Comparative Study of Short- and Long-Term Urban Freeway Work Zones

NAGUI M. ROUPHAIL, ZHAO SHENG YANG, AND JOSEPH FAZIO

Freeway construction and maintenance work in major metropolitan areas is often limited to off-peak daytime or nighttime periods because of the heavy traffic volumes served by these facilities. Previous research has focused primarily on long-term work zones that continuously occupy the road space for several days or months, but little information exists regarding the safety and operational performance of short-term and intermittent sites. The objectives of this study were to compare the accident experience at both long-term and short-term sites before, during, and after freeway construction or maintenance work. In addition, an evaluation of traffic flow and traffic control device (TCD) layout in terms of adherence to state standards was undertaken for both types of zones. It was found that at long-term sites the accident rate increased by an average of 88 percent during the existence of the work zone site, in comparison to the before period, and decreased by an average of 34 percent in the after period. For short-term sites, a nearly constant accident rate of 0.80 accident/mile-day of construction or maintenance was observed. The evaluation of TCD layout revealed significant discrepancies between standards and practice. In general, devices were placed closer to the lane taper than is allowed by standards. Discrepancies were more frequent at the short-term sites, where an average of two TCDs were missing, in comparison to one TCD missing at long-term sites. Moreover, wider variations in warning signs placement were observed at the short-term sites. Finally, sites characterized by short tapers, missing arrow boards, signs, or any combination of these factors exhibited higher speed variations in the work zone when speed was not dictated by traffic.

Provision of traffic congestion relief in U.S. urban areas is a major challenge facing today's transportation engineers (*1*). The problem of providing safe and efficient conduct of traffic in and around highway work zones, coupled with the need to maintain and upgrade the physical facilities, has received national attention in recent years. In large metropolitan areas, it is becoming exceedingly difficult to serve the needs of motorists while providing adequate protection to the work crew at the same time. In addition, providing access to and from the work site for construction and maintenance vehicles, especially during peak flow periods, is not an easy task. To alleviate some of these problems, highway agencies have adopted procedures whereby routine construction and maintenance work (as opposed to major reconstruction or rehabilitation) is confined to off-peak daytime and nighttime hours. For example, in the Chicago Metropolitan Area, freeway lane closures on weekdays are typically limited to a 6-hour period between 9 a.m. and 3 p.m., but some continuous closures are allowed during weekends. These intermittent work zones pose problems to motorists because

- The location of the closure may vary from one day to the next;
- In comparison to the peak hours, the driving population during these periods contains fewer commuters, thus increasing the element of surprise; and
- Motorists are not likely to divert onto alternate routes because the work activities were scheduled only in the previous 24 to 48 hours.

In summary, driver anticipation of the geometric restrictions posed by the presence of the intermittent work zones is considerably less than it is for long-term closures. The ways in which this affects traffic operations and safety during construction or maintenance will be the focus of this paper.

This study had two major objectives. The first objective was to compare the accident experience at both long-term and short-term sites before, during, and after construction or maintenance work. The comparison was accomplished by developing a relative accident rate to allow examination of the variation in accidents at short-term and long-term sites. Because of volume data deficiencies, an absolute accident rate was not developed. Moreover, because of the nature of the comparison, the development of an absolute accident rate was not necessary. The second objective was to make a comparative evaluation of traffic flow and traffic control device layout in terms of adherence to Illinois Department of Transportation (IDOT) standards. This evaluation was undertaken for both short-term and long-term work zones.

LITERATURE REVIEW

The literature abounds with traffic safety and operational studies of work zones. Some authors use the term "construction zone" as a synonym for "work zone." To date, the study by Graham et al. (2) is the most comprehensive, encompassing 79 construction projects in seven states. Their analysis indicated an average increase of 7.5 percent in accidents during construction, although some sites actually experienced a reduction in accidents (the range varied from −3.4 to +37.6 percent by state). All the projects, however, were long term, ranging in duration from 2 months to almost 2 years. Regression models that were developed to consider the relationships between construction accident rates and the project length and duration indicated that long-length and high-duration projects normally exhibit lower accident rates. Whether this trend can be extrapo-

Urban Transportation Center and Department of Civil Engineering, Mechanics, and Metallurgy, University of Illinois, P.O. Box 4348, Chicago, Ill. 60680.

lated to the short-term sites, however, remains to be seen. Finally, the study found that sites that had the most restrictive geometry during construction (i.e., six- to eight-lane freeways reduced to one lane in each direction) exhibited the sharpest increase in accident rates from the before period. Unfortunately, no results were reported separately for urban and rural Interstate facilities. Data of this type would help identify specific problems associated with urban construction projects.

A cross-sectional study of highway work zones was conducted by Martin and Hargroves in Virginia (*3*). In the study, all reported work zone accidents in Virginia (2,127 in 1977) were analyzed and compared to statewide accident characteristics (142,170 in 1977). The authors found that urban work zone accidents constituted about 1.72 percent of all urban accidents (versus 1.21 percent for rural areas) and that these accidents were more likely to occur on dry pavement (81.5 percent versus 72.7 percent overall), in daylight (69.4 percent versus 63.4 percent overall), and in clear weather (68.6 percent versus 58.2 percent overall). Moreover, passenger automobiles were slightly less involved in work zone accidents (77 percent versus 80.3 percent overall), whereas heavier vehicles were more involved (20 percent versus 15.5 percent overall). In terms of accident type, fixed object collisions were more likely in work zones (10.4 percent versus 2.8 percent overall), but collision accidents remained fairly stable (70 percent versus 70.5 percent overall). Although the results were very informative, many of these statistics were aggregated for all roadway types and for varying project durations, making it difficult to assess the effect of short-term freeway construction projects. A similar approach was adopted by Nemeth et al. (*4*) in their comparison of freeway work zone accidents and all accidents on the Ohio Turnpike.

