REDUCING IMBALANCE OF INTERSECTING FREEWAYS BY ON-FREEWAY CONTROL

Roy C. Loutzenheiser, Texas Transportation Institute, Texas A&M University; and Donald M. Henderson, Wilbur Smith and Associates

Because of a heavy traffic demand on merging ramps during peak periods and a lane imbalance at the merge areas, an interchange of Interstate 610 and Interstate 10 in Houston has ramp queues that frequently extend onto upstream freeways. A morning and an evening study was made to evaluate the effects of on-freeway control as a means of improving the merge operation. Standard maintenance procedures were used to close the outside freeway lane upstream of the merge area for a short period of time at the beginning of the merge congestion. Based on vehicle counts and average vehicle data that were collected before and during the closure study, a comparison of changes in flow rates and in total delay was made. Because accident data were not available, only nonincident days were analyzed. During morning and evening closures, the flow rates through the merge areas did not change; however, the morning closure caused a 9 percent increase in delay, whereas the evening closure reduced delay by 2 percent. The average flow rate on the 2 open freeway lanes during closure was about 1,650 vehicles per hour per lane. Implementation of positive lane closure was too time-consuming for a short-term closure. Therefore, the method of positive closure used in this study was not the optimal solution for this interchange. Further studies using other methods of on-freeway control have been recommended.

•MANY major interchanges are experiencing severe traffic congestion during peak-period operation. The problem is usually associated with a merge area where there is a lane imbalance and where there is a heavy traffic demand on the merging ramp during the early part of the peak period. At the beginning of the peak period, the ramp demand exceeds the ramp capacity at the merge area while the upstream freeway demand is below capacity. The heavy ramp demand results in reduced traffic flow in the merging lanes and usually in the total merging area. Hazardous operation may cause a breakdown in the merge area operation, and ramp queues that extend into the crossing freeway may result.

The premise is that better interchange operation is achieved by traffic control or minor geometric modifications. Control of modifications would permit a balanced lane operation at the merge points when traffic demands approaching the merge area exceed the merge capacity. Three general solutions to the problem are add a lane in the merge area, reduce the number of lanes approaching the merge area, and reduce the traffic demand approaching the merge area. Any one, or combination, of these 3 approaches can provide relief to the problem.

The success of adding lane in the merge area depends on the length of the added lane. If the lane is extended to an exit ramp, the solution should be valid. If it is lengthened a few hunderd feet and then dropped, the problem will not be completely resolved. However, the prolonged lane may result in an improved situation because of a longer tapered design and additional sight distance.

Sponsored by Committee on Operational Effects of Geometrics.

Reducing the number of lanes approaching the merge area to the same number as those leaving the merge area will not directly increase the capacity of the freeway, but it should improve the flow characteristics. That, in turn, would improve the safety of the area and would result in improved capacity because of the reduction of incidents. The method of closing a lane on a freeway has been investigated by several people. In general, two approaches have been used:

1. Positive closure of a lane—lane closure is usually needed only during the peak period, and therefore permanant closure is considered impractical. To manually close a lane on a daily basis is impractical; however, there is not a good method at present for effective automatic positive closure of a lane.
2. Voluntary lane closure—The most practical way to effect a lane closure is to use signs and signals that can be activated when needed. Several devices that could be used in an installation of this type are available. Some examples of these are advanced warning signs with fixed or variable messages and a red X and green arrow display. The obvious problem is that motorists may not obey the control devices if they know there is little danger of being involved in an accident or being fined by the police.

Reduction of the demand on approaches to the merge area may, in some instances, be feasible by using traffic control devices on the approaches. Ramp metering, a successful traffic control system for entrances to the freeway, could be used on the interchange roadways. The objective here is to reduce demand for very short time periods or to coordinate the flows approaching the merge area. Bulk metering would be used.

Each day miles of freeway lanes are being closed for the purpose of maintenance and construction. Kermode and Myyra (1) developed a procedure that will enable field personnel to schedule lane closures at a time when these closures will cause the least inconvenience to the motorists. Lee (2) discussed special procedures to be used during nighttime work.

Studies are being made to determine the best procedure to implement reversible lanes for unbalanced flow. Waight (3) described how a 2-lane, reversible tunnel was built in San Francisco to increase the traffic flow on 2 parallel roadways, 2 lanes each way. A system of movable, flexible barriers and changeable signs has been developed to control the traffic during the rush hours. DeRose (4) studied the operation of a reversible center-lane traffic system on an undivided roadway. The signing consisted of lane control signals (red X and green arrow) and NO LEFT TURN signs.

