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A New Methodology to Estimate Capacity for Freeway Work Zones

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ABSTRACT

The objectives of this study were to investigate various independent factors that contribute to capacity reduction in work zones and to suggest a new methodology to estimate the work zone capacity. To develop the new capacity estimation model, traffic and geometric data were collected at 12 work zone sites with lane closures on four normal lanes in one direction, mainly after the peak-hour during daylight and night.

The multiple regression model was developed to estimate capacity on work zones for establishing a functional relationship between work zone capacity and several key independent factors such as the number of closed lanes, the proportion of heavy vehicles, grade and the intensity of work activity. The proposed model was compared with other existing capacity models, and showed improved performance for all of the validation data.

Keywords: work zones, capacity estimation, multiple regression

INTRODUCTION

Construction and maintenance activities in work zones result in significant impacts on traffic conditions, such as reduced freeway capacities, increased delay to road users, and increased accident rates and fuel consumption. Moreover, sometimes lane closures are required for several types of work activities, such as pavement repair, resurfacing, asphalt removal, installation of pavement markers, etc. Therefore, work zone traffic control strategies and methods must be carefully planned, selected, and applied to minimize these impacts. For these reasons, we need to predict various traffic–related characteristics such as traffic capacities, queue lengths, delays, speeds, etc.

The work zone capacity is the principal determinant of most of the other traffic impacts, including maximum queue length and delay caused by work zone activity during a given time period. Most computer models, such as Queue and User Cost Evaluation of Work Zones (QUEWZ, *1*) and QuickZone (*2*) have used the capacity as a key input parameter to help quantify queue length and delay, and to calculate delay costs. Therefore, it is very important to identify the appropriate estimate for capacity values in freeway work zones.

Literature Review

Many studies have been conducted to estimate work zone capacity based on field data analysis. Kermode and Myyra (*3*) collected capacity data for some typical maintenance and construction operations on freeways in the Los Angeles area to determine the effects of lane closures and to help improve operation of freeways during lane closures. Dudek and Richards (*4*) performed capacity studies at urban freeway maintenance and construction work zones in Houston and Dallas. Studies were conducted on 5-, 4-, and 3-lane freeway sections. These capacity values have been used as guidelines for the work zone analysis in the Highway Capacity Manual (HCM, *5*). Krammes and Lopez (*6*) suggested new capacity values for short-term freeway work zone lane closures in the early 1990s. They showed that the new capacity values are higher than the older capacity values in the HCM. Other studies (*7, 8, 9*) also were conducted to determine the mean capacity for different types of work zone lane closure configurations. However, previous studies related to models for estimating the capacity of freeway work zones are very few and limited in scope.

Abrams and Wang (*10*) developed a model that takes into account both HCM adjustment factors (truck adjustment factor, lane width and lateral clearance adjustment factor) and a new work duration factor that was calibrated from their own field studies.

Memmott and Dudek (*1*) developed a computer model, QUEWZ, to estimate the user costs caused by lane closures. In the QUEWZ model, various mean capacity values and coefficients were derived for different types of lane closure configurations to estimate the restricted capacity in work zones through regression analyses of the capacity data collected by Dudek and Richards (*4*).

Krammes and Lopez (*6*) offered some recommendations to estimate the capacities of short-term freeway work zone lane closures. The recommendations were based on 45 hours of capacity counts at 33 work zones in Texas between 1987 and 1991. They recommended a base capacity value of 1600 passenger cars per hour per lane for all short-term freeway lane closure configurations, and suggested several adjustments that reflect the effects of the intensity of the work activity, the percentage of heavy vehicles and the presence of entrance ramps near the beginning of the lane closure. This model has been used to obtain capacities for work zone lane closures in the updated version of QUEWZ (*11*).

Work zone characteristics vary significantly from one site to another. In addition, the work zone capacity is influenced concurrently by a number of independent factors such as lane closure configurations, intensity of work activities, traffic and roadway condition, work duration, etc. However, existing capacity estimation models did not consider and include a number of independent factors that are expected to affect the work zone capacity. Moreover, most of the existing models are based on an HCM-type method, and employ adjustment factors from the chapter on freeways that are not supported by data specific to work zones. The objectives of this study were to investigate various independent factors that contribute to capacity reduction in work zones and to suggest a new methodology to estimate the work zone capacity.

DETERMINING FACTORS AFFECTING WORK ZONE CAPACITY

It is essential to determine independent factors that are expected to affect work zone capacity, and to identify the relationship between these factors and capacity to ensure proper estimation of capacity. We have investigated previous studies to accomplish these objectives, and the following are some of the results. Data shown in the figures have often been amalgamated from several sources, and are labeled accordingly.

Work Zone Configurations

Work zone capacity might be affected by work zone configurations such as the number of closed lanes, the location of those closed lanes, and the number of open lanes. Figure 1 shows the work zone capacity values observed from the four states. It was found that there is significant variation in the range of observed work zone capacities according to the lane closure configurations in several areas.

Number of Opened and Closed Lanes

We hypothesize that the numbers of opened and closed lanes are important contributors to per-lane work zone capacity reduction. The per-lane work zone capacity might decreased as the number of closed lanes increases, and it might increase as the number of opened lanes increases. As seen in Figure 1, we notice that there is significant variation in the resulting capacities for different work zone lane closure configurations that involve opening and closing the same number of lanes. Because of the limited amount of data, it is difficult to tell visually (and statistically) whether the numbers of opened and closed lanes are significant contributors to capacity reduction. However, clearly there are other important factors that must account for the observed variance in the data.

