly to freeway work zone lane closure capacity and was adopted for this study. A similar definition was used in the previous capacity studies in Texas (*2*, *3*), in that full-hour volumes were used as capacity values. The principal difference between Study 1108 and previous studies in this regard is the treatment of sites where several hours of capacity counts were taken. In the previous studies, each hourly volume was considered as a separate capacity study or observation. Whereas, in Study 1108, the capacity was taken as the average flow rate during the entire period (i.e., several hours of capacity counts at a site were averaged and considered as one capacity study or observation). The approach adopted in Study 1108 is more consistent with the current definition of capacity and more appropriate for statistical analysis purposes than the previous approach.

A principal use of the capacity values recommended herein is as an input to demand-capacity analysis as implemented in the QUEWZ model. Therefore, it is imperative that the values be consistent with the assumptions and analysis approach used in QUEWZ. QUEWZ models a work zone lane closure as a simple bottleneck with all traffic entering at the upstream end and exiting at the downstream end. QUEWZ has no provision for considering ramps within the work zone. The traffic volume inputs to QUEWZ generally are the historical demands on the freeway segment in which the work zone is located. The most critical analysis is estimating the extent of queuing upstream of the work zone when demand exceeds capacity. Therefore, the capacity used in QUEWZ should be the rate at which vehicles can enter the upstream end of the lane closure.

OBSERVED CAPACITIES

The new capacity data for short-term freeway work zone lane closures are presented in Appendix A. Table 4 summarizes the new data. A comparison of Table 4 with the corresponding older values in Table 1, indicates that for the [3,1] and [2,1] lane closure configurations the averages (in both vphpl and pcphpl) for the new data are significantly higher than for the old data (based upon a t-test at a 0.05 significance level). For the other configurations, the averages of the old and new data are not significantly different. The higher observed capacities might be attributable to better and more consistent work zone traffic control and a driving population more experienced with work zone lane closures.

TABLE 4. NEW DATA ON THE CAPACITY OF SHORT-TERM LANE CLOSURES AT FREEWAY WORK ZONES

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

[1] Calculated using a passenger car equivalent for heavy vehicles of 1.7.

The average capacities for the five lane closure configurations for which new data are available range only from 1,588 to 1,629 pcphpl--a difference of only 41 pcphpl. When the statistical procedure analysis of variance was performed on the data summarized in Table 4, the results indicated that there were no statistically significant differences among the average capacities in pcphpl for the five lane closure configurations (at a 0.05 significance level).

The overall average capacity (for all lane closure configurations combined) is approximately 1,600 pcphpl. This value compares logically to the capacities of 2,200 pcphpl for freeways and multilane highways and of 1,800 pcphgpl for signalized intersections, which represent the queue discharge rates under ideal conditions for the corresponding facility type.

The peak hour factor is the ratio of the hourly capacity divided by the highest 15-min flow rate. The relatively high average peak hour factors (ranging from 0.92 to 0.96) suggest that, although some variability exists at a site over time, the average capacities are reasonably stable.

Figure 3 illustrates the range among the capacities observed at individual work zones. Across all lane closure configurations, capacities ranged between 1,414 and 1,741 pcphpl (with one value of 1,913 pcphpl). The data collected as part of Study 1108 together with observations from previous studies suggest that factors contributing to below-average capacities include unusual or unusually intense work activities and the presence of ramps within the taper area or immediately downstream of the beginning of the lane closure. These factors distract the driver and complicate the driving task more than the "average" work zone and, as a result, reduce the efficiency of traffic flow. Unfortunately, the available data are not sufficient to quantify the magnitude of these factors' capacity-reducing effect.

