The authors gratefully acknowledge the assistance of Olga Pendleton for the statistical analysis, and Carlton Allen and Nada Huddleston who served as test administrators.

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Some Effects of Traffic Control on Four-Lane Divided Highways

Conrad L. Dudek, Stephen H. Richards, and Jesse L. Buffington

Nine field studies were conducted on four-lane divided highways in Texas and Oklahoma to evaluate two alternative traffic control approaches: single-lane closure in one direction versus a crossover with two-lane, two-way traffic operations (TLTWO). The variables studied were: worker productivity, job duration, construction costs, traffic control device costs, highway-user costs, accidents, conflicts, and capacity. Worker productivity was measured indirectly from job duration and construction costs. Because of limited data, it was not possible to identify the conditions under which one traffic control alternative offers costs savings over the other. Highway-user costs for each study site were calculated using a modified version of a work-zone queue and user-costs evaluation model. Graphs and tables show the relationships between hourly traffic volumes and road-user costs for the sites studied.

There is a growing concern among highway agencies and construction contractors about the effects of traffic control management requirements on construction work productivity, safety, and cost. For example, less restrictive traffic control management approaches are generally easier and cheaper to install. However, these approaches may adversely affect worker productivity and therefore increase the duration of work, with accompanying increases in overall cost. Safety may also be adversely affected. On the other hand, highly restrictive traffic control management approaches may improve work productivity, but may result in traffic congestion and delays and therefore increase road-user costs.

This concern is evident at work zones on four-lane divided highways where there are two basic work-zone traffic control practices available:

1. One lane in one direction is closed resulting in little or no disruption of traffic in the opposite direction (e.g., single-lane closure); and
2. One roadway is closed and the traffic that normally uses that roadway is crossed over the median, and two-lane, two-way traffic operation (TLTWO) is maintained on the other roadway.

Single-lane closures are generally less restrictive because they only affect traffic in one direction; however they may tend to increase the duration of construction, and consequently the construction cost. Conversely, a TLTWO traffic control plan may reduce the construction duration and cost, but it may also result in traffic congestion, and consequently it may increase road-user costs. There is a need to select the approach that balances work-zone productivity and safety with costs (e.g., construction, traffic control, and road-user costs). There may be levels of traffic volumes when one traffic control approach (single-lane closure versus TLTWO) becomes the better alternative. The need for highway agencies to objectively evaluate the single-lane closure and the TLTWO traffic control approaches to select the best of the two alternatives prompted FHWA to fund research to begin collecting the necessary data and developing cost relationships.

BACKGROUND

Objectives and Scope

The objectives of the research in this paper were to

1. Conduct field studies to evaluate the current traffic control requirements for work sites on four-lane divided highways to determine their effects in time, cost, and safety to perform the work; and

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2. Develop a procedure or methodology that quantifies productivity, worker and motorist safety, and user and construction costs.

Originally 16 case studies were to be conducted in Texas on four-lane divided highways involving pavement resurfacing or bridge reconstruction repair work where a single-lane closure (eight sites) or a TLTWO (eight sites) traffic control plan was used. As the studies progressed, the study design was modified by FHWA.

Case studies were initially conducted at five sites following a pilot study on the Central Expressway in Dallas. The types of work at the sites were concrete pavement repair, pavement resurfacing, bridge repair, bridge deck repair, and pavement reconstruction. After reviewing the results of the initial field studies, the decision was made to conduct all future studies at long-term work sites (24-hr duration or longer). The important consideration was that both the TLTWO traffic control approach and the single-lane closure approach had to be viable alternatives. Bridge reconstruction or repair projects were preferred. Activities such as pavement repair or pavement resurfacing no longer met the necessary site criteria.

The small number of TLTWO sites in Texas prompted the researchers to explore the surrounding states for other potential study sites. One additional single-lane closure and three TLTWO sites were located near Oklahoma City, Oklahoma. After a preliminary visit to the sites, arrangements were made with the Oklahoma Department of Transportation (DOT) to conduct studies at the four sites.

The added cost of the studies in Oklahoma prompted a decision by FHWA to reduce the total number of case study sites to nine, (four single-lane closures and five TLTWO sites, in addition to the pilot study).

Data were collected at each site to assess the following variables: worker productivity, job duration, construction costs, traffic control device costs, highway-user costs, accidents, conflicts, and capacity.

Field Study Approach

A study team consisting of a study coordinator, video cameraman, and two other technicians collected the following types of data at each study site: video, conflicts, road-user characteristics, volumes, and site characteristics. Video data were collected from the most advantageous location, generally from an overpass or a bucket truck furnished by the highway agency. The video data provided a record of work activities, adjacent traffic patterns, and work-zone traffic interactions.

One technician, positioned near the work area, observed and recorded the time and frequency of conflicts. Conflicts were classified as the following types:

1. Vehicle-traffic control device,
2. Vehicle-vehicle,
3. Equipment-traffic control device,
4. Vehicle-equipment, or
5. Vehicle-worker.

The data necessary to evaluate road-user costs included traffic volumes, speed changes, vehicle classifications, and vehicle occupancies. Speed changes were calculated from speed profiles recorded using a study vehicle equipped with a tachograph. The driver of the study vehicle made several runs through the work zone on each lane in both directions of flow during each study period. During each run, continuous speed data were gathered, and key locations (e.g., beginning of cone taper, end of cone taper, end of lane closure, etc.) were recorded on the tachograph using a remote push-button event recorder. Vehicle classification and occupancy counts were made by an observer who sampled the traffic during each study period and recorded the type of vehicle and number of occupants.

Tube-type traffic counters were installed upstream of the work zone in both directions of travel. Volumes were recorded every 15 min for a minimum of 24 hr so that the average daily traffic (ADT) and hourly demand volumes could be determined for both directions of travel. Additional counters were installed within the work zone to collect lane-distribution and service-volume data through the study site.