Location of Closed Lanes

The *location* of closed lanes (e.g., left or right) might have a different impact on work zone capacity beyond that predicted simply by the *number* of closed lanes. For example, closing a single outside lane on a three-lane facility may cause additional interference (and hence a capacity reduction) with on-ramps and off-ramps, whereas closing a single inside lane might have less influence. Moreover, closing the single middle lane might be the worst case because drivers cannot change lanes and pass other cars if they drive behind slow cars or trucks. However, from the previous data in several areas, we observe that it is hard to tell clearly the difference between different types of location of closed lanes.

Traffic and Roadway Condition

Work zone capacity might be affected by a number of traffic and roadway conditions such as percentage of heavy vehicles, driver population, lateral distance to the open travel lanes, entrance ramp volumes, length of work zone, and work zone grade.

Effect of Heavy Vehicles

Heavy vehicles occupy more space on the roadway than passenger cars. Moreover, heavy vehicles accelerate slowly and their presence makes other drivers more apprehensive. These factors reduce the overall capacity of the work zone. From Figure 2, which shows regression lines representing best fits to the data from the North Carolina and Texas treated separately, we notice that the work zone capacity tends to decrease as the percentage of heavy vehicles increases.

Driver Population

There might be different traffic behavior between peak period and non-peak period because peak period traffic mainly consists of commuter drivers. Ahmed et al. (*9*) suggested that commuter drivers are expected to be more familiar with the route and the work zone configuration. Therefore, they can proceed through the work zone with shorter headways, and higher flows. The Highway Capacity Manual (*5*) suggests some adjustment factors to account for this effect, but they are not supported by data collected in work zones.

Entrance Ramp Volume

Ramps near the work zone, especially entrance ramps inside of the work zone activity area, might create additional turbulence to the users who enter the work zone. The available data are not sufficient to quantify their effect on capacity reduction. However, Krammes and Lopez (*6*) suggested that the work zone capacity can be reduced by the average volume of entrance ramps located within the channelizing taper or within 152 m (500 ft) downstream of the beginning of a full lane closure, but by no more than one half of the capacity of one open lane through the work zone.

Lateral Distance to the Open Travel Lanes

Lateral distance to the open travel lanes might be a possible contributor to work zone capacity reduction. When obstructions such as warning devices and rubber cones are too close to the open travel lanes, drivers will be forced to slow down and travel closer to each other laterally. Work zone capacity might be decreased as lateral distance to the open travel lanes decreases. However, there are not enough data to support this factor.

Length & Grade of Work Zone

Work zone capacity can be affected by the grade and the length of the work zone. Longer work zones might be indicative of more intense activity, and might exhibit more visual distractions that would cause people to travel more cautiously. It seems reasonable to suspect that the presence of grades would exacerbate any flow constriction that would otherwise exist, particularly in the presence of heavy vehicles. Unfortunately, the previous studies did not include sufficient data to investigate these impacts on work zone capacity.

Intensity of Work Activity

Work zone capacity might decrease as the intensity of work activity increases. The intensity of work activity depends on the types of work activities, the number of workers, the size of equipment, etc. In California and Texas (*3*, *4*), researchers classified the intensity of work activity into 6 levels. From Figure 3, while the Texas data are not very indicative, we can observe from the California data that work zone capacity tends to decrease as the work intensity increases from light (e.g., median barrier or guardrail installation) to heavy (e.g., bridge repair). Moreover, Figure 4 shows the relationship between work zone capacity and intensity of work activity by the number of opened lanes for the California data. We observe an obvious pattern, which shows that the capacity decreases as the work intensity increases, and a consistent relationship between capacity and the number of open lanes within all levels of work activities. Of course, “work intensity” is a qualitative and subjective term, and an appropriate classification scheme is an open question that we hope to address in the future.

Work Duration

The characteristics of long-term work zones might be different from those of short-term work zone if drivers become familiar with the long-term work zone. Because of the limited amount of data available, it is not easy to quantify the difference. However, if we compare long-term data to short-term data with respect to [2,1] and [3,2] lane closure configurations in Texas (*4*) during the late 1970s and early 1980s, we can observe that the average capacity at long-term sites for each lane closure configuration is noticeably greater than that at short-term sites. Of course, this could also be the result of some other factor highly correlated with work duration.

Weather Conditions

Freeway capacity is affected by a variety of weather conditions (i.e., heavy snowfall and rain). The Highway Capacity Manual (*5*) suggests that 10 to 20 percent capacity reductions are typical, and higher percentages are quite possible. Ahmed et al. (*9*) also found that the weather conditions influenced freeway capacity in work zones. They observed that the average capacity reduction during wet snow, freezing rain, and shower conditions, compared to sunny conditions, was about 19%.

Work Time

To avoid heavy congestion caused by lane closures during daylight hours, many work activities around the country take place at night. There might be different driver behavior and traffic characteristics during day and nighttime work. Shepard and Cottrell (*12*) observed that some drivers are less attentive and drive fast during night as compared to daylight, and relatively more impaired drivers are reported to be involved in work zone incidents and accidents.