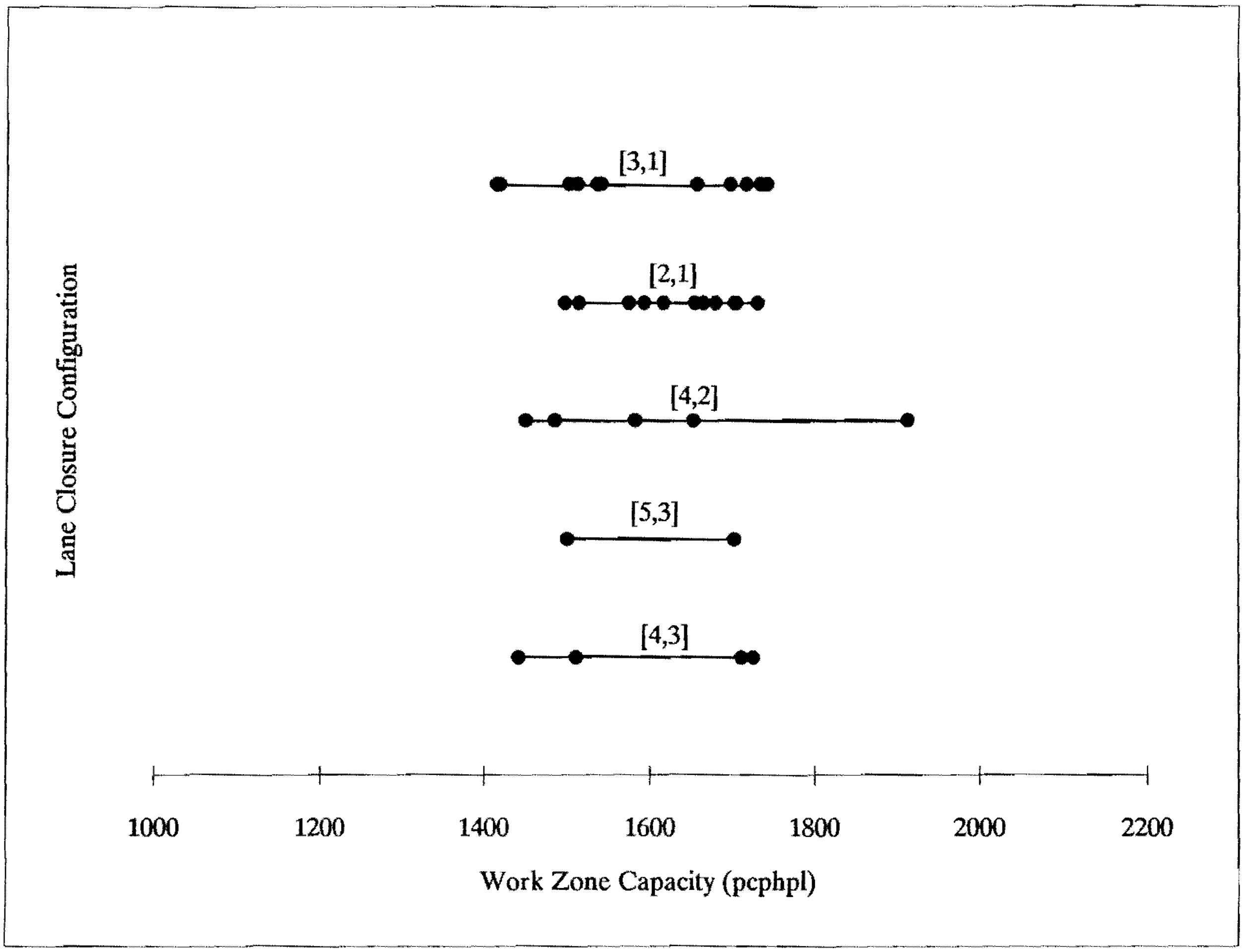

Figure 3. Recently Observed Short-Term Freeway Work Zone Lane Closure Capacities

EFFECT OF LANE CLOSURE PLACEMENT RELATIVE TO ENTRANCE RAMPS

The capacity of a work zone is typically limited by the efficiency with which vehicles can discharge from the upstream queue, merge into the reduced number of travel lanes, and enter the lane closure. Ramps within a work zone, especially entrance ramps near the beginning of the lane closure, create additional turbulence that further reduces the efficiency with which the traffic stream can enter the work zone.

In some cases the most constrained point within the work zone with respect to traffic throughput may be some distance downstream of the beginning of the lane closure. Examples include a high volume entrance ramp or an unusual or unusually intense work area within the lane closure which cause queueing upstream beyond the beginning of the lane closure. These cases are not common and are not treated herein.

Traffic delays through work zones can be minimized by maximizing the total vehicular throughput of the work zone. Vehicles may enter the work zone either from the upstream end or through entrance ramps within the work zone.

