

1. Report No. FHWA/TX-82/2+228-10F		2. Government Accession No.		3. Recipient's Catalog No.																													
4. Title and Subtitle Traffic Management During Urban Freeway Maintenance Operations				5. Report Date January 1982																													
				6. Performing Organization Code																													
7. Author(s) C. L. Dudek, S. H. Richards, M. J. S. Faulkner				8. Performing Organization Report No. Research Report 228-10F																													
9. Performing Organization Name and Address Texas Transportation Institute The Texas A&M University System College Station, Texas 77843				10. Work Unit No. (TRAIIS)																													
				11. Contract or Grant No. Study No. 2-18-78-228																													
12. Sponsoring Agency Name and Address Texas State Department of Highways and Public Transportation; Transportation Planning Division P. O. Box 5051 Austin, Texas 78763				13. Type of Report and Period Covered Final September 1977-July 1981																													
				14. Sponsoring Agency Code																													
15. Supplementary Notes Research performed in cooperation with DOT, FHWA. Study Title: Traffic Management During Urban Freeway Maintenance Operations																																	
16. Abstract This report summarizes results of studies conducted to develop better and more specific guidelines for traffic control during urban freeway maintenance activities. The following topic areas are addressed: <table border="0" style="width: 100%;"> <tr> <td style="width: 50%;">1. Sight distance,</td> <td style="width: 50%;">5. Freeway work zone capacity,</td> </tr> <tr> <td>2. Arrowboards,</td> <td>6. Moving maintenance operations,</td> </tr> <tr> <td>3. Middle lane closure,</td> <td>7. Real-time displays, and</td> </tr> <tr> <td>4. Special traffic management requirements,</td> <td>8. Flagger signals and signaling devices</td> </tr> </table> <p>This is the final report of a ten-report series. Other Study 228 reports are as follows:</p> <table border="0" style="width: 100%;"> <thead> <tr> <th style="text-align: left;">Report No.</th> <th style="text-align: left;">Short Title</th> </tr> </thead> <tbody> <tr> <td>228-1/263-1</td> <td>Annotated Bibliography</td> </tr> <tr> <td>228-2</td> <td>Middle Lane Closures</td> </tr> <tr> <td>228-3</td> <td>Flagger Signals and Signaling Devices</td> </tr> <tr> <td>228-4</td> <td>Moving Maintenance Operations</td> </tr> <tr> <td>228-5</td> <td>Arrowboards</td> </tr> <tr> <td>228-6</td> <td>Work Zone Capacity</td> </tr> <tr> <td>228-7</td> <td>Sight Distance Requirements</td> </tr> <tr> <td>228-8</td> <td>Special Traffic Management Requirements</td> </tr> <tr> <td>228-9/263-2</td> <td>Changeable Message Signs and Highway Advisory Radio</td> </tr> </tbody> </table>						1. Sight distance,	5. Freeway work zone capacity,	2. Arrowboards,	6. Moving maintenance operations,	3. Middle lane closure,	7. Real-time displays, and	4. Special traffic management requirements,	8. Flagger signals and signaling devices	Report No.	Short Title	228-1/263-1	Annotated Bibliography	228-2	Middle Lane Closures	228-3	Flagger Signals and Signaling Devices	228-4	Moving Maintenance Operations	228-5	Arrowboards	228-6	Work Zone Capacity	228-7	Sight Distance Requirements	228-8	Special Traffic Management Requirements	228-9/263-2	Changeable Message Signs and Highway Advisory Radio
1. Sight distance,	5. Freeway work zone capacity,																																
2. Arrowboards,	6. Moving maintenance operations,																																
3. Middle lane closure,	7. Real-time displays, and																																
4. Special traffic management requirements,	8. Flagger signals and signaling devices																																
Report No.	Short Title																																
228-1/263-1	Annotated Bibliography																																
228-2	Middle Lane Closures																																
228-3	Flagger Signals and Signaling Devices																																
228-4	Moving Maintenance Operations																																
228-5	Arrowboards																																
228-6	Work Zone Capacity																																
228-7	Sight Distance Requirements																																
228-8	Special Traffic Management Requirements																																
228-9/263-2	Changeable Message Signs and Highway Advisory Radio																																
17. Key Words Maintenance, Construction, Work Zones, Safety, Freeway Operations, Traffic Control Devices, Lane Closures, Capacity, Sight Distance, Changeable Message Signs, Highway Advisory Radio			18. Distribution Statement No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161																														
19. Security Classif. (of this report) Unclassified		20. Security Classif. (of this page) Unclassified		21. No. of Pages 52	22. Price																												

TRAFFIC MANAGEMENT DURING
URBAN FREEWAY MAINTENANCE OPERATIONS

by

Conrad L. Dudek
Research Engineer

Stephen H. Richards
Engineering Research Associate

and

Michael J. S. Faulkner
Assistant Research Engineer

Research Report 228-10F

Traffic Management During
Urban Freeway Maintenance Operations
Research Study 2-18-78-228

Sponsored by

State Department of Highways and Public Transportation

In Cooperation with the

U. S. Department of Transportation
Federal Highway Administration

Texas Transportation Institute
The Texas A&M University System
College Station, Texas

January 1982

ACKNOWLEDGMENTS

The project was conducted with the guidance of a Technical Advisory Committee. The contributions of the Committee members are gratefully acknowledged:

W. R. Brown, Supervising Maintenance Engineer, D-18M
R. G. Biggs, Administrative Assistant, District 11
Walter Collier, District Maintenance Engineer, District 15
Milton Dietert, Senior Traffic Engineer, District 15
Larry Galloway, Engineer Technician IV, District 12
Hunter Garrison, District Maintenance Engineer, District 12
Henry Grann, Supervising Traffic Engineer, District 18
Herman Haenel, Supervising Traffic Engineer, D-18T
Bobby Hodge, Supervising Traffic Engineer, District 2
Tom Newbern, Traffic Engineer, D-18T
Russell G. Taylor, Engineering Technician V, District 14
Milton Watkins, District Maintenance Engineer, District 18
John Wilder, District Maintenance Engineer, District 14

Mr. Tom Newbern served as the technical monitor for this study. His assistance and counsel are greatly appreciated. The constructive suggestions by Messrs. Tom Newbern and Blair Marsden of D-18T during the preparation of this report are also acknowledged.

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

TABLE OF CONTENTS

	<u>Page</u>
INTRODUCTION	1
SIGHT DISTANCE REQUIREMENTS (Report 228-7)	2
Background	2
Advance Signing	2
Importance of Sight Distance	2
Implementation	3
Field Procedure for Checking Sight Distance	3
ARROWBOARDS (Report 228-5)	4
Background	4
Recommendation	4
MIDDLE LANE CLOSURE (Report 228-2)	8
Traffic Control at Locations with Shoulders	9
Traffic Control at Locations without Shoulders	11
Summary of Estimated Capacities	13
SPECIAL TRAFFIC MANAGEMENT REQUIREMENTS (Report 228-8)	14
Ramp Closures	14
Permissive Use of Ramps	14
Frontage Road Operations	17
Advance Notification	17
Traffic Control Coordinator	23
Traffic Control Specialist	23
Use of Police	23
FREEWAY WORK ZONE CAPACITY (Report 228-6)	25
Capacity with Work Crew at Site	25
Capacity with No Work Activity at Site	29
MOVING MAINTENANCE OPERATIONS (Report 228-4)	30
Freeway Design Related Problems	30
Operational Problems	31
REAL-TIME DISPLAYS (Report 228-9/263-2)	34
Changeable Message Signs	34
Highway Advisory Radio	34

	<u>Page</u>
FLAGGER SIGNALS AND SIGNALING DEVICES (Report 228-3)	36
1980 Texas MUTCD Signals	36
1973 Texas MUTCD Signals (Deleted Signals)	36
Stopping Traffic	42
Encouraging Traffic to Proceed	42
Alerting and Slowing Traffic	42
Encouraging Traffic to Turn Left	43
Needed Messages	43
Training	43
Job Title	44
Attire	44
REFERENCES	45
APPENDIX - METRIC CONVERSION FACTORS	47



INTRODUCTION

Maintenance operations on urban freeways oftentimes result in major problems in managing traffic through the affected zone to assure adequate safety of the work crew and motorists while minimizing delay and congestion to the motorists. Guidelines for urban freeway traffic control are almost non-existent in the Manual on Uniform Traffic Control Devices for Streets and Highways (MUTCD) (1). Several studies were therefore conducted as part of Study 228 in an attempt to provide better and more specific guidelines. A concerted effort was devoted to conducting studies in the field during actual maintenance operations to obtain more meaningful driver response data. The studies were conducted after a thorough review of the literature which is summarized in Report 228-1/263-1 (2).

The sections that follow contain summaries of the following reports.

	<u>Title</u>	<u>Report No.</u>
1.	Sight Distance Requirements at Lane Closure Work Zones on Urban Freeways	228-7
2.	Field Evaluation of Flashing Arrowboards at Freeway Work Zones	228-5
3.	Traffic Management for Middle Lane Maintenance on Urban Freeways	228-2
4.	Special Traffic Management Requirements for Maintenance Work Zones on Urban Freeways	228-8
5.	Traffic Capacity Through Work Zones on Urban Freeways	228-6
6.	Moving Maintenance Operations on Texas Urban Freeways: A Limited Overview of Current Practices and Problem Identification	228-4
7.	Feasibility of Changeable Message Signs and Highway Advisory Radio for Freeway Maintenance	228-9
8.	Driver Understanding of Work Zone Flagger Signals and Signaling Devices	228-5

SIGHT DISTANCE REQUIREMENTS

Background

Maintenance operations performed on urban freeways oftentimes require the temporary closing of one or more travel lanes. In these situations, motorists should be encouraged to vacate the closed lane(s) in advance of the work area using effective traffic control devices (e.g., advance signing, cone tapers, arrowboards, etc.). If the traffic control system fails, severe safety and operational problems can result as high speed traffic is surprised by the lane closure and/or is "trapped" in the closed lane.

A series of field studies was conducted to evaluate current traffic control practices at lane closure work zones on urban freeways in Texas. The studies, which are documented in Report 228-7, identified problem areas and provided input for the development of improved traffic control practices (3).

Advance Signing

The field studies revealed that the advance signs normally used to warn drivers of freeway lane closures during maintenance operations are only partially effective in encouraging drivers to vacate the closed lane(s). The signs become less effective as traffic volumes increase.

Importance of Sight Distance

Sight distance as related to work zone lane closures is defined as the distance from the beginning of the cone taper to where a driver can identify that his or her lane is closed, provided the line of sight is not obstructed by another vehicle. The field studies revealed that many drivers wait until sighting the lane closure before attempting to merge out of the closed lane(s).

Therefore, adequate sight distance to the lane closure must be provided to assure safe and efficient traffic flow. As traffic volumes increase, more and more drivers will be "trapped" at the lane closure if adequate sight distance is not provided.

Implementation

The use of arrowboards is recommended for all lane closures on urban freeways. Report 228-5 (3) indicates the typical placement location for the arrowboards. A minimum sight distance of 1500 feet should be provided at work zone lane closures on urban freeways. If it is not possible to provide a sight distance of at least 1500 feet, a supplemental arrowboard should be placed upstream of the cone taper for median and shoulder lane closures. The supplemental arrowboard will encourage more drivers to vacate the closed lane before they see the closure itself.

Field Procedure for Checking Sight Distance

A field procedure for checking sight distance at work zone lane closures on urban freeways to insure that a minimum sight distance of 1500 feet is provided is presented in Report 228-7.

ARROWBOARDS

Background

Flashing arrowboards have become an important traffic control device for work zone traffic management over the past several years. Because of this, arrowboards have been the subject of many research reports which cover a wide range of topics including design, human factors considerations and application guidelines. The results have been very positive indicating that arrowboards have a very high target value and motorists respond positively to the arrowboard's indications.