A minimum of 4 hr of data were collected at each site during a 1- or 2-day period. Data collection was accomplished using one of two approaches. The method employed depended on the work activities at the site. At some sites, data were collected continuously for a minimum of 4 hr. At other sites, data were collected for 1-hr intervals several times throughout the work day. Typical study-time periods were as follows: 9:00-10:00 a.m., 10:30-11:30 a.m., 1:30-2:30 p.m., and 3:00-4:00 p.m. The intervening periods allowed latitude for personnel rest periods, on-site coordination, and adjustment of data collection activities.

Site Characteristics

A summary of the characteristics of the nine study sites and the pilot study site is given in Table 1. Two of the five TLTWO sites had specific peculiarities. The site in Amarillo, Texas (Site 3) was on a six-lane freeway. The freeway was reduced to one lane in each direction before traffic was crossed over. One lane was maintained in each direction through the work area. The TLTWO site at Carthage, Texas (Site 5) was accomplished in a novel way. Instead of using a normal crossover, traffic was diverted from the main lanes through a signalized diamond interchange.

JOB DURATION, CONSTRUCTION COSTS, AND TRAFFIC CONTROL DEVICE COSTS

Work productivity was measured indirectly by considering project duration and construction and road-user cost relationships. Other approaches to evaluate work productivity proved to be unsuccessful.

An attempt was initially made to evaluate overall work productivity by analyzing individual worker productivity, including work delays or slowdowns encountered by workers because of traffic interaction. The work productivity estimates derived from this analysis, however, did not adequately reflect the complex nature of work-zone activities. Worker and equipment efficiency ratings were also explored as approaches to quantify worker productivity, but these also proved to be of questionable value.

The effects of the traffic control approach on worker productivity are indeed reflected in the duration of the construction project, and project duration affects both the cost of construction and road-user costs resulting from the degree and duration of congestion. Therefore, the most logical and meaningful approach to evaluating alternative traffic control strategies is to analyze the total construction and road-user costs and the safety impacts of the alternatives. This was the approach adopted, and the following relation-

TABLE 1 SITE CHARACTERISTICS

Site	Location	Type of Work	Traffic Control Plan[a]	Range of Hourly Volumes[b]	Left Side Traffic Control Device[c]	Right Side Traffic Control Device[c]	Taper/ Cross-over Traffic Control Device[c]	Available Travel Width (ft)	Length of Closure (ft)	Length of Bridge (ft)
1	Leon, Tex.	Concrete pavement repair	L/C	225-280	Cones	–[d]	Barrels	22.0	600	–[d]
2	New Braunfels, Tex.	Pavement resurfacing	L/C	705-875	Cones	–[d]	Cones	22.0	6,900	–[d]
3	Amarillo, Tex.	Bridge repair	TLTWO[e]	1,080-1,795	PCB	PCB	BA	18.0	3,400	400
4	Amarillo, Tex.	Bridge deck repair	L/C	175-240	BR	Cones	Barrels	19.0	2,400	225
5	Carthage, Tex.	Pavement reconstruction	TLTWO[f]	165-210	PM	–[d]	Barricades	12.0	12,000	–[d]
6	Oklahoma City, Okla.	Overhead structure repair	TLTWO	1,275-1,810	PCB	BR	Drums/PCB	15.0	3,100	–[d]
7	Oklahoma City, Okla.	Bridge repair	L/C	250-350 1,020-1,890	PCB	–[d]	Drums/PCB	15.0	2,500	990[g]
8	Edmond, Okla.	Base excavation and pavement resurfacing	TLTWO	600-960	Tubes	–[d]	Drums/PCB	20.0	22,700	–[d]
9	Oklahoma City, Okla.	Bridge repair and pavement resurfacing	TLTWO	550-680	Tubes	–[d]	Drums/PCB	20.0	25,500	–[d]
Test	Dallas, Tex.	Bridge repair	L/C	1,600+	Cones	–[d]	Barrels	15.0	2,135	200

[a] L/C = single-lane closure, and TLTWO = two-lane, two-way operation.
[b] In direction of lane-closure or crossover.
[c] PCB = portable concrete barrier, BA = barricades, BR = bridge rail, and PM = pavement markings.
[d] No data.
[e] Normal six-lane freeway.
[f] Crossover accomplished by exiting roadway, crossing an overpass, and reentering roadway using off-ramp on opposite side.
[g] Two bridges (270 and 160 ft long) 560 ft apart.

ship was applied to decide whether TLTWO (T/O) should be used rather than the single-lane closure (L/C):

$$\text{construction costs}_{T/O} + \text{user costs}_{T/O} < \text{construction cost}_{L/C} + \text{user costs}_{L/C}.$$

Discussions on worker productivity, worker and equipment efficiency, and work-zone efficiency, work space, and total cost are presented elsewhere *(1)*. Available data on job duration, construction costs, traffic control device costs, road-user cost, accidents, and conflicts are presented in the following sections.

Job Duration and Construction Costs

Table 2 gives the job duration and construction cost (as bid) for each site. Where data were available from the contractor or highway agency, the estimated job duration and construction cost for the alternative traffic control approach are also given for each site. For example, the contracted duration for Site 4 using the lane closure traffic control approach was 6 working days at a cost of $70,012. The contractor estimated that the same work would take 5 days and cost $78,012 using a TLTWO traffic control plan.

Alternative job duration and construction cost estimates were available for only three sites. Every effort was made to obtain data for the other sites, but the contractors and highway agencies did not have the resources to prepare confident estimates. Based on the limited data that were obtained, it is not possible to say that one approach (single-lane closure or TLTWO) definitely offers an advantage in terms of reduced construction cost or time. However, for the two large projects for which data were provided (Sites 3 and 5), a TLTWO apparently would result in significant construction cost and time savings, compared to a single-lane closure traffic control approach.