DATA COLLECTION

Previous Studies on Work Zone Capacity

We reviewed all available previous studies on work zone capacity estimation, as mentioned before. Table 1 shows the work zone capacity values measured in several areas under different conditions. It can be seen from the table that none of these studies were operating from the same set of independent factors; several studies did not include information on key independent factors that might affect capacity reduction in work zones, therefore relatively simple data collection was performed.

Field Data Collection

To develop a new capacity estimation methodology that takes into account key independent factors, traffic and geometric data were collected at 12 work zone sites with lane closures on four normal lanes in one direction. Traffic data were collected mainly after the peak-hour during daylight and night because Maryland State Highway Administration (SHA) has a policy that lanes cannot be closed during the peak-hour to avoid excessive traffic delays, congestion, and motorist aggravation. Traffic volumes were recorded with a video camera at the ends of transition areas when the work zone became a bottleneck, resulting in queue and delays upstream of the work zone. Care was taken to ensure that no queues existed downstream. Speed data were collected at 1-min intervals using a laser speed gun. Additional data such as work zone configuration, geometry, intensity and type of work activity, work duration, weather condition, and work time were also recorded.

Table 2 summarizes the data collected for each site. At each site, traffic volume was divided into two classes: (a) passenger cars and (b) heavy trucks, and work time also was divided into two types, i.e., day and night. The intensity of work activity was classified into three levels such as low, medium, and heavy based on the types of work activities, the number of workers and the size of the equipment. We assumed that the driver population was not commuters because traffic data were collected after the peak-hour during daylight and night. The durations of all the work zone sites were short-term, and the weather was sunny during lane closures.

CAPACITY ESTIMATION MODEL FOR WORKZONES

We developed a multiple regression model to estimate capacity for work zones because it provides a simple method for establishing a functional relationship between work zone capacity and several key independent factors such as the number of closed lanes, the proportion of heavy vehicles and the intensity of work activity. Several categorical variables, such as the location of closed lanes (e.g., left or right) and intensity of work activity (e.g., low, medium or heavy), were represented as dummy variables such as 1 or 0. For the variable of the location of closed lanes, it was classified into two types as right and left because we have no data where middle lanes were closed. The following variables were identified as potential independent factors for estimating the capacity at work zone sites:

- Number of closed lanes
- Location of closed lanes (right = 1, otherwise = 0)
- Proportion of heavy vehicles
- Lateral distance to the open lanes
- Work zone length

- Work zone grade
- Intensity of work activity (1 or 0 for medium intensity, and 1 or 0 for heavy intensity)

Table 3 shows the correlation matrix between independent variables. We notice that the number of closed lanes and the intensity of work zone activity in category heavy are highly correlated with work zone capacity. Moreover, it shows that the grade and the combination of grade and heavy vehicles are also another important factors that are highly correlated to work zone capacity. The capacity estimation model is developed based on the field data collected at 12 work zone sites as shown in Table 2. Stepwise addition and subtraction were used to refine the variable set. Table 4 summarizes the final results of the stepwise regression analysis.

$$\begin{gathered}\mathrm{CAPACITY} = 1857 - 168.1\mathrm{NUMCL} - 37.0\mathrm{LOCCL} - 9.0\mathrm{HV} + 92.7\mathrm{LD} \\ - 34.3\mathrm{WL} - 106.1\mathrm{WI}_{\mathrm{H}} - 2.3\mathrm{WG} * \mathrm{HV}\end{gathered}$$

MODEL PERFORMANCE

We compared models by investigating the root mean square (RMS) error between actual and predicted capacity values, for a particular data set. This statistic is equivalent (in the sense that it is monotonically transformable) to the objective being minimized under least squares regression. To compare models objectively, it was critical to use a validation set that was not used to calibrate any of the models being compared.

Existing capacity estimation models

The following existing capacity estimation models were considered:

Memmott and Dudek (*1*): $C = a - b\ (CERF)$,

where

C = estimated work zone capacity (vphpl)

CERF = capacity estimate risk factor suggested in the research

a, b = coefficients given in the research

Abrams and Wang (*10*): $C = 2000 * TF * WCF + WZF$

where

C = estimated work zone capacity (vphpl)

TF = truck adjustment factor given in the HCM

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

WZF = work zone capacity adjustment factor determined in the research

Krammes and Lopez (*6*): $C = (1600\ \text{pcphpl} + I - R) * H * N$

where

C = estimated work zone capacity (vph)

I = adjustment for type and intensity of work activity (pcphpl) suggested in the research

R = adjustment for presence of ramps (pcphpl) suggested in the research

H = heavy vehicle adjustment factor given in the HCM

N= number of lanes open through the work zone

Comparison between the existing models and the new capacity model

We used work zone capacity data collected in North Carolina (*7*) and Indiana (*8*) to perform an objective comparison between the existing three models, the HCM, and the proposed model. In order to do so, we compared the model estimates with the actual capacities collected in North Carolina and Indiana. Because of the limited subset of data that is available in North Carolina and Indiana, it was necessary to use some *a posteriori* anecdotal data from the original researchers to fill out the data sets. We used 0 % for grades, 1 mile as work zone length for both states, and 1 foot as lateral distance with obstructions on one side for Indiana. Also, we assumed that there are no ramps inside of the work zone activity area that might have created additional turbulence to the users who entered the work zone.

Table 5 shows the RMS error for each model, including the new capacity estimation model. We observe from the table that RMS error of the new capacity estimation model is smaller than the others.