Two reports, however, differ concerning the placement of a flashing arrowboard for the most effective use. One report (4) recommended the placement of the arrowboard at the beginning of the taper; another (5) recommended that the most effective arrowboard placement is 100 ft. to 500 ft. in advance of the beginning of the taper. A study was therefore conducted on I-35 in Austin, Texas to further evaluate arrowboard placement. Report 228-5 documents the results of the study (6).

Recommendation

The research documented in the report indicates that the placement of an arrowboard in advance of the beginning of a taper is beneficial only when the sight distance to the work zone is improved. For the maximum benefit in arrowboard usage, a minimum sight distance must be maintained. The minimum allowable sight distance for urban freeway operations, as developed in a related study (6), is 1000 ft. (also supported in related studies (3, 4)). The desired sight distance is 1500 ft.

Locating an arrowboard in advance of the beginning of the taper does not necessarily increase the sight distance. The vertical and/or horizontal geometrics at each worksite would control the sight distance and the resulting placement of a flashing arrowboard. Figure 1 represents an example of when sight distance is not improved. Figure 2 represents a situation where moving the arrowboard in advance of the taper can be of great benefit.

Work zones on a tangent section of roadway would not require a supplemental arrowboard in advance of the cone taper because, again, sight distance to the work zone is not critical (less than 1500 ft.). Figure 3 represents this situation.

The limitations of the study prohibited the determination of the distance in advance of the beginning of the taper at which the supplemental arrowboard becomes ineffective. From the two sites studied, the arrowboard, when placed 2000 ft. in advance of the beginning of the taper, was most effective in shifting traffic from the blocked lane. Little improvement in shifting traffic was observed after locating an arrowboard 2500 ft. in advance of the beginning of the taper at one of the sites. However, it appears that positioning an arrowboard too far in advance of the beginning of the taper does not improve the effectiveness of the supplemental arrowboard. Shifted traffic was observed returning to the closed lane when an arrowboard was placed 4000 ft. in advance of the beginning of the cone taper.

In conclusion, an arrowboard should be used at the cone taper for lane closures on urban freeways. When the sight distance to the work zone is less than 1500 ft., a supplemental arrowboard should be placed on the shoulder in advance of the beginning of the taper for right-side or left-side lane

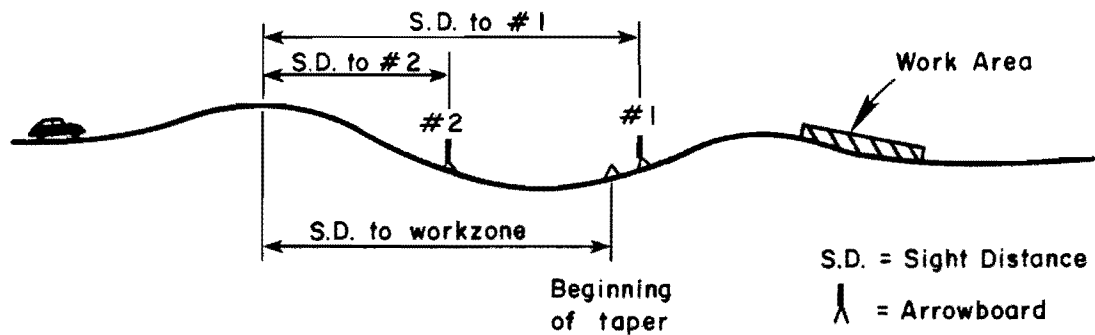


Figure 1. Typical Work Zone Where Critical Arrowboard Sight Distance is not Improved (Controlled by Geometrics)

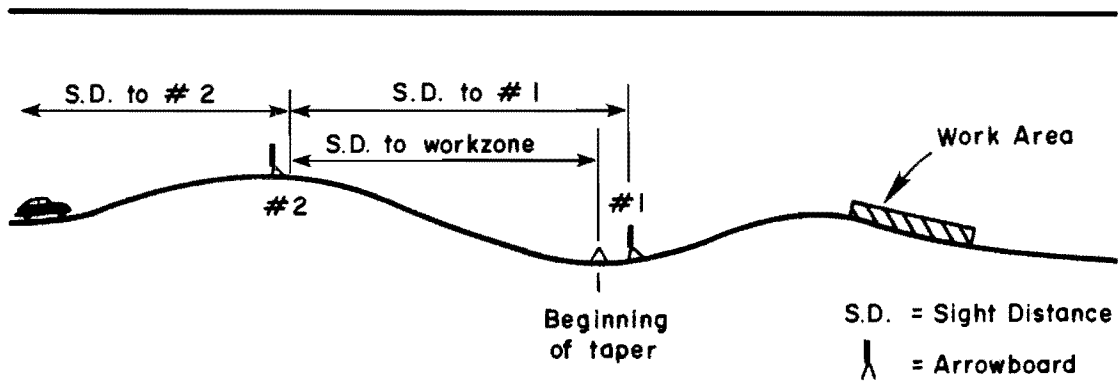


Figure 2. Typical Work Zone Where Critical Arrowboard Sight Distance is Improved

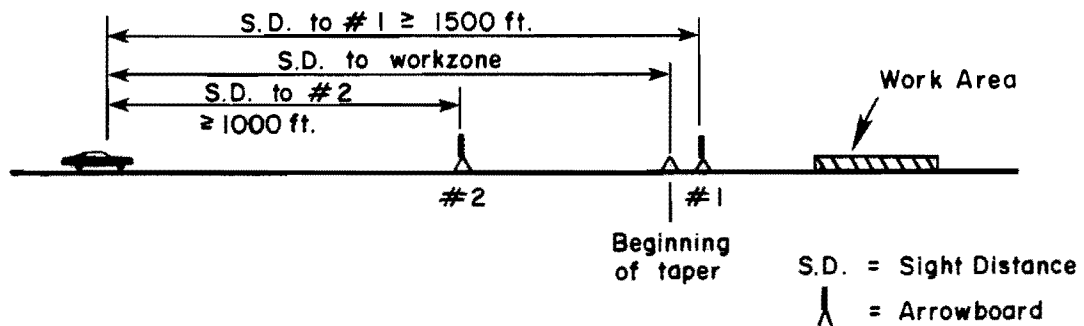


Figure 3. Typical Work Zone Where Critical Sight Distance is not Improved (Not Controlled by Geometrics)

closures. The supplemental arrowboard can be placed up to 2500 ft. in advance of the cone taper to increase the effective sight distance to the work zone. The supplemental arrowboard should not be placed more than 2500 ft. upstream because drivers will have a tendency to re-enter the closed lane before they reach the closure.

MIDDLE LANE CLOSURE

Generally, when maintenance work is required on the middle lane of a 3-lane freeway section, both the middle lane and one of the exterior lanes are closed (Figure 4). Capacity flow in the open exterior lane ranges between 1400 and 1600 vehicles per hour (vph).



Figure 4. Multi-Lane Closure Strategy Commonly Used to Accommodate Middle Lane Maintenance Operations

In planning for middle lane work on a 2.5 mile section of I-45 in Houston, available volume data indicated that use of the multi-lane closure strategy illustrated in Figure 4 would result in severe congestion. District 12, therefore, developed a traffic management plan intended to maximize work zone capacity and reduce mainlane demand. This plan is discussed in Report 228-2 and is summarized in this section of the Final Report (8).

The primary feature of the management plan was the attempt to increase work zone capacity through innovative management practices. On days when the work was on sections with shoulders, traffic was "shifted" out of the median and middle lanes, then encouraged to use the shoulder lane and outside shoulder as travel lanes. When the work was on bridges and overpasses without shoulders, the middle lane alone was closed and traffic was permitted to travel in the median and shoulder lanes.

To reduce mainlane demand, entrance ramps in the 2.5-mile work area were closed. Generally, two to four ramps were involved. Motorists normally using these ramps had to remain on the frontage road and enter the freeway downstream from the work area.

Traffic Control at Locations with Shoulders

Figure 5 shows the traffic control devices used to manage mainlane traffic during work on sections with shoulders. All signs shown in the figure were temporary work zone signs and had a black legend on an orange background.

The evaluation studies conducted by TTI and discussed in Report 228-2 revealed that drivers will begin using the shoulder when some degree of congestion develops on the mainlanes (8). Shoulder usage will increase with increased demand and congestion on the mainlanes. Prior to any significant speed restrictions, little or no traffic will use the shoulder. In Houston, about 8% of the drivers used the shoulder when the traffic demand flow rate was 1600 vph. Approximately 40% of the drivers used the shoulder when the rate was 2400 vph.

Some drivers were slow in reacting to the shoulder use signs. The "follow-the-rabbit" phenomenon was noticeable. When one driver entered the shoulder, several others followed. District 12 personnel observed that when a flagger was posted at the BEGIN SHOULDER LANE sign and pointed to the sign, more drivers entered the shoulder much sooner.

The advance sign employed to encourage shoulder use presented the message CARS MAY USE SHOULDER 500 FT. AHEAD, thus implying only passenger cars should use the shoulder. The signs, located intermittently in the shoulder-use zone, contained the message SHOULDER USE OK CAUTION.

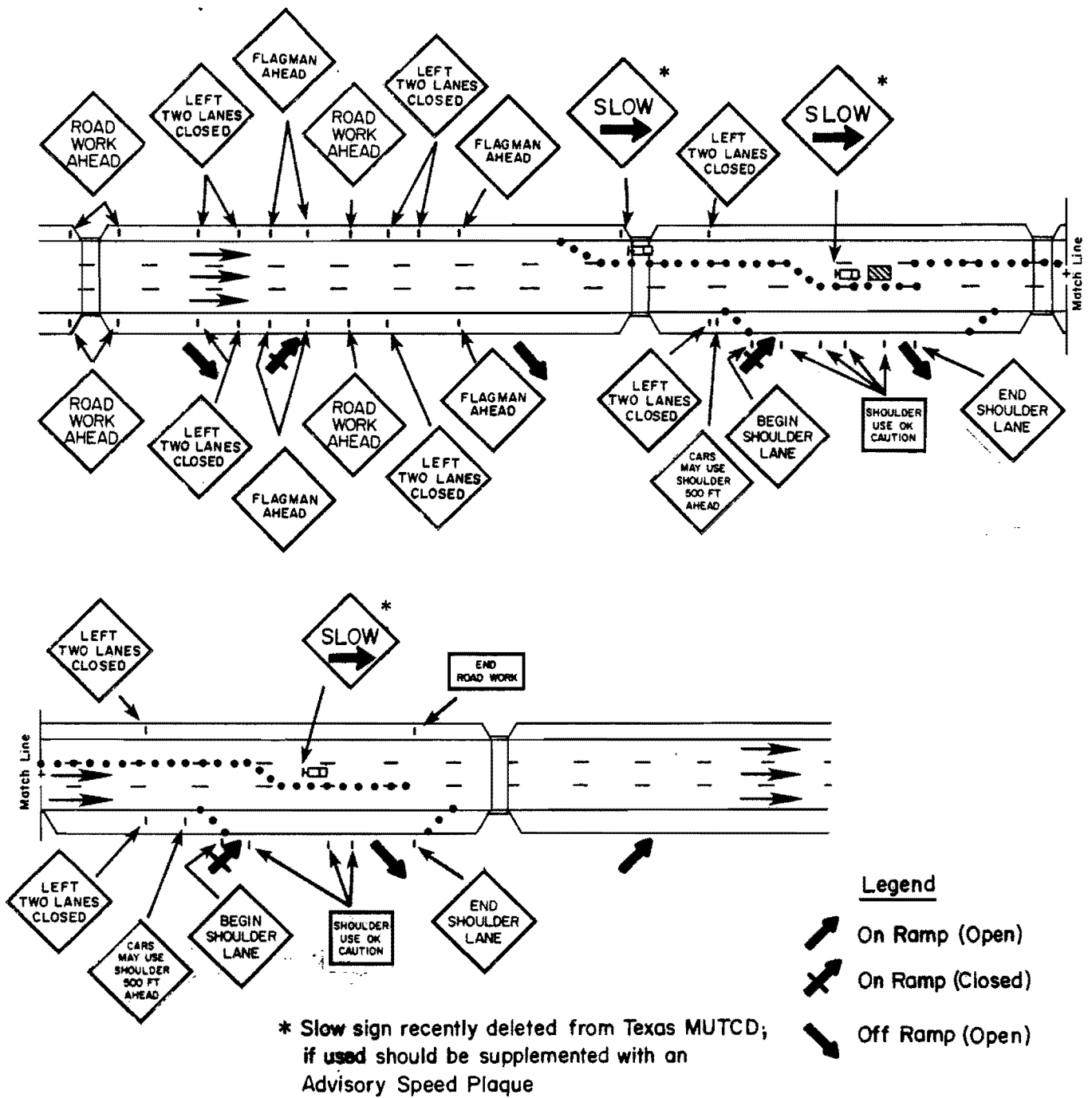


Figure 5. Traffic Control Strategy Used to Perform Center Lane Work on Sections of I-45 with Shoulders (Traffic Shifting)

Observations in Houston revealed that shoulder usage by each type of vehicle increased with traffic volumes. When mainlane demand was approximately 1600 vph, 9% of all passenger cars, 8% of all the pickup trucks and vans, and 3% of the trucks used the shoulder. When the demand increased to 2400 vph, 40% of all the passenger cars, 41% of all the pickup trucks and vans, and 25% of all the trucks used the shoulder.

