EVALUATION OF ON-FREEWAY TRAFFIC CONTROL AT AN INTERCHANGE

by

Roy C. Loutzenheiser

and

Donald M. Henderson

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ABSTRACT

Due to imbalance of traffic demand during peak hours and to a lane reduction at merge areas, traffic congestion is occurring at major interchanges during peak period operation. The premise is that better interchange operation is achieved by traffic control or minor geometric modification. In Houston, the merge areas at two interchanges were considered as possible study sites for evaluation of part of the previous premise. Preliminary analysis indicated that one of the interchanges would be a desirable site for a pilot study.

A morning study and an evening study at the Interstate 610 and Interstate 10 West interchange were made to evaluate the effects of on-freeway control as a means of improving the merge operation. Using standard maintenance procedures, the outside freeway lane upstream of the merge area was closed for a short period of time at the beginning of the merge congestion. Based on vehicle counts and "average" vehicle studies which were collected before and during the closure study, a comparison of changes in flow rates and in total delay was made. Since accident data were not available, only non-incident days were analyzed.

During the morning and evening closures, the flow rates through the merge areas did not change; however, the morning closure caused a nine per cent increase in delay, whereas the evening closure reduced delay by two per cent. The average flow rate on the two open freeway lanes during the closure was about 1650 vehicles per hour per lane. It was found that implementation of positive lane closure was too time consuming for a short closure. Therefore, it was concluded that 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.

Key Words: Interchange Ramps; On-Freeway Control; Geometric Design; Communication; Freeways; Traffic Operation.

DISCLAIMER

SUMMARY

One of the objectives of Project 139 entitled "Freeway Control and Information Systems" is to develop a freeway control system that will control demand on freeway lanes. Toward this development, a study during peak traffic flows was undertaken at a major freeway interchange in Houston to test the practicality of freeway lane control in the merge areas. This report pertains to the findings of this study.

Due to the imbalance of traffic demand during peak hours and to a lane reduction at the merge areas, the Interstate 610 and Interstate 10 West interchange in Houston has ramp queues that frequently extend onto upstream freeways. Using standard maintenance procedures, the outside freeway lane upstream of the merge area was closed for a short period of time at the beginning of the merge congestion during the morning and evening peak periods. Based on vehicle and "average" vehicle studies which were collected before and during the closure study, a comparison of changes in flow rates and in total delay was made. The following findings may be drawn from the evaluation presented in this report:

1. During the morning and evening lane closures the freeway volumes upstream of the merge point decreased; however, the ramp volumes increased by an amount approximately equal to the freeway reduction.
2. The average flow rate on the two open freeway lanes during both the morning and evening closure was about 1650 vehicles per hour per lane.
3. The total delay for the interchange during the morning closure

increased by nine per cent, while the total delay during the evening closure decreased by two per cent.

4. The motorists on the morning ramp did not fully utilize the inside lane since 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.
5. Manual implementation of positive lane closure is too time consuming and distracting to provide desirable on-freeway control.
6. The results of this study indicated that a better operational solution would be geometric modifications for the morning site and automatic voluntary lane closure for the evening site. Better communications with the motorist concerning changes in operations are needed.
7. Public opinion supporting the lane closure was greater than disapproval.
8. A solution to interchange congestion caused by short periods of imbalanced demand is on-freeway control; however, further research is needed to determine when this control should be applied.

Implementation

The results of this study suggest that further research is needed. The following recommendations are made:

1. A geometric modification at the morning site should be studied. The lane drop, instead of occurring at the existing merge area,

should be moved downstream about 1000 feet by extending the outside ramp lane.

2. Fixed or variable signs should be provided on the I-10 eastbound to I-610 southbound ramp to inform motorists of merge area operation.
3. A voluntary-lane closure system should be installed at the evening site. Such a system should be turned on by a manual method when visual inspection of the interchange indicates the need.
4. During the voluntary-lane closure, data should be collected to determine parameters and detector location needed for a real-time, automatic control system using voluntary-lane closure.

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INTRODUCTION

The study of traffic control systems for urban freeways is an active subject in the research program. The purpose of the study is to develop and apply traffic control systems which provide the most efficient and safest operations for all conditions on an urban freeway. Most traffic control systems are directed toward control of traffic input at entrance ramps. However, special freeway bottlenecks, such as at an interchange, may require an on-freeway control system that will control demand on the freeway lanes.

To broaden the scope of traffic control systems, the Texas Transportation Institute and the Texas Highway Department, in cooperation with the U. S. Department of Transportation, began a research project entitled "Freeway Control and Information Systems." This project is an outgrowth of previous research on the Gulf Freeway in Houston, Texas which was directed toward an operational ramp control system. One of the objectives in the project is to develop a Freeway Control System that will control demand on the freeway lanes. Toward this development, a pilot study during peak traffic flows was undertaken at a major freeway interchange in Houston to test the practicality of freeway lane control in the merging areas. This is a report of the findings of this pilot study.

Congestion at Major Interchanges

Major interchanges are experiencing severe traffic congestion during peak period operation. The design of connections between two freeways usually requires more lanes entering the interchange area than leaving the interchange area. The resultant lane drops at points of merge cause little or no operational problem when traffic is light to moderately heavy. However, when traffic demands increase on the several approaches to the interchange, the coincidence of heavy flows on two merging roadways at the lane drop causes a reduction in operating efficiency. Depending on the traffic demand function, storage facilities and the geometric design, operating conditions can become very hazardous on the mainlanes as well as the connecting roadways of the interchange. Queues, forming upstream of the merging points, may extend back into lanes of traffic following other paths through the interchange. Thus, the chain reaction of these events can cause severe loss of capacity to the total interchange.

Possible Solutions

The premise is that better traffic operations in the interchange is achieved by traffic control and/or minor geometric modifications. Control or modifications would permit a balanced lane operation at the merge points when traffic demands on several approaches exceed the capacity of the merge area. Three general approaches to the solution of the problem are:

1. Add a lane in the merge area.
2. Reduce the number of lanes approaching the merge area.

3. Reduce the traffic demand approaching the merge area.

Any one, or combination, of these three approaches may provide relief to the problem.

Addition of a Lane in the Merge Area - The success of adding capacity at the merge area will depend on how far the added lane will be carried downstream of the merge area. If the added lane is extended to an exit ramp, the solution may be valid. If it is carried down a few hundred feet and then dropped, the problem may not be completely resolved. However, the added lane may result in an improved situation because of the long tapered design and additional sight distance achieved in the merge area.

This solution may be too expensive, depending on the design for widening the pavement. If existing pavement, such as shoulders, can be used for the movement of traffic, the cost may not be prohibitive. If, however, a structure has to be widened, the modification will probably be expensive.

Reduction of the Number of Lanes Approaching the Merge Area - 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. This design could improve the safety of the area, which would result in an improved capacity due to 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 permanent 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. There are, however, several possible designs that use automated devices that are operated manually. The horizontal gates used to close the entrances to reversible lanes on freeways in Seattle and St. Louis offer promise for applications of lane closure.

2. Voluntary Lane Closure - The most practical way to affect a lane closure is by signs and signals that can be activated when needed. There are several devices that could be used in an installation of this type.

   a. Advanced warning signs that have a fixed message which reads "This Lane Closed During AM Peak" or "This Lane Closed When Flashing"
   b. Advanced warning flashers
   c. Blankout signs that flash "This Lane Closed / Move Left"
   d. Red "X" and green "↓" displayed over the lane to be closed
   e. Blankout sign with slanted flashing arrows "↓↓"

The obvious problem is that motorists may not obey the control devices if they know that the probability of being involved in an accident or being fined by the police is small.

Reduction of Demand on Approaches to the Merge Area - In some instances, it may be feasible to control the demand at the merge area by traffic control devices located on the approaches. Ramp metering, which has proven to be a successful traffic control system for entrances to the freeway, may be employed on the interchange roadways. The objective is to reduce demand for short periods of time or to coordinate the flows that approach the merge area from different directions. Bulk metering would have to be used to control the high volume flows.

Some Previous Work in Freeway Lane Closure

Each day miles of freeway lanes are being closed for the purpose of maintenance and construction. Procedures for lane closures are outlined in state highway department manuals (for example 1) and in the Manual on Uniform Traffic Control Devices (2). Kermode and Myyra (3) developed a procedure which will enable field personnel to schedule lane closures at a time when they will cause the least inconvenience to the motorists. Lee (4) discussed special procedures to be used during nighttime maintenance work on freeways. Ashworth (5) developed a simulation model to determine the delay to motorists traveling at various speeds when one lane of a four-lane divided roadway is closed for maintenance.

Studies are being made to determine the best procedure to implement reversible lanes for unbalanced flow. Waight (6) describes how an additional two-lane, reversible tunnel was built in San Francisco to increase the traffic flow through existing parallel two-lane, one-way tunnels. A system of movable, flexible barriers and changeable signs has been de-

veloped to control the traffic during the rush hours. De Rose (7) 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 (8) made a study of the effectiveness of symbols for lane control signals. Their studies showed that the red X and green arrow provided the desired meaning for proper control. When holiday travelers returned to the Los Angeles area, ramp control on a two-lane, high-speed, high-volume entrance ramp was initiated to provide partial relief to congestion at a major interchange. Hoack, Madsen and Newman (9) found the ramp control to be successful and planned to use it on subsequent holidays.

An Interchange Problem in Houston

Several interchanges in Houston experience serious breakdown in operation during the morning and evening peak periods. The reduction is caused by an imbalance in the traffic demand on the several approaches to an interchange and the available capacity at the merge points. During peak periods, the ramp approaches have heavy traffic demands while main lanes have moderate to heavy demands. This results in the demand exceeding the capacity in the merging lanes, while total freeway capacity is not being exceeded. The resultant ramp congestion frequently backs onto the connecting freeway.

Three study sites were initially considered:

1. The merge area on U. S. Route 59 (US-59) eastbound at Interstate 610 (I-610) during the morning peak period.
2. The merge area on I-610 southbound at Interstate 10 West (I-10) during the morning peak period.
3. The merge area on I-10 westbound at I-610 during the evening peak period.

Preliminary data were collected at each site to determine which sites would be desirable to study. These data were also used to establish a means of control which might reduce the problem of imbalance.