TABLE 2 COMPARISON OF JOB DURATION AND CONSTRUCTION COSTS FOR ALTERNATIVE TRAFFIC CONTROL APPROACHES

			Single-Lane Closure		TLTWO	
Site	Type of Work	Job Length (ft)	Job Duration (days)[a]	Total Cost ($)	Job Duration (days)[a]	Total Cost ($)
1	Concrete pavement repair	12	1	2,779		
2	Pavement resurfacing	21,120	60	416,712	–[b]	–[b]
3	Bridge repair	400	240[c]	1,162,683[c]	200	849,372
4	Bridge deck repair	225	6	70,012	5[c]	78,012[c,d]
5	Pavement reconstruction	12,000	300[c]	3,500,000[c]	225	2,925,660
6	Overhead structure repair	3,100			200	1,589,859
7	Bridge repair	430	130	996,708		
8	Base excavation and pavement resurfacing	22,700			120	1,708,201
9	Bridge repair and pavement resurfacing	25,500			270	5,195,980

[a] Contracted duration.
[b] No estimate given because job was dependent on the ability of the hot-mix plants to furnish materials. Hot-mix plants could not furnish materials as fast as the contractor could handle.
[c] Indicate alternative traffic control approaches.
[d] Contractor was working on bridges in both directions of travel. A TLTWO control plan would have prevented simultaneous work on both bridges, accounting for the higher cost for the TLTWO alternative.

Traffic Control Device Costs

During the gathering of traffic control cost data, it became apparent that the term traffic control has a variety of connotations among contractors and highway agency personnel. Traffic control may refer to (a) signs, barricades, and other work-zone traffic control devices; (b) the physical layout of traffic routes and detours through a work zone; or (c) both traffic control devices and traffic routing. These different meanings certainly have an impact on traffic control cost estimating and reporting, and were evident in the cost data obtained.

Traffic Control Bid Costs

Traffic control bid prices were available for three of the study sites in Texas. These bid price data are are given in Table 3, along with a comparison of the bid prices for traffic control with the bid prices for the entire construction project. As shown, the actual amounts bid for traffic control represented a small fraction of the total project bid (3 percent or less for all the projects). The Site 2 contractor actually bid less than $1 for traffic control on a $400,000 project.

Actual Traffic Control Costs

After determining that traffic control bid prices were misleading, the contractors and highway agencies for each job were requested to provide a realistic estimate of actual traffic control costs. These estimates are given in Table 4. Comparing the estimates in Table 4 with the bid prices in Table 3, it is apparent that work-zone traffic control generally costs more than is reflected in the bidding process. Traffic control cost estimates, as seen in Table 4, ranged from 4 to 39 percent of the total construction cost, and averaged 15 percent of the total construction cost.

Traffic control costs averaged 21 percent of the total cost for the single-lane closure work zones and only 9 percent for the TLTWO work zones. It is important to note that three of the four TLTWO sites were accomplished without barrier separation of traffic in the two-lane, two-way sections. The one TLTWO site where barriers were used was very short. If extensive concrete barriers had been used at all the sites, the cost of TLTWO traffic control would have been much higher. For example, prefabricated portable concrete barriers cost approximately $2.70 per foot to install and remove *(2)*. This cost does not include barrier construction. If barriers had been used for the full length of the two-lane, two-way section at Site 8, an additional traffic control cost of $122,500 would have been incurred for placement of barrier sections alone.

Project Size Versus Traffic Control Costs

The relationship between project size and traffic control costs was also investigated. Based on the limited data obtained, no significant trends were established. However, intuitively it would appear that traffic control costs relative to total project costs would decrease on larger projects. Also, as seen from the Site 1 data, traffic control can represent a major cost on small projects. Site 1 was a $4,500 project, and 39 percent of the total cost was incurred in handling traffic.

Alternative Traffic Control Approach Costs

Table 5 gives a comparison of the estimated cost for traffic control used at each project with the estimated cost for the alternative traffic control approach. Alternative cost data were available for

TABLE 3 COMPARISON OF BID PRICE ON TRAFFIC CONTROL WITH BID PRICE OF TOTAL PROJECTS

Site	Work Performer	Type of Work	Traffic Control Plan	Total Cost Bid ($)	Traffic Control Cost	
					Bid	Percentage
2	Contractor	Pavement resurfacing	Single-lane closure	416,712	1	1
3	Contractor	Bridge repair	TLTWO	849,372	12,000	1
4	Contractor	Bridge deck repair	Single-lane closure	70,012	1,990	3

TABLE 4 TRAFFIC CONTROL COST ESTIMATES

Site	Work Performer	Type of Work	Traffic Control Plan	Traffic Control Cost Estimate ($)	Percentage of Total Project Cost
1	State	Concrete pavement repair	Single-lane closure	1,798	39
2	Contractor	Pavement resurfacing	Single-lane closure	14,850	4
3	Contractor	Bridge repair	TLTWO	NA[a]	NA
4	Contractor	Bridge deck repair	Single-lane closure	10,500	15
5	Contractor	Pavement reconstruction	TLTWO	125,000	4
6	Contractor	Overhead structure repair	TLTWO	113,356	7
7	Contractor	Bridge repair	Single-lane closure	246,098	25
8	Contractor	Base excavation and pavement resurfacing	TLTWO	344,693	20
9	Contractor	Bridge repair and pavement resurfacing	TLTWO	287,595	6

[a] NA = not available.

TABLE 5 COMPARISON OF ESTIMATED TRAFFIC CONTROL COSTS FOR ALTERNATIVE TRAFFIC CONTROL APPROACHES

				Traffic Control Approach	
Site	Work Performer	Type of Work	Traffic Control Plan	Single-Lane Closure ($)	Crossover ($)
1	State	Concrete pavement repair	Single-lane closure	1,798	NA[a]
2	Contractor	Pavement resurfacing	Single-lane closure	14,850	NA
3	Contractor	Bridge repair	TLTWO	NA	12,000
4	Contractor	Bridge deck repair	Single-lane closure	10,500	38,500[b]
5	Contractor	Pavement reconstruction	TLTWO	225,000[b]	125,000
6	Contractor	Overhead structure repair	TLTWO	44,178[b]	113,356
7	Contractor	Bridge repair	Single-lane closure	246,098	288,142[b]
8	Contractor	Base excavation and pavement resurfacing	TLTWO	NA	344,693
9	Contractor	Bridge repair and pavement resurfacing	TLTWO	1,644,076[b]	287,595

[a] NA = not available.
[b] Indicates alternative traffic control approach.

five of the nine sites, and based on these data, it is difficult to make any generalizations. The lane closure approach would be (a) much more costly at two sites, (b) much less costly at two other sites, and (c) approximately the same as the TLTWO approach at the remaining site. Also interesting is the fact that the less costly traffic control approach was not used at Site 6. The highway agency indicated that it opted for the more costly approach in order to save construction time and thereby overall costs.