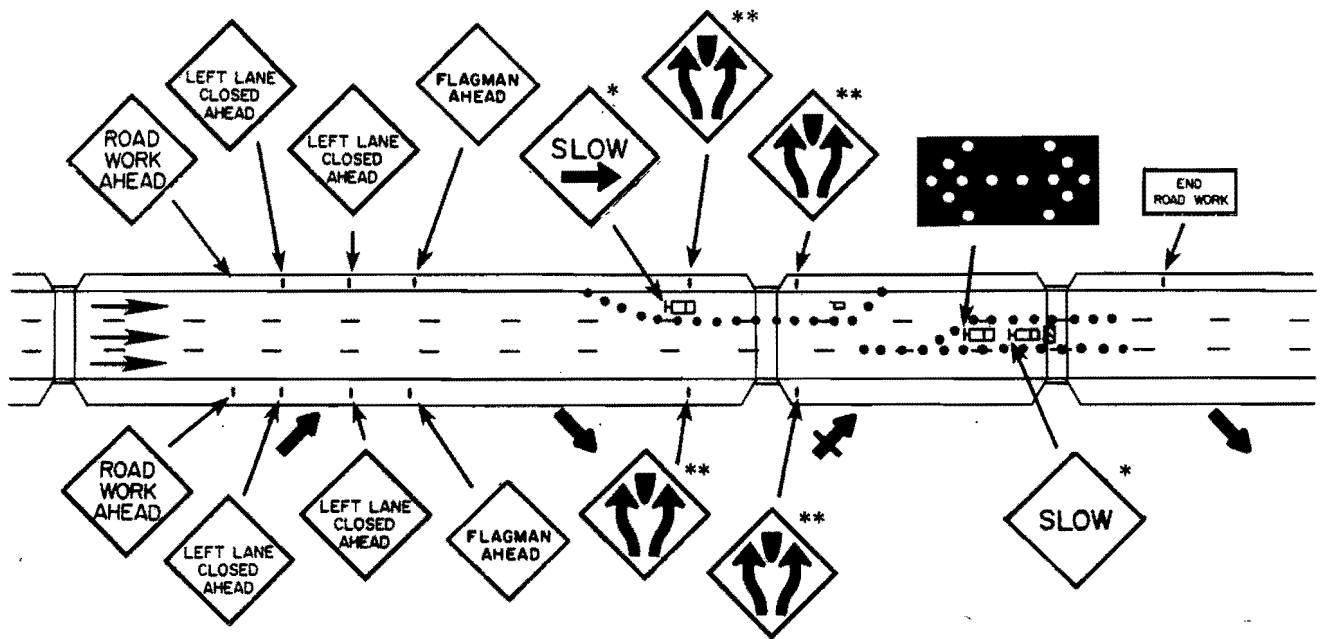
Traffic Control at Locations without Shoulders

Figure 6 shows the traffic control scheme used to manage traffic during middle lane work on sections of I-45 without shoulders. All signs shown in the figure were temporary work zone signs and, except for the flashing arrowboard, they had a black legend on an orange background. Special symbolic signs were used to warn drivers that the middle lane was blocked ahead, but they could proceed through the work area by remaining in their lanes.

Observations revealed that only 1.5% of the drivers changed lanes in a section within 1000 feet immediately upstream from the middle lane closure. There did not appear to be any noticeable adverse driver reaction.

Based on observed lane change maneuvers and flow past the worksite, the strategy appeared to provide an adequate level of safety to both motorists and the work crew. This fact, combined with the increased work zone capacity achieved, indicates that traffic splitting is a useful strategy for managing traffic at relatively short middle lane worksites where no shoulders exist.

The "traffic splitting" approach should only be used for short sections and should not be used immediately upstream from high-volume exit ramps. There is a possible danger that drivers desiring to exit could be trapped in the left lane; erratic maneuvers may occur.



* Slow sign recently deleted from Texas MUTCD ;
if used should be supplemented with an
Advisory Speed Plaque

** Special "Traffic Split " Sign

Legend




-  On Ramp (Open)
-  On Ramp (Closed)
-  Off Ramp (Open)

Figure 6. Traffic Control Strategy Used to Perform Center Lane Work on Sections of I-45 without Shoulders (Traffic Splitting)

Summary of Estimated Capacities

Table 1 summarizes the estimated capacities of the three strategies used to close the middle lane of a three-lane freeway section. The capacities are based on the results of the Houston studies.

TABLE 1. TRAFFIC CAPACITY OF CLOSURE STRATEGY

Strategy	Number of Lanes Open	Estimated Capacity (vph)
Conventional 2-Lane Closure	1	1,400-1,600*
Traffic Shifting (shoulders)	1 + Shoulder	3,000
Traffic Splitting (no shoulders)	2	3,000

*Influenced by site conditions

SPECIAL TRAFFIC MANAGEMENT REQUIREMENTS

Special attention must be given to handling mainlane, ramp, and frontage road traffic during urban freeway maintenance activities. Although the MUTCD provides minimum standards, there are additional operational and signing procedures that can enhance traffic flow during freeway closures for road work.

Report 228-8 identifies and describes the special traffic handling requirements for maintenance work zones on urban freeways (9). These special requirements stem from the high speeds, heavy traffic volumes, and unique design features (e.g., ramps and frontage roads) which characterize urban freeways in Texas. The information and guidelines presented are based on field studies and interviews conducted at over 50 work zones in six Texas cities.

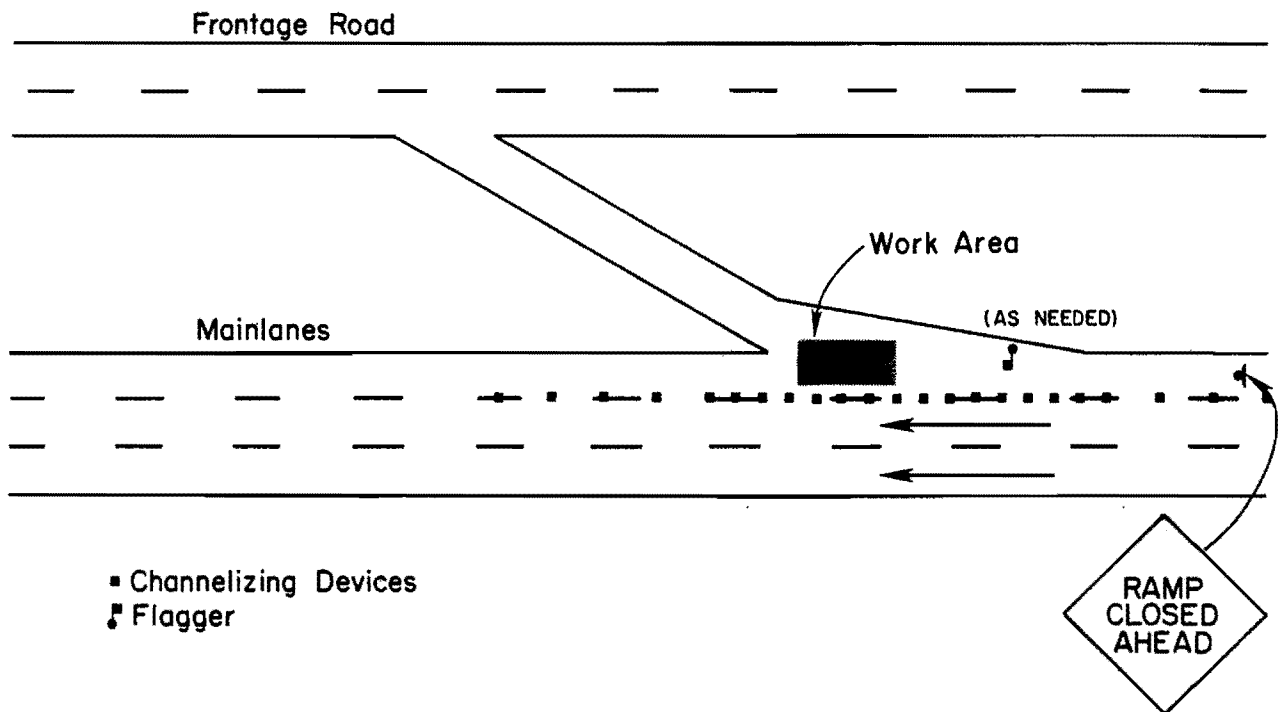
Ramp Closures

Entrance and exit ramps may need to be closed at freeway work zones to protect the work crew and/or facilitate the work activity. Entrance ramps may also be closed to reduce mainlane traffic flow at work zones where capacity is a problem.

Ramps should be closed only when needed and as long as needed. The public should be notified in advance of ramp closures by special signing, newspaper releases, etc. Typical ramp closure strategies for exit ramps and entrance ramps are illustrated in Figures 7 and 8.