CONCLUSIONS

It was found that the work zone capacity can be affected by various independent factors such as traffic and roadway conditions, and therefore these factors should be included in capacity estimation models to obtain accurate capacity values. A new capacity estimation model was developed to estimate capacity for work zones using multiple linear regression analysis. The proposed model was compared with the existing capacity models and the HCM, and it performed better than the others that excluded various key independent factors that might affect work zone capacity.

Our study focused on the work zones with lane closures on freeways with 4 lanes in one direction. Work zones with 3- and 2-lane freeway sections were not analyzed because of lack of traffic data. We hope to continue to improve this capacity estimation model, by including the work zones on 3- and 2-lane sections.

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REFERENCES

1. Memmott, J. L., and C. L. Dudek. Queue and User Cost Evaluation of Work Zones (QUEWZ). In *Transportation Research Record* 979, Washington, D.C., 1984.
2. Federal Highway Administration. *User's Manual for QuickZone Beta 0.5 (unpublished).* U.S. Department of Transportation, 2000.
3. Kermode, R. H., and W. A. Myyra. Freeway Lane Closure. *Traffic Engineering,* Vol. 40, No. 5, 1970.
4. Dudek, C. L., and S. H. Richards. *Traffic Capacity Through Work Zones on Urban Freeways.* Report FHWA/TX-81/28+228-6. Texas Department of Transportation, Austin, 1981.
5. Transportation Research Board. Special Report 209. *Highway Capacity Manual*, Washington, D.C., 1994.

6. Krammes, R. A., and G. O. Lopez. *Updated Short-Term Freeway Work Zone Lane Closure Capacity Values.* Report FHWA/TX-92/1108-5. Federal Highway Administration, U.S. Department of Transportation and Texas Department of Transportation, Austin, 1992.
7. Dixon, K. K., J. E. Hummer and A. R. Lorscheider. Capacity for North Carolina Freeway Work Zones. In *Transportation Research Record* 1529, Washington, D.C., 1996.
8. Jiang, Yi. Traffic Capacity, Speed and Queue-Discharge Rate of Indiana's Four-Lane Freeway Work Zones. In *Transportation Research Record* 1657, Washington, D.C., 1999.
9. Ahmed, A. K., M. Zhou and F. Hall. New Insights into Freeway Capacity at Work Zones: An Empirical Case Study. presented at the Transportation Research Board 79th annual meeting, 2000.
10. Abrams, C. M., and J. J. Wang. *Planning and Scheduling Work Zone Traffic Control.* Report FHWA-IP-81-6. Federal Highway Administration, U.S. Department of Transportation, 1981.
11. Krammes, R. A., G. L. Ullman, J. L. Memmott and C. L. Dudek. *User's Manual for QUEWZ-92*. Report FHWA/TX-92/1108-7. Federal Highway Administration, U.S. Department of Transportation, and Texas Department of Transportation, Austin, 1993.
12. Shepard, F. D., and B. H. Cottrell. Jr. Benefits and Safety Impact of Night Work-Zone Activities. In *Transportation Research Record* 1086, Washington, D.C., 1986.

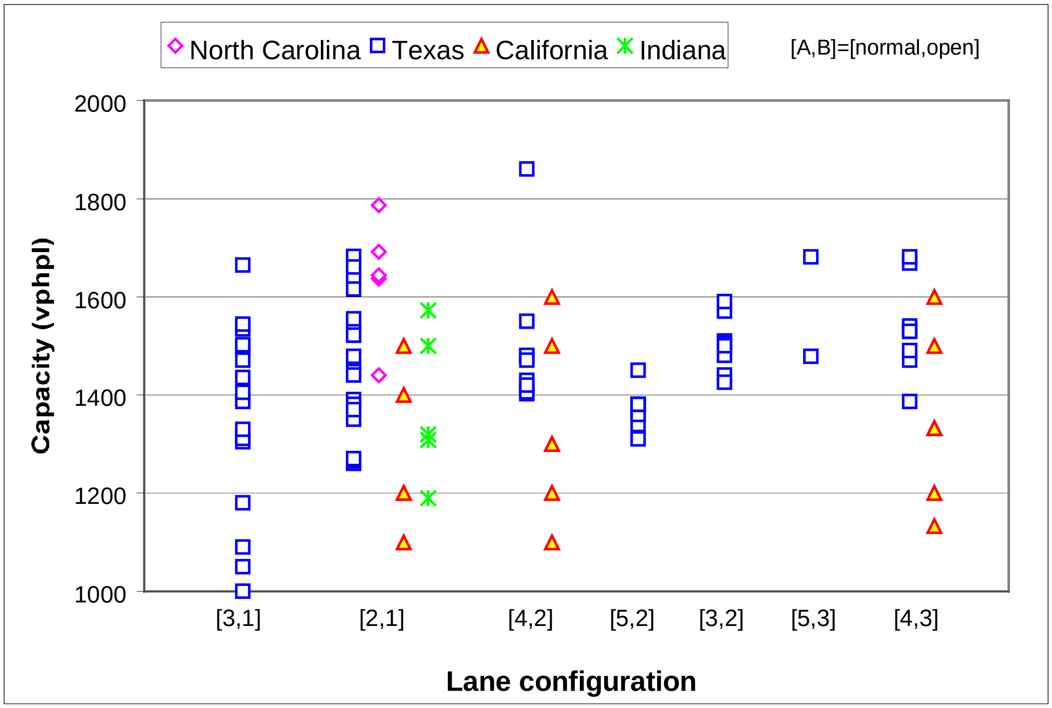

FIGURE 1 Work zone capacities under different lane closure configurations in several areas.

