Updated Capacity Values for Short-Term Freeway Work Zone Lane Closures

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Recommendations on estimating the capacities of short-term freeway work zone lane closures are presented. The recommendations are based on 45 hr of capacity counts at 33 work zones in Texas between 1987 and 1991. These new data indicate average capacities for short-term freeway work zone lane closures from three lanes to one lane and from two lanes to one lane that are significantly higher than older values reported in the 1985 *Highway Capacity Manual.* A base capacity value of 1,600 passenger cars per hour per lane is recommended for all short-term freeway work zone lane closure configurations. Adjustments are recommended for the effects of 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. 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.*

This paper presents new capacity values for short-term freeway work zone lane closures. The values are based on data collected in Texas between 1987 and 1991. 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 on 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.

This introductory section includes a discussion of the uses of work zone capacity values and a review of previous research on work zone capacity. Then the new capacity values are presented and compared with the older values. Finally a recommended procedure for estimating work zone capacity is outlined.

USES OF WORK ZONE CAPACITY VALUES

Maintenance and construction projects should be conducted in a manner and at a time that minimize the total cost of the project. The two principal components of the total cost of a project are: (a) the costs of administering and performing the required work and (b) the increased road user costs associated with decreased levels of service through the work zone. In the past the first component was of primary concern. More recently, however, minimizing the adverse traffic impacts on motorists has become an important goal.

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 the 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-92 is one computer program that performs such an analysis. The new capacity values presented herein have been incorporated into QUEWZ-92 (*4*).

PREVIOUS RESEARCH ON WORK ZONE CAPACITY

Chapter 6 of the 1985 *Highway Capacity Manual* (*1*) 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 in Texas during the late 1970s and early 1980s (*2,3*). Capacity data are presented for both short-term maintenance work zones and long-term construction sites.

Short-Term Maintenance Work Zones

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 each 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). Insufficient data were available to quantify the effects of these factors, and therefore the capacity values presented in Figure 1 represent averages for a given configuration over the range of typical work, traffic, and geometric conditions.

Table 1 summarizes the average capacities in vehicles per hour per lane (vphpl) observed in Texas during the late 1970s and early 1980s on the basis of the datum points in Figure 1 (*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

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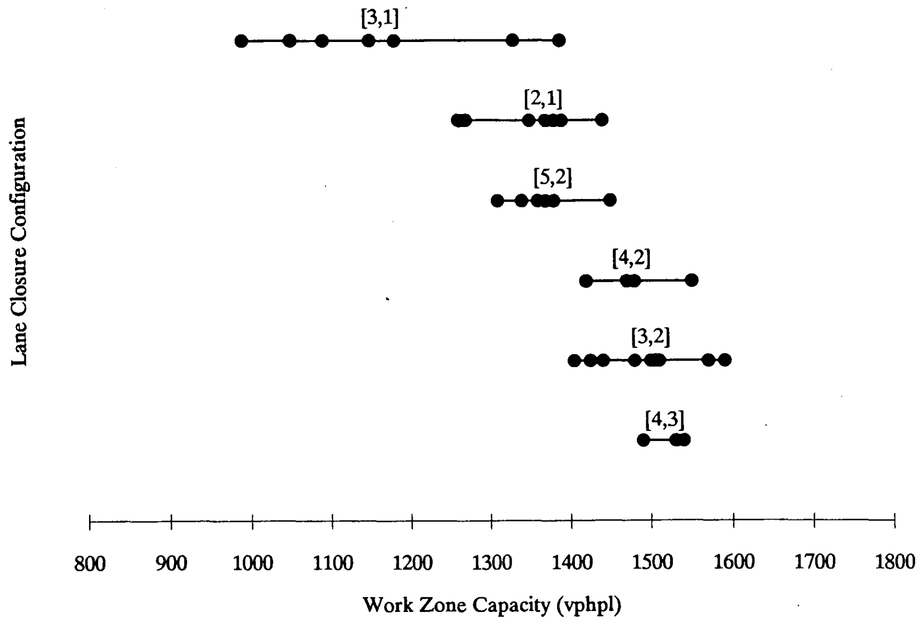

FIGURE 1 Previous data on short-term freeway work zone lane closure capacity.

average capacity in passenger cars per hour (pcph) per lane (pcphpl) for those configurations for which traffic composition data were available. The average capacities in pcphpl were computed by 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. Adjustment for the percentage of heavy vehicles narrows the range of average capacities among the lane closure configurations.