Forbes and Gervais (5) made a study of the effectiveness of symbols for lane control signals. Their studies showed that the red X and green arrow were meaningful in providing proper control. Hoack, Madsen, and Newman (6) found that ramp control on a 2-lane, high-speed, high-volume entrance ramp in the Los Angeles area reduced the holiday congestion at a major interchange.

Several interchanges in Houston experience serious breakdown in traffic operation during the morning and evening peak periods. The reduction is caused by a heavy traffic demand on the ramps prior to the heavy freeway demand. After some preliminary investigation, the interchange at Interstate 610 and Interstate 10 west was selected as a location where part of the preceding premise could be studied. The study design was based on reducing the number of lanes approaching the merge area by temporarily closing the outside freeway lane by positive means.

With the cooperation and assistance of the Texas Highway Department, the Texas Transportation Institute proposed that a traffic control system be designed, installed, operated, and evaluated at this major interchange to improve traffic operations and safety during peak periods. This paper presents some of the more important findings in the study; details of the study can be found in another report (7).

STUDY PROCEDURES

Description of Sites

Traffic operations at the I-610 and I-10 interchange frequently break down because of heavy traffic demands on the ramps. During the morning peak period, the queue on the ramp extending from I-10 eastbound to I-610 southbound (AM site) frequently backs onto the I-10 eastbound freeway lanes. In a similar manner, the queue on the ramp extending from I-610 northbound to I-10 westbound (PM site) backs onto I-610 northbound lanes. The 2 sites are shown in Figure 1. Each site has 3

Figure 1. Study sites.

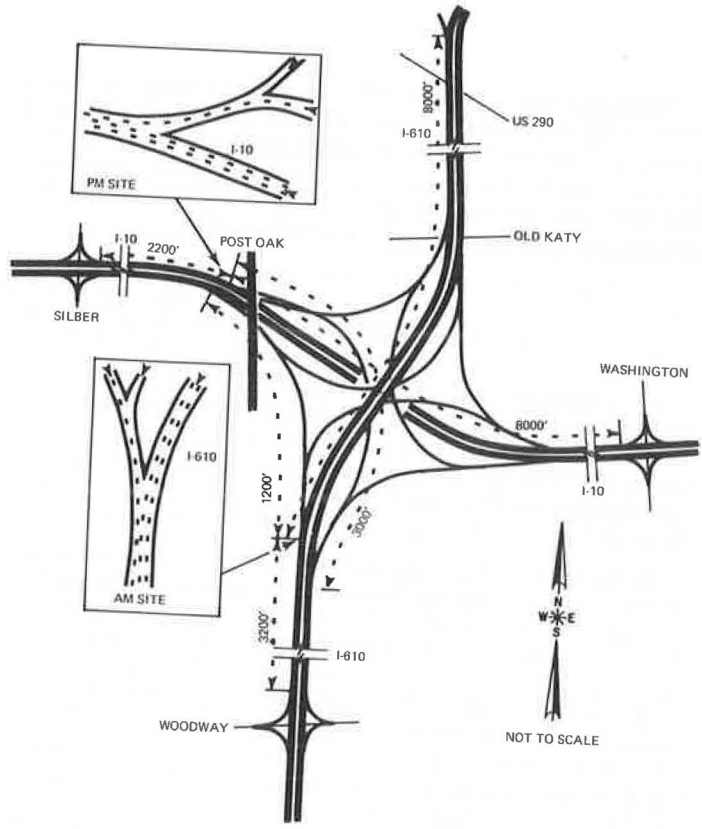
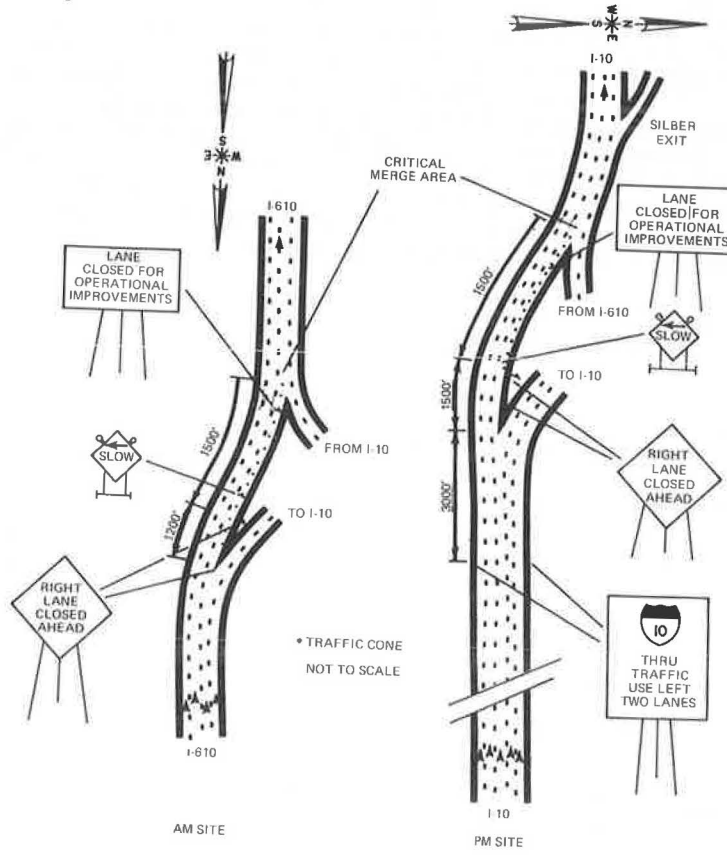