Although sufficient data are not available to test for statistical significance, three general observations can be made, based upon the data collected during Study 1108 and previous studies, about the effect of lane closure placement relative to entrance ramps on the total vehicular throughput of a work zone:

1. Even though vehicles may be entering the beginning of a lane closure at its capacity, as vehicles release from the queue and accelerate at varying rates through the lane closure gaps develop in the traffic stream that are large enough for additional vehicles to enter the lane closure from entrance ramps downstream from the beginning of the lane closure.

2. Entrance ramps either within the taper area or a short distance downstream from the beginning of the lane closure appear to reduce the queue discharge rate entering the upstream end of the lane closure (because of the turbulence created by ramp vehicles forcing their way into inadequate gaps in the mainlane traffic stream), whereas entrance ramps further downstream within the work zone appear to have less impact.

3. Fewer vehicles can enter the work zone from an entrance ramp close to the beginning of the work zone without disrupting the mainlane traffic stream (because of the uniformity of the headways in the traffic stream near the queue discharge point) than from a ramp further downstream (where the traffic stream is more dispersed).

These observations suggest that the location of the channelizing taper and beginning of the lane closure relative to entrance ramps influences the total throughput of the work zone. In some situations, there is flexibility to adjust the location of the beginning of the lane closure in a manner that can increases total vehicular throughput. Therefore, a detailed study was undertaken at one work zone to analyze the effect of the placement of freeway work zone lane closures relative to entrance ramps based upon ramp merging capacity.

The basic approach was to study the distribution of headways at the beginning of the lane closure and at various points within the work zone (500, 1,000, and 1,500 ft downstream from the beginning of the lane closure). Gap acceptance procedures developed by Drew (*11*) were applied to estimate the entrance ramp merging capacity based upon the observed headway distributions. This section summarizes the study results. Lopez (*12*) provides complete documentation of the study.

Although the mean time headway (the inverse of the flow rate) within a lane closure remains constant, unless or until the flow rate changes due to entering or exiting traffic, the distribution of headways changes as vehicles in the traffic stream release from the queue and accelerate at varying rates. At the work zone studied, the headways at the beginning of the lane closure and 500 ft downstream from the beginning were relatively uniform (as evidenced by a large K parameter for the best-fitting Erlang distribution). Whereas, by a point 1,000 ft downstream, headways approached a random distribution (as evidenced by a K parameter approaching 1 for the best fitting Erlang distribution). For a given mean time headway, a more random distribution has more individual headways large enough for ramp vehicles to merge into without disrupting the mainlane traffic stream. Conversely, a more uniform the headway distribution has fewer such individual headways.

These findings regarding the change in headway distributions within a work zone support the three observations stated earlier. Near the beginning of a lane closure there are fewer headways large enough for ramp vehicles to merge into without disrupting the mainlane traffic stream, whereas further downstream there are more headways adequate for use by entrance ramp vehicles. More ramp vehicles can enter a work zone with less disruption to the mainlane traffic stream (and, therefore, with less effect on the queue discharge rate entering the upstream end of the lane closure) at an entrance ramp further downstream of, rather than closer to, the beginning of the closure.

Therefore, if conditions permit, it is desirable to locate the lane closure such that any entrance ramps within the work zone are as far as possible (preferably at least 500 ft) downstream from the beginning of the lane closure while at the same time avoiding ramps within the channelizing taper.

3. RECOMMENDATIONS FOR ESTIMATING THE CAPACITY OF SHORT-TERM FREEWAY WORK ZONE LANE CLOSURES

This chapter summarizes the recommendations for estimating the capacity of short-term freeway work zone lane closures. The recommendations include a base capacity value and a series of adjustments to that base value.

RECOMMENDED BASE WORK ZONE CAPACITY VALUE

The capacity data collected during Study 1108 suggest that it would be appropriate to use the overall average capacity of 1,600 pcphpl as the base capacity value for short-term freeway work zone lane closures, regardless of the lane closure configurations. This value is based upon work zones whose traffic control is in compliance with the *Manual on Uniform Traffic Control Devices*.

