Flow Characteristics at Freeway Lane Closures

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ABSTRACT

The findings of a limited study aimed at examining the basic characteristics of freeway traffic flow at construction zones are presented. The intent is to expand the scope of previous research efforts in this area, which have focused on the determination of point estimates of work zone capacity, under a variety of freeway lane configurations upstream of and in the vicinity of the work area. Field studies conducted in Illinois, encompassing more than 21,000 vehicle observations, were used to examine the entire range of the speed-flow relationship in the open lane of traffic. A normalizing procedure was devised to isolate and quantify the impact of work zone activity descriptors, such as the location of work relative to the traveled lanes, crew size, equipment, and other pertinent parameters, on the observed traffic speed. It was found that the effect of work activity on traffic flow is significant in periods of (a) high approach flow rates, (b) high truck percentages, and (c) intense work activity near the traveled lanes.

Estimating capacity and level of service (LOS) at freeway construction zones is essential to planning and scheduling work zone traffic control. A comprehensive evaluation of alternate control strategies, including their respective traffic impacts, must be carried out before a particular procedure is recommended for implementation. Traffic performance measures such as delays, stops, fuel consumption, and operating costs are directly related to the capacity and operating speed on the roadway segment. Thus a thorough examination of the basic speed-flow relationship at freeway lane closures is warranted.

It may be stated that traffic speed through a lane closure is primarily governed by the following factors:

- Geometrics including lane configuration before and at the work area; grades and curvatures; effective lane width and lateral clearance; sight distance and proximity to on and off ramps;
- Traffic stream including flow rates past the work area and truck occurrence in the traffic stream;
- Traffic control including signing, arrow board, and channeling devices; speed zoning; presence of flagmen or patrolmen, or both; and
- Work activity descriptors including activity location, crew size, equipment type, noise and dust level generated and length of the work area.

Although considerable research has focused on the problem of speed control at work zones, little is known about the correlation between traffic speed and work zone activity. A procedure is thus required to isolate the effect of work zone activity from geometrics, traffic stream, and traffic control impacts. This study is a first attempt to address these issues. Specifically, the following objectives are sought:

1. Review previous work related to speed-volume-capacity relationships at freeway lane closures.
2. Conduct uncontrolled field studies to generate a data base for developing speed-flow models at the visited work sites.
3. Estimate the magnitude and direction of work activity impact on observed traffic speed; segregate by flow rate, truck occurrences, and work activity levels to study the contribution of each parameter.

LITERATURE REVIEW

In the relatively few years since the problem of work zone safety has received national recognition (e.g., 1975 FHWA coordinated research program project 1Y Traffic Management of Construction and Maintenance Zones), speed control at work zones has been a persistent problem. Traffic engineers have yet to agree on whether speed reduction is desirable or whether traffic speed should be maintained throughout the work zone by means of higher geometric standards. There is a consensus, however, that posted regulatory or advisory speed limits are ineffective in reducing speeds (1). Speed measurements collected to test the effectiveness of speed control measures were essentially limited to free-flowing vehicles (headways ≥ 5 sec). The impact of construction activity was not specifically analyzed in these studies (2-4).

A majority of the work reviewed in the course of this study dealt with the analysis of flow rates approaching capacity at lane closures (i.e., in situations in which a queue developed and was sustained upstream of the work zone). Dudek and Richards (5) have studied the impact of lane geometry on capacity at a number of urban freeway lane closures in Texas, and Kermode and Myrra (6) attempted to correlate observed capacity on the San Diego Expressway in California with the type (rather than the intensity) of construction activity (e.g., resurfacing, stripping). Their results, however, are based on 3-min observations of maximum flow rates past the work area and therefore tend to overestimate the hourly capacity expected at the sites.

It is interesting to note that the Texas study included limited observations of work zone capacity with no construction activity under way. The study found average lane capacity to be approximately 20 percent higher than that observed at similar sites with the work crew present. Although this result is based on data from a single site, it clearly demonstrates the degree to which work zone activity affects capacity and level of service at lane closures. In an earlier study by Butler (7), volume-to-capacity ratios and corresponding speeds measured at work zones were overplotted on the typical Highway Capacity Manual (HCM) curves (8). The author stated that the field data show tremendous scatter at particular volumes (unspecified) around HCM values but that they could still be approximated by the HCM curves. However, no numerical justification was provided for that argument. This approach was also followed in a recent study by Wang and Abrams (9) in developing a rational planning process for the selection of the most effective work zone traffic control strategy for a given project.

In a study by Dudash and Bullen (10), traffic speed and flow rates on the Penn-Lincoln Parkway in Pennsylvania were measured in order to estimate single-lane capacity during reconstruction. Their estimates were not substantially different from those observed in California and Texas. Although this study used speed-flow "envelopes" in a before-and-during construction comparison, their value is limited to a qualitative assessment of the lane closure impact under three types of control.