Summary

The cost analysis failed to indicate if either of the traffic control approaches offered cost savings under certain conditions. Instead, it supported the premise that the cost-effectiveness of a given traffic control approach depends on a number of individual site factors, and that these factors must be evaluated on a site-by-site basis. However, the data base is admittedly very limited. In order to fully address the cost issue, cost and alternative cost data would have to be reviewed for many more sites (20 to 30 more sites), along with detailed information on the nature of the work, job duration, special site conditions, and other pertinent project information.

The findings of the cost analyses, although based on very limited data, are generally consistent with a study conducted by Graham and Migletz *(3)*. Both studies imply that it may be difficult to generalize whether the single-lane closure or TLTWO approach offers inherent construction or traffic control cost savings. The best approach from a cost standpoint appears to depend on site characteristics and the details of the construction work.

HIGHWAY-USER COSTS

Data Analysis

The analysis was based on the assumption that the data sampled (e.g., traffic volumes, traffic speed changes, vehicle classifications, and vehicle occupancies) were in fact representative of the traffic streams at the individual work sites. Changes in highway-user costs were estimated by comparing the normal road-user costs without the work zone (before) to the costs with the work zone (during). Although before-work-zone data were not actually collected, it was assumed that in the absence of the work zone, drivers traveled through the area unimpeded. Therefore, the speeds upstream and downstream of the work zone with the work zone in place were representative of the unimpeded speeds on the entire length of the study area without the work zone.

Changes in user costs included changes in travel time or delay costs, vehicle running costs, and costs of additional speed-change cycles. Accident costs were not included in the analysis because of insufficient data to establish reliable accident rates before and during the work at each site. Costs were updated to 1982 prices.

Changes in user costs for each study site were calculated using a modified version of a work-zone queue and user costs evaluation model (QUEWZ) that relates vehicle volumes and speeds to user costs *(4)*.

As mentioned earlier, individual study vehicle runs were made in each lane of travel in both directions, and at least one run was made during each study hour. Therefore, the additional user costs for each study site were calculated for each lane and each direction of travel during each study hour. In cases where more than one instrumented vehicle run was made in the same lane, direction, and hour, the hourly user costs for each run were averaged.

Because the primary purpose of this analysis was to determine the differences in additional user costs resulting from the type of work-zone traffic control approach (single-lane closure and TLTWO), as many data points as possible were generated for the two approaches. All but one of the nine work zones studied involved closing one lane in the direction of the single-lane closure or the crossover. In the one exception (Site 3), two lanes were closed. However, all of the work zones had only one lane open in the closure or crossover direction. In the opposite direction, all the TLTWO sites and two of the single-lane closure sites had just one lane open.

User-Costs Results

Table 6 gives the user costs at the nine work sites by direction of travel during periods when no significant queues were present. User costs during periods when significant queues were present (Site 7 and the Dallas pilot test site) are given in Table 7.

From Table 6, the average additional user costs, when no significant queues were present, were found to be $0.11 per vehicle in the direction of the single-lane closure or crossover (TLTWO), and $0.08 in the opposite direction. Based on the volumes at the sites during the studies, this translates to $94 and $55 per hour of additional user costs. In contrast, the average additional user costs

TABLE 6 USER COSTS WITH NO SIGNIFICANT QUEUES PRESENT

Site	Direction of Travel[a]	Type of Traffic Control	Average Additional User Cost per Vehicle ($): Delay Cost	Operating Cost[b]	Total Cost	Average Hourly Vehicle Volume	Average Additional User Cost Per Hour ($)
1	C	L/C	0.03	−0.01	0.02	273	5
	O		<.01	<.01	<.01	286	<1
2	C	L/C	0.13	0.01	0.14	865	120
	O		NA[c]	NA	NA	NA	NA
3	C	TLTWO	0.16	0.03	0.20	1,139	228
	O		0.14	0.03	0.18	1,249	220
4	C	L/C	0.04	0.00	0.04	204	9
	O		0.01	0.01	0.02	175	3
6	C	TLTWO	0.15	0.02	0.17	1,625	276
	O		0.13	0.01	0.14	1,621	229
7	C	L/C	0.07	0.03	0.10	1,114	117
	O		0.04	0.01	0.05	260	14
8	C	TLTWO	0.21	−0.06	0.15	943	145
	O		0.20	−0.09	0.10	596	61
9	C	TLTWO	0.12	−0.02	0.10	662	64
	O		0.11	−0.03	0.08	601	46
Average							
	C		0.11	0.00	0.11	853	94
	O		0.09	−0.04	0.08	684	55

Note: Totals may not match separate values because of rounding errors and weighting of each run by the corresponding traffic volume.

[a] C = direction of single-lane closure or crossover, and O = opposite direction.

[b] Operating costs include vehicle running costs and speed change cycle costs.

[c] NA = not available.

when significant queues were present (Table 7) were found to be $0.64 per vehicle at Site 7 and $1.96 per vehicle at the Dallas test site. Evaluations with respect to queue length resulted in user costs of $0.96 per vehicle per mile of queue at Site 7 and $1.43 per vehicle per mile of queue at the Dallas test site.

Figure 1 shows regression curves that represent additional user costs per work-zone mile at different hourly demand volumes based on the data collected in this study. The three sets of data points shown on the graph are those for the single-lane closure direction (A1), crossover direction (A2), and crossover opposite direction (B2) when no significant queues were present. The curves A1, A2, and B2 explain a large portion of the variation in the data points, as evidenced by the high R^2 values 0.8383, 0.8592, and 0.9881, respectively. All three curves reflect similarly low hourly additional user costs per work-zone mile for demand volumes of less than 1,200 vehicles per hour (vph). As volumes increase beyond 1,200 vph, additional road-user costs per mile of work zone increase rapidly.