Other studies were aimed at testing the accident performance of traffic control procedures, such as lane closures and two-lane, two-way operations (TLTWO) by Graham et al. (*5*) and Dudek et al. (*6*). A recent study by Shepard and Cottrell (*7*) alluded to the potential benefits of night work zone activities but provided no information regarding their accident experience. The authors commented that there was a lack of comparable data. A comprehensive summary of the accident literature for highway work zones is available in the final report of the study (*8*). In summary, although the literature provided in-depth coverage of the accident problem at work zones, the specific issues relating to short-term work sites on urban freeways were not fully addressed.

ACCIDENT STUDY

Data Collection

Accident data for this study were provided by the Illinois Department of Transportation Division of Highway Safety. They were available in summary form on a magnetic tape that contained a 6-year accident history (1980–1985) of the Chicago Area Expressway System (CAES). Work zone accidents were identified by matching the locations and activity dates of a selected number of construction projects (three long-term and 23 short-term projects) to the data on the accident tape. This required a thorough examination of the construction logs for each project, including the precise hours during which the work activity was under way and the mileposts or other identifying information for the location of the work. If a project involved a point location rather than a segment of highway, then a segment 1/2 mile upstream and 1/2 mile downstream of the work location was assumed.

One crucial parameter in analyzing accidents is a measure of exposure that is routinely taken as the million vehicle miles (MVM) of travel through the work site in different time periods. This represented a major obstacle in this study for several reasons:

- Average daily traffic (ADT) data for CAES are summarized in odd years only, hence no record of annual ADT was available for this study;
- Communications with IDOT surveillance project personnel indicated that many of the surveillance detectors installed on CAES were not functioning while roadway work was in progress; and
- The nature of intermittent or short-term sites makes it quite difficult to estimate the hourly flow rates during construction so that the vehicle miles of travel can be computed.

Nevertheless, it is precisely because of the nature of these sites that the flow rates should not be expected to vary considerably during construction. The reason is that motorists are typically not advised of the presence of the work in time to alter the course of their trip. In addition, a review of ADT data on CAES revealed that during 1981–1985 the vehicle miles of travel on the system increased by less than 10 percent, while the overall systemwide accident rate was virtually unchanged in the same period (3.43 accidents/MVM in 1981, 3.79 in 1983, and 3.45 in 1985) (*9–13*). As will be explained in the next section, a different exposure measure that takes into account both the duration and length of the work zone was utilized in this study.

Data Analysis

An absolute accident rate is based on the exposure of vehicle miles of travel (equal to ADT * hours * miles). Because the objective of this study was to perform a comparative analysis, it was assumed that, as described previously, ADT will not vary for short-term sites. It is also assumed that ADT will not vary for long-term sites. This is a conservative assumption because ADTs may actually drop in the presence of long-term work zones.

The common (relative) exposure measure derived in this study is expressed as the product of the project duration and length. For long-term projects this procedure is self-explanatory. For intermittent locations (i.e., less than 24 hours), the cumulative hours in which construction was under way were recorded and converted into an equivalent number of full days. For those projects that overlap 2 years, the exposure was computed separately in each year. Thus mile days of exposure/year = $1/24 \, \Sigma \, L * H_c$, in which L equals the project length in miles and H_c equals the hours of construction in which the roadway is occupied.

Because there is only one "during" period and several "before and after" periods, each corresponding to 1 year, the total mile days of travel were multiplied by the number of years in the corresponding analysis period. In essence, a comparison is made of the accident performance of each roadway segment under construction over 6 years (1 year during and 5 years before and after). The designation mentioned previously yielded a sample of four long-term project periods and 25 intermittent or weekend project periods for further analysis. All these projects were undertaken between 1981 and 1983.

Long-Term Sites

Of the four long-term cases, only one experienced a significant increase in accidents during construction. That site involved extensive pavement resurfacing on the I-55 (Stevenson) Expressway between Wolf Road and California Avenue, a distance of roughly 13 mi. This project was by far the most extensive in terms of exposure (1,372 mile days versus 249 combined for the other three cases) as well as accident frequencies (1,147 accidents versus 198 combined for the other three cases). Accident rate summaries for each case are given in Table 1. The results also indicate that in one case no accidents occurred during the 6-year period for the segment under study. It is also evident from Table 1 that the after accident rates are consistently higher than the before rates. When it is noted that the vehicle miles of travel have increased by 10 percent between 1981 and 1985, it appears that this increase in accident rates is in part a reflection of the higher exposure rate during that period. Because Project 34916 is dominant in terms of accidents and exposure, the following analysis will be limited to this project as representative of long-term construction sites.

Initially, mean daily accident occurrences were computed for the "during construction" and "no construction" periods. These were estimated at 3.0 and 1.694 accidents per day, respectively, with a standard deviation of 0.473. A Z-test on the difference between the daily number of accidents under each situation was conducted for the purpose of testing the hypothesis that both values were essentially derived from the same distribution. Simply stated, it was desirable to determine the probability of observing three or more accidents per day on the roadway segment, given that the long-term average (in this case a 5-year average) is 1.694. Mathematically, this can be stated as follows. Find α, such that

$$\text{Prob}\,[Z > Z_\alpha] = \text{Prob}\,[Z > (3 - 1.694)/0.473]$$
$$= \text{Prob}\,[Z > 2.75]$$

yielding $\alpha = 0.003$. Hence it can be stated that the during accident rate is significantly higher than the rates experienced without construction at a 99.97 percent confidence level.