SITE DESCRIPTION AND PRELIMINARY ANALYSIS

The three preliminary study sites are located in west Houston where rapid land development has been experienced. This development has caused traffic flow patterns to deviate from those on which the geometric configuration of the two interchanges was designed (Figure 1). The resulting imbalance of flow at the three sites indicates a need for additional capacity on the ramps for short periods of time during peak traffic flow.

Geometric Description

The three sites have similar lane configurations: three freeway lanes approaching the merge area; a one-lane ramp and a two-lane ramp merging into a single two-lane ramp; and the combined ramp and the freeway lanes merging into four lanes. Site One, at US-59 and I-610 in the morning, has an extra lane on the ramp for approximately 1,000 feet downstream of the merge.

The heavy traffic flow at Site One occurs on the ramp from I-610 southbound, which is two lanes wide and approximately 2,200 feet in length. The motorists using the ramp have a clear view of the merge area since they cross over US-59. On US-59 the last entrance ramp is approximately 3,000 feet upstream of the interchange. Just beyond the downstream exit ramp, a bottleneck is caused by a major overpass and an upgrade entrance ramp.

The ramp from I-10 eastbound to I-610 southbound on Site Two is on an upgrade and a horizontal curve which results in restricted visi-

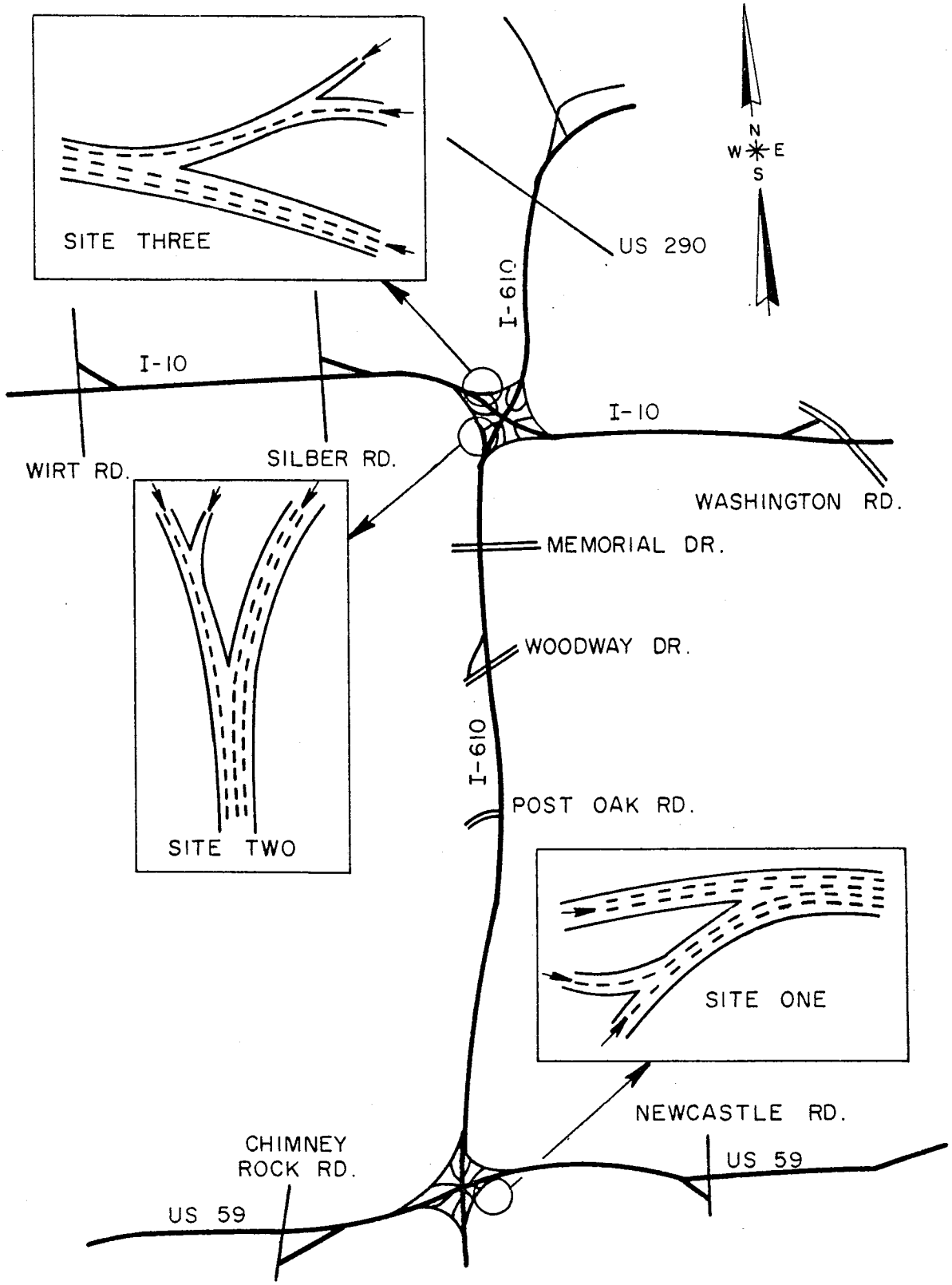

Figure 1. Location of the three sites considered in the preliminary analysis.

bility of the merge area. The ramp is two lanes wide and approximately 1,200 feet in length. Interstate 610 crosses over I-10, and the southbound freeway motorists have a good view of the merge area and the I-10 entrance ramp. The last entrance ramp on I-610 southbound is about 8,000 feet upstream of the I-10 entrance ramp. The merge area is on a downgrade. The Memorial Drive overpass and the first exit ramp are about 1,500 feet and 3,200 feet downstream of the merge area.

Site Three, at I-10 and I-610 in the evening, is similar to Site One since the heavy ramp movement from I-610 northbound crosses over I-10. The ramp is about 3,000 feet in length, and motorists on the ramp have a clear view of the merge area and the I-10 freeway lanes approaching the merge area. The first exit ramp is approximately 2,200 feet downstream of the merge area, and the freeway lanes on I-10 are reduced from four to three lanes about 4,400 feet downstream of the exit ramp. The last entrance ramp on I-10 westbound is about 8,000 feet upstream of the merge area.

Preliminary Data Analysis

Traffic studies were made in October, 1970 and January, 1971 to provide information for both subjective and objective analyses. Data collected during a freeway incident were not used in the objective analysis. In the preliminary analyses, the sites for an actual closure study were determined.

Site One Preliminary Analysis - As shown in Figure 2 the input flow rate on US-59 eastbound exceeded an equivalent volume of 4000 vehicles

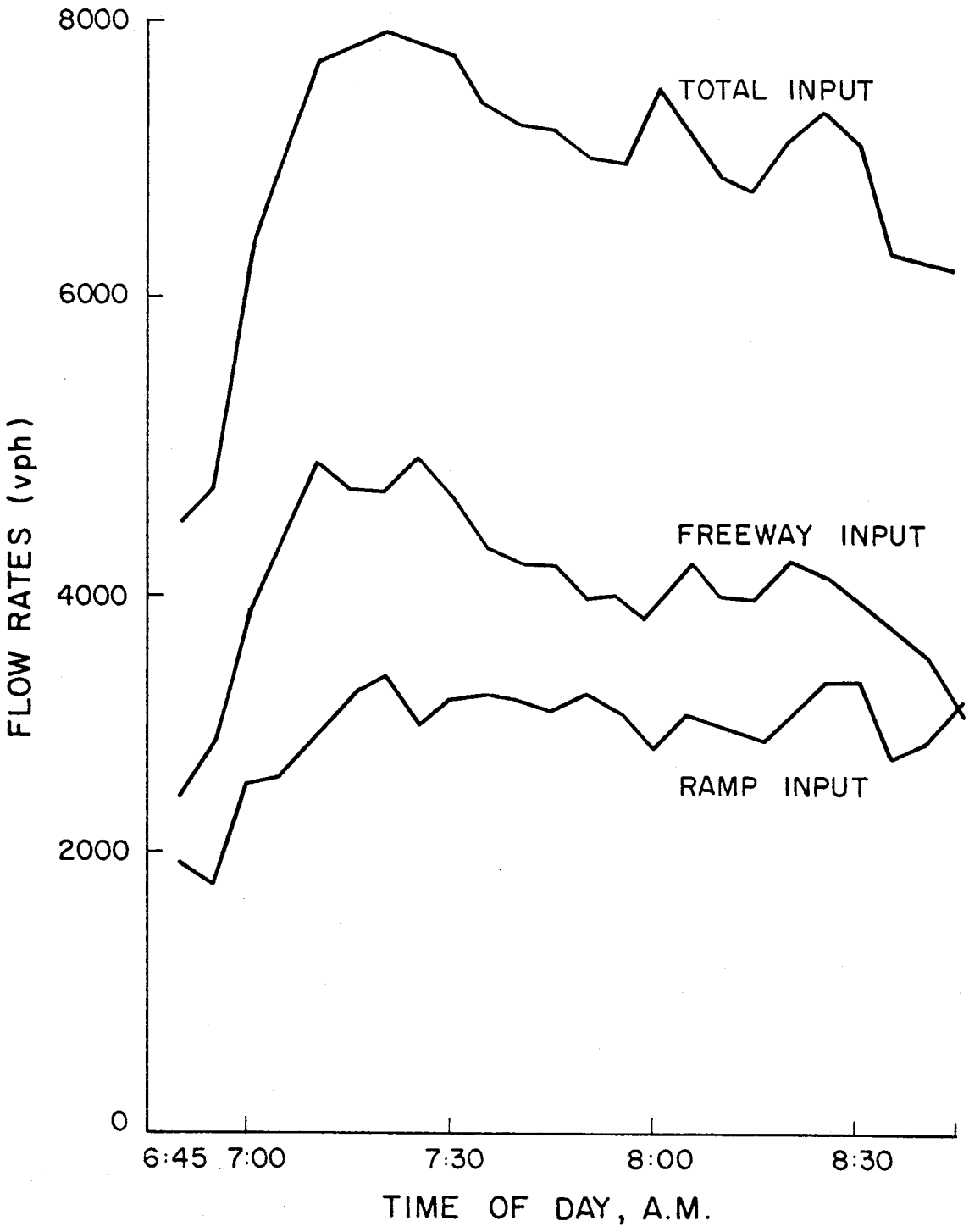

Figure 2. Preliminary vehicle counts at U. S. Route 59 and Interstate 610-site one.

per hour (VPH) for about fifty minutes (about 7:00 to 7:50 a.m.) and exceeded 4500 VPH for about twenty minutes. The total ramp flow rate from both northbound and southbound I-610 was about 3000 VPH between 7:00 and 8:30 a.m. Between 7:00 and 8:00 a.m. the freeway and ramp input volumes were about 4400 and 2850 vehicles, respectively. During the rush hour about 40 per cent of the merge area traffic came from the I-610 ramp, as shown in Figure 3. When the merge operation was poor, the ramp backed onto I-610 southbound lanes; otherwise the ramp queue did not affect the I-610 flow for more than a few minutes.