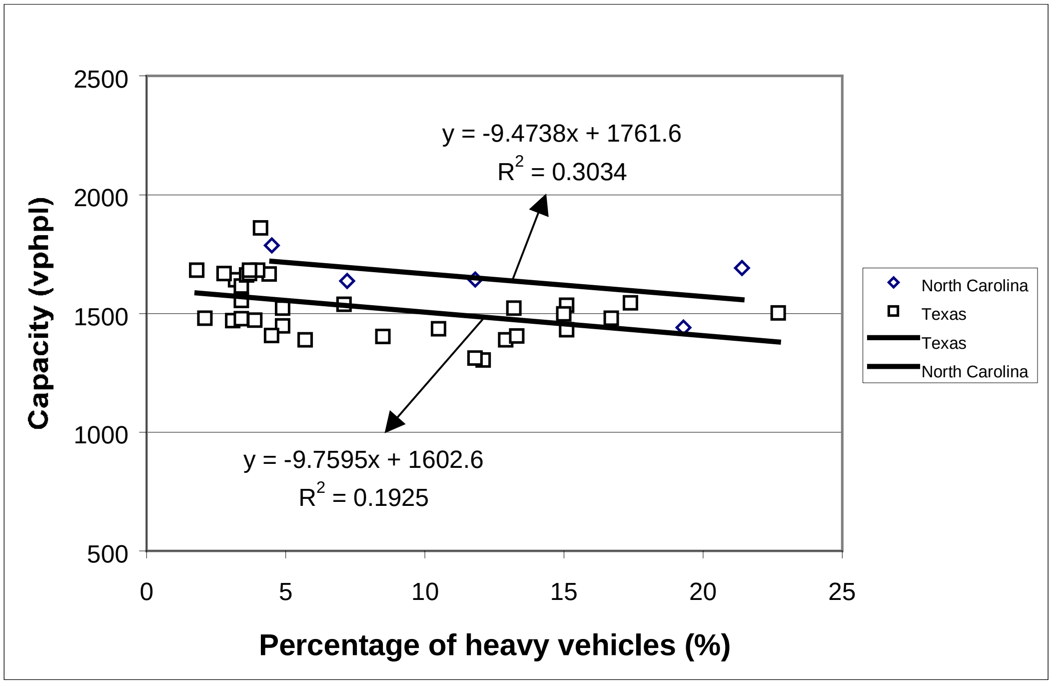

FIGURE 2 Relationship between work zone capacity and percentage of heavy vehicles in Texas and North Carolina.

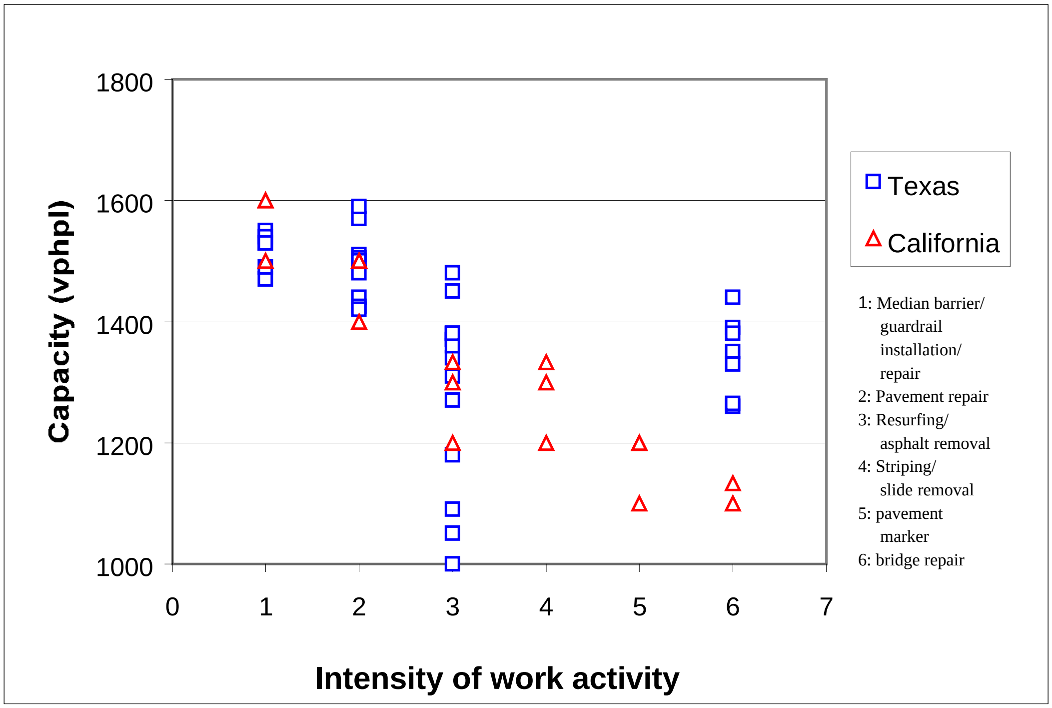

FIGURE 3 Relationship between work zone capacity and intensity of work activity.