Permissive Use of Ramps

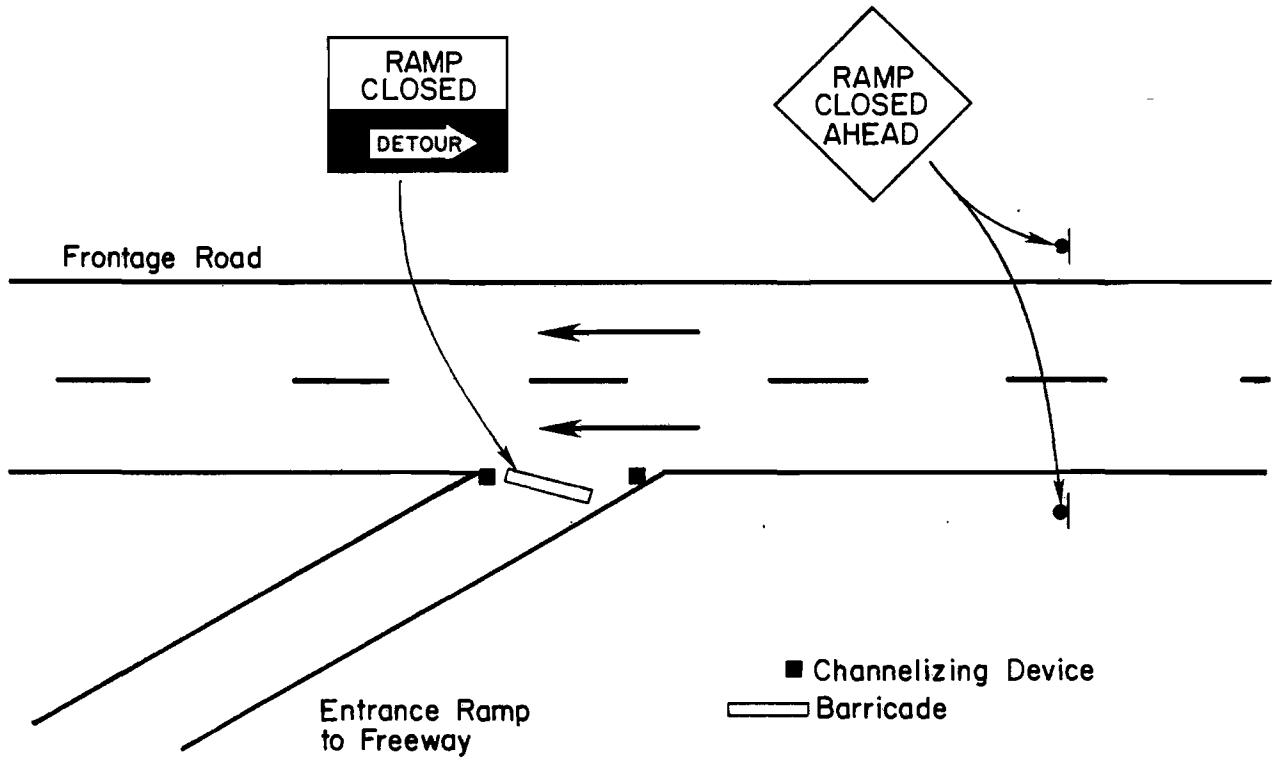
It may be desirable to keep certain work area exit and entrance ramps open. In these situations, ramp traffic should be controlled with signing and channelizing devices to protect the work crew and prevent driver confusion.



Notes

1. Cone spacing should be reduced at the ramp and ramp deceleration lane to discourage ramp use.
2. Barricades, barrels, or a parked vehicle with beacons will be used to block the exit ramp to prevent ramp use. Barricades and barrels are preferred at night, however, because of their increased visibility.
3. A flagman or policeman may be stationed at the ramp as needed.
4. Standard advance warning signs must be used upstream from the "Ramp Closed Ahead" sign.

Figure 7. Typical Exit Ramp Closure



Notes

1. A parked vehicle may be used to block ramp entry.
2. A flagman or policeman may be stationed at the ramp as needed.

Figure 8. Typical Entrance Ramp Closure

Typical traffic control strategies for permissive use of work area exit and entrance ramps are illustrated in Figures 9 and 10.

Frontage Road Operations

Freeway maintenance activities can have an adverse effect on frontage road traffic operations. Frontage road operations are particularly critical when large volumes of traffic are diverted to the frontage road. Diversion to the frontage road occurs when an entrance ramp or the freeway is closed. Diversion also occurs "naturally" when congestion develops on the mainlanes.

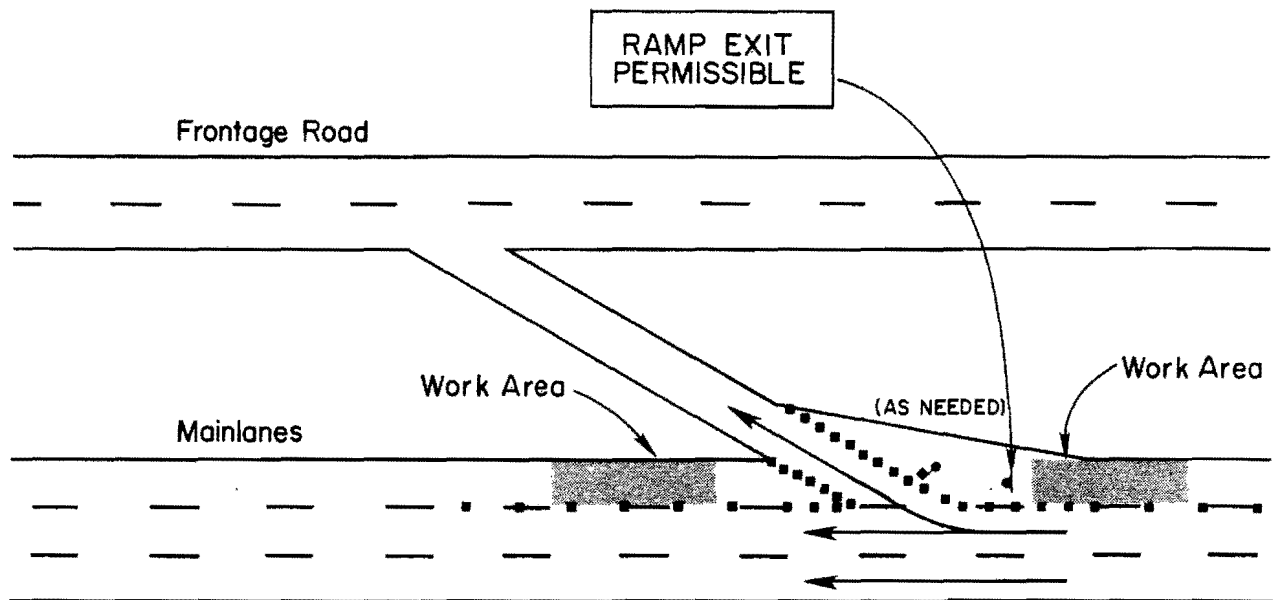
When traffic is diverted to the frontage road during a freeway maintenance activity, it may be necessary to re-time traffic signals at some frontage road intersections or provide special intersection traffic control (e.g., flagman or police). Parking on the frontage road should also be prohibited and no-parking zones enforced. These traffic control measures will increase frontage road capacity, thus reducing motorist delay and inconvenience.

Ramp capacity can also be a problem at freeway work zones where traffic is diverted to the frontage road. Several approaches for increasing ramp capacity are available, including the following:

1. Encouraging two-lane flow at single lane entrance ramps (Figure 11).
2. Providing a "free lane" at exit ramps (Figure 12)
3. Encouraging diversion at several ramps (Figure 13).

Advance Notification

Drivers should be given advance notification of freeway work activities wherever possible. Advance notification of freeway and ramp closures is particularly important.

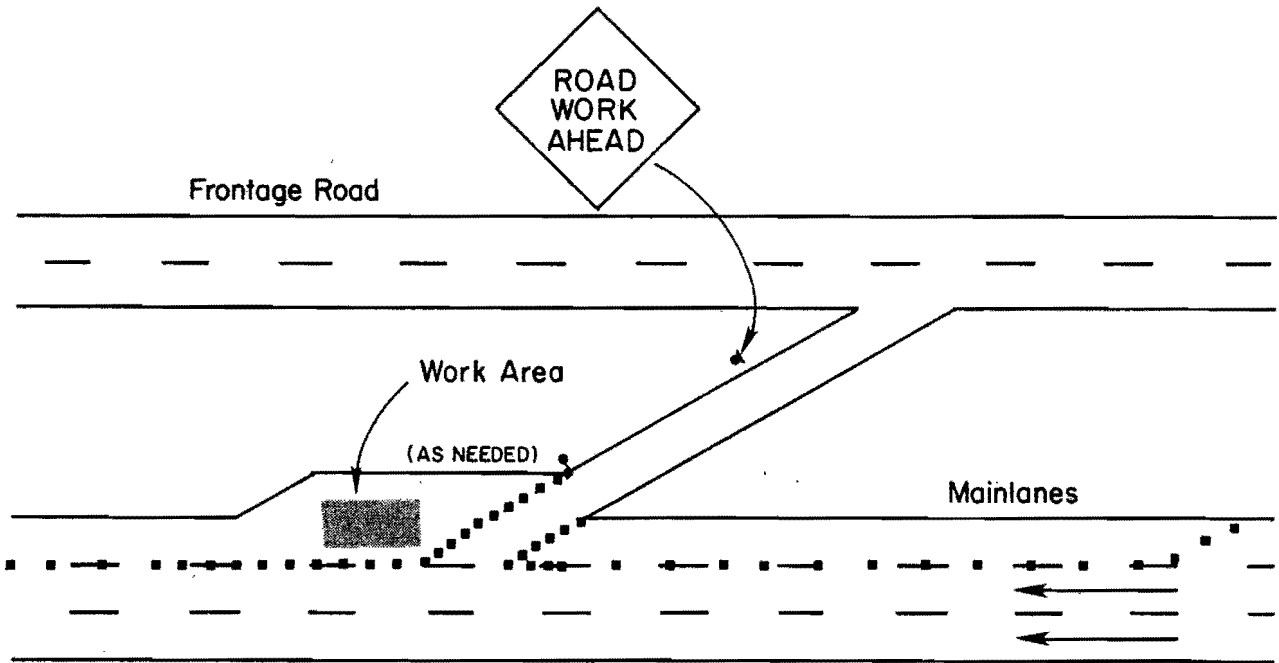


- Channelizing Devices
- ♫ Flagger

Notes

1. Cone spacing should be reduced at the ramp and deceleration lane.
2. A "shadow truck" may be positioned downstream of the exit ramp to protect the work crew.
3. A flagman or policeman may be stationed at the ramp as needed.
4. Standard advance warning signs must be used upstream from the "Ramp Exit Permissible" sign.
5. Where traffic volumes, speeds, sight distance or other such factors may warrant a deceleration lane and where a deceleration lane will not infringe upon the work area, it may be desirable to delineate a deceleration lane with channelizing devices to allow exiting traffic a lane in which to reduce speed.