The next series of tests involved specific accident categories. In each, a Z-test on proportions is constructed as follows (*14*):

$$Z = (P_d - P_b)/[p(1-p)\ (1/N_d + 1/N_b)]^{1/2}$$

in which

$$P_d = X_d/N_d$$

$$P_b = X_b/N_b$$

$$p = (X_d + X_b)/(N_b + N_d)$$

where X_d and X_b equal the number of accidents in a specific category (e.g., injuries, rear ends, etc.) in the during and before periods, respectively, and N_d and N_b are the total number of accidents in the during and before periods, respectively.

Similar tests were conducted for the during versus after periods as well. The results are summarized in Table 2 and discussed next.

- Accident severity decreased significantly during construction. For this project, the decrease in fatal and injury accident proportions was over 20 percent, quite consistent with the findings from the literature.
- Rear end accidents increased significantly during construction. For this project, the proportional increase was almost 50 percent, and this result again corroborates the findings from previous studies.
- The presence of construction had a marginal effect on the proportion of object-on-road accidents. This reflects good site management on this project in terms of improving the visibility of TCDs, clearing debris, and so on.
- The proportion of multiple-vehicle accidents increased significantly during construction (by about 15 percent). This is very consistent with the higher occurrence of rear end collisions and points to the problem of increased speed variations between the lane closure and upstream segments.
- Accident categories that were not significantly altered by the presence of construction included sideswipe accidents, heavy vehicle accidents, and those caused by roadway defects (holes, bumps, and low shoulders).
- The proportion of ramp-related accidents increased significantly during construction. In this project, the increase was 45 percent compared to the before period and 142 percent compared to the after period. This was a very important finding that warranted further investigation. A review of the project logs revealed that in the conduct of this project, two specific

TABLE 1 ACCIDENT SUMMARIES FOR LONG-TERM PROJECTS

	Time in Relation to Construction					
	Before		During		After	
Project	Total	Rate	Total	Rate	Total	Rate
34916	282	0.103	300	0.219	565	0.137
35912	0	0	0	0	0	0
35359[a]	27	0.132	13	0.127	47	0.151
35359[b]	60	0.145	8	0.058	43	0.152

NOTE: Rates measured in accident/mile-day of construction.
[a]1982 construction period.
[b]1983 construction period.

TABLE 2 ANALYSIS OF ACCIDENT CATEGORIES FOR LONG-TERM PROJECTS

Category	Proportions by Period Before	During	After	Z	Significance Level
Fatal and injury	0.29	0.22		−1.93	0.027[a]
		0.22	0.27	−1.67	0.048[a]
Rear end on road	0.387	0.58		+4.65	0.000[a]
		0.58	0.37	+4.32	0.000[a]
Object on road	0.014	0.03		+1.31	0.095
		0.03	0.026	+0.36	0.36
Sideswipe	0.29	0.27		−0.53	0.300
		0.27	0.28	−0.41	0.350
Holes, bumps, low and soft shoulder	0.018	0.013		+0.49	0.31
		0.013	0.018	+0.50	0.31
Coded repair work	0.018	0.52		+13.52	0.000[a]
		0.52	0.018	+13.50	0.000[a]
Involving multiple vehicles	0.71	0.83		+3.43	0.0003[a]
		0.83	0.74	+2.99	0.0014[a]
Involving heavy vehicles	0.195	0.137		−1.88	0.03[a]
		0.137	0.17	−1.27	0.102
Ramp-related	0.117	0.17		+1.82	0.035[a]
		0.17	0.07	+4.56	0.000[a]

[a]Significant at the 5 percent level.

traffic control procedures were implemented at different points in time:

(a) In the earlier part of the project, the median lane and left shoulder were closed for construction, and traffic was allowed to use the two remaining lanes.

(b) In the latter part of the project, the two right lanes were closed to traffic, and traffic was allowed to only use the left lane and shoulder, a procedure known as traffic shifting (*15*). In this case, traffic entering or leaving the freeway must cross two lanes of traffic with little room for acceleration or deceleration, as shown in the schematic in Figure 1.

A comparison of accident categories under these two procedures is summarized in Table 3. The results indicate the following:

- There was a slight, albeit nonsignificant, increase in accident frequency and severity when the traffic shifting procedure was in effect.
- There is an evident shift in the distribution of rear end accidents. In case a, fewer rear end accidents involved stopped vehicles than in case b. This may be a reflection of the capacity constraints evident in case b and the absence of adequate acceleration-deceleration space at the ramp junctions.

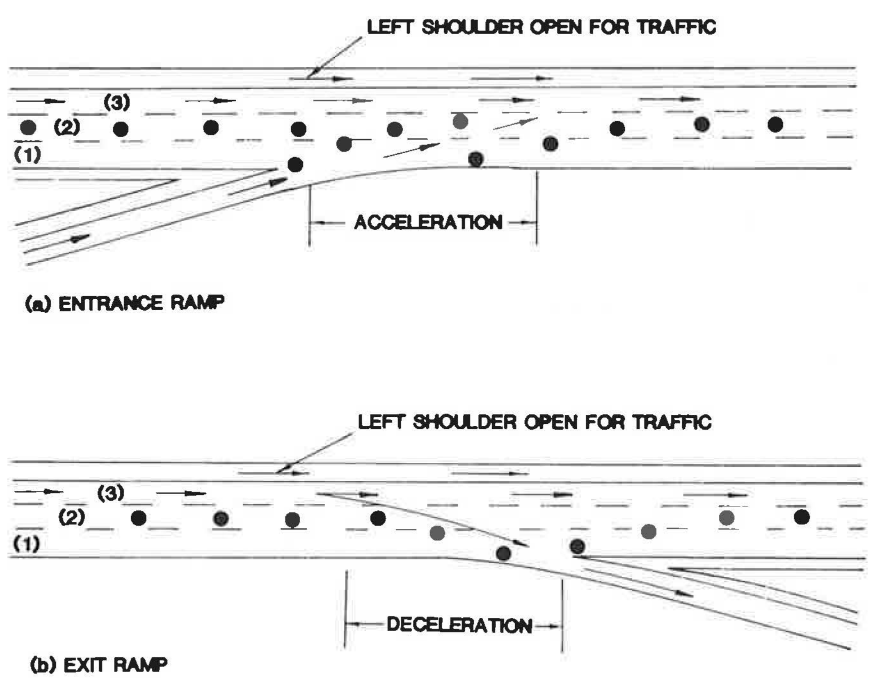

FIGURE 1 Right lane(s) closure procedures near ramp junctions.