There was traffic congestion upstream of the interchange on US-59. Between 7:00 and 8:00 a.m. about 1700 motorists entered the freeway at the Chimney Rock entrance (see Figure 1) ramp and weaved with the 2200 motorists traveling from US-59 to I-610. The weave area is about 2500 feet in length. Flow over Newcastle overpass, which is downstream of the merge area, was near capacity during most of the rush hour. The peak-hour volume frequently exceeded 2000 vehicles per hour per lane.

Site Two Preliminary Analysis - The flow rate on I-610 southbound, upstream of the merge, exceeded a two-lane capacity of 4000 VPH for about fifty minutes (7:15 to 8:05 a.m.); however, the flow rate did not exceed 4500 VPH at anytime during the rush hour. The ramp flow rate from I-10 fluctuated between 2000 and 3000 VPH between 7:00 and 8:30 a.m. The 7:00 to 8:00 a.m. volumes for the freeway and ramp were 4150 and 2700 vehicles, respectively. Figure 4 shows the comparison of flow rates. The ramp traffic accounted for 35 to 40 per cent of merge area during the rush hour, as shown in Figure 3.

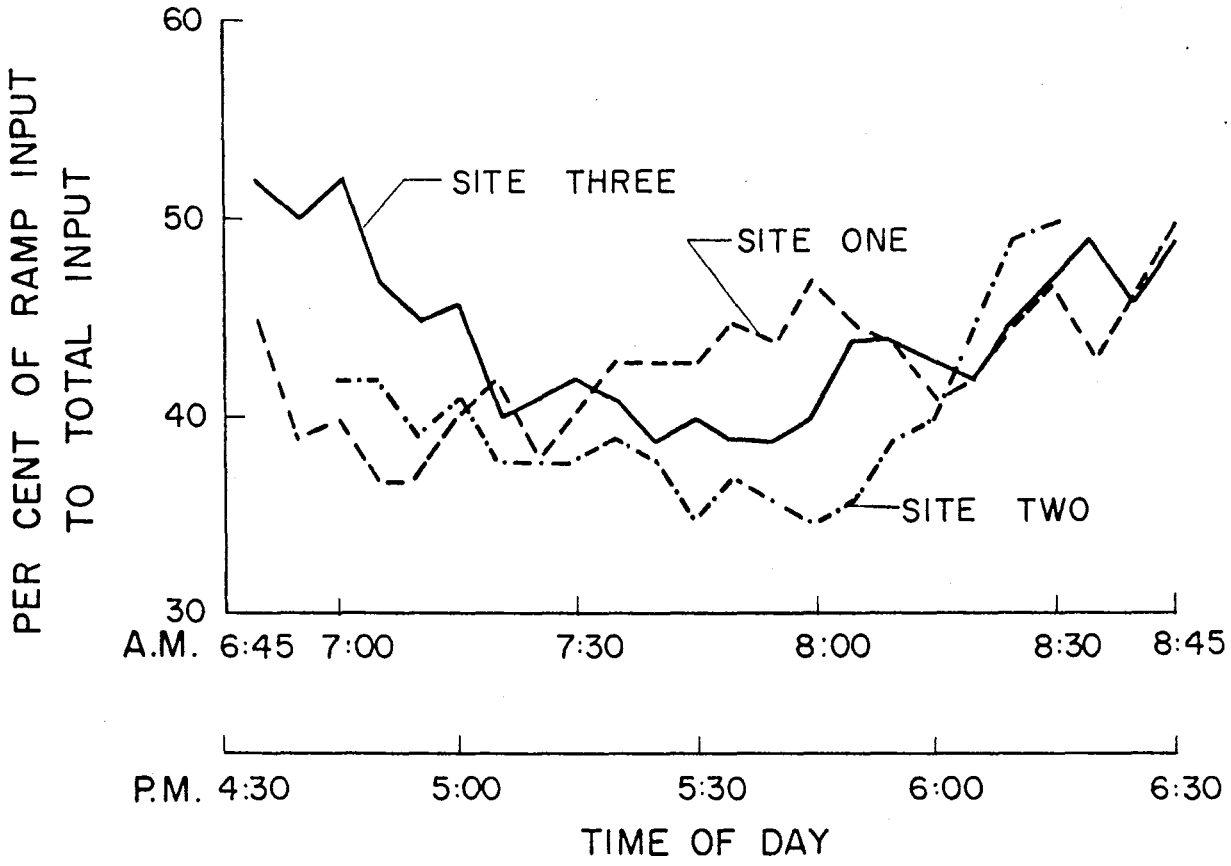

Figure 3. Ratio of ramp input to total input traffic flow before closure study.

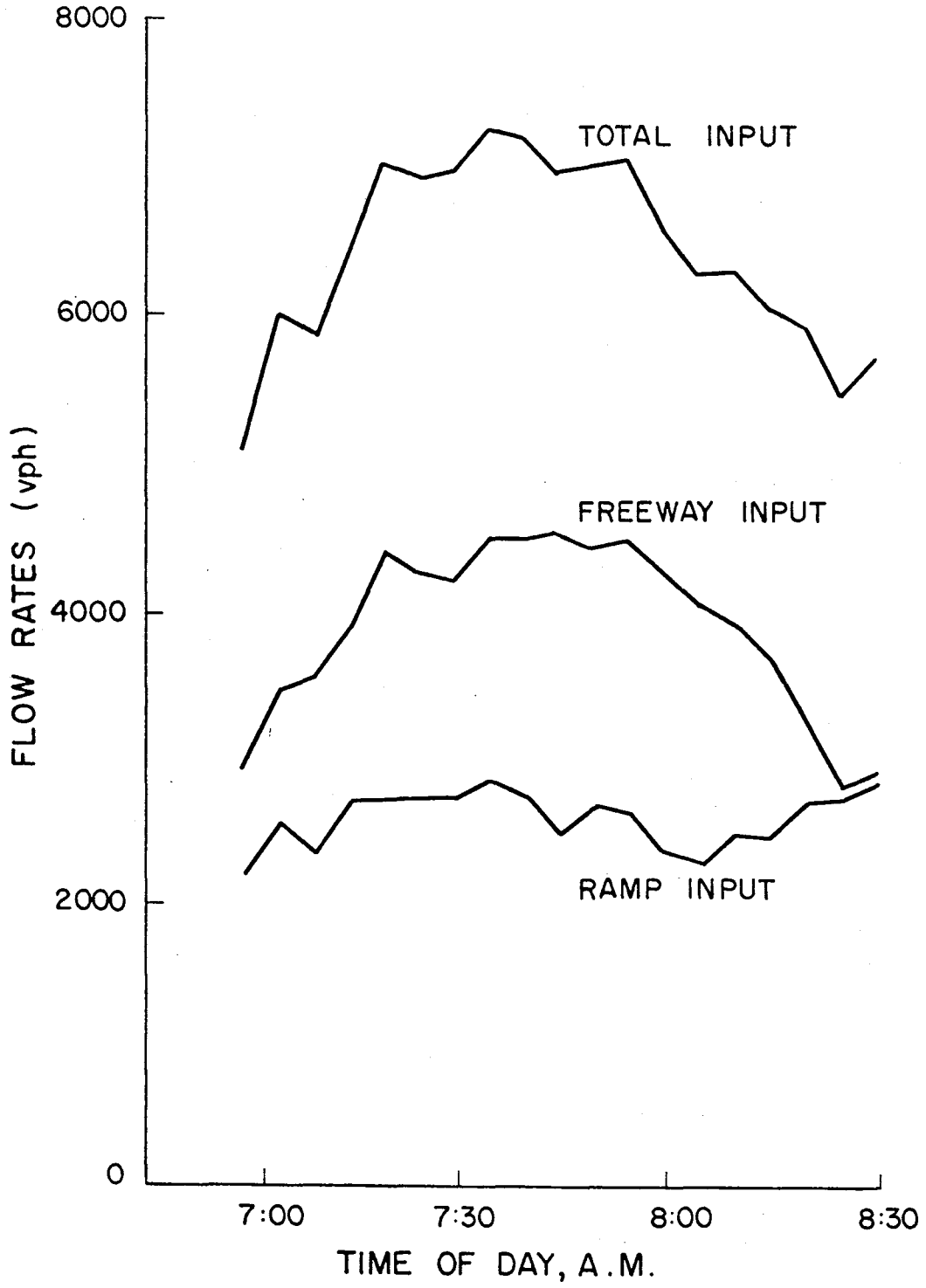

Figure 4. Preliminary vehicle counts at Interstate 610 and Interstate 10 West - site two.

The motorists using the ramp from I-10 eastbound to I-610 southbound were reluctant to use the inside ramp lane, even when the ramp queue backed onto I-10. The merge area is not visible to ramp motorists until they are about 500 feet upstream from the area. The three lanes on I-610 southbound usually operated without congestion.

Site Three Preliminary Analysis - The three-lane flow rate of I-10 westbound did not exceed 4500 VPH during the evening rush hour, but was over 4000 VPH from 4:50 to about 5:40 p.m. The ramp flow rate from I-610 has a peak equivalent volume of 3500 VPH just before 5:00 p.m. Figure 5 shows the comparison of flow rates. The ramp volume had a steady drop after the peak and was about 2500 VPH at 6:00 p.m. The volumes for the freeway and ramp between 5:00 and 6:00 p.m. are 3950 and 2700 vehicles, respectively. From 5:00 and 6:00 p.m. the ramp volume was between 40 and 45 per cent of the total traffic in the area, as shown in Figure 3.