The recommendation of a single base capacity value departs from previous procedures which recommended a different base value in vph for each lane closure configuration. The new data reported in Chapter 2, however, indicate that after adjusting for the percentage of heavy vehicles, there were no statistically significant differences among the average capacities of the five lane closure configurations observed. The use of a single base value is also consistent with the other procedures in the 1985 *Highway Capacity Manual*. Furthermore, the value of 1,600 pcphpl relates logically to the base capacity values used in those procedures.

ADJUSTMENTS TO THE BASE WORK ZONE CAPACITY VALUE

The recommended base value of 1,600 pcphpl represents the average of all recently observed work zone capacities. Figure 3 illustrates that the capacities of individual work zones fell within a range of approximately $\pm$ 10 percent of 1,600 pcphpl. Therefore, when certain conditions are present, the base capacity value should be adjusted for better predictions. Recommendations are made on adjustments for the intensity of work activity, effect of heavy vehicles, and presence of entrance ramps.

Adjustment for the Intensity of Work Activity

Research results were presented in Chapter 2 which suggest that work zone capacity decreases as the intensity of work activity increases. Work zone capacity also may be decreased when the type of work activity is unusual and causes more rubbernecking than a more common activity. The intensity of work activity increases with the number and size of work vehicles, the number of workers, the magnitude of noise and dust, and the proximity of work to the open travel lanes. In Table 2, for example, capacities were lower than average for work that occurs close to the open travel lanes and that involves more and larger equipment and workers; whereas, capacities were higher than average for work that occurs further from the open travel lanes and that requires less and smaller equipment.

Unfortunately, the available data are not sufficient to quantify the relationship between the intensity of work activity and the adjustment to the base capacity value. Therefore, the only guidance that can be provided is to adjust the base capacity value up or down within the $\pm$ 10 percent (160 pcphpl) range for work activities that are significantly more minor or more intense than average.

Adjustment for the Effect of Heavy Vehicles

It is recommended that the heavy vehicle adjustment factors in the 1985 *Highway Capacity Manual* be used to account for the effect of heavy vehicles. The heavy vehicle adjustment factor H is calculated as follows:

$$H = \frac{100}{[100 + P \times (E - 1)]}$$

where,

H	=	heavy vehicle adjustment factor (vehicle/passenger car)
P	=	percentage of heavy vehicles (%)
E	=	passenger car equivalent (passenger cars/heavy vehicle)

A passenger car equivalent of 1.7, which is recommended in the 1985 *Highway Capacity Manual* for trucks on freeway segments in level terrain, was used convert the observed capacity counts and percentage of heavy vehicles to capacities in pcphpl. Reference should be made to the *Highway Capacity Manual* for passenger car equivalent values for rolling or mountainous terrain and for extended individual grades.

Table 5 provides heavy vehicle adjustment factors for passenger car equivalents ranging from 1.5 to 6 and percentages of heavy vehicles ranging from 1 to 25. The range of passenger car equivalents covers the terrain types and individual grades that are likely to be encountered on a freeway.

Adjustment for the Presence of Ramps

In demand-capacity analysis, care must be taken to appropriately adjust either demand or capacity for the presence of ramps. The upstream end of the channelizing taper should be used as the reference point for estimating both demand and capacity. That is, the demand used for analysis purposes should be the hourly volume of vehicles that attempt to enter at the beginning of the lane closure, and capacity is the hourly rate at which vehicles actually can enter.

Typically, historical mainlane volume data are used to estimate the approach demand volume. If there are ramps between the mainlane count location and the beginning of the lane closure, then the mainlane counts should be adjusted by exit and entrance ramp volumes to estimate the mainlane volume at the beginning of the lane closure.