Figure 2. Sign placement in lane-closing operation.



upstream freeway lanes and 2 ramp lanes merging into 4 downstream freeway lanes. Interstate 610 is elevated above I-10.

At the AM site the I-10 eastbound to I-610 southbound ramp is about 1,200 ft in length and provides limited storage capacity. The ramp has an uphill grade that reduces visibility of the merge area. The upgrade also increases the recovery time that is required when ramp vehicle speeds are reduced. The first downstream exit ramp on I-610 southbound is about 3,200 ft from the merge point, and the last upstream entrance ramp is about 8,000 ft from the merge point.

Drivers using the I-610 northbound to I-10 westbound ramp at the PM site can see both the merge area and the input freeway lanes because of the downgrade approaching the merge area. The ramp is long (about 3,000 ft) and has some storage capacity. Because the I-10 freeway is depressed at the interchange, the freeway driver is unable to see the merge area until he is close to it. The first exit ramp downstream on I-10 is about 2,200 ft from the merge point, and the last entrance ramp upstream is about 8,000 ft from the merge point. About 6,600 ft downstream of the merge point, the freeway lanes on I-10 are reduced from four to three.

Preliminary Traffic Evaluation Before Closure

Visual observation indicated that the ramp backup at the AM site contributes to the daily reduced flow on I-10 eastbound. Flow on I-10 eastbound improved once vehicles were beyond the interchange. Peak flow through the merge area usually occurred around 7:45 a.m.; however, there was a significant secondary peak around 8:15 a.m. The inside lane of the ramp, which merges with the outside freeway lane, carried a small percentage of the ramp movement. Consequently, the outside ramp lane had frequent queuing that extended onto I-10 eastbound and formed shock waves. Traffic flow on I-610 southbound, upstream of the merge area, remained at a high level of service and was impeded only when an accident occurred.

The evening peak period at the merge on I-10 occurred around 5:20 p.m. However, the ramp usually had a significant increase in flow around 5:00 p.m., which was 5 to 10 min earlier than the initial freeway buildup. The ramp had reduced operations during this time, and a queue frequently extended onto I-610 northbound. This queuing caused reduced flow on the outside lane and frequently the 2 outside lanes on I-610 northbound. The reduced freeway operation caused a slowly moving queue on the I-610 freeway for several miles upstream. The upstream I-10 freeway demand remained below capacity until congestion occurred in the merge area. Because of the freeway lane drop or an incident, downstream operation on I-10 westbound occasionally backed into the merge area and caused the interchange operation to break down prematurely.

Lane Closure Technique

For a pilot study of on-freeway control, 2 of the 3 control methods mentioned earlier were not feasible. Because the AM site is on an embankment and the PM site is in a depression, construction of an additional freeway lane would be costly. Reducing the traffic demand approaching the merge area is unreasonable because one objective is to increase the ramp flow.

Inasmuch as both sites have an input freeway demand of less than capacity, a reduction in the number of lanes approaching the merge area was considered feasible. Closing the outside freeway lane by positive means was recommended and was accomplished in the same manner used by maintenance forces to block a lane. Advanced signing alerted motorists of the closure, and traffic cones and signs effected the physical closure. A special trailer-mounted sign with flashing beacons was used to enhance the safety of operations. The actual lengths of closure were about 1,500 ft, which included a 750-ft taper. Additional warning signs were placed about 3,000 ft upstream of the beginning of closure for the PM site. Figure 2 shows the location of closure signs.