TABLE 3 COMPARATIVE ANALYSIS OF CONSTRUCTION ACCIDENT FREQUENCIES BY LOCATION OF LANE CLOSURE(S)

	Case a	Case b	Z	Significance Level
Total accidents	102	169	NA	NA
Daily accidents	2.9	3.38	NA	NA
Proportion of fatal and injury	0.187	0.231	+0.856	0.195[a]
Proportion of rear end, both vehicles moving	0.314	0.266	−0.856	0.195[a]
Proportion of rear end, one vehicle stopped	0.245	0.349	+1.8	0.036[a]
Proportion of ramp-related accidents	0.078	0.231	+3.17	0.0008[b]

NOTE: In Case a, lanes 1 and 2 were open to traffic. In Case b, lane 3 and the left shoulder were open to traffic (see Figure 1).
[a]Significant at 20 percent level.
[b]Significant at 5 percent level.

• The effect of closing the right two lanes is dramatically evident in the occurrence of ramp-related accidents. About 25 percent of all accidents in case b took place in the vicinity of the ramps, in comparison to only 7.8 percent in case a. Thus it appears that the preponderance of ramp-related accidents evident in Table 2 can be attributed primarily to the weaving problem that is encountered at the ramp junction by merging and diverging vehicles. The implications for the layout of TCDs in the ramp vicinity, especially for the rather heavy volumes serviced by this facility (over 100,000 ADT) are evident but fall beyond the scope of this study.

Intermittent or Weekend Projects

A total of 25 cases were incorporated in this analysis. Average accident rates per mile-day were 0.538, 0.78, and 0.67 in the before, during, and after periods, respectively. The rates indicate an increase in accident rates during construction and maintenance. In six cases, no accidents occurred during the 6-year period under study. Preliminary investigation revealed a linear relationship between construction accident frequency and mile-days. Because ADT is approximately constant throughout the before, during, and after periods, the use of mile-days as an exposure measure yields the same results that would have been derived if vehicle miles had been used.

With the exception of the two outliers, accident frequency shows an increase at a rate of 0.80 accident/mile day. A plot of construction accident rate versus mile-days is shown in Figure 2. As expected, no distinct pattern emerges. The implication from this sample is that a fixed accident rate occurs during short-term construction work and that this rate is independent of the length and duration of the work activity. It can also be inferred from the information given previously that in cases for which the control (i.e., before and after) accident rates are low (less than 0.80 accident/mile day), the presence of construction will generally result in an increase in accident rate and vice versa. This phenomenon is best represented graphically, as in Figure 3, in which a set of hypothetical during and control accident rates is plotted. The dashed line represents the "ideal" condition for which the presence of construction has no effect on the accident rate. The solid line represents a best fit to the data, and the two curves depict the upper and lower 95th-percentile estimates of the regression line. Thus the shaded area to the left of point A represents cases that experience a

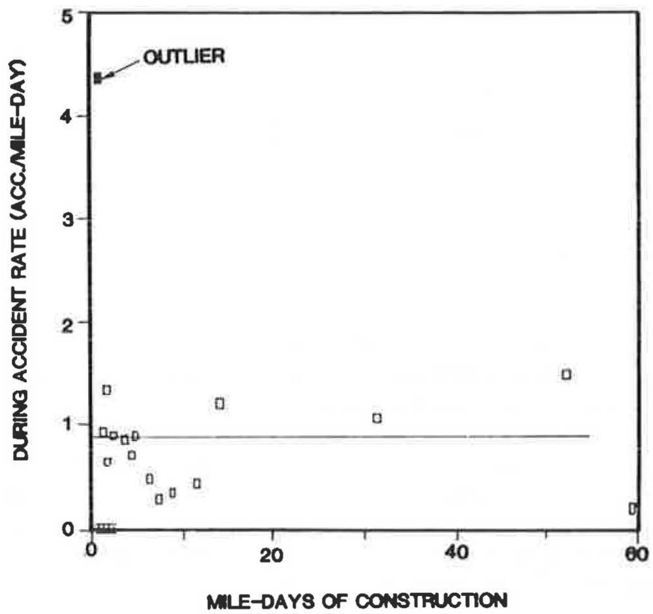

FIGURE 2 Work zone accident rate versus mile-days: short-term sites.

significant increase in accident rates during construction, whereas the shaded area to the right of point B represents cases that experience a significant decrease in accident rate during construction. These tests were carried out for several subsets of accidents (all accidents, rear end accidents, property damage, etc.). The results are summarized in Table 4, which presents the various subsets analyzed, the regression line parameters, and the range of control variables for cases in which significant deviations in work zone accident rates occurred.

• In general, the models yielded a poor fit to the data. Work zone accident rates were significantly higher than the before rates at sites experiencing less than 0.50 accident/mile-day in the before period and less than 0.20 accident/mile-day in the after period. The during accident rates were significantly lower at sites that experienced more than 0.80 accident/mile-day in the after period.