TABLE 5. HEAVY VEHICLE ADJUSTMENT FACTORS *H*

Percentage of Heavy Vehicles *P*	Passenger Car Equivalent *E*						
	1.5	1.7	2	3	4	5	6
1	1.00	0.99	0.99	0.98	0.97	0.96	0.95
2	0.99	0.99	0.98	0.96	0.94	0.93	0.91
3	0.99	0.98	0.97	0.94	0.92	0.89	0.87
4	0.98	0.97	0.96	0.93	0.89	0.86	0.83
5	0.98	0.97	0.95	0.91	0.87	0.83	0.80
6	0.97	0.96	0.94	0.89	0.85	0.81	0.77
7	0.97	0.95	0.93	0.88	0.83	0.78	0.74
8	0.96	0.95	0.93	0.86	0.81	0.76	0.71
9	0.96	0.94	0.92	0.85	0.79	0.74	0.69
10	0.95	0.93	0.91	0.83	0.77	0.71	0.67
11	0.95	0.93	0.90	0.82	0.75	0.69	0.65
12	0.94	0.92	0.89	0.81	0.74	0.68	0.63
13	0.94	0.92	0.88	0.79	0.72	0.66	0.61
14	0.93	0.91	0.88	0.78	0.70	0.64	0.59
15	0.93	0.90	0.87	0.77	0.69	0.63	0.57
16	0.93	0.90	0.86	0.76	0.68	0.61	0.56
17	0.92	0.89	0.85	0.75	0.66	0.60	0.54
18	0.92	0.89	0.85	0.74	0.65	0.58	0.53
19	0.91	0.88	0.84	0.72	0.64	0.57	0.51
20	0.91	0.88	0.83	0.71	0.63	0.56	0.50
21	0.90	0.87	0.83	0.70	0.61	0.54	0.49
22	0.90	0.87	0.82	0.69	0.60	0.53	0.48
23	0.90	0.86	0.81	0.68	0.59	0.52	0.47
24	0.89	0.86	0.81	0.68	0.58	0.51	0.45
25	0.89	0.85	0.80	0.67	0.57	0.50	0.44

Another issue that must be addressed in estimating demand is the percentage of normal traffic volumes that divert from the freeway in response to work-zone-induced delays. QUEWZ has an algorithm for estimating diversion and adjusting demand accordingly. If the analysis is performed manually, then demand volumes should be adjusted based upon local experience.

The work zone capacity (i.e., the rate at which the mainlane queue upstream of the lane closure discharges into the work zone) appears to be affected by entrance ramps within the taper area or immediately downstream of the beginning of the full lane closure. It has been observed that headways near the beginning of the closure are fairly uniform. Therefore, vehicles on entrance ramps near the beginning of the closure must force their way into the traffic stream, reducing the upstream mainlane queue discharge rate into the work zone. Merging opportunities for entrance ramp traffic within the work zone increase, because the queue disperses and traffic flow becomes more random with increasing distance downstream of the beginning of the closure.

The available data are not sufficient to quantify precisely the magnitude of the effect on capacity as a function of ramp location and volume. As a conservative approximation, however, when entrance ramps are located within the taper area or within 500 ft downstream of the beginning of the full lane closure, it is recommended that the work zone capacity be reduced by the average entrance ramp volume during the lane closure period, but no more than one half of the capacity of one lane open through the work zone. This approximation assumes that each entrance ramp vehicle entering the work zone prevents one vehicle in the upstream mainlane queue from entering the work zone. At high volume entrance ramps, one would expect mainlane and ramp vehicles to alternate; therefore, the maximum adjustment for the presence of ramps would be one half of the capacity of one lane open through the work zone.

If possible, the work zone should be set up to avoid entrance ramps within the taper area or near the beginning of the lane closure and, thereby, avoid the capacity-reducing effect of those ramps. Data from one work zone suggest that traffic flows became nearly random within 1,500 ft downstream of the beginning of the full closure. Adjusting the location of the beginning of a work zone lane closure such that the first entrance ramp is at least 1,500 ft downstream from the beginning of the full closure should maximize the total work zone throughput (i.e., the sum of volumes that can enter the work zone from upstream and from entrance ramps within the work zone).

CALCULATION OF ESTIMATED WORK ZONE CAPACITY

The following equation, which combines the base capacity value and recommended adjustments may be used to estimate work zone capacity:

$$c = (1600\ pcphpl + I - R) \times H \times N$$

where,

c	=	estimated work zone capacity (vph)
I	=	adjustment for the type and intensity of work activity (pcphpl)
R	=	adjustment for the presence of ramps (pcphpl)
H	=	heavy vehicle adjustment factor (vehicles/passenger car)
N	=	number of lanes open through work zone

In review, the recommended values for the base capacity and the various adjustments are as follows:

I	=	range {-160 to +160 pcphpl} depending on the type, intensity and location of work activity
R	=	minimum of {average entrance ramp volume in pcphpl during the lane closure period for ramps located within the channelizing taper or within 500 ft downstream of the beginning of the full lane closure, or one half of the capacity of one lane open through the work zone (i.e., 1600 pcphpl/2N)}
H	=	given in Table 5 for various percentages of heavy vehicles and passenger car equivalents

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APPENDIX A.