In brief, the literature review revealed two unresolved issues related to flow characteristics at freeway lane closures:

1. The applicability of the typical HCM speed-flow curve to traffic flow in construction zone lane closures and
2. The degree to which the work zone activity parameters influence speed for the entire range of volume-to-capacity (V/C) ratios.

FIELD STUDIES

Rationale and Scope

An exhaustive field investigation of all factors affecting operating speed at freeway lane closures requires an extensive data collection effort far beyond the resources of this study. In reference to geometric impact, it was decided to confine the sampling effort in this study to four-lane Interstate-type facilities with a single lane closure and no crossovers, for the following reasons:

- The effect of lane geometry is likely to be confounded with the impact of worksite activity, thus jeopardizing one of the principal objectives of this study. Moreover, lane geometry impact on capacity appears to be adequately documented in the literature.
- The study was originally designed to investigate rural freeway lane closures, where the four-lane divided roadway configuration is most prevalent.

Traffic control devices at the visited sites were in general conformance with the standards of the Illinois Manual of Traffic Control Devices (11). No advisory or regulatory speed limit signs were posted at any of the sites.

Site Description

Four projects were covered in the course of this study. The study sites were located within 60 mi of the Chicago area and all but one can be characterized as rural.

Site 1 was located on the northbound lanes of I-57, 1/4 mi north of US-30, at the southern boundary of Cook County, Illinois. At that site, a bridge repair project consisting primarily of steel joist replacement was under way. A crew of three workers, a foreman, and a flagman was present at the site. The work activity consisted of (a) breaking up concrete deck, (b) dusting, and (c) removing and replacing steel joists. Traffic control included advanced warning signs, a flashing arrow panel, and 18-in. cones for channelization in the lane closure area.

Site 2 was located on the eastbound lanes of I-80, east of the Illinois Route 7 interchange. The construction activity was similar to that of Site 1, except that relatively smaller drilling equipment and a larger crew size were present at this site. Also, a flagman was located just next to the work area; the flagman was located near the arrow panel at Site 1. No major differences in geometrics or traffic control devices were noted between the two sites.

Site 3 was located on the eastbound lanes of I-290, 3/4 mi east of Illinois Route 53. This section of I-290 was heavily congested during the data collection period, with queues extending to the Route 53 on-ramp. Flow rates past the work area were thus indicative of the lane closure capacity. Work activity at this site consisted of concrete pavement patching, which at times infringed on the open lane of traffic. Traffic control devices included advanced warning signs, arrow board, and vertical posts in the taper and lane closure areas.

Site 4 was located on the northbound lanes of I-55, 1 mi south of I-80 near Joliet, Illinois. Work at this site consisted of bridge deck repair. This site was characterized by a physical separation of work activity and vehicular traffic by means of a portable concrete barrier.

A summary of other pertinent site characteristics is given in Table 1.

TABLE 1 Summary of Site Characteristics

Site	Lane Closed	Length of Closure (ft)	Channelizing Device	Average Hourly Volume
I-57	Left	3,000	18-in. cones	535
I-80	Left	1,035	Type I barricades	1,193
I-290	Right	530	Tubular posts	435[a]
I-55	Left	435	Portable concrete barrier	760

[a]Measured in queuing conditions; does not reflect traffic demand.

Data Gathering

Three data elements were collected at each site:

1. Traffic speed and composition upstream of the work zone,
2. Simultaneous 5-min counts of speeds and flow rates at the beginning and end of the lane closure section, and
3. Work area activity descriptors for the intervals indicated in part 2.

Traffic speed upstream of the work zone was collected on a random sample of approaching vehicles via a radar gun. Vehicle types were recorded by a time-lapse camera located at a vantage point at each site. The recording interval varied from 1 to 3 sec, depending on the approach speed prevalent at the site. Speed and flow rate counts were collected using two Stevens PPRII print-punch classifiers located at both ends of the closure. All data were collected for a period of approximately 4 hr per site, except for Site 1 where equipment problems limited the data collection to 1 hr.

Because construction activity does not lend itself to numerical description, it was necessary to devise an ordinal-level scale to quantify the intensity (in terms of its vehicular impact) of the work activity. Six activity indicators, which have a potential impact on traffic flow characteristics, were selected:

1. Proximity of work activity to travel lane (PL). A numerical code from zero to four denotes the

location of the activity. An assigned zero code implies no work activity (e.g., lunch break), and a code of four describes work activity carried out at the lane edge (e.g., stripping). PL increases by one unit for each 3-ft shift in construction activity closer to the travel lane.

2. Crew size (CS). Active crew size in the work area.

3. Equipment code (EC). A numerical code from zero to three denotes the relative size of equipment operating at the site. A zero code implies no operating equipment, and a code of three indicates heavy equipment usage.

4. Flagman code (FC). Binary code indicating the presence (FC = 1) or absence (FC = 0) of a flagman in a particular time interval.