Downstream of the merge area, the freeway lanes on westbound I-10 are reduced from four to three lanes. This lane drop is significant and usually causes a shock wave to move upstream into the merge area. The downstream exit ramp at Silber had high flow rates which resulted in weaving between the entrance ramp and some upstream freeway motorists. There was good traffic operation on I-10 westbound, upstream of the merge area. The I-610 northbound to I-10 westbound ramp frequently backed onto I-610, causing reduced operation for a mile or more on I-610. Frequently the two outside lanes on I-610 northbound were affected.

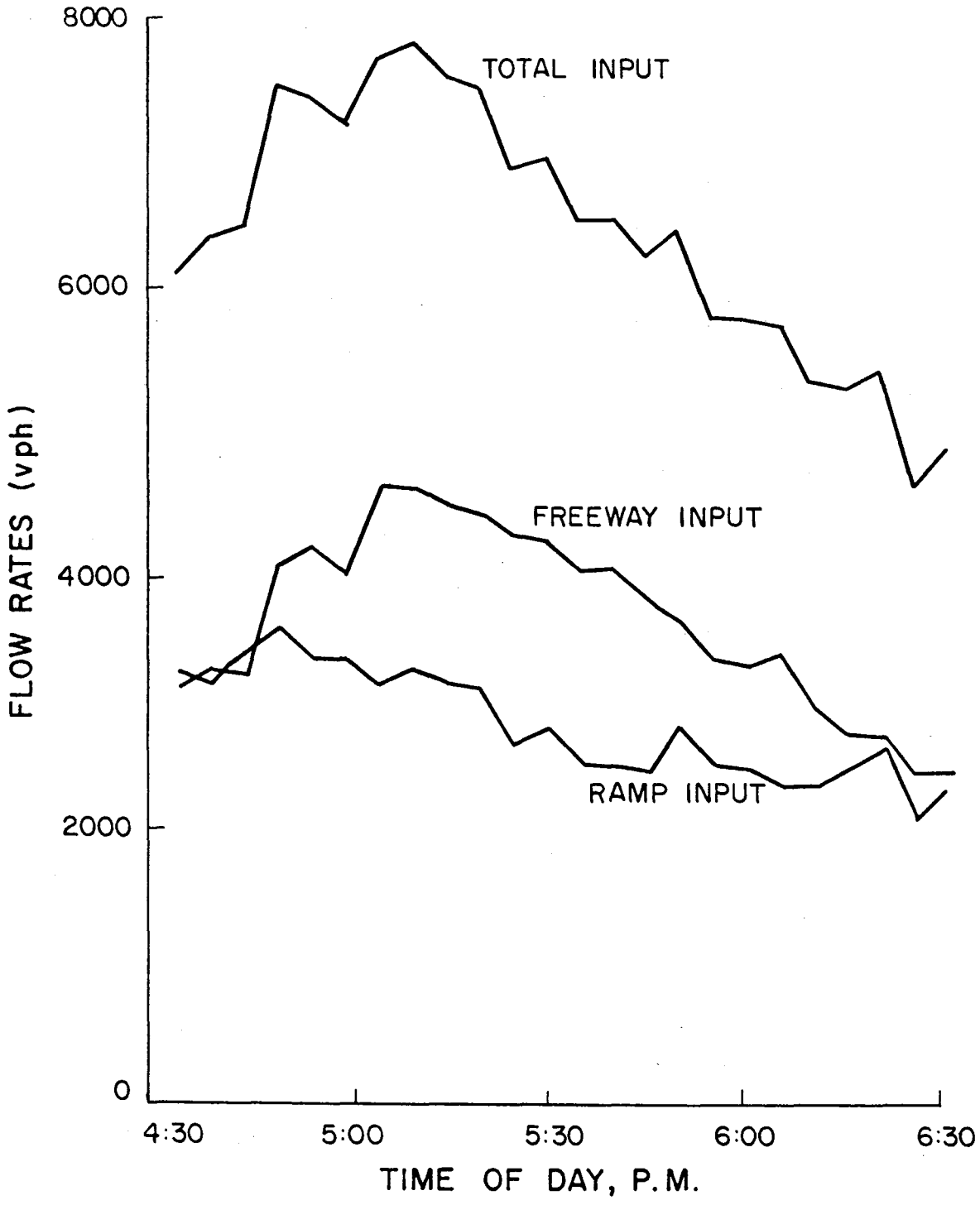

Figure 5. Preliminary vehicle counts at Interstate 10 West and Interstate 610 - site three.

Accident Data - An attempt was made to establish a correlation between accidents and the merge area congestion. However, available information proved to be inconclusive since most of the accident reports did not provide an accurate description of the locations. Of the available information in 1969 for the interchanges, more than seventy per cent of the accidents during the rush hour involved only two cars. This suggested the occurrence of accidents that were caused by sudden speed reductions which are common in congested merge areas.

Field Study at I-610 and I-10

A summary of the hourly volumes for the three sites is shown in Table 1. A field study of lane closure at Site One was not recommended due to the instability of the interchange operation. The freeway input was too heavy and congestion frequently occurred on US-59 upstream of the interchange. After further studies are made, a field study at this site might be recommended.

For a pilot study of on-freeway control, two of the three control methods mentioned earlier were not feasible. Because the Site Two is on an embankment, and the Site Three is in a depression, construction of an additional freeway lane would be costly. Reducing the traffic demand approaching the merge area is unreasonable since one objective is to increase the ramp flow.

Since both sites have an input freeway demand 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 main-

TABLE 1

SUMMARY OF PRELIMINARY VEHICLE COUNTS

Site	Location	Time Period	Number of Vehicles
1	U S-59 and I-610		
	Freeway Input	7:00 - 8:00 a.m.	4415
	Ramp Input	7:00 - 8:00 a.m.	2855
	Total		7270
2	I-610 and I-10		
	Freeway Input	7:00 - 8:00 a.m.	4160
	Ramp Input	7:00 - 8:00 a.m.	2690
	Total		6850
3	I-10 and I-610		
	Freeway Input	5:00 - 6:00 p.m.	3945
	Ramp Input	5:00 - 6:00 p.m.	2710
	Total		6655

tenance 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 feet, which included a 750 feet taper. Additional warning signs were placed about 3,000 feet upstream of the beginning of closure for the Site Three. Figure 6 shows the location of closure signs.

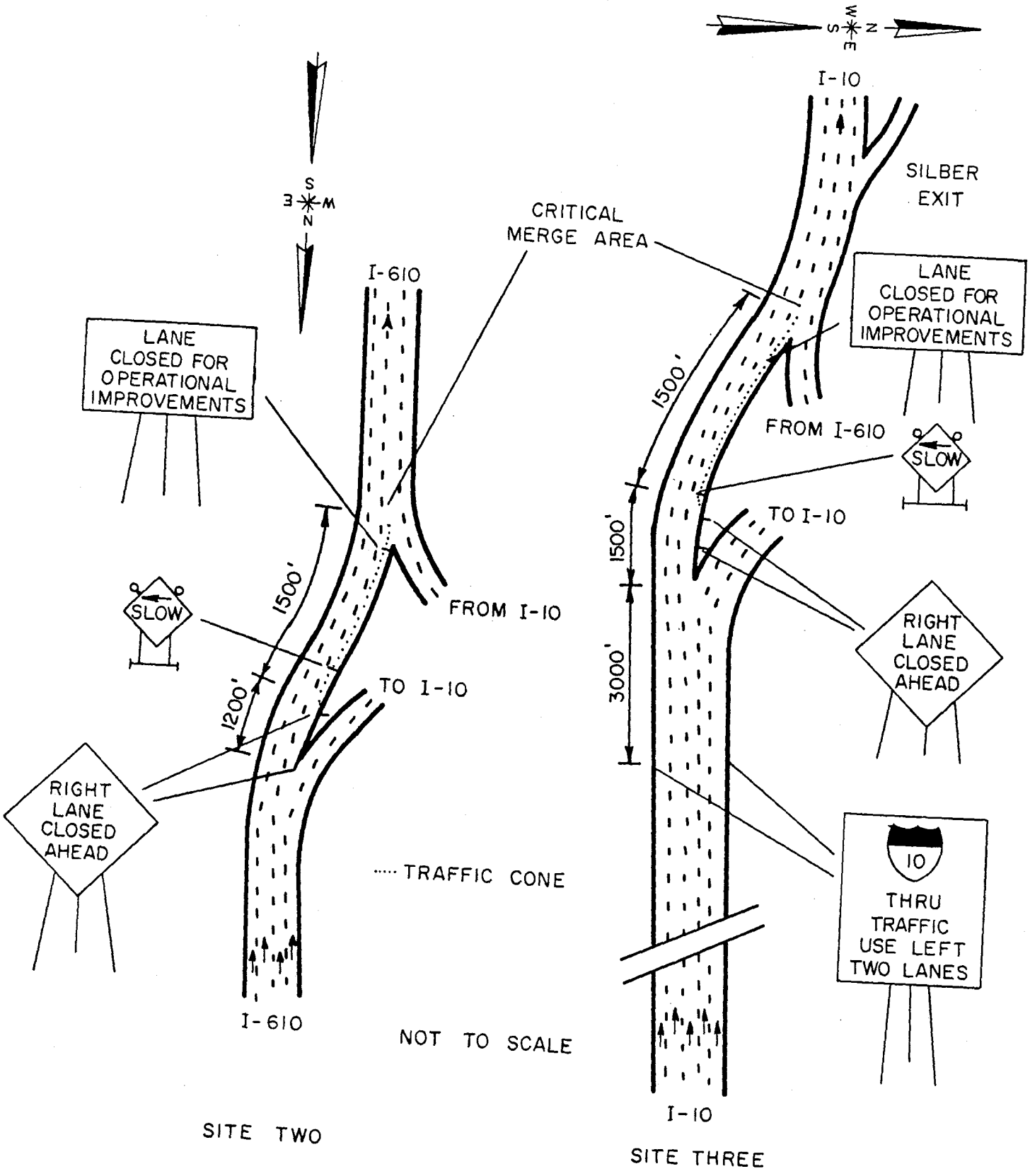

Figure 6. Sign placement used in lane closure operation.