On the first day of closure, the outside lane at each site was closed from 6:40 to 7:40 a.m. and from 4:35 to 5:30 p.m. The capacity of the remaining 2 lanes of the freeway proved inadequate, so closure was reduced to less than 1 hour on the second day. Closure time was further reduced to less than 40 min for the remainder of the study. Beginning closure time and the total closure time for each day were based on real-time

field decisions and the results of the previous closures. The study was conducted on weekdays from the evening of June 7 to the evening of June 23, 1971. Because of rain, the closure was cancelled on 2 evenings (June 18 and 22). The morning closures were conducted as planned.

ANALYSIS OF DATA

Several months prior to the closure study, preliminary data were collected to establish a basis for comparison. For this report, only data collected during nonincident periods were used in the analyses. Usable vehicle counts before closure were obtained on only 3 days because of the limitation of available manpower. An "average" vehicle study was made in 2 vehicles during a period of several weeks. In this study, each driver was instructed to follow a predetermined route as a typical driver. The second person in each vehicle recorded travel times to various predetermined stations, queue formations, and a general subjective evaluation of the interchange operation. Current accident data for this interchange were not available or were insufficient.

During the closure study, similar data collection was made. In addition, some observations were made from an airplane during 2 mornings and 4 evenings. So that a meaningful comparison could be made, data collected during an incident were not used. Also, data from the first 2 days of closure for each site were not used so that more "typical" findings could be provided. During the study, data for 8 mornings and 5 evenings were analyzed.

Analysis of Traffic Flow

The initial closure for each site lasted about 1 hour and caused upstream freeway queues of several miles in length and resulted in significant delay. Some reasons for this queuing were insufficient advance notice to the public, extended time required to manually close the lane, and a larger than expected reduction in capacity by the closed outside lane. After the first 2 days of closure, intervals of closures varied from 15 to 37 min.

Typical volumes for a nonincident day before closure and a day during closure are given in Table 1. In general, the total output volumes were the same. The reduced upstream freeway flow was compensated by the increased ramp flow. Figure 3 shows the percentage of ramp flow to total flow through the merge area for 5-min intervals before and during closure. These percentages were based on typical, nonincident days.

AM Site—The total volume through the merge area was about 6,850 vehicles (1,710 vehicles per lane) between 7:00 and 8:00 a.m. for both before and during the study. During the period from 6:45 to 8:15 a.m., the volume increased by more than 200 vehicles during the closure. Between 7:00 and 8:00 a.m., the freeway input volume decreased from 4,150 to 3,800 vehicles, while the ramp input volume increased from 2,700 to 3,100 vehicles. During the closure, the 2 open freeway lanes had an average flow rate of more than 1,650 vehicles per hour per lane. Table 2 gives a summary of the daily closure time and merge operation.

Because the number of vehicles leaving the freeway at the upstream exit ramp on I-610 increased by 40 vehicles, it was assumed that the closure caused only minor diversion. The downstream exit ramp on I-610 has minor effect on the operation in the merge area because of the light flow rate. During the closure, the exit ramp volume decreased by 25 vehicles.

Without closure, the AM site ramp usually carried about 40 percent of the total flow through the merge area; however, this percentage decreased during the peak half-hour (Fig. 3). With closure, the percentage increased to about 50 percent during the peak half-hour. Preliminary counts before closure indicated that the left lane of the ramp was used by less than 20 percent of the ramp traffic flow during the peak flow, except for a short period of time. During the closure, it was anticipated that more vehicles would use the left lane; however, counts showed little change in the percentage of usage. The percentages are shown in Figure 4. The apparent reason for this lack of utilization was inability of ramp drivers to see the closed outside freeway lane or the merge area. Some form of information sign was needed on the ramp.

Table 1. Volume counts made at I-10 and I-610 interchange before and during closure.

Location of Vehicles When Counted	Number of Lanes	Vehicles at AM Site				Vehicles at PM Site			
		7:00-8:00		6:45-8:15		5:00-6:00		4:45-6:15	
		Before	During	Before	During	Before	During	Before	During
On freeway	3	4,159	3,781	5,882	5,459	3,945	3,673	5,706	5,327
Entering at ramp	2	2,686	3,113	3,729	4,367	2,707	3,000	4,108	4,535
Total	4	6,845	6,894	9,611	9,826	6,652	6,673	9,814	9,862
Leaving at downstream exit	1	189	164	305	278	719	718	1,002	1,057
Leaving at upstream exit	2 and 3	1,956	1,992	2,791	2,524	2,156	2,302	3,665	3,165

Table 2. AM site volume counts downstream of merge.