5. Noise level code (NL). A numeric code from zero to three designating the relative noise level at the site.

6. Dust level code (DL). A numeric code from zero to three designating the relative dust level at the site.

The sum of the numerical codes is termed the activity index (AI). It serves to identify those intervals during which construction activity interferes with traffic flow in an attempt to test the hypothesis that traffic speed is directly correlated to the intensity of the construction activity at the visited sites.

It should be noted that the work activity data were collected manually in 5-min intervals that corresponded to the speed-flow observations obtained by the traffic classifiers. A sample plot of the activity index history for Site 3 is shown in Figure 1.

Results

The results of data analysis are presented in three parts:

1. Speed distribution upstream of and at the lane closure area,
2. Speed-flow relationships at each site and comparison with HCM, and
3. Impact of work zone activity on traffic flow parameters.

Analysis of Speed Distribution

Speed distributions observed upstream of the work zone were tested for normality. Except for Site 3, speeds followed the normal distribution. It should be emphasized that at Site 3 traffic upstream of the work zone was operating in stop-and-go conditions; this made it impossible to derive an estimate of approach speeds before joining the queue because free-flow conditions did not occur within the instrumented segment of the road. It is interesting to note that mean speeds for the remaining sites were all within 2 mph of each other, as indicated in Table 2. Further testing by approach lane and vehicle type showed no significant differences.

Speed measurements taken at the beginning and end of the lane closures exhibited a consistent pattern of skewness, as shown in the sample histogram in Figure 2 for Site 1. A statistical test for skewness of speed distribution was borrowed from a study by Bleyl (12) in which the sampling distribution of the spot speed skewness index (SI) was found to be normal with a mean skewness index of 1.00 and a standard

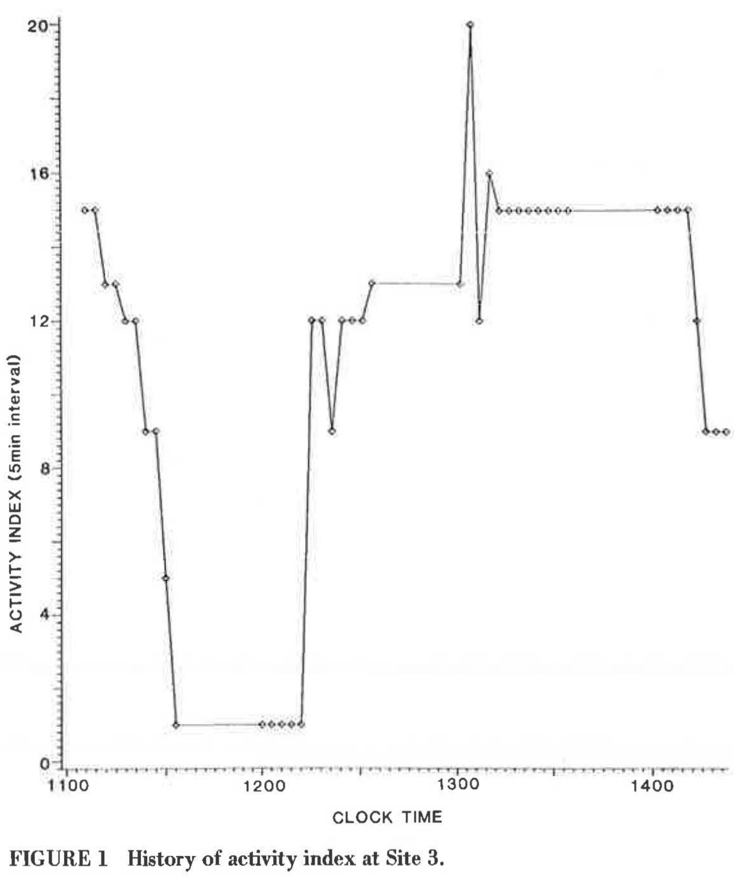

FIGURE 1 History of activity index at Site 3.

TABLE 2 Observed Speed Distribution Upstream of Lane Closure

Site	Sample Size	Mean Speed (mph)	Standard Deviation	χ^{2a}	Level of Significance
I-57	125	54.78	4.695	3.88	0.700
I-80	144	52.33	5.854	7.25	0.123
I-290	N/A	N/A[b]	N/A	N/A	N/A
I-55	157	53.25	4.971	1.38	0.636

[a] χ^2 goodness of fit statistic for normal distribution.
[b] Approach speeds upstream of lane closure could not be measured because of queue buildup.

error (SE), provided that the parent population is normal, where

SI = 2 * $(P_{93} - P_{50})/(P_{93} - P_7)$,
P_c = ith percentile speed,
SE = (0.002 + 0.949)/SQRT(N), and
N = sample size.