Figure 9. Typical Traffic Control at Work Area Exit Ramps

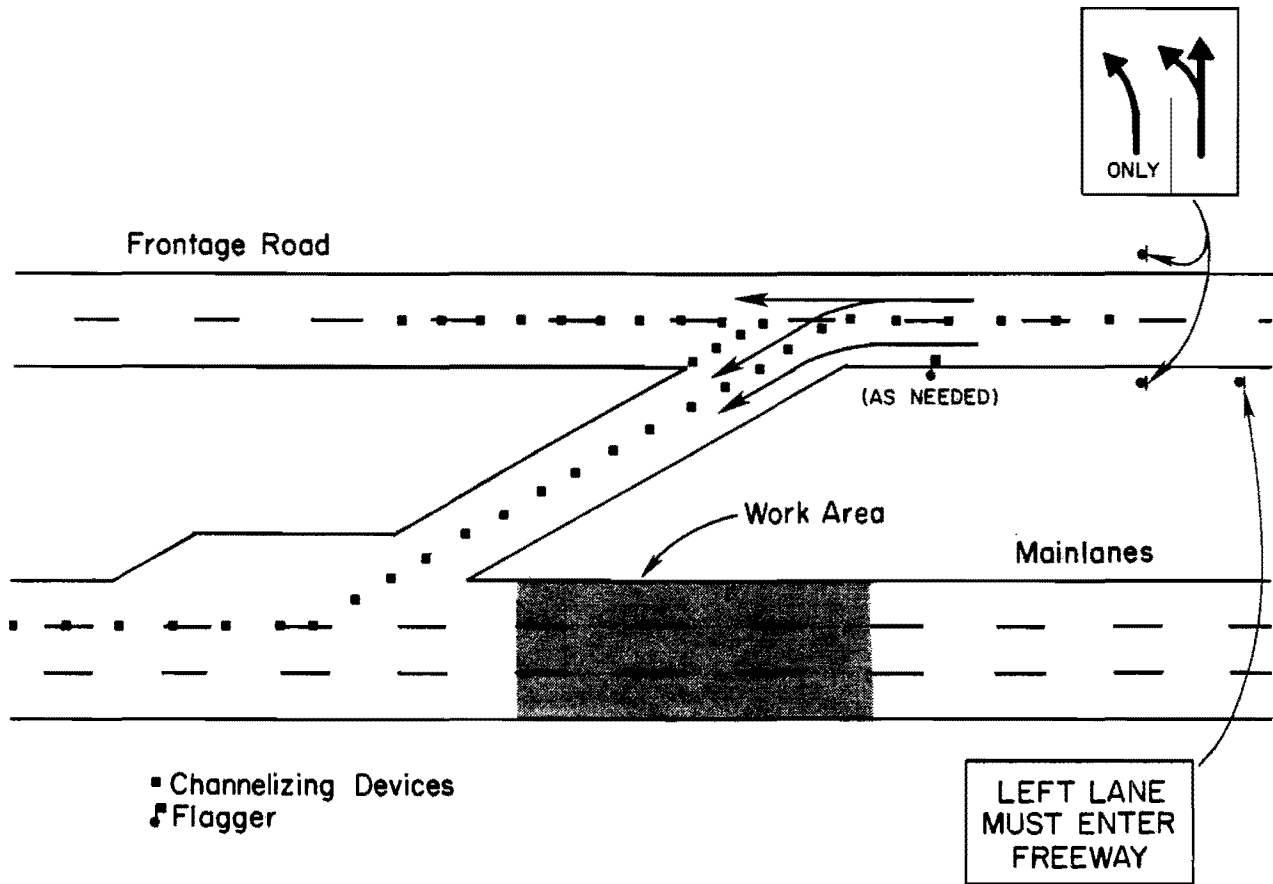


- Channelizing Devices
- ▣ Flagger

Notes

1. Cone spacing should be reduced at the ramp.
2. A "shadow truck" should be placed in the closed lane(s) between the entrance ramp and work crew.
3. A flagman or policeman may be stationed at the ramp as needed.
4. Standard advance warning signs must be used upstream from the lane closure.
5. Where traffic volumes, speeds, sight distance or other such factors may warrant an acceleration lane and where an acceleration lane will not infringe upon the work area, it may be desirable to delineate an acceleration lane with channelizing devices to allow entering traffic a lane in which to gain speed.

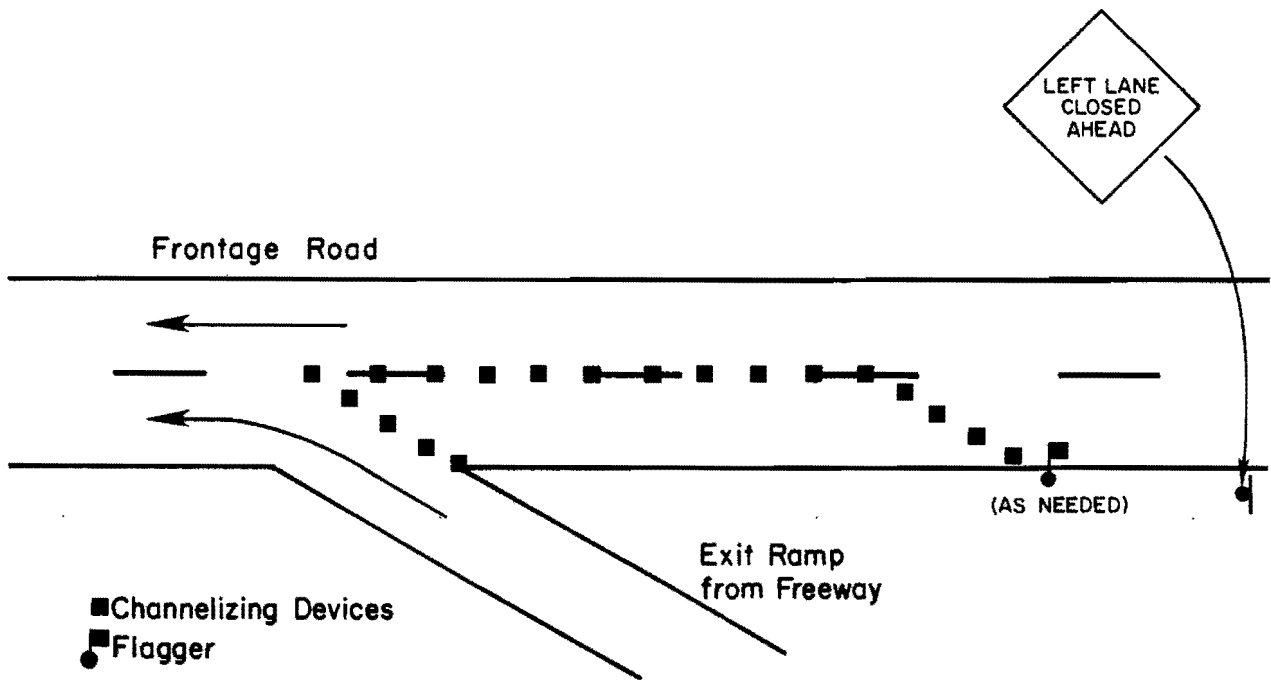
Figure 10. Typical Traffic Control at Work Area Entrance Ramp



Notes

1. Temporary pavement markings may be used in place of the channelizing devices.
2. A flagman or policeman may be stationed at the ramp as needed.

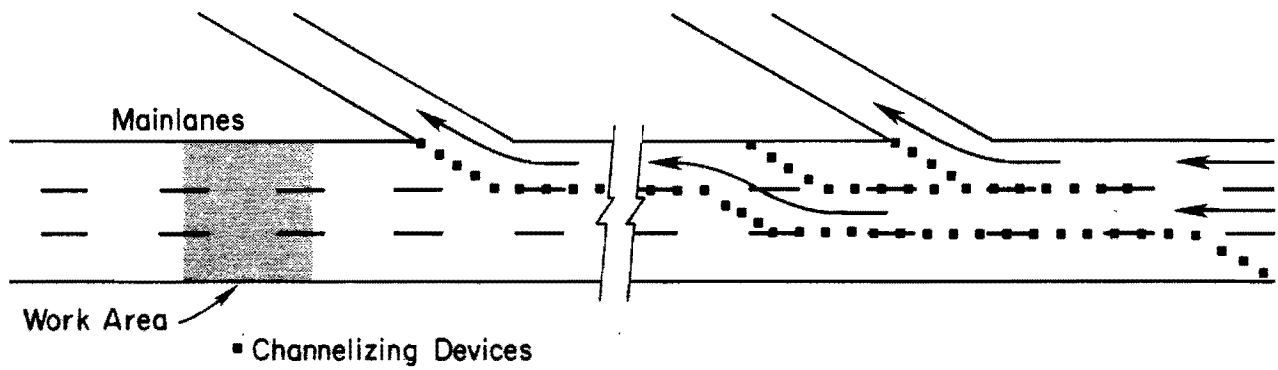
Figure 11. Providing Two Lanes at a Single-Lane Entrance Ramp



Notes

1. A flagman or policeman may be stationed at the ramp as needed.
2. This approach may not be practiced if the exit ramp is very close to a frontage road intersection since weaving problems can result.

Figure 12. Providing a "Free Lane" on the Frontage Road for Exiting Traffic



Note

Appropriate signing, arrowboards, etc., should be installed at work zone, depending on site conditions.

Figure 13. Encouraging Diversion at Two Exit Ramps

There are several methods for notifying drivers of a scheduled work activity, including newspaper releases, radio and television reports, and special signing. Advance notification signing is particularly effective since it displays specific information to those drivers who will be affected by the work activity.

Traffic Control Coordinator

There should be an individual, called a "Traffic Control Coordinator," at every freeway maintenance work zone who has the responsibility and authority to make important traffic control decisions. The Traffic Control Coordinator should continuously monitor changing work and traffic conditions at the work zone. He or she should open and close ramps, station flagmen, request police assistance, alter the traffic control plan, etc., as needed.

Traffic Control Specialist

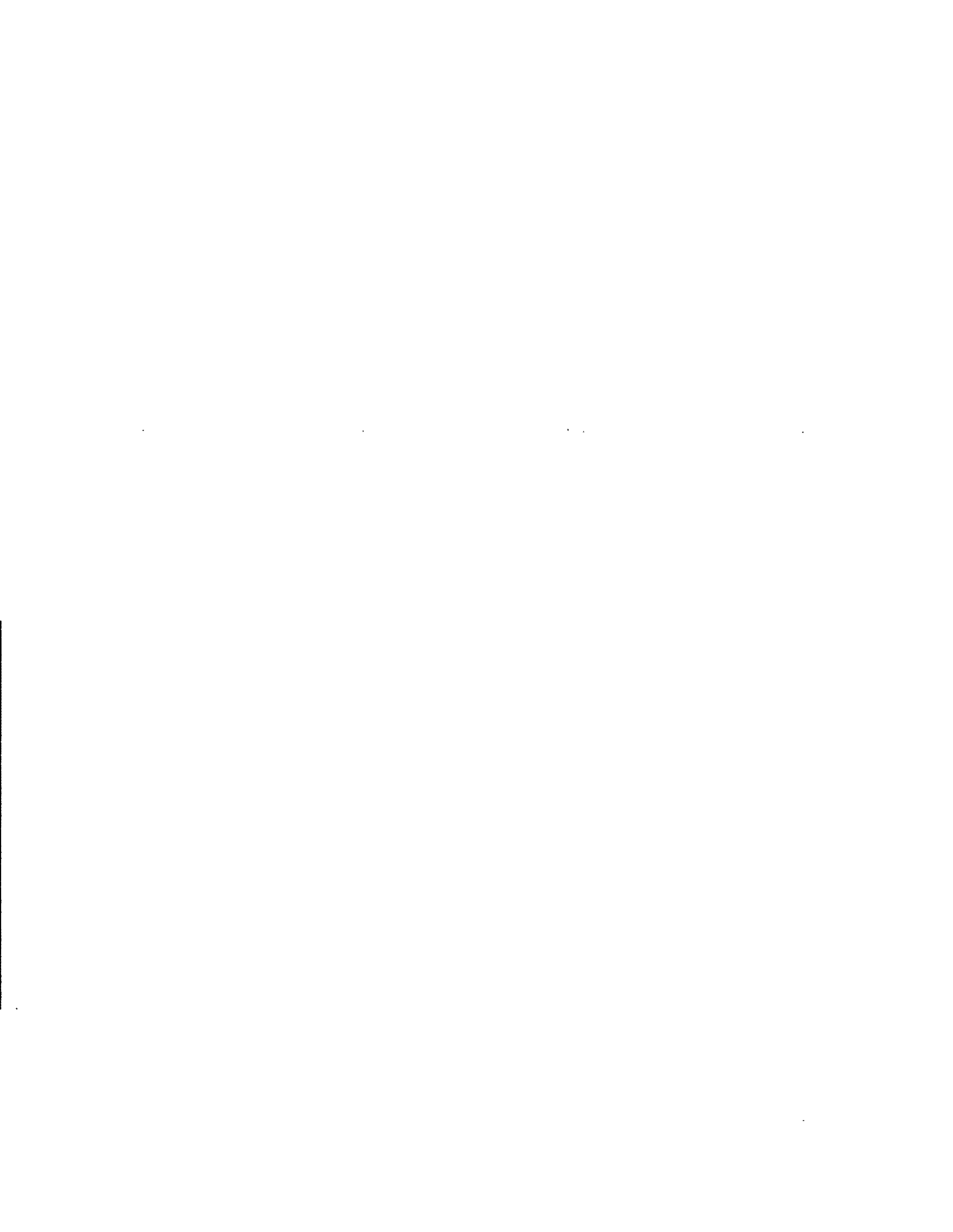
At freeway work zones, flagmen perform several critical and somewhat unique traffic control functions. In order to reflect their expanded roles, they should be called "Traffic Control Specialists."

These specialists should be supervised by the Traffic Control Coordinator and used only where needed. Normally, Traffic Control Specialists are best utilized at ramps and frontage road intersections. They may have less success in controlling high speed mainlane traffic. The effectiveness and safety of Traffic Control Specialists may be enhanced if they wear special clothing.