Date	Vehicles 7:00-8:00	Vehicles 6:45-8:15	Flow Rate on I-610 During Actual Closure	Closure Time	Closure Duration (min)
10-13-70	6,510	9,655		Before	
1-13-71	6,835	9,733		Before	
1-14-71	6,827	9,612		Before	
6-08-71	—[a]	—[a]		6:40-7:40	60
6-09-71	6,529	9,500	1,703	7:02-8:00	58
6-10-71	6,894	9,826	1,698	7:16-7:51	36
6-11-71	6,450	9,700	1,728	7:16-7:53	37
6-14-71	6,751	9,818	1,760	7:22-7:52	30
6-15-71	6,604	9,579	1,632	7:30-7:55	25
6-16-71	6,747	9,829	1,639	7:30-7:57	27
6-17-71	6,718	9,746	1,608	7:29-7:52	23
6-18-71	6,538	9,424	1,633	7:29-7:51	22
6-21-71[b]	6,463	9,237	1,706	7:29-7:45	16
6-22-71	6,668	9,547	1,562	7:29-7:47	18
6-23-71[c]	6,748	9,546	1,690	7:30-7:45	15

[a]No counts.
[b]Stalled car on ramp at merge from 7:21 to 8:10.
[c]Minor accident on ramp at merge from 7:45 to 7:48 and then moved to shoulder.

Figure 3. Ramp flow as a percentage of total flow through the merge area on a typical nonincident day.

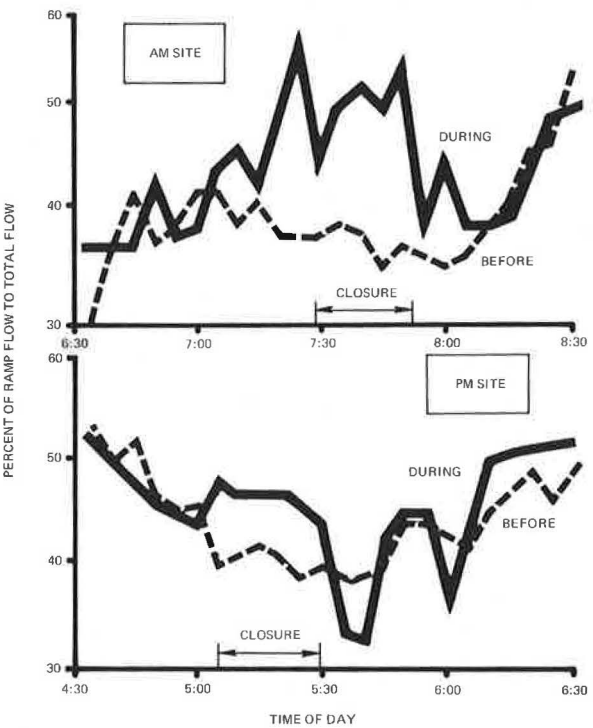
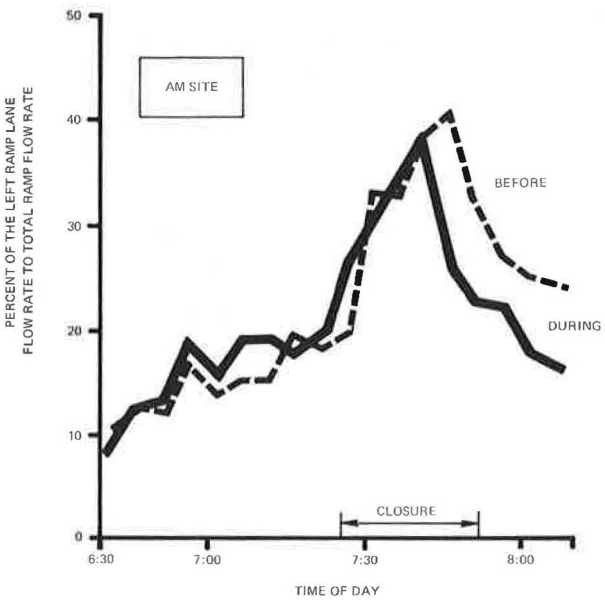


Figure 4. Lane distribution of traffic flow from I-10 eastbound to I-610 southbound ramp before and during closure.



PM Site—The total volume through the merge area was about 6,650 vehicles between 5:00 and 6:00 p.m. (1,660 vehicles per lane) before and during the study (Table 1). Between 4:45 and 6:15 p.m., the total volume increased by fewer than 50 vehicles during the study. The freeway input between 5:00 and 6:00 p.m. decreased from 3,950 to 3,650 vehicles, while the ramp input volume increased from 2,700 to 3,000 vehicles. During the closure, the 2 open freeway lanes had an average flow rate of about 1,650 vehicles per lane. Table 3 gives a summary of the daily closure time and merge operation.