The preceding test was applied to the pair of speed distributions observed at each end of the lane closure. The results given in Table 3 led to the rejection of the null hypothesis (i.e., parent population is normal) in all but one location at Site 4. This site exhibited higher speeds than other sites despite the presence of a concrete barrier at the edge of the traveled lane and a considerable reduction in lateral clearances on both sides of the lane.

It is interesting to note that, for skewed speed distributions with a left skew (SI < 1), the geometric condition (e.g., lane closure) is more restrictive than is perceived by the driver; that

TABLE 3 Observed Speed Distributions at Lane Closure

Site Location	Mean Speed (mph)	Standard Deviation (mph)	Skewness Index[a]	Level of Significance
I-57				
Start of closure	38.18	6.81	1.056	<0.01
End of closure	37.63	5.43	1.115	<0.01
I-80				
Start of closure	38.11	7.82	0.99	<0.01
End of closure	38.49	7.85	1.157	<0.01
I-290				
Start of closure	26.75	9.81	1.45	<0.01
End of closure	31.51	4.10	1.30	<0.01
I-55				
Start of closure	51.36	7.33	1.004	0.389
End of closure	51.14	7.22	0.987	<0.01

[a] $SI = 2(P_{93} - P_{50})/(P_{93} - P_7)$.

situation occurs at Sites 2 (start of closure) and 4 (end of closure). On the other hand, a right skew (SI > 1) indicates that the geometric condition appears worse than it actually is; this results in a large number of drivers slowing down to an "apparent" physical speed limited (13). This situation occurred at Sites 1, 2 (end of closure), and 3.

Speed-Flow Relationship

Speed-flow patterns were analyzed at each site by aggregating the speed observations in each 5-min interval into a space-mean speed and corresponding mean flow rate. The time interval was selected such

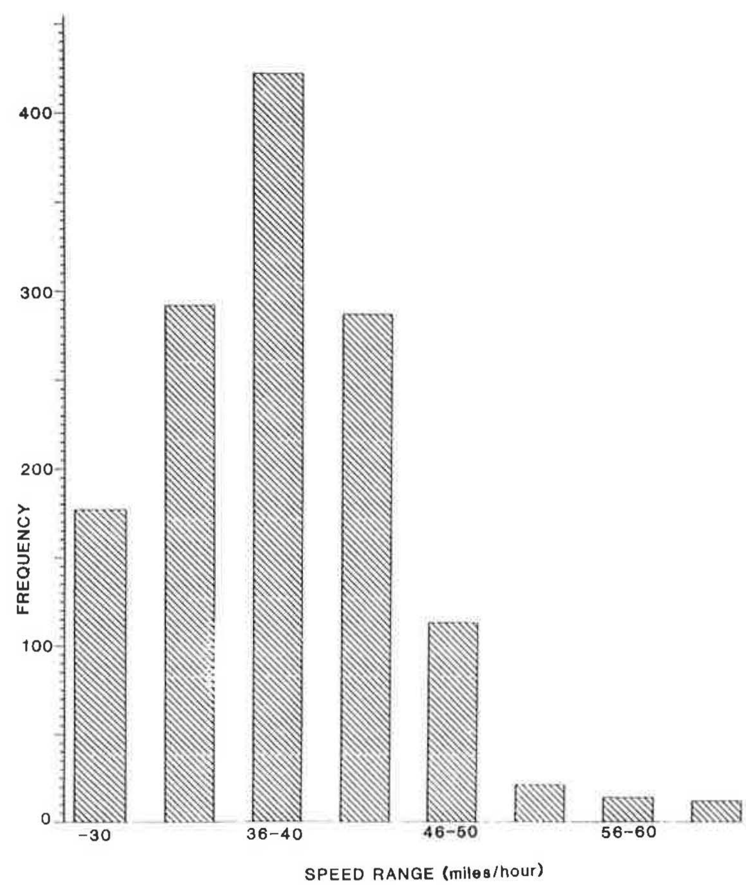

FIGURE 2 Speed distribution, Site 1, start of lane closure.

that the uniform flow assumption stated in the HCM was met and traffic fluctuations associated with short counting intervals were avoided.

A graphic representation of the observed speed-flow data is shown in Figure 3. The general shape formed by the data is surprisingly similar to the typical speed-flow curve in the HCM; that is, non-linear in the high service volume regime and flow-independent speed values at the lower end of the service volumes. Site 3 data were concentrated in the congested and forced-flow regimes of the speed-flow curve.

The maximum observed flow rate was approximately 130 vehicles/5-min interval or 1,560 vehicles per hour, and the highest sustained hourly flow rate was 1,507 vehicles per hour, which corresponds to a peak-hour factor of 0.97.

A second degree polynomial fitted to the data is

$$V = -13.2 + 4.571S - 0.055S^2 \quad (1)$$

where V and S refer to the observed flow rates and corresponding space-mean speed, respectively. A capacity estimate can be derived from Equation 1 by setting the conditions

$$dV/dS = 0,\ d^2V/dS^2 < 0 \text{ at } V = V_{max} \quad (2)$$

From Equations 1 and 2, V_{max} = 975 vph and S_{opt} = 41.3 mph.