These results indicate that for the range of hourly vehicle demand volumes studied when no significant queues developed, additional hourly user costs per mile of work zone remain about the same for vehicles traveling in the direction of the single-lane closure (A1) or crossover (A2). Curve B2 suggests that vehicles traveling in the opposite direction to the crossover experience lower additional hourly user costs per mile of work zone than those traveling in the direction of the single-lane closure or crossover.

Figure 2 shows the same data points as in Figure 1 for the single-lane closure (A1), crossover (A2), and crossover opposite (B2) directions fitted with one composite cost curve. Again, an R^2 of 0.8226 indicates that a high amount of the variation in the data points is explained. Figure 2 indicates that hourly user costs per mile of work zone increase rapidly when vehicle demand volumes are nearing the capacity of the open lane in the work zone, as expected.

Total additional hourly user costs are plotted against hourly demand volume without regard to work-zone length in Figure 3. The curve fits the data points well, yielding an R^2 of 0.8773. The curve indicates that additional user costs at a single-lane closure or TLTWO work zone were less than $200 per hour for demand volumes of 1,200 vph or less. However, additional hourly user costs increased rapidly as the hourly volumes increased. For example they exceed $500 per hour at demand volumes of 1,600 vph.

Simulated User Costs

Although the data collected at the nine study sites were limited, it was of interest to explore the effects of work-zone length (dis-

TABLE 7 USER COSTS WITH SIGNIFICANT QUEUES PRESENT

Site	Direction of Travel[a]	Average Queue Length (miles)	Average Additional User Cost per Vehicle ($): Delay Cost	Operating Cost[b]	Total Cost	Vehicle Cost Per Mile of Queue	Average Hourly Vehicle Volume	Average Hourly User Cost ($)	Average Hourly User Cost Per Mile of Queue ($)
7	CQ	0.66	0.53	0.11	0.64	0.96	1,407	895	1,356
Test[c]	CQ	0.728	1.32	0.11	1.43	1.96	1,700	2,424	3,329

Note: Totals may not match separate values because of rounding errors and weighting of each run by the corresponding traffic volume.

[a] CQ = direction of crossover or lane closure while queue was present.

[b] Operating costs include vehicle running costs and speed-change cycle costs.

[c] Located on Central Expressway in Dallas, Texas.

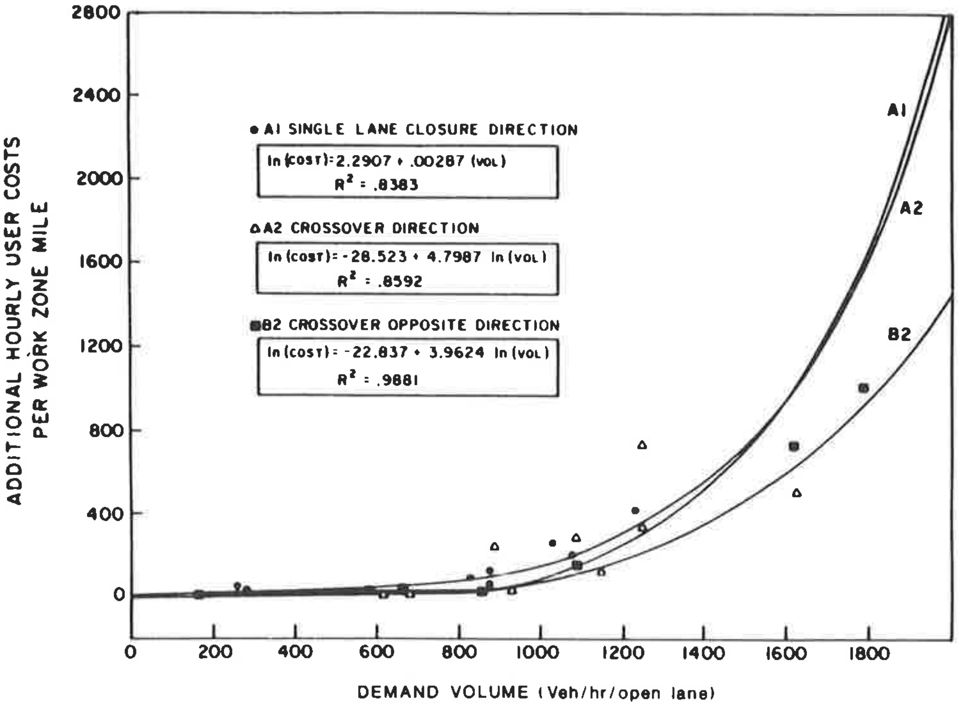

FIGURE 1 Additional hourly user costs per mile of work zone by direction of travel.

tance) on user costs. This was accomplished by using a queue and road-user cost evaluation computer model (QUEWZ) developed by Memmott and Dudek *(4)*. The simulation involved a single-lane closure approach on a four-lane divided highway, and considered traffic only in the closure direction. The simulation considered only the first hour of the closure.

The set of data assumptions for the simulated work zone example were as follows:

1. Four-lane divided facility before closure;
2. A single-lane closure through work zone;
3. Capacity restricted for 1 hr during day to calculate hourly user costs;
4. Normal capacity of 2,000 vehicles per hour per lane;
5. Restricted capacity through work zone of 1,332 vehicles per hour;
6. Eight percent of vehicles are trucks;
7. No queue present immediately before lane closure;
8. When demand exceeds capacity, a queue forms;
9. When a queue develops, the impacts of the queue on subsequent time periods are not taken into account; and
10. No diversion takes place, even if a queue is present.