During the lane closure, the upstream exit ramp volume on I-10, between 5:00 and 6:00 p.m., increased by 150 vehicles (about 7 percent), and some queues were observed on this exit ramp. Apparently some motorists were diverting from I-10 upstream of the closure. The downstream exit ramp on I-10 had little change in volume. It had been anticipated that there would be a decrease in volume at this ramp. Occasionally poor operation at this downstream exit ramp continued to generate shock waves that affected the merge area.

Prior to the closure study at the PM site, the percentage of ramp flow to total merge flow varied from 50 percent before the peak hour to about 40 percent during the peak hour. Figure 3 shows that the closure permitted the ramp flow to remain slightly higher than usual. As anticipated, the flow on the left ramp lane increased. This increase was due to the clear view of the merge area and lane closure. Figure 5 shows the change in percentage of left lane flow to total ramp flow with time.

Average Vehicle Study

A parameter used in determining the effectiveness of on-freeway lane closure is the change in total delay at the interchange as calculated from the average vehicle study. A successful study is one in which total delay is reduced. The anticipated effect in lane closure is improvement of operation at the merge, downstream from the merge, on the ramp, and on the crossing freeway. Reduction in operation upstream of the merge on the freeway is expected. For this study, analysis was made for 1½ hours at each site (6:45-8:15 a.m. and 4:45-6:15 p.m.) to include most delayed effects of closure.

As expected, the AM site had an increase in delay upstream of the merge on I-610 because of the reduction in lanes. There are no good alternate routes for I-610 southbound traffic. A reduction in the increased delay was expected once closure procedures were improved and motorists became familiar with the closure; however, this reduction did not occur. The I-10 eastbound flow also had an increase in delay. The conclusion is that other factors, such as upstream entrance ramps, were causing delay on I-10 in addition to the extended queue on the I-610 exit ramp. It was previously determined (Fig. 4) that the left lane of the exit ramp was not fully used as anticipated and, therefore, the ramp queue was only partially reduced. Delays to the motorists on the ramp and downstream of the merge area decreased slightly. Total delay for the AM site increased by 132 vehicle-hours or by 9 percent. A summary of the data is given in Table 4 (7, 8). The different subsystems used in analysis of the delay are shown in Figure 6.

Closure at the PM site was successful in decreasing delay on the crossing freeway (I-610) and on the ramp from I-610 to I-10 westbound. A queue on this ramp began to form prior to closure but dissipated after the closure was initiated. The delay increase on I-10 upstream of the merge was significant, and some diversion was taking place near the end of the 13-day study. Diverting motorists probably found less delay on alternate routes. The freeway flow immediately downstream of the merge improved and had a reduction in delay. Farther downstream, where the I-10 freeway lanes decrease from 4 to 3, there was a slight increase in delay. Total delay for the PM site decreased by 23 vehicle-hours or by 2 percent (Table 4).

Operational Effects

Even though some public announcements were made before the study, it was apparent that the motorists were not prepared for the closure. Two accidents on the freeway occurred upstream of the merge and might have resulted from the extended queue formation. As previously mentioned, data on accidents were not available. Three stalled

Table 3. PM site volume counts downstream of merge.

Date	Vehicles 5:00-6:00	Vehicles 4:45-6:15	Flow Rate on I-10 During Actual Closure	Closure Time	Closure Duration (min)
10-13-71	6,501	9,615		Before	
1-13-71	6,635	9,810		Before	
1-14-71	6,610	9,875		Before	
6-07-71	5,478	8,447	1,661	4:35-5:50	75
6-08-71[a]	6,435	9,424	1,695	4:47-5:29	42
6-09-71[b]	6,057	9,345	1,692	4:52-5:20	28
6-10-71[c]	6,293	9,465	1,531	5:03-5:25	22
6-11-71	6,487	9,524	1,555	4:57-5:31	34
6-14-71[d]	6,594	9,712	1,729	4:55-5:27	32
6-15-71	6,255	9,287	1,694	5:05-5:24	19
6-16-71	6,219	9,314	1,709	5:05-5:30	25
6-17-71[e]	6,347	9,435	1,566	5:05-5:29	24
6-18-71	—[f]	—[f]	—[f]		
6-21-71	6,673	9,862	1,615	5:05-5:36	31
6-22-71	—[f]	—[f]	—[f]		
6-23-71	6,103	9,238	1,648	5:09-5:29	20