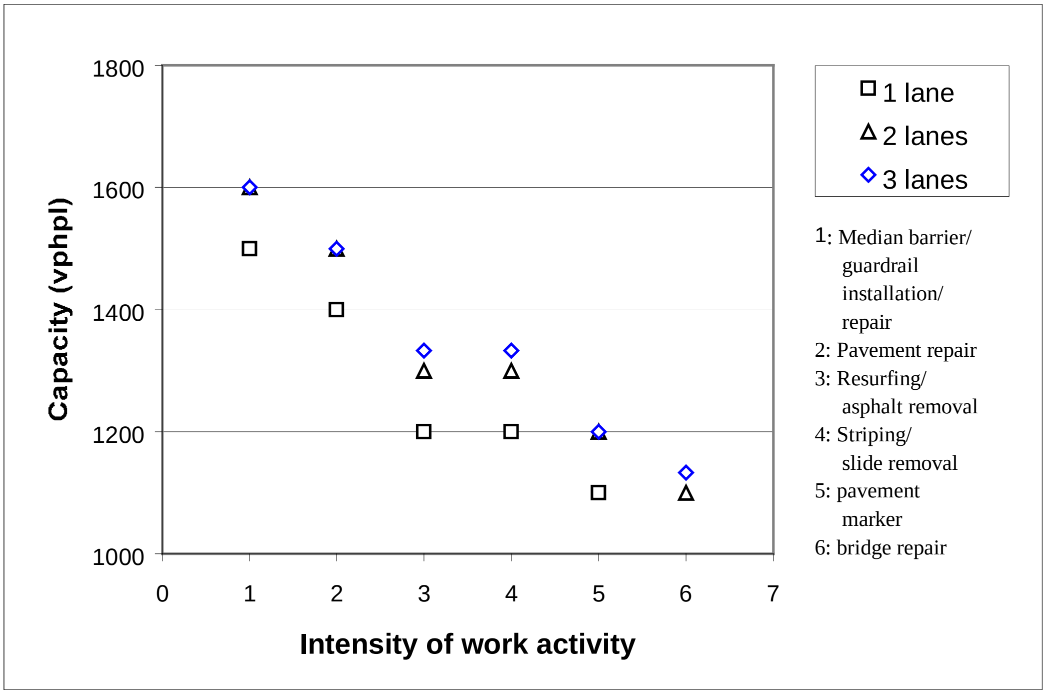

FIGURE 4 Relationship between work zone capacity and intensity of work activity by # of opened lanes in California.

TABLE 1 Previous studies on work zone capacity measured in the field under different conditions

Site	Factors influencing work zone capacity							Average capacity (vphpl)	Source
	Workzone configuration	Heavy vehicle (%)	Lateral distance (m)	Intensity of work activity	Work duration	Work time	Weather		
North Carolina freeway	[2,1]* Left lane closed	7.2	2.4	Moderate		Day		1637	Dixon *et al.* (*7*)
	[2,1] Left lane closed	11.8	2.4	Light		Night		1644	
	[2,1] Right lane closed	4.5	2.4	Moderate		Night		1787	
	[2,1] Left lane closed	21.4	2.4	Heavy		Night		1692	
	[2,1] Left lane closed	19.3	0.6	Heavy		Night		1440	
Texas freeway	[3,1] Left lane closed	12.1			Short-term			1304	Krammes *et al.* (*6*)
	[3,1] Left lane closed	12.9			Short-term			1387	
	[3,1] Left lane closed	15.1			Short-term			1534	
	[3,1] Left lane closed	4.4			Short-term			1665	
	[3,1] Left lane closed	10.5			Short-term			1435	
	[3,1] Right lane closed	11.8			Short-term			1311	
	[3,1] Right lane closed	3.1			Short-term			1470	
	[3,1] Right lane closed	13.3			Short-term			1405	
	[3,1] Right lane closed	15.0			Short-term			1498	
	[3,1] Right lane closed	22.7			Short-term			1502	
	[3,1] Right lane closed	17.4			Short-term			1544	
	[2,1] Left lane closed	4.9			Short-term			1447	
	[2,1] Left lane closed	7.1			Short-term			1539	
	[2,1] Left lane closed	3.2			Short-term			1641	

Texas freeway	[2,1] Left lane closed	3.4			Short-term			1555	Krammes *et al.* (*6*)
	[2,1] Left lane closed	3.4			Short-term			1478	
	[2,1] Left lane closed	2.8			Short-term			1668	
	[2,1] Right lane closed	13.2			Short-term			1522	
	[2,1] Right lane closed	4.9			Short-term			1521	
	[2,1] Right lane closed	3.4			Short-term			1615	
	[2,1] Right lane closed	4.0			Short-term			1682	
	[2,1] Right lane closed	3.6			Short-term			1661	
	[4,2] Left lane closed	16.7			Short-term			1479	
	[4,2] Left lane closed	15.1			Short-term			1430	
	[4,2] Left lane closed	4.1			Short-term			1860	
	[4,2] Left lane closed	8.5			Short-term			1402	
	[4,2] Left lane closed	4.5			Short-term			1406	
	[5,3] Left lane closed	1.8			Short-term			1681	
	[5,3] Left lane closed	2.1			Short-term			1479	
	[4,3] Left lane closed	3.7			Short-term			1668	
	[4,3] Left lane closed	3.9			Short-term			1471	
	[4,3] Left lane closed	3.7			Short-term			1681	
	[4,3] Left lane closed	5.7			Short-term			1387	
	[2,1]	-			Long-term			1550**	Dudek *et al* (*4*)
	[3,2]	-			Long-term			1860**	
	[2,1] Left lane closed	-		Resurfacing, asphalt removal	Short-term			1370	
	[2,1] Left lane closed	-		Resurfacing, asphalt removal	Short-term			1270	