The regression model in Equation 1 thus gives unrealistic estimates of optimum speed and capacity, a very poor fit to the observed data (R^2 = 0.068) and, therefore, would have limited value for capacity estimation purposes.

The preceding analysis indicates that the derivation of capacity and level of service without regard to individual site variations, especially the extent of construction activity, the impact of truck traffic, the site geometrics, and so forth, will generally result in a tremendous scatter of the data points, as pointed out in an earlier study by Butler (7). To eliminate intersite variations, individual site models were generated using the linear form:

$$S = a + bV \quad (3)$$

where a and b are the regression coefficients and S and V are as defined earlier. These models were developed at locations adjacent to the work area (either start or end of the lane closure). A total of 146 sample points were included in this analysis.

The models are given in Table 4 and shown in Figure 4. It is observed that the flow rates at Sites 1, 2, and 4 varied from 40 (480 vph) to 120 (1,440 vph), with some overlap between sites. The regression coefficients were quite realistic in that as volume increased the slope b in Equation 3 consistently decreased and the corresponding intercept a consistently increased. However, slopes that were statistically significant (i.e., $b \neq 0$) occurred in the volume range of 50 to 100 vehicles per interval, or at an average hourly volume of 900 vph (i.e., about 57 percent of maximum observed flow). In contrast, HCM speed-flow curves start to exhibit a substantial reduction in speed at a V/C ratio of approximately 0.80. Thus it appears that a lane closure will result in a greater speed reduction for a given volume or V/C ratio than would be expected on the full cross section.

At Site 3, forced-flow conditions prevailed as speeds were clustered at the bottom half of Figure 3.

A final observation in Figure 4 is the discontinuity in the speed-flow lines from site to site.

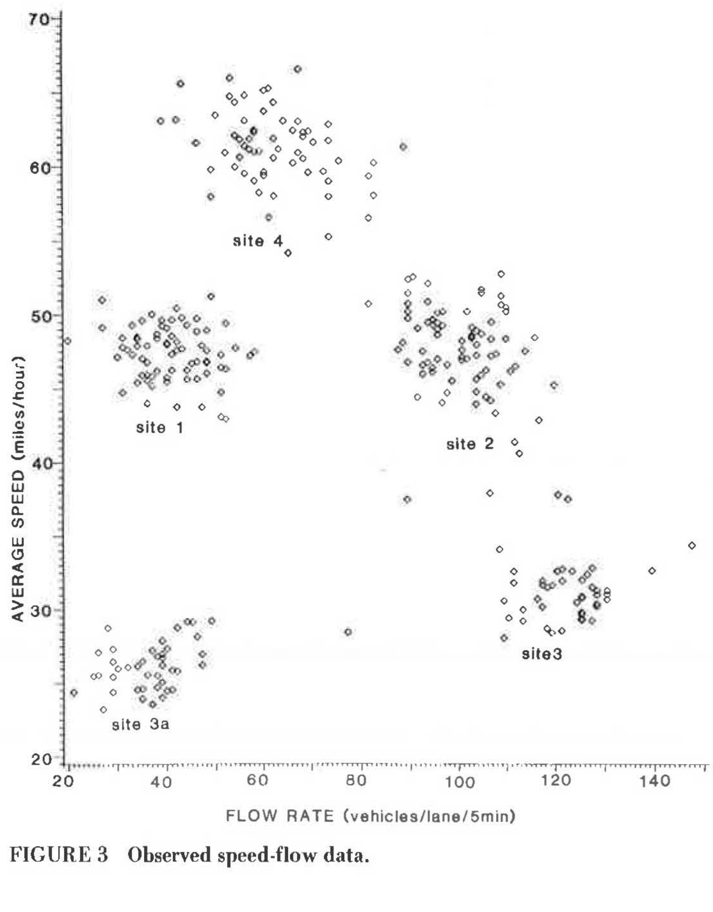

FIGURE 3 Observed speed-flow data.

TABLE 4 Derived Linear Speed-Flow Models Near Work Area

Site	Range of 5-Min Flow Rates Observed	Intercept	Slope	Correlation Coefficient Level of Significance
I-57	34-58	49.04	−0.018	0.85
I-80	88-122	72.50	−0.24	<0.01[a]
I-290	109-147	25.90	+0.04	0.23
I-290[b]	26-49	23.16	+0.08	0.11[c]
I-55	39-88	56.72	−0.087	<0.01[a]

[a] Significant at the 1 percent level.
[b] Observations at start of closure under forced-flow conditions.
[c] Marginally significant at the 10 percent level.