[a]Minor accident on I-10 upstream from 5:12 to 5:25, and stall downstream on I-10 at 5:45.
[b]Stalls downstream on I-10 from 5:00 to 5:23, 5:32 to 5:54, and 5:53 to 5:59.
[c]Stall on I-10 in closure area from 5:13 to 5:34, and car smoking on shoulder of ramp from 5:36 to 5:50.
[d]Minor accident on I-10 upstream from 5:23 to 5:37, and stall downstream on I-10 from 5:20 to 5:35.
[e]Minor accident downstream on I-10 from 4:50 to 5:05, and stall on ramp in merge area from 5:43 to 5:46.
[f]Rain.

Figure 5. Lane distribution of traffic flow from I-610 northbound to I-10 westbound ramp before and during closure.

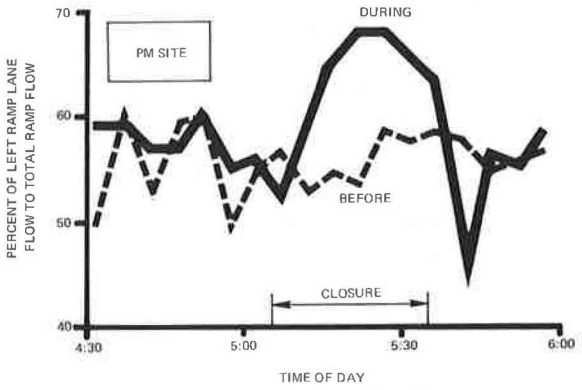
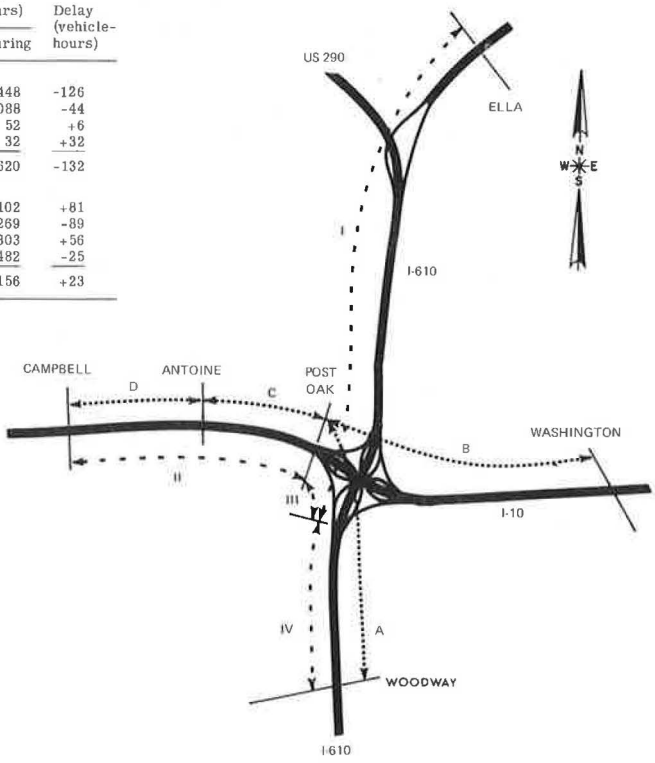


Table 4. Change in minimum average speed and total travel time due to lane closure based on average vehicle study.

Section	Length of Section (miles)	Minimum Avg Speed (mph) Before	Minimum Avg Speed (mph) During	Avg Total Travel Time[a] (vehicle-hours) Before	Avg Total Travel Time[a] (vehicle-hours) During	Delay (vehicle-hours)
AM site						
Ella to merge	3.0	46	19	322	448	-126
Campbell to Post Oak	3.0	20	20	1,044	1,088	-44
Post Oak to merge	0.6	27	32	58	52	+6
Merge to Woodway	0.8	32	34	64	32	+32
Total				1,488	1,620	-132
PM site						
Woodway to Post Oak	1.1	12	23	183	102	+81
Washington to Post Oak	1.5	30	12	180	269	-89
Post Oak to Antoine	1.1	18	23	359	303	+56
Antoine to Campbell	1.8	29	29	457	482	-25
Total				1,179	1,156	+23

[a]Time period is 6:45 to 8:15 a.m. for AM site and 4:45 to 6:14 p.m. for PM site.

Figure 6. Subsystems used in average vehicle study.



vehicles in the merge area and downstream of the merge could not be attributed to the effects of the closure.