Use of Police

During freeway maintenance activities, police can provide vital traffic control services. They can control traffic at ramps and intersections,

prevent illegal freeway access, enforce frontage road no-parking zones, and increase driver alertness and obedience to traffic control devices. It is essential, therefore, that Districts establish good communication and cooperation with local police agencies.



FREEWAY WORK ZONE CAPACITY

Report 228-6 summarizes findings of capacity studies conducted at 28 maintenance and construction work zones on freeways in Houston and Dallas (10).

Capacity with Work Crew at Site

Figure 14 illustrates the range of volumes measured at several worksites while the work crew was at the site. All volumes were measured while queues were formed upstream from the lane closures, and thus, essentially represent either the capacities of the bottlenecks created by the lane closures or the effects of drivers gawking because of the work crew and machinery. Each point in the figure represents the volume observed during one study; therefore, it is easy to view how the data cluster for each lane closure situation.

The average capacity for each closure situation studied is shown in Table 2. The data show that the average lane capacity for the (3,2) and (4,2) combinations was approximately 1500 vehicles per hour per lane (vphpl). (The designation (A,B) is used to refer to the various lane closure situations evaluated. "A" represents the number of lanes in one direction during normal operations; "B" is the number of lanes open in one direction through the work zone.)

The studies conducted at worksites with (5,2) and (2,1) closure situations indicate significant reductions in capacity (compared to 1500 vphpl). The average capacity for these two situations was approximately 1350 vphpl.

Studies at (3,1) sites revealed even a greater reduction in capacity. The average capacity was found to be only 1130 vphpl.

Figure 15 shows the cumulative distributions of the observed work zone capacities. The function of the figure is to assist the Districts in

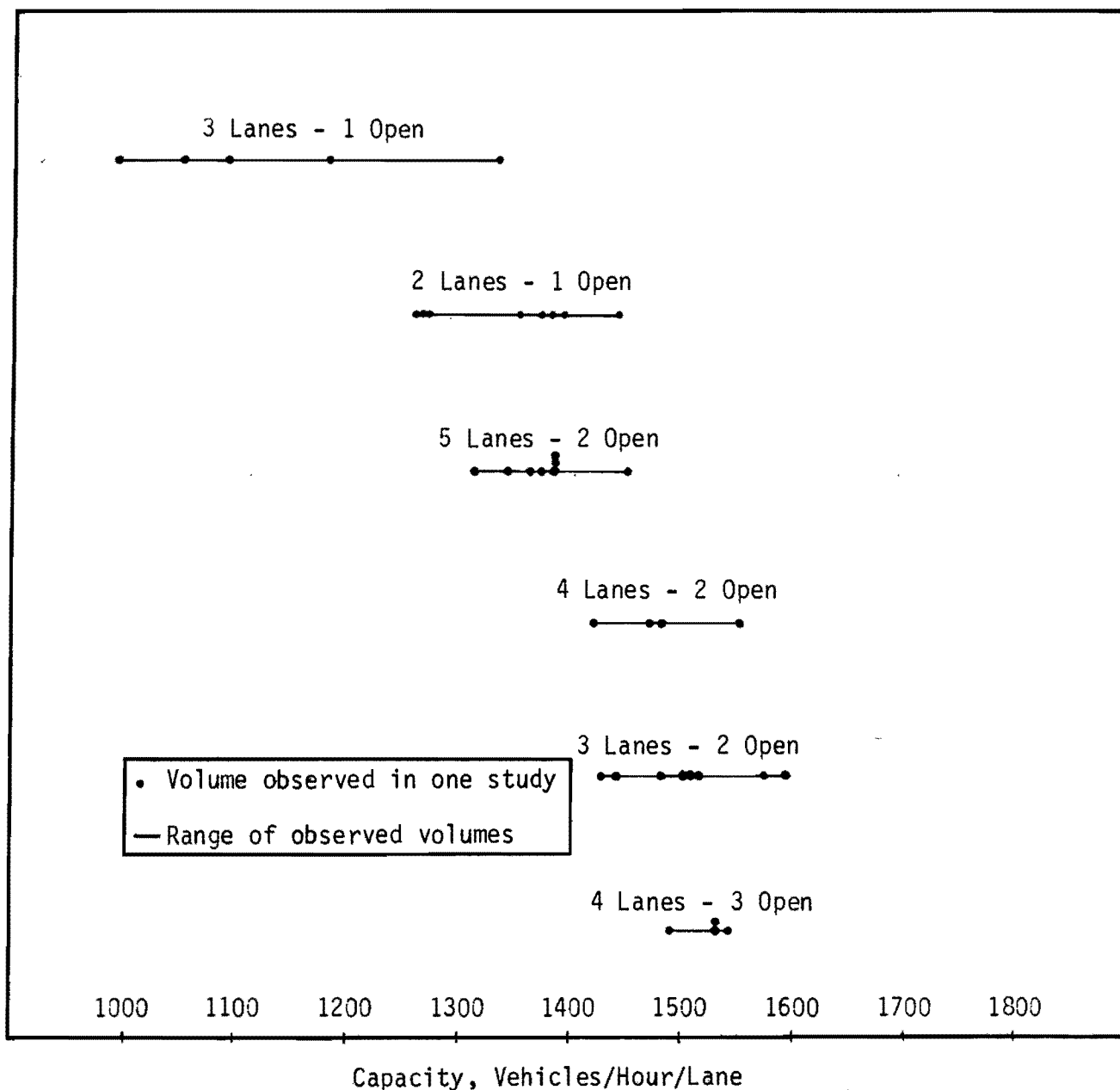


Figure 14. Range of Observed Work Zone Capacities for Each Lane Closure Situation Studied (Work Crew at Site)

TABLE 2. MEASURED WORK ZONE CAPACITY

Number of Lanes		Number of Studies	Average Capacity	
Normal	Open		vph*	vphpl**
3	1	5	1130	1130
2	1	8	1340	1340
5	2	8	2740	1370
4	2	4	2960	1480
3	2	8	3000	1500
4	3	4	4560	1520

* Vehicles per hour

** Vehicles per hour per lane

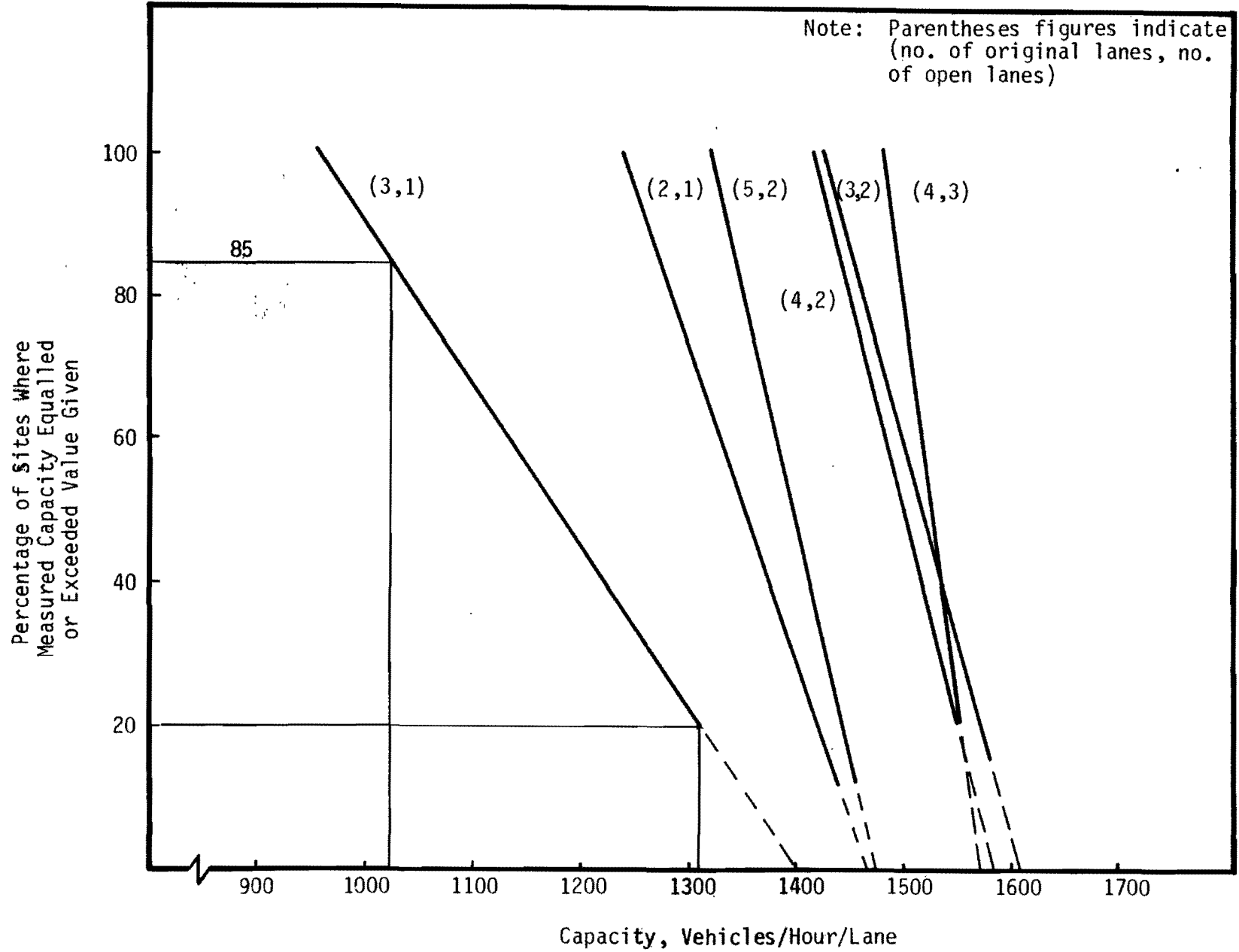


Figure 15. Cumulative Distribution of Observed Work Zone Capacities

identifying risks in using certain capacity values for a given lane closure situation to estimate the effects of the lane closures (e.g., queue lengths).

Capacity with No Work Activity at Site

Three studies were conducted at construction sites during the peak period while the work crew was not at the site. These studies were conducted in Houston on a 3-lane section of southbound I-45. Two lanes were open during the studies. The average capacity for this (3,2) lane closure situation was 1800 vphpl.

One study was conducted on the north I-610 Loop in Houston. The right two lanes of a 4-lane section were closed. There was no work activity in the closed lane immediately adjacent to traffic. A work crew and its machinery did occupy the shoulder lane, however, which was one lane removed from moving traffic. The volumes measured on the two open lanes over a period of 30 minutes were as follows: 925 vehicles in the lane adjacent to the closure and 730 vehicles in the median lane. These 30-minute volumes are equivalent to flow rates of 1850 vph and 1475 vph. It was apparent from field observations that the demand volumes were lower than the capacity of the two open lanes. Queues did not form upstream from the work activity or the cone taper. There was available capacity in the median lane. The work crew (one lane away from an open traffic lane) did not affect flow thru the work zone. It is estimated that the capacity of the two open lanes under the above-cited conditions was about 1800 vphpl. This volume could probably be sustained as long as queues do not form.

MOVING MAINTENANCE OPERATIONS

Report 228-4 documents problem areas identified following the observation of five moving maintenance operations on urban freeways in Texas (11). Recommended approaches to alleviating these problems are also discussed.

The safety problems identified were grouped into two categories. The first category is freeway design-related; the second is operational-related.

Freeway Design-Related Problems

Freeway design elements that contribute to potential safety problems during moving maintenance activities are:

- entrance and exit ramps,
- major interchanges (freeway-to-freeway), and
- horizontal and vertical curvature.

Problems at entrance and exit ramps are most frequent when the maintenance caravan is on the shoulder or middle lanes. The problems result from driver confusion at ramps near the work activity. Frequently drivers cross through the caravan or make erratic maneuvers because they are uncertain about how to use the work area ramps.