• Property damage only (PDO) accident rates during construction were significantly higher than the before rate when the latter is less than 0.30 accident/mile-day and the corresponding after rate is less than 0.10 accident/mile-day. The

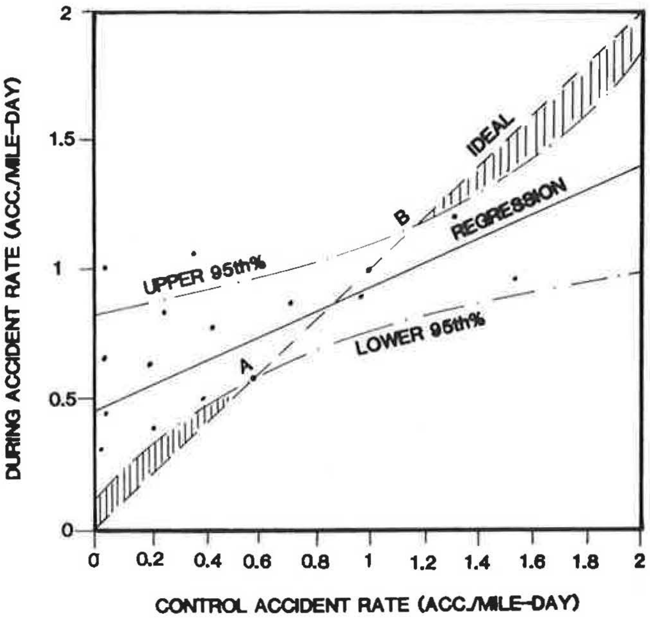

FIGURE 3 During accident rates versus control accident rates at short-term sites: hypothetical model.

during PDO accident rates were lower than the corresponding after accident rates when the latter were above 0.50 accident/mile-day.

• Highway accident rates yielded a moderate fit to the data, showing a similar pattern to the total accident rate. The during highway rates were higher than the corresponding before rates when the latter were less than 0.40 accident/mile-day and higher than the corresponding after rates when the latter were less than 0.10 accident/mile-day.

• Modest correlations were found only between daytime during and before accident rates. The during accident rates were higher then the corresponding before rates when the latter were less than 0.40 accident/mile-day. This is not unexpected because all construction activities in this category were carried out primarily during daytime off-peak hours.

• The other accident rates presented in Table 4 gave very poor fit to the data and did not produce any meaningful results for work zone accident rates.

Summary

In summary, the study indicated that there is evidence at long-term lane closures of an increase in accident rates during construction. On urban freeways, which were the focus of the study, most accidents appear to be attributable to the capacity constraints imposed by the lane closure and the resulting speed variations between the bottleneck and the approach areas to the zone. This is demonstrated by the preponderance of rear end and multiple vehicle accidents, which also tended to reduce the overall accident severity during construction. The problem was even more acute at ramp junctions, where the capacity problems are compounded by the merging and diverging traffic in relatively short distances (as is evident in Figure 1).

At short and intermittent construction sites, an average accident rate of 0.80 accident/mile-day was observed; the rate appears to be independent of the length or duration of the work

TABLE 4 SUMMARY OF ACCIDENT RATES FOR SHORT-TERM PROJECTS

	Accident Rate Categories			Regression Line		Range of Control Variables for Significant Deviations During Acceleration	
Model	During	Control	R^2	Slope	Intercept	Increase	Decrease
1	Total	Total, before	0.32	0.29	0.63	0–0.5	NS
2	Total	Total, after	0.14	0.36	0.27	0–0.2	0.8–1.8
3	PDO	PDO, before	0.36	0.21	0.69	0–0.3	NS
4	PDO	PDO, after	0.29	0.19	0.47	0–0.1	0.8–1.4
5	Rear end	Rear end, before	0.29	0.15	0.64	0–0.2	NS
6	Rear end	Rear end, after	0.16	0.14	0.39	0–0.1	0.5–1.4
7	Object on road	Object on road, before	NA	NA	NA	NA	NA
8	Object on road	Object on road, after	NA	NA	NA	NA	NA
9	Wet/other	Wet/other, before	0.05	0.10	−0.27	0–0.03	0.15–0.6
10	Wet/other	Wet/other, after	0.01	0.09	−0.04	0–0.1	0.2–1.8
11	Repair work	Repair work, before	0.00	0.05	−0.37	NS	NS
12	Repair work	Repair work, after	0.02	0.05	−0.08	NS	0.1–1.4
13	Road defects	Road defects, before	0.00	0.02	0.12	NS	NS
14	Road defects	Road defects, after	0.00	0.02	0.06	NS	NS
15	Highway	Highway, before	0.33	0.30	0.73	0–0.4	NS
16	Highway	Highway, after	0.33	0.23	0.57	0–0.1	NS
17	Daytime	Daytime, before	0.21	0.30	0.57	0–0.4	NS
18	Daytime	Daytime, after	0.08	0.37	0.21	0–0.2	0.8–1.8
19	Rain/other	Rain/other, before	0.05	0.11	−0.35	0–0.03	0.18–0.48
20	Rain/other	Rain/other, after	0.01	0.09	−0.03	NS	0.2–1.8
21	First car	First car, before	0.28	0.26	0.65	0–0.4	NS
22	First car	First car, after	0.20	0.24	0.43	0–0.1	1.0–1.6
23	First tractor-trailer	First tractor-trailer, before	0.00	0.04	0.01	NS	>0.1
24	First tractor-trailer	First tractor-trailer, after	0.04	0.03	0.19	NS	0.16–0.48

NOTE: R^2 is a coefficient of determination. NS signifies "not significant"; NA, "no accidents."

zone. Again, accident severity appears to be lower during construction, but rear end collisions are higher. Thus the effect of short-term construction on accidents is in fact dependent on the accident history of the segment during other periods.