Table 2, which is derived from Table 6-3 in the 1985 *Highway Capacity Manual* (*1*), 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)" (*5*). These data suggest, however, that the type of work affects the work zone capacity, but they are not sufficient to quantify the relationship between the intensity of work activity and the work zone capacity. In relative terms the reported 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 the capacities are higher for median barrier/guardrail installation/repair, which occur farther from the open travel lanes, and for pavement repairs, which typically involve less equipment.

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 (*6*). The results suggest that mean speeds through a work zone decrease as the intensity of work activity increases. Work intensity was quantified by using an index based on 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 3-km/hr (2-mph) drop in mean speeds was observed for every 0.9-m (3-ft) shift of work activity closer to the travel lanes.

TABLE 1 Previous Data on Short-Term Freeway Work Zone Capacity by Lane Closure Configuration (*1–3*)

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 Previous Data on Short-Term Freeway Work Zone Capacity (vph) by Lane Closure Configuration and Type of Work (*1*)

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 (*5*)
[2] Texas data reported by Dudek and Richards (*2*)

Further evidence of the effect of the intensity of work activity is the reported capacity data in the 1985 *Highway Capacity Manual* (*1*) for one [4,2] work zone in Texas at which no work was under way 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 to be 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 an FHWA study for which capacities were measured at two [2,1] lane closures (*7*). 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 because of "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* (*1*) 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 those data. As with the short-term work zone capacities reported in the 1985 *Highway Capacity 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 could not be computed in pcphpl.

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 ranging from 1,030 to 1,600 pcph in the crossover direction and 1,520 to 1,910 pcph in the opposite direction (*7*).

NEW WORK ZONE CAPACITY VALUES

This section summarizes the new data on short-term freeway work zone lane closure capacity that were collected in Texas from 1987 through 1991. First the data collection methodology is described. Next the new data are presented and are then compared with the older values reported in the 1985 *Highway Capacity Manual* (*1*). 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 hr of capacity counts at 33 different freeway work zones with short-term lane closures. Data were collected for five different lane closure configurations: [3,1], [2,1], [4,2], [5,3], and [4,3]. More than 15 hr of data collected at eight additional sites were excluded from the analysis because they violated the requirements described below; they provided insights, however, into the capacity-reducing effects of nonideal conditions.

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. The most common types of maintenance activities at the work zones observed included pavement repairs, seal coating, and the placement or repair of concrete median barriers. All of the work zones were in general compliance with the *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 the vehicles entered the activity area through the transition area of the work zone by using the standard terminology recommended by Lewis (*10*). The count location is illustrated in Figure 2. Data were used only for time periods during which traffic was queued in all lanes upstream of the activity area. Therefore the capacity counts represent the rate at which vehicles discharge from the upstream queue, merge into the reduced number of lanes through the transition area, and enter the activity area. Sites at which ramps were located within the transition area or the upstream end of the activity area were not analyzed.

In previous work zone capacity studies, some capacity data were collected at points within the activity area (i.e., other than at the downstream end of the transition area and the upstream end of the activity area) where the traffic flow appeared to be the most constrained. At some such sites there were intervening ramps between the upstream end of the activity area and the capacity count location; in these cases the counts within the work zone would differ from the queue discharge rate entering the activity area by the volume of traffic entering or exiting at the intervening ramps.

In the present study, however, it was determined that capacity counts should be taken only at the upstream end of the activity area for the following reasons:

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

Counting of the capacity only at the upstream end of the activity area eliminates the variability among sites because of differences

TABLE 3 Previous Capacity Data for Long-Term Construction Zones with Portable Concrete Barriers (*1,3*)

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

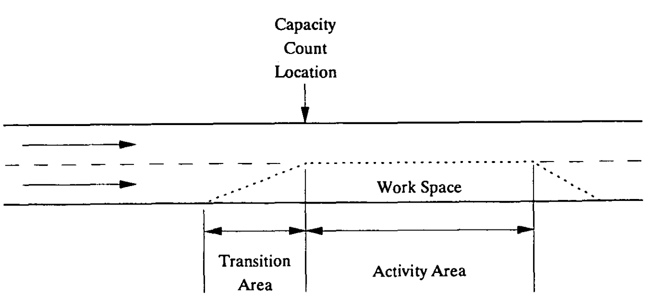

FIGURE 2 Work zone capacity count location.