Problems created by entrance and exit ramps can be alleviated by temporary ramp control, advance signing, and/or better control of the caravan length. When the shoulder lane is blocked at entrance ramps, entering traffic can be controlled through the use of a ramp control vehicle. An advance signing vehicle, coupled with control of the caravan length, is recommended to reduce the confusion and indecision of motorists near exit ramps, or when the caravan is blocking one of the middle lanes upstream from an exit ramp.

Major problems at freeway-to-freeway interchanges generally occur when the caravan is near the exit ramp connectors or the entrance ramps from the crossing freeway. The problems are due to lane drops and driver confusion in identifying the proper lane they should be in for the desired routing. Special interchange signing and temporary ramp closure are recommended solutions.

The major problem associated with horizontal and vertical curvature is one of providing adequate driver sight distance to the maintenance caravan. This problem can be reduced through advance signing and by controlling caravan length. Advance signing would help drivers identify the blocked lane. Maintaining a controlled caravan length can be accomplished in two ways. The first method requires that the caravan retain uniform vehicle spacing and travel at its normal speed. In the second method, the trail vehicle stops at a point on the curve where there is sufficient sight distance for approaching motorists to leave the blocked lane. The trail vehicle remains stopped until the leading portion of the caravan clears the curve. When sufficient sight distance is available the trail vehicle should move to its normal spacing.

Operational Problems

The second category of problems is termed "operational" because the problems are related to the manner in which the moving maintenance is performed. Operational problems observed include:

- improper use of arrowboards,
- lack of uniform procedures for freeway entry and exit,
- large spacing between caravan vehicles, and
- unnecessary lane blockage by the caravan.

These problems can be alleviated through the development of improved guidelines and uniform procedures.

Flashing arrowboards have recently become the primary signs for the trailing vehicles on urban freeways because of their high target value. The problems observed were ones of misuse or overuse. When the caravan was off the roadway or not performing maintenance, the arrowboard remained in operation. Thus, incorrect information was displayed to approaching motorists. Arrowboards also displayed incorrect information when they were left on after the caravan entered or exited the freeway. These problems can be eliminated by placing the arrowboard in the "caution" display mode when the crew is not in the act of performing maintenance. (Note: The arrowboard controls on most vehicles are mounted outside the truck. Placement of additional controls inside the truck cab would allow the display message to be changed as needed.)

The movement of the caravan onto or off of the freeway can have a major impact on the operation of the facility in terms of roadway capacity, flow, speeds, lane changes, and driver confusion. The entry and exit procedures differed for each maintenance crew observed, indicating a lack of uniform procedures.

The development of uniform procedures is required to eliminate the problems observed during caravan entry and exit onto and off of the freeway. The suggested procedures are discussed in Report 228-4.

Large spacing between caravan vehicles encourages motorists to cross through the caravan. This violates one of the primary purposes of a caravan. This problem can be reduced through the development of guidelines for caravan spacing.

Poor planning resulted in prolonged and unnecessary lane closures during some of the observed maintenance operations. In particular, the failure of maintenance crews to anticipate supply requirements (e.g., paint, pavement markers, or epoxy) caused unnecessary delays while the caravan occupied the travel lane. The work stoppage observed ranged from momentary to more than one hour. These work delays extend the time that a lane is closed to traffic. Supplies were normally kept on one of the vehicles in the caravan; thus workers were forced to walk adjacent to fast moving traffic to carry the supplies to the applicator vehicle.

Unnecessary lane blockage can be eliminated with proper planning and scheduling. Planning is accomplished by dividing the project into sections. These sections should be no longer than the capabilities of the loaded striper or epoxy applicator. This will allow the striper or applicator to be serviced while the caravan is out of the main lanes and off of the roadway.

REAL-TIME DISPLAYS

Changeable message signs (CMSs) and Highway Advisory Radio (HAR) are playing increasing roles in managing traffic. Studies were conducted to determine the feasibility of using these management tools during freeway maintenance and construction. The results are summarized in this section of the Final Report. Details are presented in Report No. 228-9 (12).

Changeable Message Signs

The studies revealed that CMSs can be effective traffic management tools for freeway roadwork when they are properly used in work zones. Drivers change lanes farther upstream from the closure. In addition, many drivers are willing to divert to other freeway alternate routes to avoid the freeway work area.

CMSs should not be used in place of flashing arrowboards. Arrowboards are very effective devices and should be used for most lane closures on urban freeways.

Highway Advisory Radio

Studies were conducted at a major maintenance work zone on a rural Interstate highway in Texas to evaluate the use of Highway Advisory Radio (HAR) for work zone traffic management. The studies revealed that the HAR had little or no effect on traffic operations at the work zone because of two factors. First the conventional signing at the work zone was excellent and the HAR functioned only as a supplemental information source. Second, the advanced signing used to encourage motorists to tune to the HAR broadcasts was apparently inadequate in terms of legibility and visibility.

Even though the HAR system did not significantly affect traffic operations at the work zone evaluated, the studies indicated that HAR may have good potential for work zone traffic management in certain applications (e.g., for displaying long or complicated diversion messages at long-term work zones). HAR is not practical for most maintenance operations because of current Federal Communication Commission regulations and licensing requirements.

The studies also revealed that existing HAR hardware (with a monopole antenna system) performs adequately. Motorists, generally speaking, were satisfied with the quality of the broadcasts and supportive of this innovative approach to work zone traffic management.

FLAGGER SIGNALS AND SIGNALING DEVICES

An exploratory human factors laboratory study was developed to evaluate drivers' understanding of various flagger signals and signaling devices for work zone traffic control. Details are presented in Report 228-3 (13). The study evaluated 13 signals (Figure 16) including:

1. Seven standard signals recommended in the 1980 *Texas MUTCD*.
2. Two signals recommended in the original 1973 *Texas MUTCD*, but not included in the 1980 *Texas MUTCD*.
3. Two signals recommended for use by police by the Northwestern University Traffic Institute.
4. Two non-standard signals which combined standard signals from the 1980 *Texas MUTCD*.

1980 Texas MUTCD Signals

Five of the seven signals recommended in the 1980 *Texas MUTCD* (Signals 1, 3, 6, 7, and 8) appeared to be understood by most drivers. These five signals involve the use of a STOP-SLOW sign paddle and/or hand motions.

The two signals recommended in the 1980 *Texas MUTCD* which were not generally understood by the study participants (Signals 2 and 9) involve the use of only a red flag. This finding suggests that a red flag used alone is a relatively ineffective traffic control device.

1973 Texas MUTCD Signals (Deleted Signals)

The two signals recommended in the original 1973 *Texas MUTCD*, but not included in the 1980 *Texas MUTCD* (Signals 11 and 12), were not generally understood by the drivers. The deletion of these signals from the 1980 *Texas MUTCD* apparently is in the best interest of work zone safety.

①



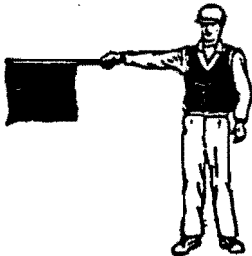
Signal Intent: Stop traffic

Description: The flagger holds the sign paddle in a stationary position with the arm extended horizontally away from the body. The free arm is raised with the palm toward approaching traffic.

Device(s) Used: STOP Sign Paddle and Hand

Source: 1980 *Texas MUTCD*

②



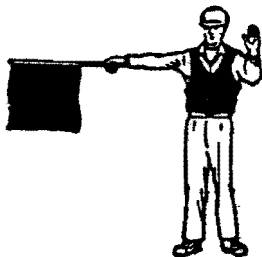
Signal Intent: Stop traffic

Description: The flagger faces traffic and extends the flag horizontally across the traffic lane in a stationary position so that the full area of the flag is visible hanging below the staff.

Device(s) Used: Flag

Source: 1980 *Texas MUTCD*

③



Signal Intent: Stop traffic

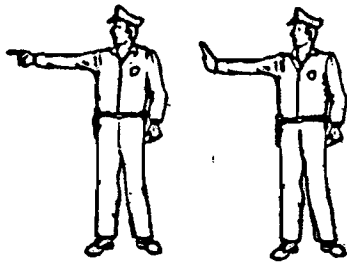
Description: The flagger faces traffic and extends the flag horizontally across the traffic lane in a stationary position so that the full area of the flag is visible hanging below the staff. The free arm is raised with the palm toward approaching traffic.

Device(s) Used: Flag and Hand

Source: 1980 *Texas MUTCD*

Figure 16. Flagger Signals Evaluated in the Study

④



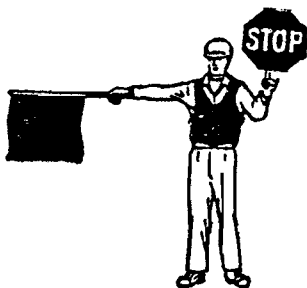
Signal Intent: Stop traffic

Description: The flagger points with his arm and finger and looks straight at the driver. He watches the driver and holds this point until seen. Then, the pointing hand is raised (but not the whole arm) so that the palm is toward the driver.

Device(s) Used: Hand

Source: Police Handbook

⑤



Signal Intent: Stop traffic

Description: The flagger faces traffic and extends the flag horizontally across the traffic lane in a stationary position so that the full area of the flag is visible hanging below the staff. The left arm is raised with the STOP sign paddle facing approaching traffic.

Device(s) Used: STOP Sign Paddle and Flag

Source: Combination of two signals from the 1980 *Texas MUTCD*, resulting in a non-standard signal.

⑥



Signal Intent: Encourage traffic to proceed

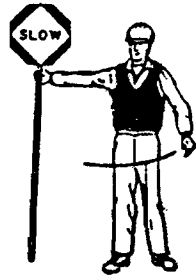
Description: The flagger stands parallel to the traffic movement, and with flag and arm lowered from view of the driver, motions traffic ahead with his free arm. The flag is not used to signal traffic to proceed.

Device(s) Used: Hand

Source: 1980 *Texas MUTCD*

Figure 16. Flagger Signals Evaluated in the Study (Continued)

7



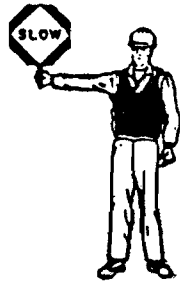
Signal Intent: Encourage traffic to proceed

Description: A SLOW sign paddle is held in a stationary position with the arm extended horizontally away from the body. The flagger motions traffic ahead with his free hand.

Device(s) Used: SLOW Sign Paddle and Hand

Source: 1980 *Texas MUTCD*

8



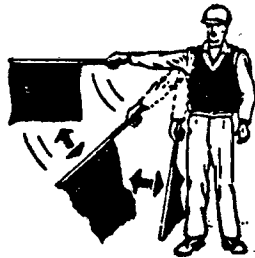
Signal Intent: Alert and slow traffic

Description: The flagger holds the SLOW sign paddle in a stationary position with the arm extended horizontally away from the body.

Device(s) Used: SLOW Sign Paddle

Source: 1980 *Texas MUTCD*

9



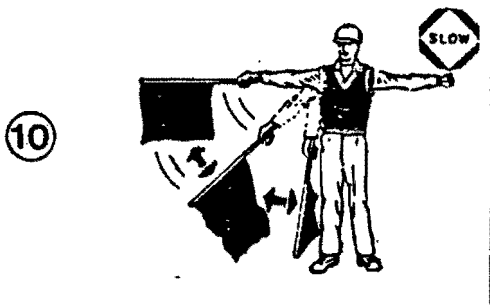
Signal Intent: Alert and slow traffic

Description: The flagger faces traffic and slowly waves the flag in a sweeping motion with the extended arm from the shoulder level to straight down without raising the arm above a horizontal position.