TRAFFIC FLOW AND CONTROL DEVICES STUDY

The purpose of this study was to provide a comparative evaluation of traffic control layouts for short- and long-term urban freeway lane closures. Evaluation criteria were derived from IDOT standards, which apply to both types of closure. Part of the analysis also focused on the problem of speed variations in the work zones, as determined from the accident study, and attempts were made to investigate correlations between TCD layouts and speed variance at the approach, transition, and closure areas.

Data Collection

An instrumented data collection system was specifically devised for this study. The system utilizes the floating automobile concept for speed measurements and is supplemented with a video recording system to gather information on the presence, location, and indication of TCDs and construction or work activity. The hardware consisted of the following:

- Two on-board video cameras, one aimed at the roadway and the other at the vehicle dashboard. The first recorded the placement and indication of traffic control devices while the second recorded speed observations.
- One ½-in. portable VCR with real-time display of 1/30-sec accuracy. A schematic of the system is shown in Figure 4. An audio channel over which information regarding site description is recorded supplements the video input. This audio link it was also used to identify sign locations that were obscured by traffic.

In all, 150 construction sites were visited. Because of time constraints, only 46 sites were coded for further analysis. The analysis group included both short- and long-term sites during the day and at night. A FORTRAN code program was developed to produce summary reports of the TCD layout, as well as the speed profile of the instrumented vehicle. A review of IDOT standards indicated there were three designations of work zones for TCD layout requirements:

- Short-term sites, at which construction lasts less than 6 hr in daytime (35 sites comprising 14 single-lane closures and 21 two-lane closures);
- Intermediate sites, at which construction lasts over 24 hours but less than 4 days (seven sites comprising four single-lane closures and three two-lane closures); and
- Long-term sites, at which construction lasts more than 4 days (four sites, all involving single-lane closures).

TCD Layout Results

Because the primary purpose of the warning signs is to provide adequate response time to the lane closures for approaching traffic, all the standards and actual locations of these devices were computed from the start of the transition taper. Table 5 summarizes the results of the four long-term sites. Except for one site, all the required devices were present at all sites. The positions of the devices, however, varied considerably from the standards, especially the Road Construction Ahead sign, which on the average was placed 1,400 ft closer to the taper than required by standards. The position of the sign also varied considerably from site to site, with a standard deviation of almost 1,200 ft. The same variation was found for all other warning signs, which were also placed closer to the taper than allowed by standards. Their locations, however, were far more consistent than that of the first sign, as is evident from the much smaller standard deviation. Finally, the actual taper lengths appear to conform very closely to standards. A similar pattern emerged for sign locations at intermediate work sites with single-lane closures. In addition, the Right/Left Lane Closed ½ Mile was missing in three of the four sites. Interestingly, the standard deviations of sign positions were consistently higher at these sites than those at the long-term sites. Table 6 summarizes the results for the short-term sites. In this case, several required devices were missing at a number of sites, including the arrow board. The first two signs were again placed closer to the taper, while the next two signs were placed further from the taper compared with the standards. Deviations of sign positions between sites were extremely high, varying by as much as 70 percent of the mean in some cases. The data for intermediate and short-term sites with two-lane closures were consistent with previous findings in that (a) signs were placed closer to the taper than required by standards, (b) many devices were missing at the short-term sites, averaging 2.5 missing devices per site, and (c) sign positioning appears to be very inconsistent at the short-term sites, as evidenced by the high standard deviations.

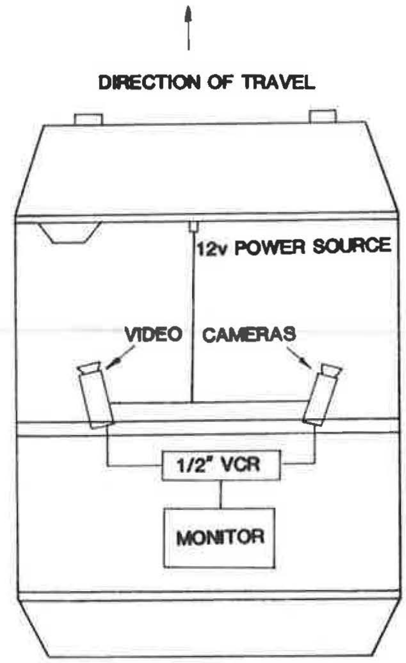

FIGURE 4 Schematic of instrumented vehicle for traffic study.

TABLE 5 TCD LAYOUT FOR LONG-TERM (> 4 DAYS) SITES, SINGLE-LANE CLOSURE

			Device Position (ft)[a]		
Device	Requirement Status	Number of Sites Not Present	IDOT Standard Location	Observed Mean	Observed Standard Deviation of Location (ft)
Road Construction Ahead (RCA)	Required	0	7,800	6,483	1,191
Right/Left Lane(s) Closed 1 miles (LC1)	Required	0	5,200	4,706	145
Right/Left Lane(s) Closed 1/2 mile (LC2)	Required	1	2,600	1,762	42
Right/Left Lane(s) Closed Ahead (LC3)	Required	0	1,500	1,293	103
First Symbolic Lane Drop Sign (SLC1)	Required	0	500	645	105
Second Symbolic Lane Drop Sign (SLC2)	Not required	NA[b]	NA	NA	NA
First Arrow Board (AB1)	Required	0	220	403	62
Second Arrow Board (AB2)	Not required	NA	NA	NA	NA
Taper Length (TAPER1)	Required	0	660	655	115
Tangent Between Tapers (TANG)	Not required	NA	NA	NA	NA
Second Taper Length (TAPER2)	Not required	NA	NA	NA	NA

NOTE: N = four sites.
[a]Measured from the start of the first taper.
[b]Not applicable.