For example, Site 1 had the lowest observed volumes, yet the space-mean speed for that site was consistently lower than that observed at Sites 2 and 4. This is precisely the discrepancy that remains to be explained. This requires the normalization of the speed data to account for variations in geometrics, traffic composition, and demand volume. The presence of any significant residual differences in traffic speed after the normalization procedure is carried out is then attributed to the presence (and intensity) of the construction or maintenance activity itself. The procedure is covered in the next section.

Determination of Construction Activity Effect on Speed

Development of Procedure

The following speed model is assumed at a freeway lane closure site:

$$S_{ot} = S_{pt} - S_t \quad (4)$$

where

S_{ot} = observed space-mean speed in time interval (t) at the lane closure area;
S_{pt} = predicted space-mean speed in time interval (t) for given geometrics, traffic, lane width, and clearance restrictions with work activity; and
S_t = speed reduction in time interval (t) due solely to the presence and intensity of the work activity.

The hypothesis tested is whether (a) S_t is indeed significantly different from zero and (b) the degree to which S_t is functionally correlated to the activity index or to one of its components (e.g., PL, NL). Furthermore, the analysis will determine whether S_t is independent of flow rate (i.e., speed-flow curve parallel to HCM curve) and truck occurrence in the traffic stream. The procedure is carried out in four steps:

1. The observed 5-min flow rates are converted into the equivalent service volume in passenger cars per hour per lane (pcph/lane), with proper adjustment factors for trucks (Q_w) and lane width restrictions (W_w) based on capacity studies of lane closures.
2. Estimates of W_w and Q_w are derived from observations of work zone operation in a study by Wang and Abrams (9). In that study, a computed work zone capacity in vph/lane is defined as

$$C_c = 2000\ V_h Q_h \quad (5)$$

where the h subscript refers to adjustment factors taken from the HCM. The observed capacity in the field is denoted as C_o. A stepwise regression analysis with (C_o - C_c) as a dependent variable and a set of independent variables related to lane geometrics,

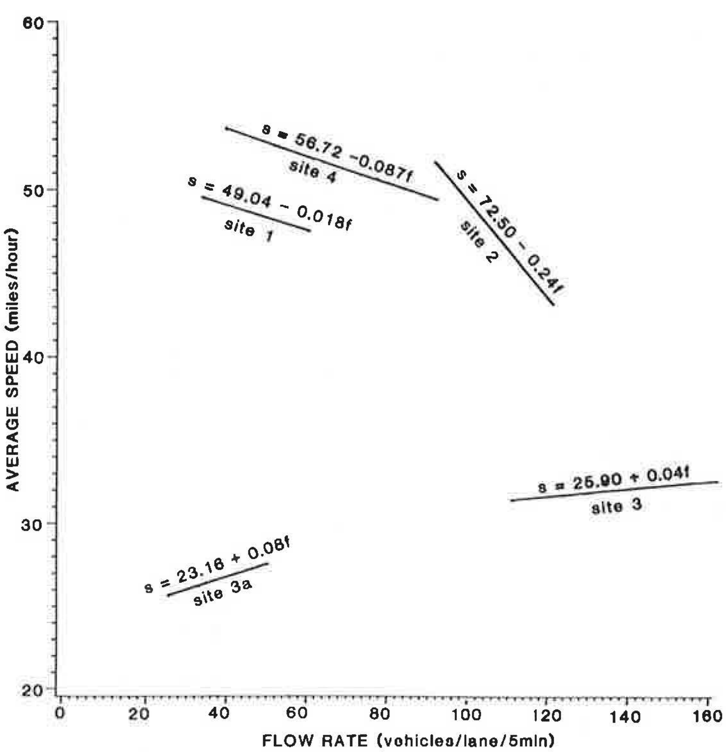

FIGURE 4 Site-specific speed-flow models.

traffic, and type of work activity gave the following equation:

$$C_o - C = 1262 - 228.6N_T - 1230Q_h + 167.4A + 90N_o, \quad R^2 = 0.7 \qquad (6)$$

where

N_T = total number of lanes before closure, per direction;
A = work activity type, 1 = long term, 2 = short term; and
N_o = number of open lanes in work zone.

For the sites considered in this study, N_T = 2, A = 1, and N = 1. Equation 6 can be rewritten as

$$C_o = 2000Q_hW_h + 1062.2 = 1230Q_h \qquad (7)$$

If a similar definition of C_c is applied for C_o, then

$$C_o = 2000Q_wW_w \qquad (8)$$

where the w subscript refer to work zone adjustment factors for trucks, lane width, and lateral clearances. Hence:

$$2000Q_wW_w = 2000Q_hW_h + 1062.2 - 1230Q_h \qquad (9)$$

For a stream of traffic consisting entirely of passenger cars, $Q_w = Q_h = 1$ and Equation 9 can be solved for W_w. This gives

$$W_w = W_h - 0.084 \qquad (10)$$

It is important to note that the stepwise procedure incorporated the type of channelizing device as an independent variable. Temporary (cones, posts) and permanent devices (concrete barrier) were tested but none was significant for inclusions in the model, except of course for implicit impact on lane width and lateral clearance in the parameters W_w and W_h. Substituting for W_w in Equation 9 and solving for Q_w gives

$$Q_w = 0.531 + Q_h(W_h - 0.615)/(W_h - 0.084) \qquad (11)$$

Equations 10 and 11 give the required adjustment factors for lane width restrictions and trucks in single lane closure work zones.