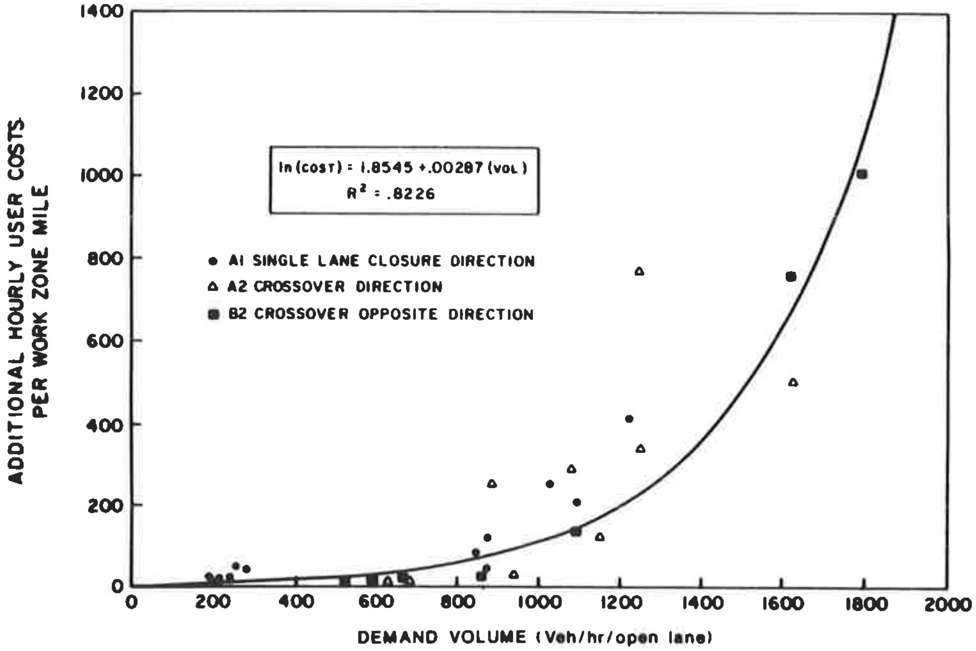

FIGURE 2 Additional hourly user costs for combined lane closures.

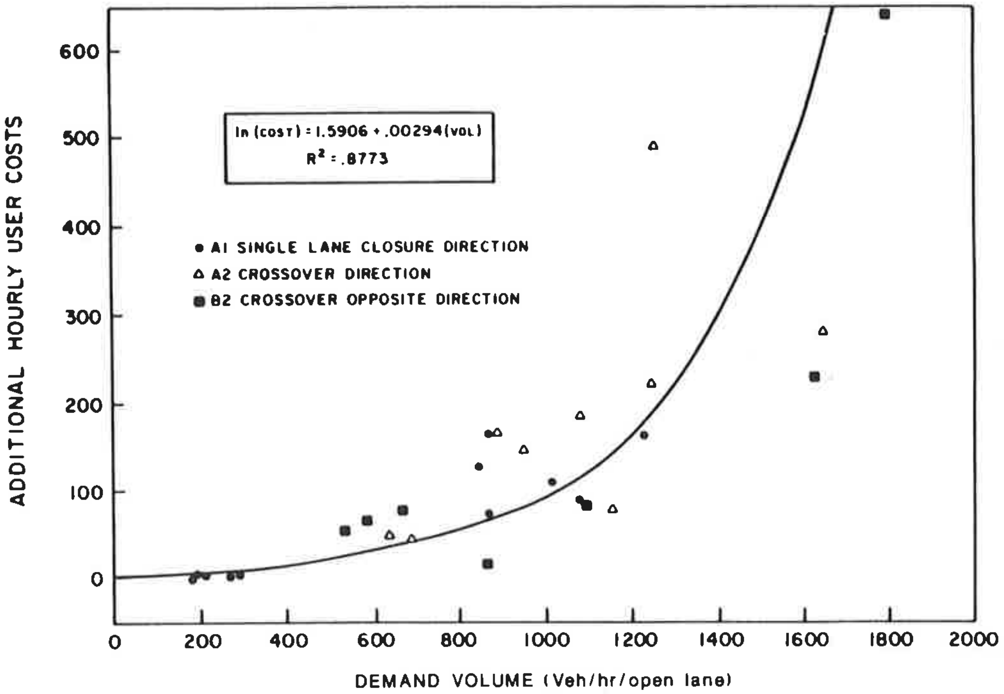

FIGURE 3 Additional hourly user costs for combined lane closure types.

Figure 4 shows the results of the simulation in the form of four curves, one for each work-zone length simulated (e.g., 0.1, 1, 2, and 5 mi). According to these results, work-zone length (at least for those studied) has only a minor effect on user costs at demand volumes below the work-zone capacity, as expected. When demands are greater than the capacity, work-zone length appears to have a significant effect on user costs.

SAFETY

Accidents

Accident experience, before and during construction, was evaluated using computerized accident data supplied by the highway agencies. A minimum of 1 year of before-construction data and all

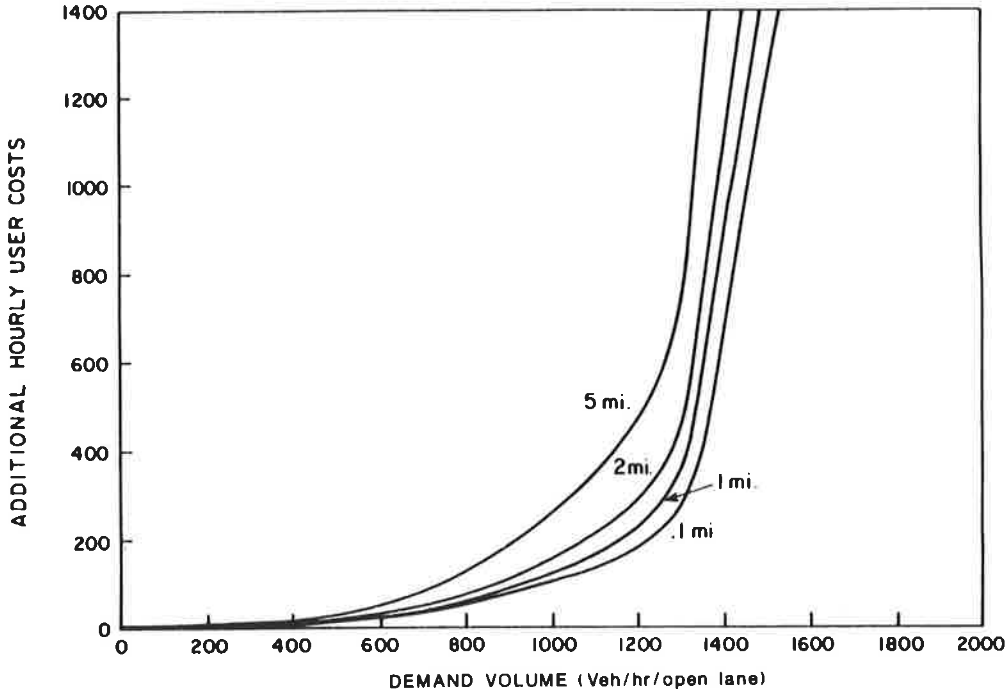

FIGURE 4 Simulated additional user costs by work-zone length for the first hour of a single lane closure.