Device(s) Used: Flag

Source: 1980 *Texas MUTCD*

Figure 16. Flagger Signals Evaluated in the Study (Continued)

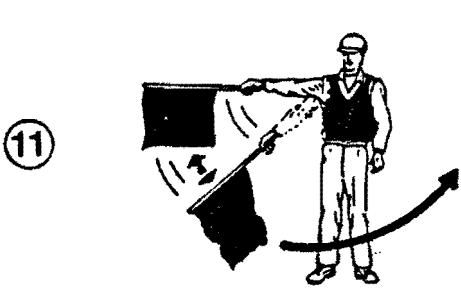


Signal Intent: Alert and slow traffic

Description: The flagger faces traffic and slowly waves the flag in a sweeping motion with the arm extended from the shoulder level to straight down without raising the arm above a horizontal position. The SLOW sign paddle is held in a stationary position with the arm extended horizontally away from the body.

Device(s) Used: SLOW Sign Paddle and Flag

Source: Combination of two signals from the 1980 *Texas MUTCD*, resulting in a non-standard signal.

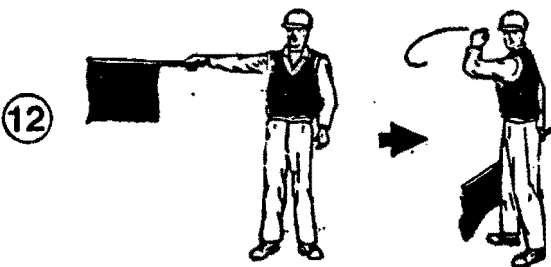


Signal Intent: Alert traffic

Description: The flagger faces traffic and waves the flag in a sweeping motion of the arm across the front of the body without raising the arm above a horizontal position.

Device(s) Used: Flag

Source: 1973 *Texas MUTCD*
(Not included in the 1980 *Texas MUTCD*)



Signal Intent: Slow traffic

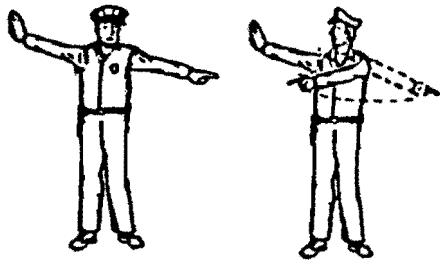
Description: The flagger faces traffic and extends the flag horizontally across the traffic lane in a stationary position so that the full area of the flag is visible hanging below the staff. Then the flagger stands parallel to the traffic movement, and with the flag and arm lowered from view of the driver, motions traffic ahead with his free arm.

Device(s) Used: Flag and Hand

Source: 1973 *Texas MUTCD*
(Not included in the 1980 *Texas MUTCD*)

Figure 16. Flagger Signals Evaluated in the Study (Continued)

13



Signal Intent: Encourage traffic to
turn left

Description: The flagger gives the stop
signal with his right arm to stop
traffic in the opposing lane.
Holding this stop signal, he gives
a turning gesture with his left arm.

Device(s) Used: Hands

Source: Police Handbook

Figure 16. Flagger Signals Evaluated in the Study (Continued)

Stopping Traffic

Signal 1 (STOP sign paddle and hand motion) and Signal 3 (flag and hand motion) were understood by most drivers in the study. Both of these signals are included in the 1980 *Texas MUTCD*. Based on the study results, their continued use is recommended.

Signal 2 (flag only), on the other hand, is apparently not understood by many motorists, even though it is included in the 1980 *Texas MUTCD*. Based on this finding, the use of Signal 2 is discouraged.

Signal 4 (police hand motion) and Signal 5 (STOP sign paddle and flag) performed well in the study, in terms of driver understanding. However, the use of these signals would probably not offer any advantages over Signals 1 or 3; therefore, Signals 4 and 5 are not recommended for work zone traffic control.

Encouraging Traffic to Proceed

Signal 6 (hand motion) and Signal 7 (SLOW sign paddle and hand motion) were understood by most motorists. Their use at work zones for encouraging stopped traffic to proceed is supported by the study results. Both of the signals are recommended in the 1980 *Texas MUTCD*.

Alerting and Slowing Traffic

Signal 8 (SLOW sign paddle) was the only signal for alerting and slowing traffic which was understood by most drivers. This signal is recommended in the 1980 *Texas MUTCD* and its use is supported by the study results.

Four other signals for alerting and slowing traffic were tested (Signals 9-12); however, none of these signals were generally understood by the

motorists. Their use, therefore, is not recommended. One of these deficient signals, Signal 9 (flag only), is included in the 1980 *Texas MUTCD*.

Encouraging Traffic to Turn Left

The police hand signal for encouraging traffic to turn left (Signal 13) was understood by over 80 percent of the drivers. This signal and others currently used by police show promise for work zone traffic control.

Needed Messages

The 1980 *Texas MUTCD* only addressed three basic flagging messages (stop, slow, and proceed), and thus the functions of the work zone flagger are currently somewhat limited. Consideration should be given to developing signals which convey other messages such as: 1) change lanes or merge into one lane, 2) turn left or right, 3) maintain speed, 4) detour or divert, and 5) use shoulder.

Training

The work zone flagger performs a vital function in promoting traffic safety and operational efficiency. Unfortunately, flagging is viewed by many as a menial, relatively unimportant task. The least experienced or productive worker is often assigned the flagging duty without receiving instruction on proper traffic control procedures. Flagger morale is usually very low.

It is recommended that the image and effectiveness of the flagger be improved. Proper training and instruction for all flaggers is essential. They should be familiar with proper work zone traffic control techniques and devices, and know how to use these tools to protect the safety of the work crew

and motoring public. Flaggers should have a basic knowledge of traffic flow characteristics (e.g., speed, volume, and capacity), and how these characteristics relate to efficient work zone traffic operation.

Job Title

It is also suggested that "flaggers" or "flagmen" be referred to by a more descriptive term, one which better reflects their function and importance (e.g., Traffic Control Specialists). In many instances, the "flagger" is the most important member of the work crew. He (or she) is responsible for traffic safety and operations at the work zone and for promoting public understanding and acceptance of the work zone operation.

Attire

It should be noted that, in addition to driver understanding, other factors influence motorist reaction to a particular flagging signal. Flagger appearance is one of these factors. A flagger should be highly visible in the work zone environment and command the attention and respect of passing motorists. As a minimum, a flagger should be attired in accordance with *MUTCD* guidelines (e.g., wear an orange safety vest and optional white hardhat). The development of a special flagger "uniform" may be the best means, however, of promoting flagger visibility and respect. In fact, special uniforms (white overalls and orange vests) have been worn by flaggers at maintenance work zones on freeways in Houston with reported success (14).

REFERENCES

1. Manual on Uniform Traffic Control Devices for Streets and Highways. Federal Highway Administration, 1978.
2. S. H. Richards, C. L. Dudek, N. L. Matlock and D. R. Hatcher. Maintenance and Construction Zones: Annotated Bibliography. Texas Transportation Institute. Report No. 228-1/263-1. February 1980.
3. S. H. Richards and C. L. Dudek. Sight Distance Requirements at Lane Closure Work Zones on Urban Freeways. Texas Transportation Institute. Report No. 228-7. April 1981.
4. B. G. Knapp and R. F. Pain. Human Factors Considerations in Arrowboard Design and Operation. BioTechnology, Inc. July 1978.
5. J. L. Graham, J. D. Megletz and J. C. Glennon. Guidelines for the Applications of Arrow Boards in Work Zones. Midwest Research Institute. Report No. FHWA-RD-79-58. December 1978.
6. M. J. S. Faulkner and C. L. Dudek. Field Evaluation of Flashing Arrowboards at Freeway Work Zones. Texas Transportation Institute. Report No. 228-5. April 1981.
7. J. W. McGee, W. Moore, B. G. Knapp and J. H. Sanders. Decision Sight Distance for Highway Design and Traffic Control Requirements. BioTechnology, Inc. Report No. FHWA-RD-78-78. February 1978.
8. C. L. Dudek and S. H. Richards. Traffic Management for Middle Lane Maintenance on Urban Freeways. Texas Transportation Institute. Report No. 228-2. March 1980.
9. S. H. Richards and C. L. Dudek. Special Traffic Management Requirements for Maintenance Work Zones on Urban Freeways. Texas Transportation Institute. Report No. 228-8. June 1981.
10. C. L. Dudek and S. H. Richards. Traffic Capacity Through Work Zones on Urban Freeways. Texas Transportation Institute. Report No. 228-6. April 1981.
11. M. J. S. Faulkner and C. L. Dudek. Moving Maintenance Operations on Texas Urban Freeways: A Limited Overview of Current Practices and Problem Identification. Texas Transportation Institute. Report No. 228-4. January 1981.
12. C. L. Dudek and S. H. Richards. Feasibility of Changeable Message Signs and Highway Advisory Radio for Freeway Maintenance. Texas Transportation Institute Report No. 228-9/263-2. July 1981.

13. S. H. Richards, N. D. Huddleston and J. D. Bowman. Driver Understanding of Work Zone Flagger Signals and Signaling Devices. Texas Transportation Institute. Report No. 228-3. January 1981.
14. R. G. Biggs. Traffic Handling around Maintenance Activities on Freeways. Report Number 555.3. Transportation Planning Division, Texas State Department on Highways and Public Transportaiton. July 1975.

APPENDIX

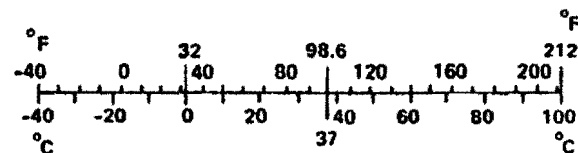
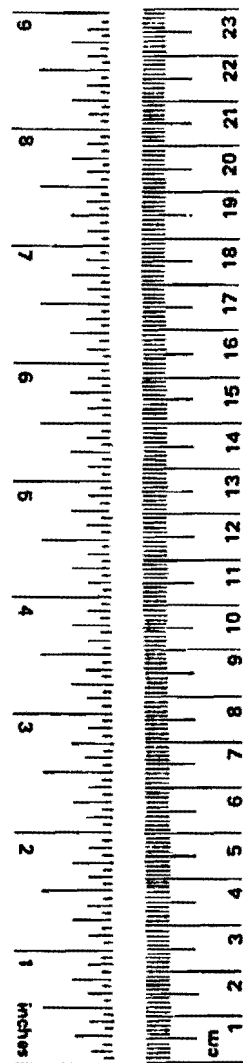
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
LENGTH				
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
AREA				
in ²	square inches	6.5	square centimeters	cm ²
ft ²	square feet	0.09	square meters	m ²
yd ²	square yards	0.8	square meters	m ²
mi ²	square miles	2.6	square kilometers	km ²
	acres	0.4	hectares	ha
MASS (weight)				
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
VOLUME				
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft ³	cubic feet	0.03	cubic meters	m ³
yd ³	cubic yards	0.76	cubic meters	m ³
TEMPERATURE (exact)				
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
LENGTH				
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
AREA				
cm ²	square centimeters	0.16	square inches	in ²
m ²	square meters	1.2	square yards	yd ²
km ²	square kilometers	0.4	square miles	mi ²
ha	hectares (10,000 m ²)	2.5	acres	
MASS (weight)				
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
VOLUME				
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m ³	cubic meters	35	cubic feet	ft ³
m ³	cubic meters	1.3	cubic yards	yd ³
TEMPERATURE (exact)				
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



* 1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price \$2.25, SD Catalog No. C13.10:286.

1
2
3
4
5
6
7
8
9
10
11
12
13
14
15
16
17
18
19
20
21
22
23
24
25
26
27
28
29
30
31
32
33
34
35
36
37
38
39
40
41
42
43
44
45
46
47
48
49
50
51
52
53
54
55
56
57
58
59
60
61
62
63
64
65
66
67
68
69
70
71
72
73
74
75
76
77
78
79
80
81
82
83
84
85
86
87
88
89
90
91
92
93
94
95
96
97
98
99
100