ANALYSIS OF CLOSURE DATA

The study occurred on weekdays from June 7 through June 23, 1971. Due to rain, the closure was cancelled on two afternoons. Therefore, a total of 12 and 11 closures were made at Sites Two and Three, respectively. Data collected during days when an accident significantly affected the operation were not included in the analyses. Also, data from the first two days of closure for each site were not used in order to provide more "typical" findings. During the study, data for eight mornings and five evenings were analyzed.

Three forms of data were collected to determine the effects of closure on the total interchange. First, traffic counts were made at input stations, the merge area, and/or output stations. Special counts were made on the ramps to determine lane distribution. "Average" vehicle studies were made in two vehicles over a period of several weeks. In these studies, each driver was instructed to follow a pre-determined route as a typical driver. The second person in each vehicle recorded travel times to various pre-determined stations, queue formations and a general subjective evaluation of the interchange operation. In addition, some observations were made from an airplane during two mornings and four evenings. Figure 7 is a drawing of the I-610 and I-10 interchange.

Analysis of Traffic Flow

The initial closure for each site lasted about one hour and caused

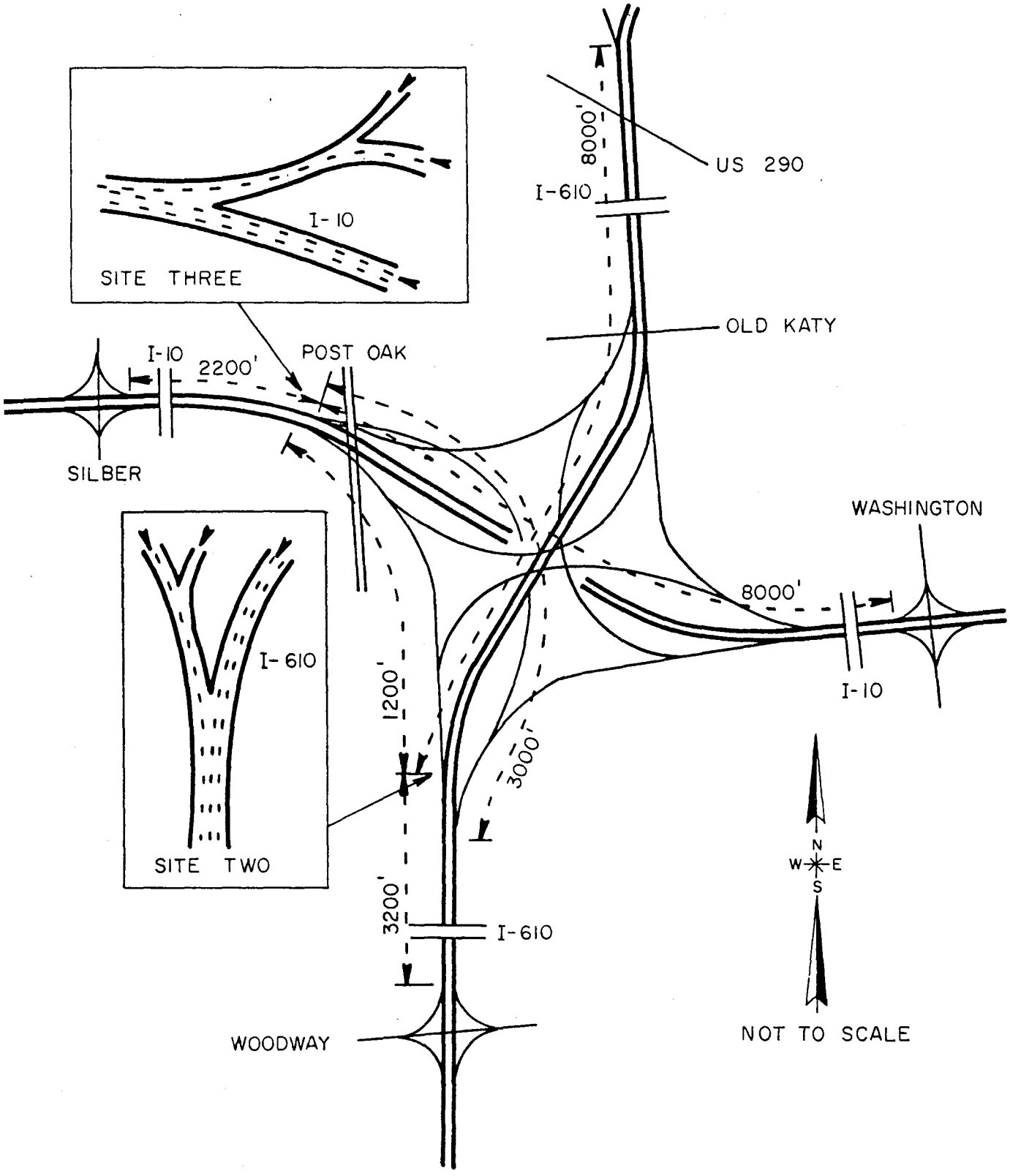

Figure 7. Study Sites at the Interstate 610 nterstate 10 West Interchange

upstream freeway queues of several miles in length resulting 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 two days of closure, intervals of closure varied from 15 to about 7 minutes.

Typical volumes for a non-incident day before closure and one during closure are compared in Table 2. In general, the output volumes were the same. The reduced upstream freeway flow was compensated by the increased ramp flow. Figure 8 shows the per cent of ramp flow to total flow through the merge area for five-minute intervals before and during closure. These percentages were based on typical, non-incident days.

Site Two - The total volume through the merge area was about 6850 vehicles (1710 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 over 200 vehicles during the closure. Between 7:00 and 8:00 a.m. the freeway input volume decreased from 4150 to 3800 vehicles, while the ramp input volume increased from 2700 to 3100 vehicles. During the closure, the two open freeway lanes had an average flow rate of over 1650 vehicles per hour per lane. Table 3 is a summary of the daily closure time and merge operation.

Since 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

TABLE 2

TYPICAL VEHICLE COUNTS MADE AT I-10 AND I-610 INTERCHANGE
BEFORE CLOSURE AND DURING CLOSURE

Vehicle Count	Number of Lanes	Site Two		Site Three	
		Before	During	Before	During
Time Period		7:00 a.m. to 8:00 a.m.		5:00 p.m. to 6:00 p.m.	
Freeway Input	3	4159	3781	3945	3673
Ramp Input	2	2686	3113	2707	3000
Total Output	4	6845	6894	6652	6673
Downstream Exit	1	189	164	719	718
Upstream Exit	2 & 3	1956	1992	2156	2302
Time Period		6:45 a.m. to 8:15 a.m.		4:15 p.m. to 6:15 p.m.	
Freeway Input	3	5882	5459	5706	5327
Ramp Input	2	3729	4367	4108	4535
Total Output	4	9611	9826	9814	9862
Downstream Exit	1	305	278	1002	1057
Upstream Exit	2 & 3	2791	2524	3665	3165

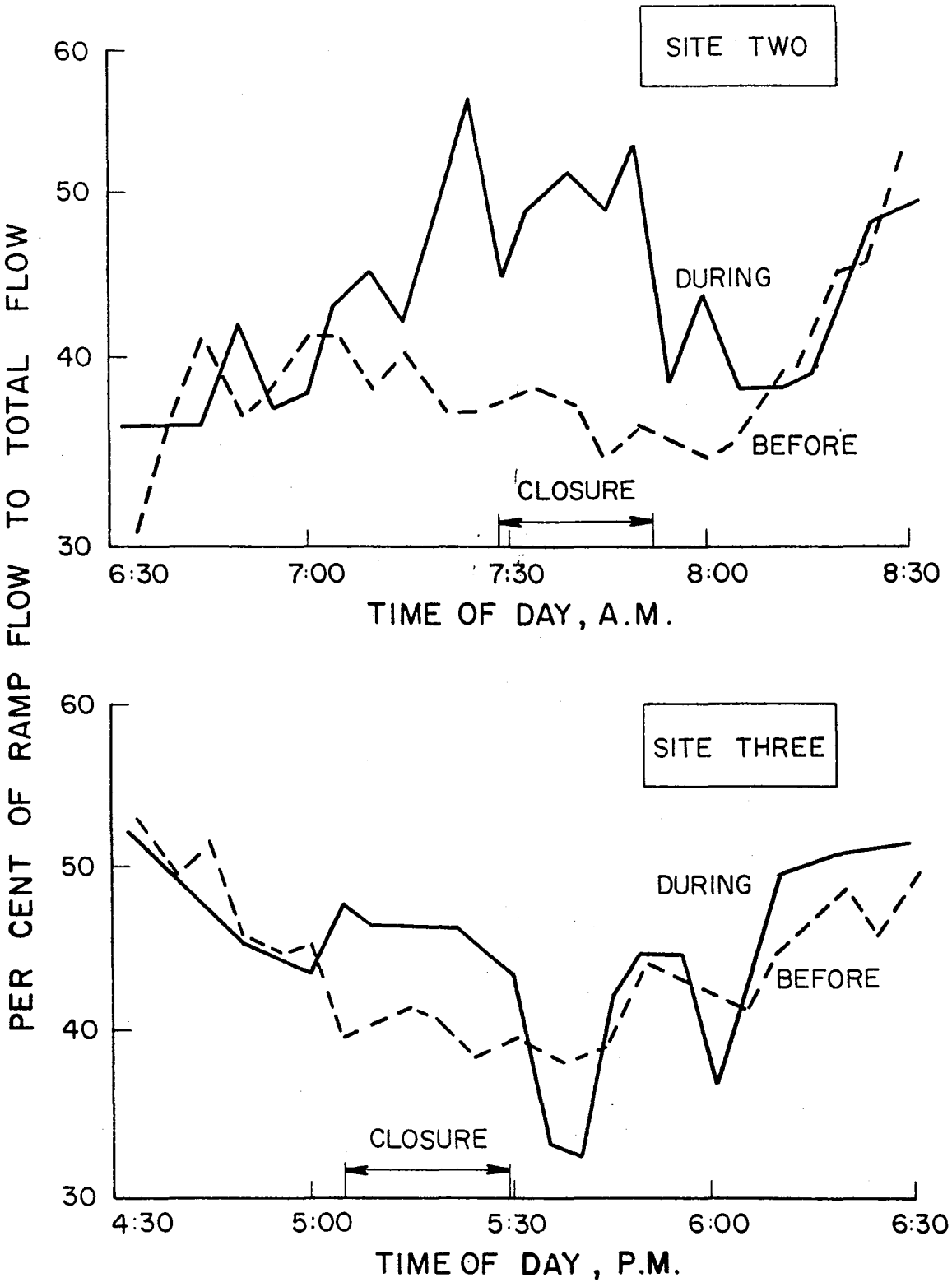

Figure 8. Per cent of ramp flow to total flow through the merge area on a typical non-incident day (10).