available during-construction data were analyzed. No during-construction data were available for Site 9, because this work zone had been in place only a few weeks at the time of the study. Also, Site 1 was totally omitted from consideration because it involved a short duration work activity (i.e., pavement repair work) at various individual points along a rural freeway. No accurate accident records were kept. Therefore, during-construction accident data were only available for seven of the nine sites, and even these data were limited. The amount of during-construction data varied from only 1.2 months at Site 6 to 10.6 months at Site 3.

Table 8 gives the number of accidents reportedly occurring during construction at each site, as well as the number that occurred 1 year before construction. Accident frequencies were combined with project length and traffic-volume data to generate the accident rates given in Table 9. Note that the rates in the table are based on very small frequencies and time periods in most cases. Nevertheless, the accident rates reveal some preliminary findings. The three lane-closure work zones experienced relatively large accident rate increases during construction. Accident rates increased at Sites 2, 4, and 7 by 60, 55, and 53 percent.

The TLTWO sites generally had better safety performance based on rates alone. Two of the TLTWO sites (Sites 3 and 6) had modest rate increases of 28 and 12 percent, and the accident rate at Site 8 (TLTWO without barrier traffic separation) actually decreased by 34 percent. The remaining TLTWO site (Site 5) was unique in that traffic was detoured through diamond intersections into the two-lane, two-way section. The accident rate at Site 5 increased 64 percent during construction, and over one-half of the reported accidents occurred within the frontage road intersections.

Conflicts and Hazards

Conflicts were evaluated as an indirect measure of work-zone safety and productivity. The evaluation was based on the premise that, if a particular traffic control approach generates more frequent and severe conflicts, then it will be likely to result in more accidents and reduced productivity. Five categories of work-zone conflicts were identified and analyzed: (a) vehicle-traffic control device, (b) vehicle-vehicle, (c) equipment-traffic control device, (d) vehicle-equipment, and (e) vehicle-worker. These conflicts and their possible effects are summarized in Table 10.

Vehicle-Traffic Control Device Conflicts

Figure 5 shows composite data for the number of vehicle-traffic control device conflicts from eight of the study sites. It shows the general relationships between vehicle-traffic control device conflicts and traffic volume for left- and right-lane closures. As shown in Figure 5, conflicts occur more frequently at right-lane closures probably for two reasons: (a) right-lane volumes on a four-lane freeway are usually higher than left-lane volumes under light- to moderate-flow conditions, and (b) drivers are apparently more

TABLE 8 ACCIDENT FREQUENCIES BEFORE AND DURING CONSTRUCTION

			Accident Frequency		Time Period During Construction (months)
Site	Type of Work	Separation	Before Construction[a]	During Construction	
1	Concrete pavement repair	–[b]	–[b]	–[b]	–[b]
2	Pavement resurfacing	Cones	24	9	2.8
3	Bridge repair	PCB	101	111	10.6
4	Bridge deck repair	Cones	3	3	7.7
5	Pavement reconstruction	Markings	18	17	7.1
6	Overhead structure repair	PCB	14[c]	5[c]	1.2
7	Bridge repair	PCB	46	27	4.6
8	Base excavation and pavement resurfacing	Tubes	38	8	3.8
9	Bridge repair and pavement resurfacing	Tubes	46	NA[d]	NA[d]

[a] 1-year period before construction.
[b] No data.
[c] Includes frontage road intersection accidents.
[d] NA = not available.

TABLE 9 ACCIDENT RATES BEFORE AND DURING CONSTRUCTION

					Accident/100 Million Vehicle-Miles			
Site	Traffic Control	Separation	Project Length, (miles)	1982 ADT	Before[a]	During	Time Period During Construction (months)	Change (%)
1	Lane closure	–[b]	–[b]	–[b]	–[b]	–[b]	–[b]	–[b]
2	Lane closure	Cones	4.4	22,000	68	109	2.8	+60
3	TLTWO	PCB	2.0	38,000	364	466	10.6	+28
4	Lane closure	Cones	1.0	20,000	42	65	7.7	+55
5	TLTWO	Markings	2.2	6,800	324	531	7.1	+64
6	TLTWO	PCB	1.5	51,800	155	173	1.2	+12
7	Lane closure	PCB	0.9	41,500	337	517	4.6	+53
8	TLTWO	Tubes	6.3	22,600	73	49	3.8	–34
9	TLTWO	Tubes	7.8	20,800	78	NA[c]	NA	NA

[a] Based on 1-year old data.
[b] No data.
[c] NA = not available.