Texas freeway	[2,1] Right lane closed	-		Bridge repair	Short-term			1390	Dudek *et al.* (*4*)
	[2,1] Right lane closed	-		Bridge repair	Short-term			1260	
	[2,1] Right lane closed	-		Bridge repair	Short-term			1265	
	[2,1] Right lane closed	-		Bridge repair	Short-term			1350	
	[2,1] Right lane closed	-		Bridge repair	Short-term			1380	
	[2,1] Right lane closed	-		Bridge repair	Short-term			1440	
	[3,1] Left lane closed	-		Resurfacing, asphalt removal	Short-term			1180	
	[3,1] Left lane closed	-		Resurfacing, asphalt removal	Short-term			1090	
	[3,1] Left lane closed	-		Resurfacing, asphalt removal	Short-term			1050	
	[3,1] Right lane closed	-		Resurfacing, asphalt removal	Short-term			1000	
	[3,1] Right lane closed	-		Bridge repair	Short-term			1330	
	[3,2] Left lane closed	-		Pavement repair	Short-term			1570	
	[3,2] Left lane closed	-		Pavement repair	Short-term			1510	
	[3,2] Left lane closed	-		Pavement repair	Short-term			1505	
	[3,2] Left lane closed	-		Pavement repair	Short-term			1440	
	[3,2] Left lane closed	-		Pavement repair	Short-term			1425	
	[3,2] Right lane closed	-		Pavement repair	Short-term			1590	
	[3,2] Left lane closed	-		Pavement repair	Short-term			1480	
	[3,2] Right lane closed	-		Pavement repair	Short-term			1500	
	[4,2] Left lane closed	-		Median barrier/guardrail installation/repair	Short-term			1550	

Texas freeway	[4,2] Left lane closed	-		Median barrier/guardrail installation/repair	Short-term			1470	Dudek *et al.* (*4*)
	[4,2] Right lane closed	-		Pavement repair	Short-term			1420	
	[4,2] Right lane closed	-		Resurfacing, asphalt removal	Short-term			1480	
	[4,3] Left lane closed	-		Median barrier/guardrail installation/repair	Short-term			1530	
	[4,3] Left lane closed	-		Median barrier/guardrail installation/repair	Short-term			1540	
	[4,3] Left lane closed	-		Median barrier/guardrail installation/repair	Short-term			1530	
	[4,3] Left lane closed	-		Median barrier/guardrail installation/repair	Short-term			1490	
	[5,2] Left lane closed	-		Resurfacing, asphalt removal	Short-term			1380	
	[5,2] Left lane closed	-		Resurfacing, asphalt removal	Short-term			1340	
	[5,2] Left lane closed	-		Resurfacing, asphalt removal	Short-term			1310	
	[5,2] Left lane closed	-		Resurfacing, asphalt removal	Short-term			1370	
	[5,2] Left lane closed	-		Resurfacing, asphalt removal	Short-term			1360	
	[5,2] Left lane closed	-		Resurfacing, asphalt removal	Short-term			1380	
	[5,2] Right lane closed	-		Resurfacing, asphalt removal	Short-term			1380	
	[5,2] Right lane closed	-		Resurfacing, asphalt removal	Short-term			1450	
California freeway	[2,1]	-		Median barrier/guardrail installation/repair	Short-term			1500	Kermode *et al.* (*3*)
	[2,1]	-		Pavement repair	Short-term			1400	
	[2,1]	-		Resurfacing, asphalt removal	Short-term			1200	
	[2,1]	-		Striping, slide removal	Short-term			1200	
	[2,1]	-		Pavement marker	Short-term			1100	

California freeway	[4or3,2]	-		Median barrier/guardrail installation/repair	Short-term			1600	Kermode *et al.* (*3*)
	[4or3,2]	-		Pavement repair	Short-term			1500	
	[4or3,2]	-		Resurfacing, asphalt removal	Short-term			1300	
	[4or3,2]	-		Striping, slide removal	Short-term			1300	
	[4or3,2]	-		Pavement marker	Short-term			1200	
	[4or3,2]	-		Bridge repair	Short-term			1100	
	[4,3]	-		Median barrier/guardrail installation/repair	Short-term			1600	
	[4,3]	-		Pavement repair	Short-term			1500	
	[4,3]	-		Resurfacing, asphalt removal	Short-term			1333	
	[4,3]	-		Striping, slide removal	Short-term			1333	
	[4,3]	-		Pavement marker	Short-term			1200	
	[4,3]	-		Bridge repair	Short-term			1133	
Indiana four-lane freeway	[2,1] Right lane closed	25.0		Bridge repair Medium intensity				1500	Jiang (*8*)
	[2,1] Right lane closed	12.0		Bridge repair Medium intensity				1572	
	[2,1] Right lane closed	11.0		Bridge repair Medium intensity				1190	
	[2,1] Left lane closed	32.0		Bridge repair High intensity				1308	
	[2,1] Left lane closed	31.0		Bridge repair High intensity				1320	
Toronto freeway	[3,2] Median lane closed	-			Long-term		Sunny	1952**	Ahmed *et al.* (*9*)
	[3,2] Median lane closed	-			Long-term		Wet snow Freezing rain	1631**	
	[3,2] Shoulder lane closed	-			Long-term		Sunny	2102**	
	[3,2] Shoulder lane closed	-			Long-term		Wet snow Freezing rain	1644**	