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 transition area or the upstream end of the activity area reduce both the queue discharge rate entering the activity area from upstream and the merging capacity of the entrance ramp. In this paper it is therefore recommended that the base capacity value represent conditions in which 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 consensus appears to be that freeway capacity should be defined and measured as the mean queue discharge rate entering a freeway bottleneck (*11*). The mean queue discharge rate over an extended continuous time period (e.g., 1 hr or more) 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 the present 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 the new data and those from 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 a separate capacity study or observation, whereas the new capacity values were 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). This approach 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. Therefore it is imperative that the values be consistent with the assumptions of that analysis. A work zone lane closure would typically be modeled as a simple bottleneck with all traffic entering at the upstream end and exiting at the downstream end. The demand would be the traffic flow rates approaching the bottleneck from upstream, and the capacity would be the rate at which that demand can enter the upstream end of the bottleneck. Therefore the capacity used in the analysis should be the rate at which vehicles can enter the upstream end of the activity area.

Observed Capacities

The new capacity data for short-term freeway work zone lane closures are presented in Table 4. 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 those for the old data (on the basis of a t-test at a .05 significance level). For the other configurations the averages of the old and new data are not significantly different.

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 no statistically significant differences among the average capacities in pcphpl for the five lane closure configurations (at a .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 1,900 pcphgpl (passenger car per hour per green per lane) for signalized intersections, which represent the queue discharge rate and saturation flow rate 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 (except for one value of 1,913 pcphpl). These data, 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 magnitudes of these factors' capacity-reducing effects.

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,

TABLE 4 New Data on Short-Term Freeway Work Zone Lane Closure Capacity

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.

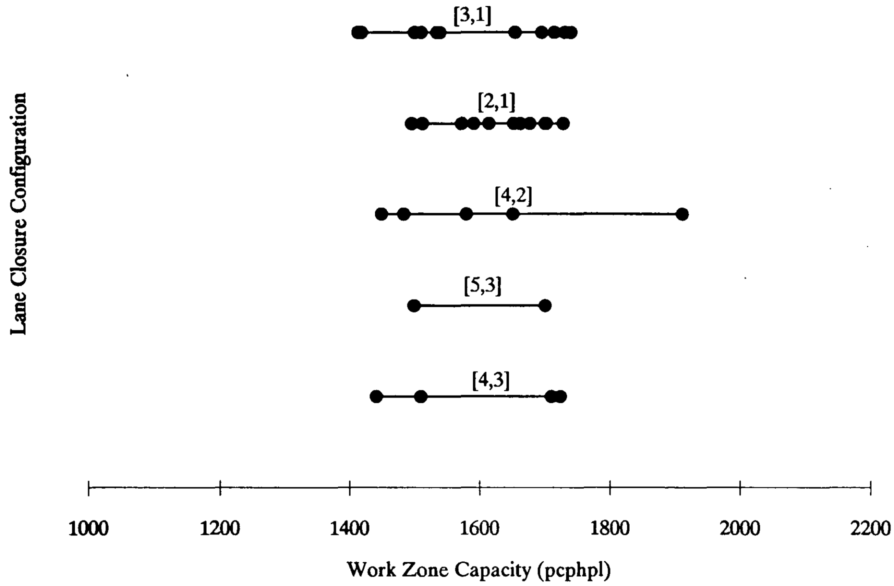

FIGURE 3 New data on short-term freeway work zone lane closure capacity.

merge into the reduced number of travel lanes through the transition area, and enter the activity area. Ramps within a work zone, especially entrance ramps in the transition area and the upstream end of the activity area, 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 activity area. Examples include a high-volume entrance ramp or an unusual or unusually intense work area within the lane closure that causes queuing upstream, beyond the beginning of the lane closure. These cases are not treated here.