TABLE 3

SUMMARY OF SITE TWO VOLUME COUNTS
DOWNSTREAM OF MERGE

Date	7:00 - 8:00 Volume	6:45 - 8:15 Volume	Flow Rate on I-610 During Actual Closure	Closure Time
10/13/70	6510	9655		Before
1/13/71	6835	9733		Before
1/14/71	6827	9612		Before
6/08/71	No Counts	No Counts		6:40 - 7:40 = 60
6/09/71	6529	9500	1703	7:02 - 8:00 = 58
6/10/71	6894	9826	1698	7:16 - 7:51 = 35
6/11/71	6450	9700	1728	7:16 - 7:53 = 37
6/14/71	6751	9818	1760	7:22 - 7:52 = 30
6/15/71	6604	9579	1632	7:30 - 7:55 = 25
6/16/71	6747	9829	1639	7:30 - 7:57 = 27
6/17/71	6718	9746	1608	7:29 - 7:52 = 23
6/18/71	6538	9424	1633	7:29 - 7:51 = 22
6/21/71[a]	6463	9237	1706	7:29 - 7:45 = 16
6/22/71	6668	9547	1562	7:29 - 7:47 = 18
6/23/71[b]	6748	9546	1690	7:30 - 7:45 = 15

a) Stalled car on ramp at merge from 7:21 - 8:10.

b) Minor accident on ramp at merge from 7:45 - 7:48 and then moved to shoulder.

has minor effect on the operation in the merge area due to the light flow rate. During the closure, the exit ramp volume decreased by 25 vehicles.

Without closure, the Site Two ramp usually carried about 40 per cent of the total flow through the merge area; however, this percentage decreased during the peak half-hour (see Figure 8). With closure, the percentage increased to about 50 per cent during the peak half-hour. Preliminary counts before closure indicated that the left lane of the ramp was used by less than 20 per cent 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 per cent of usage. The percentages are shown in Figure 9. The apparent reason for this lack of utilization was the inability of ramp drivers to see the closed outside freeway lane or the merge area. Some form of information sign was needed for the ramp.

Site Three - The total volume through the merge area was about 6650 vehicles between 5:00 and 6:00 p.m. (1660 vehicles per lane) before and during the study. Between 4:45 and 6:15 p.m., the total volume increased by less than 50 vehicles during the study. The freeway input between 5:00 and 6:00 p.m. decreased from 3950 to 3650 vehicles, while the ramp input volume increased from 2700 to 3000 vehicles. During the closure, the two open freeway lanes had an average flow rate of about 1650 vehicles per hour per lane. Table 4 is 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 per cent),

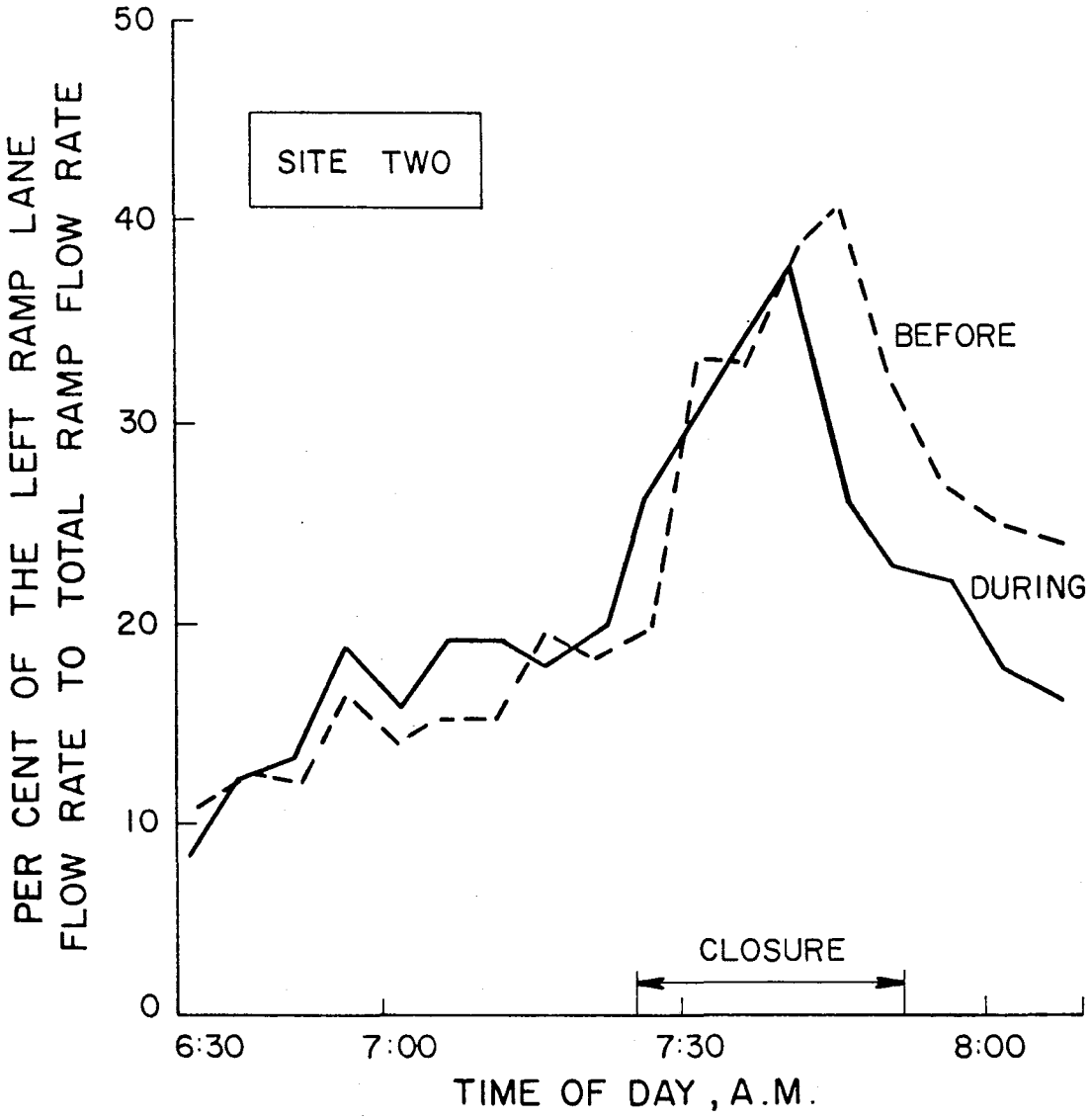

Figure 9. Lane distribution of traffic flow from I-10 eastbound to I-610 southbound ramp before and during closure (10).

TABLE 4

SUMMARY OF SITE THREE VOLUME COUNTS
DOWNSTREAM OF MERGE

Date	5:00 - 6:00 Volume	4:45 - 6:15 Volume	Flow Rate on I-10 During Actual Closure	Closure Time
10/13/71	6501	9615		Before
1/13/71	6635	9810		Before
1/14/71	6610	9785		Before
6/07/71	5478	8447	1661	4:35 - 5:50 = 75
6/08/71[a]	6435	9424	1695	4:47 - 5:29 = 42
6/09/71[b]	6057	9345	1692	4:52 - 5:20 = 28
6/10/71[c]	6293	9465	1531	5:03 - 5:25 = 22
6/11/71	6487	9524	1555	4:57 - 5:31 = 34
6/14/71[d]	6594	9712	1729	4:55 - 5:27 = 32
6/15/71	6255	9287	1694	5:05 - 5:24 = 19
6/16/71	6219	9314	1709	5:05 - 5:30 = 25
6/17/71[e]	6347	9435	1566	5:05 - 5:29 = 24
6/18/71	Rain	Rain	Rain	Rain
6/21/71	6673	9862	1615	5:05 - 5:36 = 31
6/22/71	Rain	Rain	Rain	Rain
6/23/71	6103	9238	1648	5:09 - 5:29 = 20

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

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. Occasional poor operation at this downstream ramp continued to generate shock waves which affected the merge area.

Prior to the closure study at Site Three, the per cent of ramp flow to total merge flow varied from 50 per cent before the peak hour to about 40 per cent during the peak hour. As shown in Figure 8, 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 10 shows the change in per cent of left lane flow to total ramp flow with time.

"Average" Vehicle Studies

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 studies. 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 one and one-half hours at each site (6:45-8:15 a.m. and 4:45-6:15 p.m.) to include most delayed effects of closure.