* [A, B]=[normal, open], ** Average values over several studies

TABLE 2 Summary of data collection for each site

Site	# of closed lanes	Loc. of closed lanes	# of opened lanes	Heavy vehicle (%)	Driver pop.	On-ramp at work	Lateral distance (feet)	Work zone length (mile)	Grade (%)	Work intensity	Work duration (short, long)	Weather (sun, rain)	Work time (day, night)	Avg. Speed (mph)	Capacity (vphpl)
1	1	Right	3	8.2	0	Yes	0.5	1.2	- 2	Shoulder pavement (Low)	Short	Sun	Day	22	1612
2	1	Right	3	8.1	0	Yes	0.5	0.45	- 2	Shoulder pavement (Low)	Short	Sun	Day	37	1627
3	1	Right	3	9.0	0	Yes	0	0.15	+ 3	Bridge repair (Med)	Short	Sun	Day	31	1519
4	1	Left	3	10.3	0	N/A	0.5	0.15	- 5	Median barrier repair (Low)	Short	Sun	Day	31	1790
5	1	Left	3	8.0	0	N/A	0.5	0.18	- 5	Median barrier repair (Low)	Short	Sun	Day	30	1735
6	1	Left	3	10.1	0	Yes	1.0	1.9	- 3	Median barrier repair (Low)	Short	Sun	Day	37	1692
7	2	Right	2	14.3	0	Yes	1.0	1.8	0	Pavement (Heavy)	Short	Sun	Night	23	1290
8	2	Right	2	8.5	0	Yes	0	2.2	0	Pavement (Heavy)	Short	Sun	Night	21	1228
9	2	Left	2	11.0	0	Yes	0.5	1.3	0	Pavement (Med)	Short	Sun	Night	22	1408
10	2	Left	2	11.3	0	Yes	0	0.9	0	Pavement (Heavy)	Short	Sun	Night	24	1265
11	2	Left	2	4.6	0	Yes	0.5	2.0	0	Pavement (Med)	Short	Sun	Night	17	1472
12	2	Left	2	9.9	0	Yes	0	0.9	0	Pavement (Heavy)	Short	Sun	Day	20	1298

Note) Driver population: commuter=1, otherwise=0

TABLE 3 Correlation matrix table between the independent variables

	CAPACITY	NUMCL	LOCCL	HV	LD	WL	WG	WI_M	WI_H	WG*HV	WL*WG
CAPACITY	1.00										
NUMCL	-0.89	1.00									
LOCCL	-0.18	-0.17	1.00								
HV	-0.31	0.22	0.07	1.00							
LD	0.42	-0.24	-0.04	0.25	1.00						
WL	-0.50	0.58	0.08	0.00	0.29	1.00					
WG	-0.73	0.52	0.37	0.08	-0.45	0.26	1.00				
WI_M	-0.09	0.19	-0.10	-0.32	-0.14	0.04	0.56	1.00			
WI_H	-0.84	0.71	0.12	0.49	-0.34	0.35	0.37	-0.41	1.00		
WG*HV	-0.73	0.52	0.39	0.04	-0.46	0.24	0.99	0.55	0.36	1.00	
WL*WG	-0.56	0.55	0.17	0.50	0.42	0.86	0.24	-0.16	0.52	0.22	1.00

TABLE 4 The results of regression analysis for the capacity model

Factor	Variable	Coefficient	Standard error	t-Stat	P-value
	CONSTANT	1856.64	75.83	24.49	1.65E-05
Number of closed lanes	NUMCL	-168.11	37.95	-4.43	0.011
Location of closed lanes	LOCCL	-37.00	24.06	-1.54	0.199
Proportion of heavy vehicles	HV	-9.00	6.07	-1.48	0.212
Lateral distance to the open travel lanes	LD	92.74	47.89	1.93	0.125
Work zone length	WL	-34.32	20.30	-1.69	0.166
Intensity of work zone activity in category heavy	WI_H	-106.14	39.34	-2.70	0.054
Work zone grade * Proportion of heavy vehicles	WG*HV	-2.34	0.69	-3.38	0.028
R-square					0.993
Adjusted R-square					0.981

TABLE 5 Comparison of Residual Mean Square (RMS) error

Site	Actual capacity (vphpl)	Computed capacity (vphpl)				
		Memmott & Dudek	Abrams & Wang	Krammes & Lopez	HCM	New capacity model
North Carolina Freeway	1637	1332	1971	1544	1340	1683
	1644	1332	1969	1662	1340	1641
	1787	1332	1976	1565	1340	1670
	1692	1332	1927	1301	1340	1449
	1440	1332	1879	1313	1340	1465
Indiana Freeway	1500	1332	1819	1422	1340	1481
	1572	1332	1872	1509	1340	1598
	1190	1332	1861	1517	1340	1607
	1308	1332	1798	1241	1340	1349
	1320	1332	1795	1247	1340	1358
RMS error	$\sqrt{\frac{\sum (x_i - \hat{x}_i)^2}{n}}$	231.8	366.1	171.7	226.9	145.3