After a more desirable time period for closure was established, the queue formation on the upstream freeway was limited to 1½ miles. The queue movement was usually stop-and-go. When the closure was removed, the freeway queue usually dispersed within 15 min. The queue on the ramp from I-610 to I-10 at the PM site ramp did not extend onto the I-610 northbound freeway lanes. However, at the AM site the queue on the I-10 to I-610 ramp briefly extended onto the I-10 eastbound freeway lanes because of the poor utilization of the left ramp lane.

As previously mentioned, closure of the outside freeway lane was based on experience of previous closures and usually lasted between 15 and 30 min. The closure was initiated after a queue began to form on the ramp and after the input freeway flow started to increase. There were insufficient data to determine a flow parameter for initiation of closure; however, on most of the good operational days the lane was closed when the combined 5-min input flow (freeway and ramp) exceeded 600 vehicles.

The closed freeway lane was not reopened until the ramp queue was eliminated and until the freeway downstream of the merge was operating fairly well. Before the lane was opened, sufficient capacity in the merge area was needed to handle the increased freeway input.

As expected, there were some public complaints about the closure study. Motorists who usually traveled on an unobstructed freeway upstream of the merge complained about the reduced speeds and queue on the input freeway. However, those complaints were more than offset by compliments about the improved operations of the interchange. The motorists, who no longer encountered the stop-and-go flow on the crossing freeway, approved of the lane closure. Most comments, good or bad, were about the PM site.

SUMMARY OF FINDINGS

1. During the study at the AM site, the 7:00 to 8:00 a.m. volume for the I-610 freeway flow upstream of the merge area decreased from 4,150 to 3,800 vehicles, while the ramp volume increased from 2,700 to 3,100 vehicles. The flow rate on the 2 open freeway lanes during closure was 1,650 vehicles per hour per lane.
2. The motorists on the AM site ramp did not fully utilize the inside lane because they were unable to see the merge area. Some form of information sign was needed on the ramp to advise motorists of merge area operation.
3. The total delay for the interchange between 6:45 and 8:15 a.m. increased by 9 percent because of the continued poor operation on I-10 eastbound upstream of the I-610 exit ramp.
4. During the study at the PM site, the 5:00 to 6:00 p.m. volume for the I-10 freeway flow upstream of the merge area decreased from 3,950 to 3,650 vehicles, while the ramp volume increased from 2,700 to 3,000 vehicles. The flow rate on the 2 open freeway lanes during closure was 1,650 vehicles per hour per lane.
5. The ramp queues at the PM site were eliminated, which resulted in a 2 percent decrease in total delay at the interchange between 4:45 and 6:15 p.m.
6. Manual implementation of positive lane closure is too time-consuming and distracting to provide desirable on-freeway control.
7. A better operational solution may be obtained by geometric modifications for the AM site and automatic voluntary lane closure for the PM site. Better communications with the motorist about any changes are needed.
8. Public opinion supporting the lane closure was greater than that disapproving.
9. A solution to interchange congestion, caused by heavy merge flow rates arriving at different times within a peak period, is on-freeway control; however, further research is needed to determine when this control should be applied.

ACKNOWLEDGMENT

The opinions, findings, and conclusions expressed or implied in this report are those of the authors and not necessarily those of the Texas Highway Department or of the Federal Highway Administration.

REFERENCES

1. Kermode, R. H., and Myyra, W. A. Freeway Lane Closures. Traffic Engineering, Vol. 40, No. 5, Feb. 1970
2. Lee, C. D. Nighttime Construction Work on Urban Freeways. Traffic Engineering, Vol. 39, No. 6, March 1969.
3. Waight, V.H. Traffic Control System Makes Reverse Tunnel Practicable. Public Works, Vol. 97, No. 3, Sept. 1966.
4. DeRose, F., Jr. Reversible Center-Lane Traffic System—Directional and Left-Turn Usage. Highway Research Record 151, 1966, pp. 1-17
5. Forbes, T.W., Gervais, E., and Allen, T. Effectiveness of Symbols for Lane Control Signals. HRB Bull. 244, 1960, pp. 16-29.
6. Haark, H., Madsen, L., Newman, L., and Schaefer, W. Traffic Control on a Two-Lane, High-Volume Freeway Entrance. Highway Research Record 279, 1969, pp. 56-69.
7. Loutzenheiser, R.C., and Henderson, D.M. Evaluation of On-Freeway Traffic Control at an Interchange. Texas Transportation Institute, Res. Rept. 139-10, Nov. 1971.
8. Henderson, D.M. On Freeway Traffic Control by a Lane Closure. MS thesis, Texas A&M Univ., Aug. 1971.