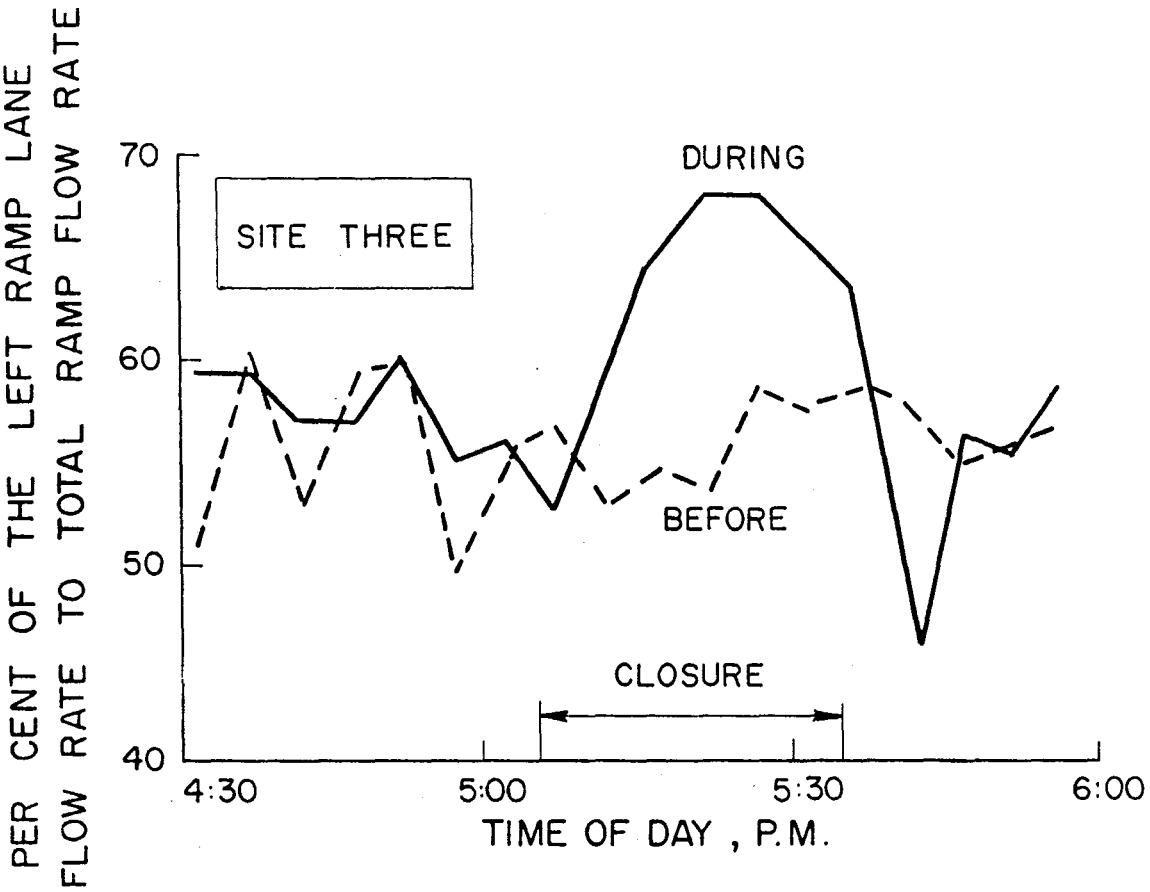

Figure 10. Lane distribution of traffic flow from I-610 northbound to I-10 westbound ramp before and during closure (10).

As expected, Site Two had an increase in delay upstream of the merge on I-610 due to the reduction in lanes. There are no good alternate routes for I-610 southbound traffic. A reduction in 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 (see Figure 9) 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 Site Two increased by 132 vehicle-hours or by 9 per cent. A summary of the data is shown in Table 5. The different subsystems used in analysis of the delay are shown in Figure 11. The changes in travel times for the different subsystems are shown in Figure 12.

Closure at Site Three 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 thirteen-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. Further downstream, where the I-10 freeway lanes decrease from four to three, there was a

TABLE 5

CHANGE IN MINIMUM AVERAGE SPEED AND TOTAL TRAVEL TIME DUE TO LANE CLOSURE
BASED ON AN "AVERAGE" VEHICLE STUDY

Section	Length of Section (miles)	Min. Avg. Speed Before (mph)	Min. Avg. Speed During (mph)	Avg. Total Travel Time[a] Before (veh. - hrs.)	Avg. Total Travel Time[a] During (veh. - hrs.)	Delay (veh. - hrs.)
AM Site						
I. Ella to Merge	3.0	46	19	322	448	-126
II. Campbell to Post Oak	3.0	20	20	1044	1088	- 44
III. Post Oak to Merge	0.6	27	32	58	52	+ 6
IV. Merge to Woodway	0.8	32	34	64	32	+ 32
Total				1488	1620	-132
PM Site						
A. Woodway to Post Oak	1.1	12	23	183	102	+ 81
B. Washington to Post Oak	1.5	30	12	180	269	- 89
C. Post Oak to Antoine	1.1	18	23	359	303	+ 56
D. Antoine to Campbell	1.8	29	29	457	482	- 25
Total				1179	1156	+ 23

a) Time period for Site Two is 7:45 to 8:15 a.m. and for Site Three is 4:45 to 6:15 p.m.

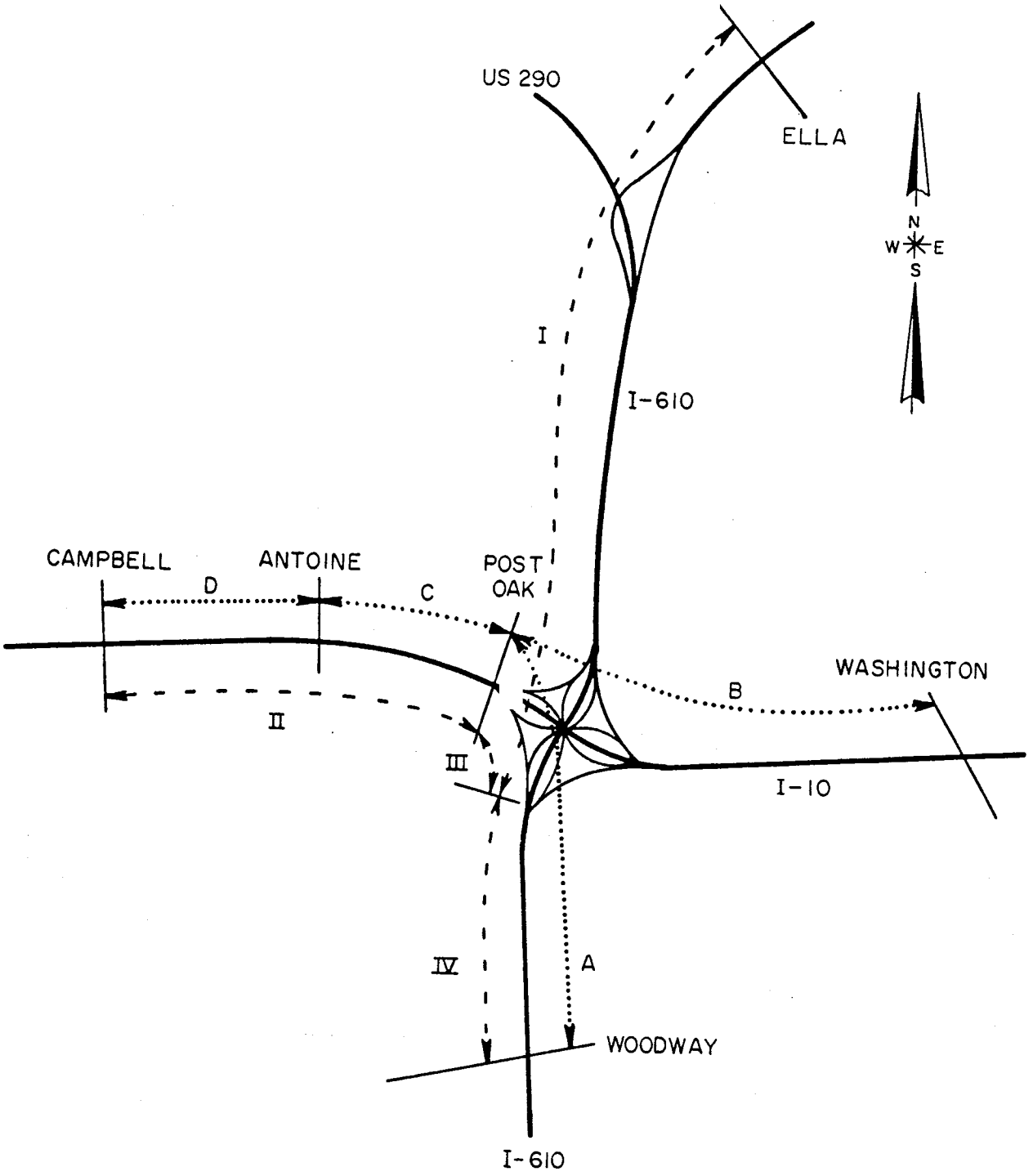

Figure 11. Subsystems used in "average" vehicle studies.