3. The service volume in Step 1 of the procedure is now calculated as

$$SV_t(\text{pcph/l}) = 12f_t/(W_w * Q_w) \qquad (12)$$

where f_t is the observed 5-min flow rate in interval t. Subsequently, the predicted space-mean speed in each interval was derived on the basis of the HCM speed-flow curve in TRB Circular 212 (14). The resulting regression equations are

$$S_{pt} = 54.41 - 0.0029SV_t \text{ for } SV_t \leq 1600 \text{ pcph/l} \qquad (13)$$

and

$$S_{pt} = 501.9 - 61.24\text{Ln}SV_t \text{ for } 1600 < SV_t \leq 2000 \text{ pcph/l} \qquad (14)$$

4. Substituting into Equation 4, the interval estimates of S_t that reflect speed reduction due to work activity are derived and analyzed.

Results

The data set used in this analysis consisted of all speed-flow observations taken in the vicinity of the work area itself, where the impact of construction activity on traffic flow would be most significant. After discarding observations with missing data or due to equipment malfunction, a total of 103 5-min observations were identified at all four sites. It was found that on the average the observed mean speed at lane closures was 3 mph lower than the predicted speed under the given volume, lane width, clearance, and truck occurrence in the traffic stream from the HCM. Individual differences varied from 10 mph higher to 18 mph lower than the predicted speeds.

A series of t-tests was performed on the difference in mean values for S_t that are associated with various levels of work zone descriptors. A brief summary follows.

Activity Index

The original data set was divided into two subsets. Subset A included all observations with AI $\leq$ 8 and Subset B the remaining observations. As the data in Table 5 indicate, the difference in speeds was found to increase as AI increased; this pattern was consistent at three of the four sites. Overall, however, the difference was less than 1 mph and not statistically significant. It should be noted that the high speeds observed at Site 4 affect Subset B more than A because only one observation at Site 4 fell into Subset A. Omitting Site 4 data, the overall difference in means increases to 2.5 mph and becomes statistically significant at the 5 percent level.

TABLE 5 Predicted Difference in Speed[a] (mph) Versus Activity Index (AI)

	Intensity of Construction Activity				
	Low (AI < 8)		High (AI > 8)		
Site	Mean	Standard Deviation	Mean	Standard Deviation	Level of Significance
I-57	N/A	N/A	4.27	2.13	N/A
I-80	−0.317	2.47	2.01	2.56	0.074[b]
I-290	6.44	2.25	10.94	3.95	0.17
I-55	−10.19[c]	N/A	−8.15	2.27	N/A
All sites combined	2.34	5.04	3.03	7.17	0.19
Sites 1, 2, 3	3.17	2.25	5.83	2.76	<0.05

[a]Positive values indicate predicted speed (HCM) greater than observed and vice versa.
[b]Significant at the 10% level.
[c]Only one observation fell into this category.

Proximity of Work Activity to Lane of Travel

Observations were categorized as those occurring while construction activity was within 6 ft of the edge of the traveled lane (Subset A, PL > 2) and all remaining observations (Subset B, PL $\leq$ 2). As the data in Table 6 indicate, the predicted difference in speed increased significantly as the work activity moved to within 6 ft of the lane edge. This conclusion held true even after Site 4 data were removed. It is also apparent that because of the precise definition of PL, as opposed to the activity index (AI) that contains a number of subjective

TABLE 6 Predicted Difference In Speed[a] (mph) Versus Activity Location (PL)

	Activity Location with Regard to Travel Lane				
	Close (PL > 2)		Far (PL < 2)		
Site	Mean	Standard Deviation	Mean	Standard Deviation	Level of Significance
I-57	4.43	0.69	2.69	2.18	0.467
I-80	1.66	1.83	1.69	3.04	0.454
I-290	12.27	3.54	7.85	3.54	0.0165[b]
I-55	N/A	N/A[c]	-7.98	2.39	N/A
All sites combined	6.37	5.43	0.563	6.79	<0.001[b]

[a]Positive number indicates predicted speed (HCM) greater than observed speed and vice versa.
[b]Significant at the 1% level.
[c]Site 4 activity physically separated from travel lane by means of portable concrete barrier.

components (e.g., EC, NL, DL), the former parameter is superior in predicting speed changes due to the presence of construction. A stepwise regression model on the original data indicated that with all other variables fixed, a 3-ft shift of construction activity toward the travel lane (i.e., a unit increase in PL) results in an average speed reduction of 2 mph.