TABLE 10 CONFLICT DESCRIPTION AND EFFECTS

Conflict	Description	Effect
Vehicle-traffic control device	Vehicle in closed lane at taper	Forced merge to open lane
Vehicle-vehicle	Vehicle slows to merge into open lane, conflicts with vehicles in open lane, or both	Traffic slowdown, reduced traffic operation on open lane
Equipment-traffic control device	Work space restricted by traffic control device configuration	Operation slowdown, reduced productivity
Vehicle-equipment	Equipment enters or crosses traffic stream	Avoidance maneuver, accident, stopping for vehicle or equipment, reduced productivity
Vehicle-worker	Worker enters or crosses traffic stream	Avoidance maneuver, accident, stopping for vehicle or equipment, reduced productivity

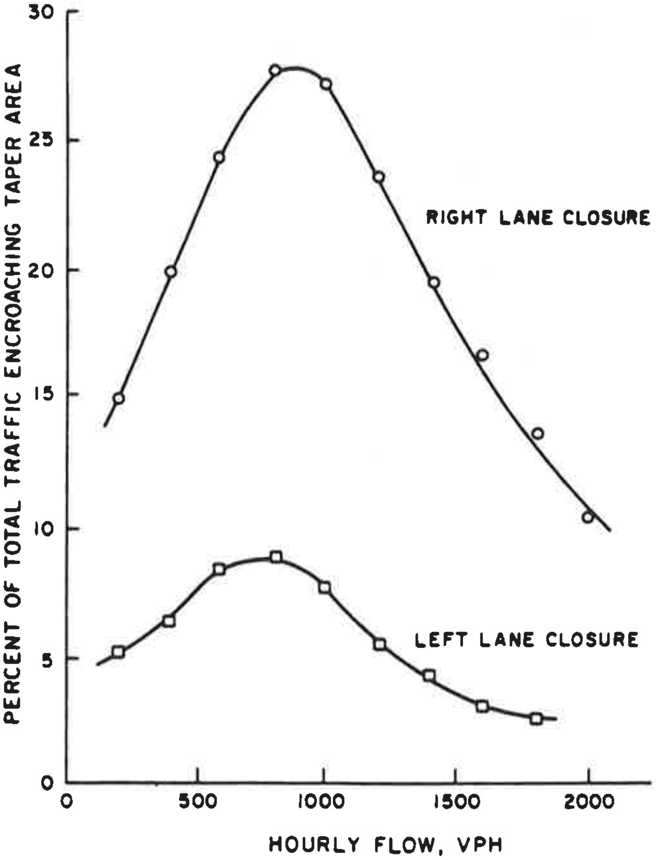

FIGURE 5 Relationship between traffic volume and vehicle-traffic control device conflicts at left- and right-lane closures.

hesitant to vacate a closed right lane, possibly because they fear missing their downstream exit ramp. No conclusions, however, could be reached from the data regarding the relative safety of right- or left-lane closures.

Figure 5 also shows that vehicle-traffic control device conflict rates (e.g., percentage of total traffic encroaching the taper area) are lower under low- and high-volume conditions, and highest under moderate-volume conditions. The conflict rate is low in light traffic probably because drivers have plenty of opportunity to change lanes without interference from other traffic. Also, visibility to the point of closure is not generally restricted by other vehicles. Under heavy-volume conditions, it is theorized that when drivers see the lane closure every effort is made to vacate the closed lane early to avoid being trapped at the taper. Because traffic is moving slower, drivers are able to merge into smaller gaps. Therefore, the vehicle-traffic control device conflict rate is relatively low.

The moderate-volume condition is most conducive to vehicle-traffic control device conflicts. Visibility to the closure is limited by other traffic. Also, some drivers may have a false feeling that they will have plenty of opportunity to change lanes at the last moment.

Vehicle-traffic control device conflict data do not indicate if the lane closure or TLTWO strategy is more desirable because both strategies require an equal number of right- and left-lane closures to complete the construction job. The data do, however, suggest that the greatest vehicle-traffic control device hazard exists during moderate-volume conditions. Also, the total number of vehicle-traffic control device conflicts can be reduced simply by minimizing the time that lanes are actually closed, particularly the right lanes.

Vehicle-Vehicle Conflicts

Vehicle-vehicle conflicts arise when drivers in the closed lane must merge into the open lane. When traffic volumes are light or moderate, the number of vehicle-vehicle conflicts will be related to the traffic volumes in each lane and the associated gaps in the open lane. When traffic demands are high and queues develop from the lane closure, drivers in the closed lane must generally force their entry into the open lane. Both the TLTWO and the single-lane closure traffic control approaches involve a lane closure; therefore, the number of vehicle-vehicle conflicts at a given traffic volume would be the same for both approaches. Because the primary interest was to compare the differences between the two approaches, a comprehensive analysis of vehicle-vehicle conflicts was not warranted.

Equipment-Traffic Control Device, Vehicle-Equipment and Vehicle-Worker Conflicts

The frequencies of equipment-traffic control device, vehicle-equipment, and vehicle-worker conflicts observed during the small sampling periods were very low at all the sites (less than five per hour). No trends were apparent in the data, because most of these conflicts resulted from actions peculiar to a site or work task. Unlike vehicle-traffic control device conflicts, these conflicts depend on a great number of factors (e.g., size of work force, equipment in use, available work space, traffic volumes, specific work task, traffic control approach, etc.). It should be noted again that the research team only observed activities for a short time period and not throughout the duration of the construction project.

CAPACITY

Table 11 gives the results of the work-zone capacity studies. As shown, the average capacities at Site 6 (a TLTWO work zone) were 1,450 vph in the crossover direction and 1,720 vph in the opposite direction. Therefore, the capacity in the crossover direction was nearly 300 vph lower compared to the opposite direction.

TABLE 11 WORK ZONE CAPACITIES

Study Site	Traffic Control Approach	Direction of Travel	Study Period	Raw Capacity Volume[a] (vph)	Average Axle per Vehicle	Average Capacity (vph)
3	TLTWO	Crossover	45 min	NA[b]	NA	1,550
		Opposite	1 hr	NA	NA	1,800
6	TLTWO	Crossover	3 hr	1,610	2.22	1,450[c]
		Opposite	3 hr	1,880	2.19	1,720[c]
7	Lane closure	Lane closure	1 hr	1,920	2.16	1,780[c]

[a] Raw volumes are based on total traffic counter actuations divided by 2.
[b] NA = not applicable because capacity counts were made directly from videotapes.
[c] Average adjusted capacity = (Raw capacity volume x 2)/Average axles per vehicle.

At Site 7, where the single-lane closure approach was used, the average capacity was 1,780 vph.

Observations of the videotapes from Site 3 indicated that at this TLTWO site, capacity flow was reached for approximately 45 min in the crossover direction and 1 hr in the opposing direction. Based on the observed data, the capacity in the opposite direction was estimated to be approximately 1,800 vph. The estimated capacity in the crossover direction was approximately 1,500 vph.

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