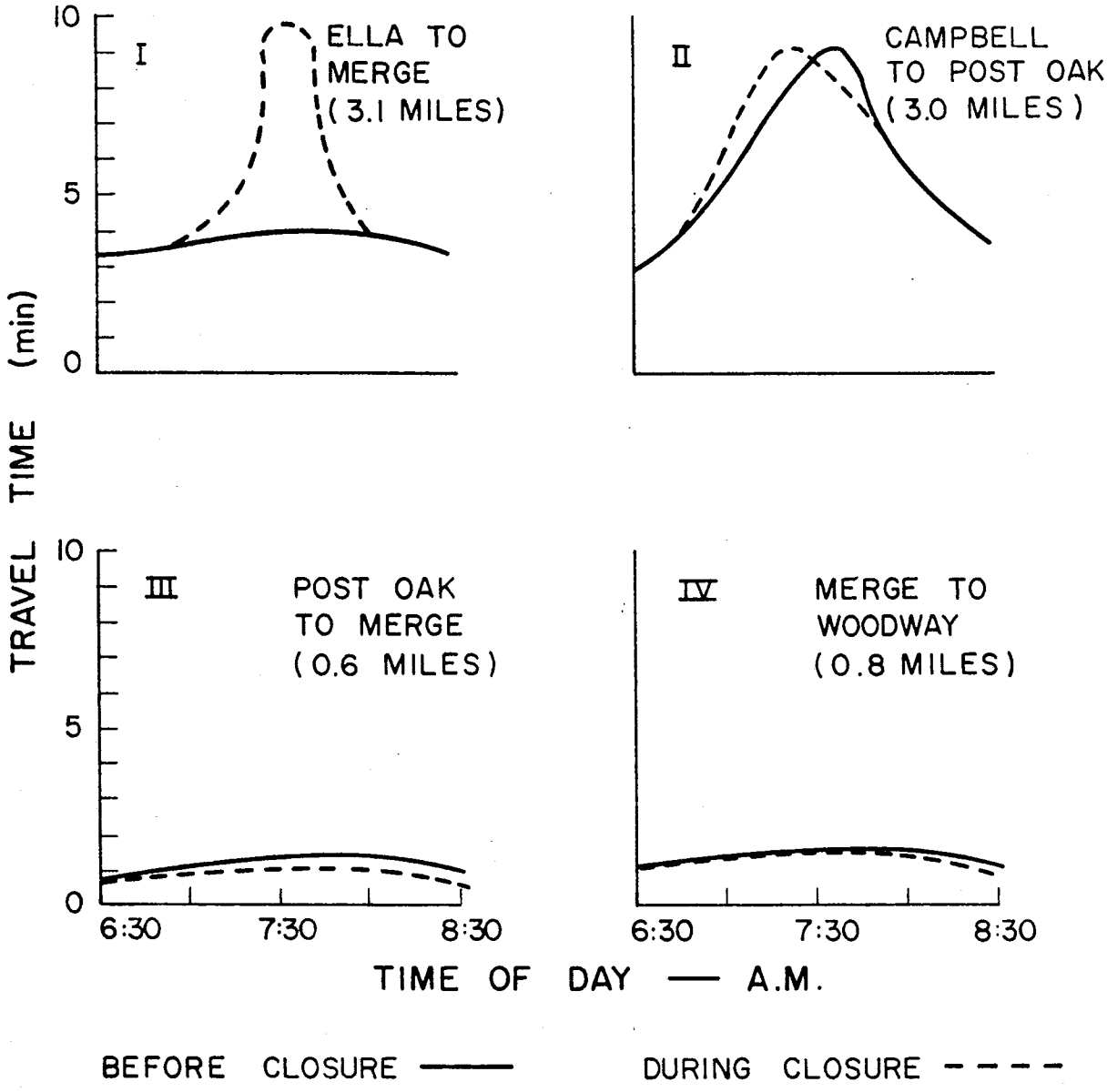

Figure 12. Comparison of travel times before and during closure - site two.

slight increase in delay. Total delay for Site Three decreased by 23 vehicle hours or by 2 per cent (see Table 5). The changes in travel times for the different subsystems at Site Three are shown in Figure 13.

Operational Discussion

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, which might have resulted from the extended queue formation. As previously mentioned, data on accidents were not available. Three stalled 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 one and one-half miles. The queue movement was usually stop-and-go. When the closure was removed, the freeway queue usually dispersed within fifteen minutes. The queue on the ramp from I-610 to I-10 at Site Three ramp did not extend onto the I-610 northbound freeway lanes. However, at Site Two the queue on the I-10 to I-610 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 fifteen and thirty minutes. 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

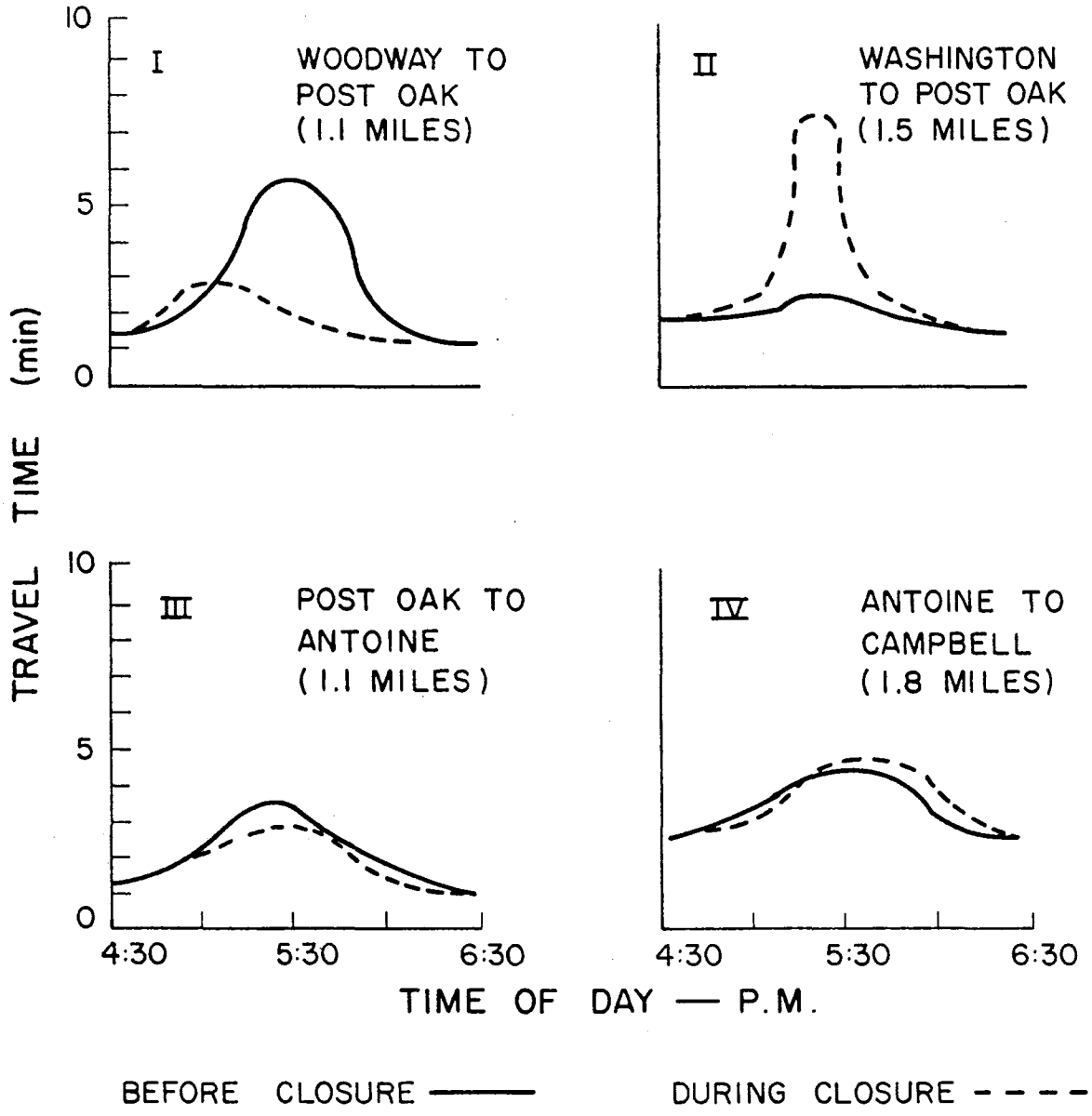

Figure 13. Comparison of travel times before and during closure - site three.

closed when the combined five-minute input flow (freeway and ramp) exceeded 600 vehicles.

The closed freeway lane was not re-opened until the ramp queue was eliminated and until the freeway downstream of the merge was operating fairly well. When 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, these 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 Site Three.

FINDINGS AND RECOMMENDATIONS

Findings

1. During the study at Site Two, the 7:00 to 8:00 a.m. volume for the I-610 freeway flow upstream of the merge area decreased from 4150 to 3800 vehicles, while the ramp volume increased from 2700 to 3100 vehicles. The average flow rate on the two open freeway lanes during closure was 1650 vehicles per hour per lane.
2. The motorists on the Site Two ramp did not fully utilize the inside lane since 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 per cent due to the continued poor operation on I-10 eastbound upstream of the I-610 exit ramp.
4. During the study at Site Three, the 5:00 to 6:00 p.m. volume for the I-10 freeway flow upstream of the merge area decreased from 3950 to 3650 vehicles, while the ramp volume increased from 2700 to 3000 vehicles. The average flow rate on the two open freeway lanes during closure was 1650 vehicles per hour per lane.
5. The ramp queues at Site Three were eliminated, which resulted in a 2 per cent 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. The results of this study indicated that a better operational solution would be geometric modifications for Site Two and automatic voluntary lane closure for Site Three. Better communications with the motorist about any changes are needed.
8. Public opinion supporting the lane closure was greater than disapproval.
9. A solution to interchange congestion caused by short periods of imbalanced demand is on-freeway control; however, further research is needed to determine when this control should be applied.

Discussion of Findings

After the initial closure, it was evident that the freeway flow next to the closure was reduced to a capacity less than a normal two-lane flow. Part of this reduction was attributed to the lack of meaningful publicity. As the study continued and motorists became aware of the closure, the reduction was still significant and probably caused by the visual distraction of maintenance equipment. The result of this reduction was unused capacity in the merge area. A less distractive method of positive closure or possible voluntary closure would probably yield a higher freeway flow rate next to the closure and a higher flow rate through the merge area.

During the morning study at Site Two, the problem appeared to be caused by geometric restrictions. The motorist using the ramp were not able to see the merge area. Some form of signing should be located on the ramp to inform motorists of a closure. Perhaps geometric modifica-

tion would be a better solution for this site. The geometric design of the evening site was more conducive to lane closure, since ramp motorists are able to see the merge area.

Both the morning and evening closures indicated that optimum initiation and termination of lane closure was variable each day. A limited form of real-time control was used during this study, since the maintenance crew was instructed to begin or end the closure after receiving a signal. However, five to ten minutes were required to install or remove the closure which was not rapid enough to provide maximum flow in the interchange. Several times a short, secondary closure of less than five minutes would probably have been useful.

Positive lane closure reduced the congestion in the merge area but did not yield optimum flow through the merge area. A more flexible system which would be responsive to real-time parameters is needed. A voluntary closure system or geometric changes may provide a better solution.

Recommendations

1. A geometric modification at the merge area of I-610 southbound and I-10 (Site Two) should be studied. The lane-drop, instead of occurring at the existing merge area, should be moved downstream about 1,000 feet by extending the outside ramp lane.
2. Fixed or variable signs should be provided on the I-10 eastbound to I-610 southbound ramp to inform motorists of merge area operation.
3. A voluntary-lane closure system should be installed at Site Three, the merge area of I-10 westbound and I-610. Such a system should

be turned on by a manual method when visual inspection of the interchange indicates the need.

4. During the voluntary-lane closure, data should be collected to determine parameters and detector location needed for a real-time, automatic control system using voluntary-lane closure.

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