TABLE 6 TCD LAYOUT FOR SHORT-TERM (≤ 6 DAYS) SITES, SINGLE-LANE CLOSURE

			Device Position (ft)[a]		
Device	Requirement Status	Number of Sites Not Present	IDOT Standard Location	Observed Mean	Observed Standard Deviation of Location (ft)
Road Construction Ahead (RCA)	Not required	7	7,800	6,000	2,063
Right/Left Lane(s) Closed 1 miles (LC1)	Required	6	5,200	3,979	1,612
Right/Left Lane(s) Closed 1/2 mile (LC2)	Required	5	2,600	3,196	542
Right/Left Lane(s) Closed Ahead (LC3)	Required	2	1,500	1,980	722
First Symbolic Lane Drop Sign (SLC1)	Required	2	500	1,236	818
Second Symbolic Lane Drop Sign (SLC2)	Not required	NA[b]	NA	NA	NA
First Arrow Board (AB1)	Required	3	220	380	296
Second Arrow Board (AB2)	Not required	NA	NA	NA	NA
Taper Length (TAPER1)	Required	0	660	499	243
Tangent Between Tapers (TANG)	Not required	NA	NA	NA	NA
Second Taper Length (TAPER2)	Not required	NA	NA	NA	NA

NOTE: N = 14 sites.
[a]Measured from the start of the first taper.
[b]Not applicable.

Speed Distribution Results

At each of the visited sites the mean and standard deviation of the test vehicle speed was computed along three subsections:

- Approach (from the location of the first construction sign to the start of the lane taper),
- Transition (in the taper zone), and
- Closure (along the closed portion of the work zone).

The driver of the test vehicle was instructed to travel in the closed lane of traffic, merging at or near the taper when appropriate. The following flow descriptors were then derived:

Mean Speed Differences Between Zones

The amount of speed reduction between the approach and transition and between transition and closure areas is indicative of potential rear-end collisions because drivers must adjust their speed ahead of the lane restrictions.

Speed Coefficient of Variation (CV) by Zone

This is defined as

CV = (Speed Standard Deviation/Zone Mean Speed) * 100

In essence, CV normalizes the amount of speed variation by the average speed to distinguish between free flow conditions in

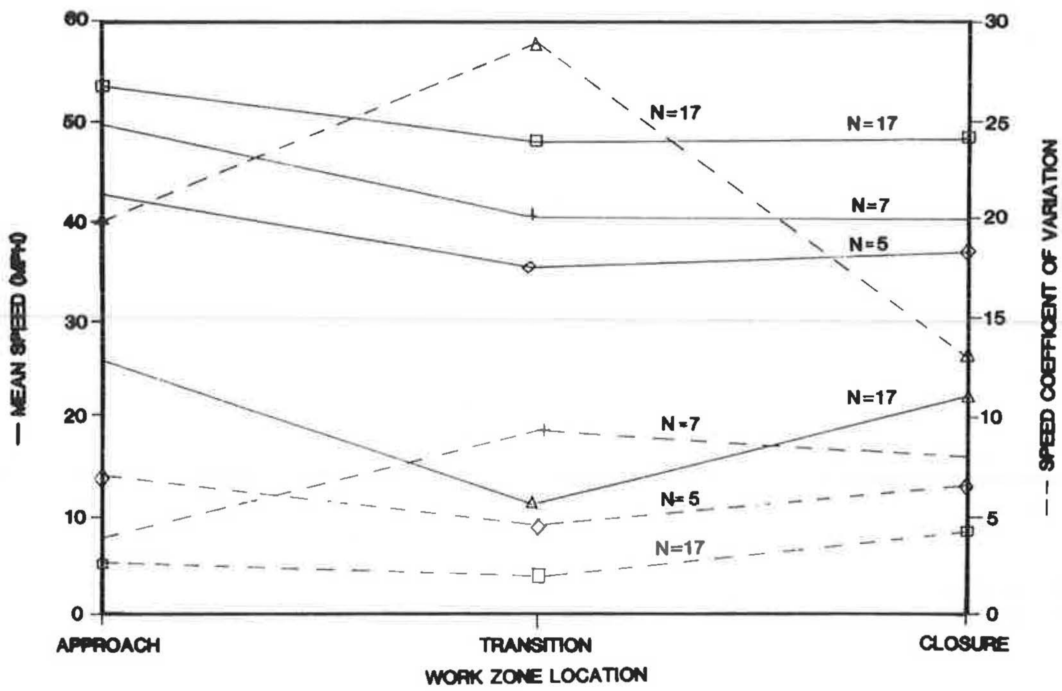

FIGURE 5 Composite speed profile versus number of lane closures and traffic volumes.

which speed variation is merely reflective of the driver's desired speed (i.e., low CV) and those due to friction between vehicles in the traffic stream (i.e., high CV). Because speeds are intimately tied to traffic volumes, all subsequent analyses were performed separately for high- and low-volume sites.

Mean speed profiles at the three zones are presented in Figure 5. The average drop in speed between the approach and transition zones increased with volume and the number of closed lanes. The observed values for single lane closures were 5.45 and 7.19 mph under low- and high-volume conditions, respectively. The corresponding values for two lane closures were 9.64 and 14.58 mph. Between the transition and closure zones the average speed did not vary considerably under light volume, increasing by 0.40 mph for single-lane closures and decreasing by 0.10 mph for two-lane closures. Speed recovery was more significant under high-volume conditions, increasing by 1.50 mph and 10.80 mph for single- and two-lane closures, respectively. Thus the amount of speed recovery in the closure area appears to be dependent on the loss of speed in the transition area. In combination with the preponderance of rear end accidents during construction, the results indicate that speed control on the approach and transition areas is of paramount importance in reducing the frequency of these accidents. It is also evident that the transition area, and not the closure area, governs the capacity of the work zone because of the number of lane change maneuvers taking place. Smooth merging thus becomes a prerequisite for enhancing the overall zone capacity.