SHORT-TERM FREEWAY WORK ZONE LANE CLOSURE CAPACITY DATA, 1987-1991

TABLE A-1. SHORT-TERM FREEWAY WORK ZONE CAPACITY DATA: [3,1] LANE CLOSURE CONFIGURATION

Site No.	Location	Observed Capacity (vphpl)	Observed Capacity (pcphpl)	Highest 15 min Flow Rate (vphpl)	Percentage of Heavy Vehicles	Duration of Counts (min)	Lane Closed (R/L)
1	Dallas	1304	1414	1468	12.1	125	L
2	Houston	1387	1512	1500	12.9	50	L
3	Houston	1534	1696	1728	15.1	360	L
4	Dallas	1665	1716	1780	4.4	60	L
5	Houston	1435	1540	1460	10.5	60	L
6	Dallas	1311	1419	1496	11.8	75	R
7	San Antonio	1470	1502	1736	301	60	R
8	Houston	1405	1536	1484	13.3	60	R
9	Houston	1498	1655	1620	15.0	60	R
10	Houston	1502	1741	1592	22.7	60	R
11	Houston	1544	1732	1640	17.4	60	R

TABLE A-2. SHORT-TERM FREEWAY WORK ZONE CAPACITY DATA: [2,1] LANE CLOSURE CONFIGURATION

Site No.	Location	Observed Capacity (vphpl)	Observed Capacity (pcphpl)	Highest 15 min Flow Rate (vphpl)	Percentage of Heavy Vehicles	Duration of Counts (min)	Lane Closed (R/L)
1	Austin	1447	1497	1504	4.9	60	L
2	Austin	1539	1615	1720	7.1	65	L
3	Dallas	1641	1678	1768	3.2	130	L
4	Dallas	1555	1592	1640	3.4	65	L
5	Dallas	1478	1513	1500	3.4	75	L
6	Dallas	1668	1701	1788	2.8	65	L
7	Houston	1522	1663	1588	13.2	60	R
8	Houston	1521	1573	1624	4.9	60	R
9	Dallas	1615	1653	1724	3.4	130	R
10	Dallas	1682	1729	1792	4.0	130	R
11	Dallas	1661	1703	1720	3.6	90	R

TABLE A-3. SHORT-TERM FREEWAY WORK ZONE CAPACITY DATA: [4,2] LANE CLOSURE CONFIGURATION

Site No.	Location	Observed Capacity (vphpl)	Observed Capacity (pcphpl)	Highest 15 min Flow Rate (vphpl)	Percentage of Heavy Vehicles	Duration of Counts (min)	Lane Closed (R/L)
1	Houston	1479	1652	1526	16.7	60	L
2	Houston	1430	1581	1520	15.1	60	L
3	Houston	1860	1913	1964	4.1	60	L
4	Houston	1402	1485	1742	8.5	50	L
5	Houston	1406	1450	1464	4.5	60	L

TABLE A-4. SHORT-TERM FREEWAY WORK ZONE CAPACITY DATA: [5,3] LANE CLOSURE CONFIGURATION

Site No.	Location	Observed Capacity (vphpl)	Observed Capacity (pcphpl)	Highest 15 min Flow Rate (vphpl)	Percentage of Heavy Vehicles	Duration of Counts (min)	Lane Closed (R/L)
1	Houston	1681	1702	1803	1.8	75	L
2	Houston	1479	1501	1609	2.1	120	L

TABLE A-5. SHORT-TERM FREEWAY WORK ZONE CAPACITY DATA:
[4,3] LANE CLOSURE CONFIGURATION

Site No.	Location	Observed Capacity (vphpl)	Observed Capacity (pcphpl)	Highest 15 min Flow Rate (vphpl)	Percentage of Heavy Vehicles	Duration of Counts (min)	Lane Closed (R/L)
1	Houston	1668	1711	1715	3.7	110	L
2	Houston	1471	1511	1608	3.9	60	L
3	Houston	1681	1725	1735	3.7	60	L
4	Houston	1387	1442	1427	5.7	60	L