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 on the basis of the new data and those from previous studies about the effects 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. These gaps 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 transition area or a short distance into the activity area appear to reduce the queue discharge rate entering from upstream (because of the turbulence created by ramp vehicles forcing their way into inadequate gaps in the main lane traffic stream), whereas entrance ramps farther downstream within the activity area appear to have less of an impact.
3. Fewer vehicles can enter the work zone from an entrance ramp near the upstream end of the activity area without disrupting the main lane traffic stream (because of the uniformity of the headways in the traffic stream near the queue discharge point) than from a ramp farther 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 increase total vehicular throughput. Therefore a detailed study was undertaken at one work zone to analyze the effects of the placement of freeway work zone lane closures relative to entrance ramps on the basis of 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 [152, 305, and 457 m (500, 1,000, and 1,500 ft) downstream from the beginning of the lane closure]. Gap acceptance procedures developed by Drew (*12*) were applied to estimate the entrance ramp merging capacity on the basis of the observed headway distributions. This section summarizes the study results. Lopez (*13*) 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 as a result of 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 152 m (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 305 m (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 vehicle mergers into the main lane traffic stream without disrupting it. Conversely a more uniform 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 vehicle mergers without disrupting the main lane traffic stream, whereas farther downstream there are more headways adequate for use by entrance ramp vehicles. More entrance ramp vehicles can enter a work zone with less disruption to the main lane traffic stream (and therefore with less of an effect on the queue discharge rate entering from upstream) at an entrance ramp farther 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 activity area are as far as possible [preferably at least 152 m (500 ft)] downstream from the end of the transition area while at the same time avoiding ramps within the transition area.

RECOMMENDED CAPACITY ANALYSIS PROCEDURE

This section recommends a procedure for estimating the capacities of short-term freeway work zone lane closures. The procedure includes a base capacity value and a series of adjustments to that base value.

Recommended Base Work Zone Capacity Value

The new capacity data 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 on work zones whose traffic control is in compliance with the *Manual on Uniform Traffic Control Devices* (*9*).

The recommendation of a single base capacity value departs from previous procedures that recommended a different base value in vph for each lane closure configuration. The new data, 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* (*1*). Furthermore the value of 1,600 pcphpl relates logically to the base capacity values used in those procedures.

Adjustments to 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 the fact that the capacities of individual work zones fell within a range of approximately ±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, the effects of heavy vehicles, and the presence of entrance ramps.

Adjustment for Intensity of Work Activity

The new data 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 farther 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 the 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 ±10 percent (160 pcphpl) range for work activities that are significantly more minor or more intense than average.

Adjustment for Effects of Heavy Vehicles

It is recommended that the heavy vehicle adjustment factors in the 1985 *Highway Capacity Manual* (*1*) 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, and
E = passenger car equivalent (passenger cars/heavy vehicle).

A passenger car equivalent of 1.7, which is recommended in the 1985 *Highway Capacity Manual* (*1*) for trucks on freeway segments in level terrain, was used to convert the observed capacity counts and percentage of heavy vehicles to capacities in pcphpl. Reference should be made to the *Highway Capacity Manual* (*1*) for passenger car equivalent values for rolling or mountainous terrain and for extended individual grades.

To test the appropriateness of the 1.7 value for work zones, passenger car equivalents were computed by using capacity count and time headway data for two [2,1] lane closures. The passenger car equivalent was computed as the ratio of the mean time headway for trucks divided by the mean time headway for passenger cars entering the activity area (*14*). At one work zone, which had a full-hour capacity count of 1,570 vehicles (1,490 passenger cars and 70 trucks), the passenger car equivalent value was 2.1. At the other work zone the full-hour capacity count was 1,657 vehicles (1,585 passenger vehicles and 72 trucks), and the passenger car equivalent was 1.8. These results, although based on a limited amount of data for only two work zones, suggest that the value of 1.7 is low but not unreasonable.

Adjustment for Presence of Ramps

In demand-capacity analysis care must be taken to adjust appropriately 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 can actually enter.

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

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-92, for example, has an algorithm for estimating diversion and adjusting demand accordingly. If the analysis is performed manually, demand volumes should be adjusted on the basis of local experience.

The work zone capacity (i.e., the rate at which the main lane 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 main lane 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 152 m (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 main lane queue from entering the work zone. At high-volume entrance ramps one would expect main lane 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 effects of those ramps. Data from one work zone suggest that traffic flows became nearly random within 457 m (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 457 m (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 the recommended adjustments, can be used to estimate work zone capacity:

$$c = (1{,}600 \text{ pcphpl} + I - R) \times H \times N$$

where

c = estimated work zone capacity (vph),
I = adjustment for type and intensity of work activity (pcphpl),
R = adjustment for presence of ramps (pcphpl),
H = heavy vehicle adjustment factor (vehicles/passenger car), and
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 type, intensity, and location of work activity;
R = minimum of average entrance ramp volume in pcphpl during lane closure period for ramps located within channelizing taper or within 152 m (500 ft) downstream of the beginning of full lane closure, or one-half of capacity of one lane open through work zone (i.e., 1,600 pcphpl/2N); and
H = given in *Highway Capacity Manual* (*1*) for various percentages of heavy vehicles and passenger car equivalents.

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