5-Min Flow Rate

This test was intended to verify whether drivers in free- and congested-flow conditions react equally to the presence of construction. The original data set was divided into two subsets. Subset A contained flow rates $\leq$ 100 (1,200 vph) and Subset B all the remaining observations. The 100 figure represents a V/C ratio of approximately 0.65 for the observed truck traffic. As the data in Table 7 indicate, the difference in speeds increased substantially as the flow rate past the work site increased. This implies

TABLE 7 Predicted Difference in Speed[a] (mph) Versus 5-Min Flow Rate (TOT)

	Observed Flow Rate				
	Low (TOT < 100)		High (TOT > 100)		
Site	Mean	Standard Deviation	Mean	Standard Deviation	Level of Significance
I-57	4.91	2.14	N/A[b]	N/A	N/A
I-80	1.12	1.96	2.11	2.98	0.2
I-290	22.8[c]	N/A[b]	11.21	5.07	N/A
I-55	-8.93	2.14	N/A[b]	N/A	N/A
All sites combined	-2.51	7.16	7.99	6.22	<0.01[d]

[a]Positive values indicate predicted speed (HCM) greater than observed speed and vice versa.
[b]No observations in category.
[c]Only one observation fell into this category.
[d]Significant at the 1% level.

that the speed-flow curve in a work zone exhibits a steeper slope than its HCM counterpart for a given service volume. The stepwise regression technique discussed earlier was applied for determining the best two-variable formulation. It was found that 52 percent of the variation in speed differences is attributed to flow rates and proximity of work to travel lane. The model form is

$$S_t = -14.17 + 2.07PL_t + 0.14V_t \quad (15)$$

Equation 15 shows that the impact of flow rates on speed differences is greater when the work activity is within 6 ft of the edge of the lane (PL > 2) at approximately 1,000 vph flow rate (V_t).

Trucks

The original data set was divided into two subsets, one with truck percentages less than 10 percent and the other containing all remaining observations. The results indicated that speed differences increased as the level of trucks increased in the traffic stream. The difference was significant at the 1 percent level. Note that S_t had already been adjusted for trucks; thus the test establishes the additional impact due to the presence of construction.

Others Parameters

The remaining work activity descriptors were not statistically significant in terms of their impact on speed. One interesting exception is the effect of the type of channelizing device. At Site 4, which had a portable concrete barrier at the taper and lane closure areas, speed was virtually independent of work zone activity. It appears that because the barrier effectively separated and visually shielded the construction activity from traffic, the observed speeds consistently exceeded predicted speeds, despite the restrictive lane geometry (width and clearances) at the closure.

SUMMARY AND CONCLUSIONS

This study represents a first attempt at a systematic analysis of freeway traffic flow at single-lane closures, including the effect of work activity interference on observed traffic speed. The following conclusions, based on the limited field observations in this study, are presented:

1. The distribution of traffic speed upstream of the work zone follows a normal distribution when no queuing conditions exist. In the closure area, however, the speed distribution shows significant skewness regardless of the quality of flow upstream of the closure.
2. Speed-flow models at the observed lane closures in this study are considerably different from HCM curves under similar volumes, truck levels, lane width, and lateral clearance restrictions. On the average a difference of 3 mph between HCM and observed speed was noted.
3. The difference in speeds noted in Conclusion 2 is quite sensitive to the location of the work activity. It was found that for every 3-ft shift in construction activity closer to the edge of the traveled lane, a drop of 2 mph in observed speed can be expected.
4. The sensitivity of traffic speed to work zone activity increases as traffic or truck volumes, or both, increase. This may help explain the considerable variations in observed lane capacities at work zones, especially when short counts of 3-6 min are expanded into an hourly flow. In this study, the observed speed at Site 3, which operated at or near capacity in the lane closure section, was on the average 10 mph lower than the corresponding HCM value.

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Operational and Safety Impacts on Freeway Traffic of High-Occupancy Vehicle Lane Construction in a Median

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ABSTRACT

In this paper are presented the results of a study by the Texas Transportation Institute to evaluate the operational and safety impacts associated with the retrofit construction of an authorized high-occupany vehicle lane in the median of the Katy Freeway (I-10W) in Houston, Texas. Because the Katy Freeway transitway is the first of a 70-mi network of transitways to be retrofitted in an existing high-volume freeway cross section in Houston, it is important to assess the traffic impacts associated with this type of construction. Operational impacts studied include travel speeds as a measure of travel time delay, traffic volumes as a measure of travel demand served, and lane distributions as a measure of driver reaction to reduced lane widths and restricted lateral clearances. Safety was assessed through an analysis of reported accidents associated with various work area segments and time periods of construction. Results indicate that a detailed traffic control plan can minimize the possible adverse effects of transitway retrofit construction.