Speed coefficients of variations are also depicted in Figure 5. For sites with two-lane closures, CV increased in the transition zone. The amount of increase was much higher in congested traffic. This confirms the results obtained previously, which are indicative of the disturbances caused by the multiple lane changes that occur in the transition area. On the other hand, CV decreased in the transition zone when single-lane closures (i.e., fewer merges) were in effect. Again, the magnitude of CV is higher under high-volume conditions.

Finally, an attempt was made to analyze zonal speed characteristics (specifically CV) with regard to the TCD layouts described in the previous section. So that the effect of traffic volumes could be excluded, observations from heavy volume sites were not considered in this analysis. The results are summarized in Table 7. In all three zones, short-term sites exhibited higher coefficient of speed variations in comparison to the intermediate and long-term sites. This was especially true in the transition zone, where the increase was over 400 percent. In addition, when either some of the warning signs or the arrow board were missing, the coefficient of speed variation increased. Finally, when the taper lengths were shorter than allowed by standards, the speed coefficient of variation increased by an average of 35 percent. One unexpected result is that during the conduct of work activity, there were fewer speed variations than when no activity was under way.

To summarize, the field observations of TCD layout and speed measurements at the 46 construction zones indicate inconsistent TCD positioning according to IDOT standards. This is much more so at short and intermittent sites. The resulting speed analyses revealed that such inconsistencies are concomitant with larger speed variations in the approach and transition zones, thus corroborating the accident findings with regard to the increased frequency of rear end collisions.

CONCLUSIONS AND RECOMMENDATIONS

This paper documents the findings of a comprehensive study aimed at investigating and comparing the safety and operational aspects of urban freeway work zones in the Chicago Metropolitan area. The following conclusions are drawn:

- At long-term lane closures (longer than 4 days), accident frequency increased and accident severity decreased during construction. The predominant accident types were rear end collisions and ramp-related accidents, especially when the lane closures involved the two right lanes adjacent to the entrance and exit ramps.

TABLE 7 COEFFICIENTS OF SPEED VARIATIONS VERSUS TCD LAYOUT AT LOW-VOLUME SITES

Factors	Value	Sample Size
Approach Area (CV1)		
1a Short-term sites	3.68	15
1b Intermediate and long-term sites	1.83	9
2a Arrow board present	2.87	22
2b Arrow board missing	4.27	2
3a All warning signs present	1.99	5
3b One or more warning signs missing	3.20	19
Transition Area (CV2)		
1a Short-term sites	5.65	15
1b Intermediate and long-term sites	1.11	9
2a Taper length less than standard	4.36	18
2b Taper length greater than or equal to standard	3.22	6
Closure Area (CV3)		
1a Short-term sites	5.67	15
1b Intermediate and long-term sites	4.67	9
2a No work activity	6.24	13
2b Work activity	4.13	11

NOTE: $N = 24$ sites.

- At intermittent or weekend closures, the accident rate during construction appears to be constant at about 0.80 accident/mile-day of work activity. Thus road segments that had a typical (i.e., without construction) accident rate of less than 0.80 accident/mile-day indeed experienced an increase in accidents during construction, and vice versa. This conclusion would still be valid if traffic volumes were introduced in the computation of accident rates: the ADT on a highway segment will not vary significantly due to the presence of a short-term construction site.
- At the 46 sites analyzed by the research team, there were discrepancies between observed and standard positioning of TCDs. In general, signs were placed much closer to the taper than allowed by standards. The deviations were of higher magnitude at short-term lane closures, as were the occurrences of missing TCDs. Speed profiles indicated that sites that had short tapers, missing arrow boards, and missing signs or that were of short duration exhibited significantly higher speed variations than other sites. This points to the importance of adhering to standards, even though the overall exposure to traffic may be quite limited.

It is evident from these findings that much work remains to be done in evaluating the safety and operational characteristics of highway work zones adequately. Continuing research needs are as follows:

Development of Uniform Standards for Reporting Work Zone Accidents

This study indicates that except for long-term activities, many accidents cannot be routinely identified from the accident tape. Indeed, only about 10 percent of accidents known to have occurred during construction were identified as such from the accident tape. Suggested modifications to current reporting procedures should be explored. The possibility of developing a supplemental work zone accident information sheet is one such modification (*16*).

Further Evaluation of the Safety Impacts of the Traffic Shifting Procedure

In this study, shifting traffic to the left lane and shoulder has resulted in doubling the proportion of ramp-related accidents from the before condition. The implications regarding the layout of the traffic control devices near the ramp area must be explored in greater detail.

Development of a User-Based Cost Model for Freeway Work Zones

The comprehensive data collected at 150 sites in the course of this study can be used to derive representative vehicle operating costs due to excess travel time, speed changes, and fuel consumption. The outcome of this study will be a model that is sensitive to the type of construction activity, number of lanes closed, traffic conditions, and visibility conditions. This information can be used in planning future work zone activities and may be supplemented with accident costs to evaluate the costs of alternative traffic control plans.

Work Zone Capacity Estimation

In contrast to the findings from the literature, it was observed that vehicle speeds (and, in essence, the work zone capacity) are primarily governed by traffic flow in the transition area rather than in the closure area itself. Therefore merging capacity appears to be a better indicator of the bottleneck capacity, especially at high approach volumes. A future study will utilize the collected operational data at construction zones to refine the capacity estimates in existing literature.

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