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IDELINES FOR THE APPLICATION OF ARROW BOARDS IN WORK ZONES

December 1978
Final Report

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DEPARTMENT OF TRANSPORTATION · UNITED STATES OF AMERICA

Prepared for
FEDERAL HIGHWAY ADMINISTRATION
Offices of Research & Development
Traffic Systems Division
Washington, D.C. 20590

FOREWORD

This report provides guidelines for the application of arrow boards in work zones including design specifications, warrants for their use, and placement details. The report will be of particular interest to highway and traffic engineers, and construction supervisors responsible for controlling traffic in and around construction work zones.

The Federal Highway Administration field offices, highway agencies, and utility companies should exercise caution and good judgment when applying the conclusions and guidelines of this report in those areas where a conflict may exist with the Manual on Uniform Traffic Control Devices (MUTCD). Where appropriate, the results of this study will be used to revise the MUTCD.

Two copies of this report are being sent to each regional office and four copies to each division office. Two of the division office copies should be forwarded to the State highway agency.

Charles F. Scheffey
Director, Office of Research
Federal Highway Administration

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16. Abstract
The purpose of this study was to develop objective criteria for the use and placement of arrow boards in work zones. The research was conducted in three phases. In the first phase all available literature on work zone traffic control was reviewed. Human factors investigations were conducted in the second phase to determine driver information requirements, expectancy and understanding of arrow boards. The third phase of the research was an intensive field study of driver responses to arrow boards in actual work zones. Twenty-six construction sites and 23 hours of maintenance activities were studied.

The research determined that arrow boards were effective in lane closure work zones because they promoted earlier merging into the open lane and fewer vehicles remained in the closed lane at the start of the lane closure taper. The arrow board was more effective when it was placed on the shoulder of the roadway near the start of the lane closure taper. Arrow boards were not found to be generally effective in traffic diversions or splits or for moving shoulder closures. However, they did prove effective in reducing some specific operational problems in these types of work zones.

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PREFACE

This final report was prepared by Midwest Research Institute for the Federal Highway Administration under Contract No. DOT-FH-11-9352. Mr. Harry Lum of the Office of Research, Federal Highway Administration was the contract manager.

We wish to acknowledge the contribution of the following people in the field study portion of the research: Mr. Charles B. Sweet and Mr. Richard Weaver, California Department of Transportation; Mr. George Moberly and Mr. Lee Bates of the Illinois Department of Transportation; and Mr. Donald C. Zimmer and Mr. Lon R. Hoglind of the Illinois State Toll Highway Authority. Many other individuals in the departments mentioned provided invaluable assistance which is gratefully acknowledged.

The work reported herein was carried out in the Economics and Management Science Division under the administrative direction of Dr. A.E. Vandegrift, and Dr. William D. Glauz. Mr. Jerry L. Graham, Associate Traffic Engineer served as the principal investigator.

Mr. Graham, Mr. Donald James Migletz, Assistant Traffic Engineer, and Mr. John C. Glennon, Transportation Consultant were co-authors of this report. The sections on Human Factors Considerations in Arrow Board Design and Operation and Driver Understanding and Expectancy of Arrow Boards were written by Beverly G. Knapp and Richard F. Pain of BioTechnology, Inc. Mr. Michael Sharp, Senior Statistician, performed the analysis of the field data and contributed to the writing of the data analysis description. Other members of the MRI staff who contributed to the work reported include Mr. Carl Clark, Mr. Douglas W. Harwood, Mr. Patrick J. Heenan, and Ms. Rosemary Moran.

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I. EXECUTIVE SUMMARY

Arrow boards are sign panels with a matrix of lights capable of either flashing or sequential displays. Although their use for advanced warning in highway work zones has grown in recent years, national specifications were not developed until 1977 and, consequently, the current use, operation, and placement of arrow boards varies greatly between agencies.

The purpose of this project was to develop objective criteria for the use and placement of arrow boards in work zones. These criteria (presented in Appendix B) determine those situations that warrant arrow boards and specify where the arrow board should be placed to provide the safest and most efficient traffic movement possible.

A. Project Scope

The project was confined to the study of arrow boards; variable word message signs and portable flashing beacon signs were not included. The project considered the application of arrow boards to all types of work zones including lane closures, roadside or shoulder work, and diversions (detours, crossovers, or bypass roadways). Moving and stationary, long-term and short-term operations were studied under both day and night conditions. The locations included two-lane and multi-lane highways in rural and urban areas.

The research was conducted in three phases including a state-of-the-art review, a human factors study, and field data collection of traffic operations in work zones. In the first phase, three sources of information were reviewed to determine the state-of-the-art of arrow board usage in work zones. The first source included all available research both on the effectiveness of arrow boards and on principles of traffic control in other lane-closure situations. The second source was 117 manuals on work-zone traffic control obtained from various states, counties, cities and utility companies. The third source of information came from telephone contacts with officials in various state and local governmental offices and utility offices.

Human factors investigations were conducted in the second phase to determine driver information requirements, expectancy, and understanding of arrow boards. These investigations determined human-factors requirements for arrow boards and compared these requirements to arrow board design and operational characteristics. Also, two laboratory studies were conducted in which subjects viewed film clips of arrow boards. The first study was designed to determine the driver's conceived meaning of arrow board modes (the patterns of lights displayed on the arrow board) and arrow board placement. The second study was a paired-comparison design to determine if any one mode was superior in encouraging drivers to change lanes. The modes tested were flashing arrow, sequential arrow and sequential chevron.

The third phase of the research included extensive field studies of driver responses to arrow boards in work zones. Conducted in California and Illinois, the studies collected data for 26 construction sites and 23 hours of maintenance activities. For long-term construction projects, data were collected using tapeswitches and a 20-pen event recorder. During short-term construction and maintenance activities, a 16 mm Bolex camera mounted on the arrow board trailer or maintenance vehicle, recorded time-lapse photographs of approaching traffic.

B. Results

Only four studies that measured the traffic effects of arrow boards were found in the literature. These studies indicated that arrow boards are generally effective in promoting earlier merging. Three studies found that arrow boards reduced speeds by 3 to 5 mph (5 to 3 km/h). Of the two studies that measured conflicts or erratic maneuvers, one study found no effect of arrow boards on conflicts, and the other revealed a trade-off between the reduction of erratic maneuvers and the increase of slow-moving vehicle conflicts.

The usage survey revealed that arrow boards were used more by state agencies than by cities, counties or utility companies. The most common applications of arrow boards were for moving-maintenance operations, freeway work zones, high-speed and heavy traffic conditions, and night work. Although, the placement of arrow boards is usually not specified, for those agencies that do have a specification, placement varies from at the start of the lane-closure taper or the point of traffic diversion to the center of the area being closed. Three of the states specified that only the flashing-arrow mode be displayed.

The human-factors investigations concluded that current arrow board design specifications are more than adequate to meet display requirements. The laboratory studies concluded that the arrow board, with either a flashing or sequential mode, connotes a lane closure ahead to most drivers, and that uses of the arrow board as a cautionary device on the shoulder or as a flashing cautionary display are confusing to the driver and may cause him to unnecessarily merge into another lane.

The human-factors studies of driver preferences for arrow board mode revealed that the flashing arrow and sequential chevron were clearly preferred over the sequential arrow (see Figure 1). Midwestern drivers regarded the chevrons as interchangeable with the flashing arrow, while Eastern drivers preferred the flashing arrow. Overall, the arrow board seemed to best convey its message when operating in the flashing-arrow mode.

The field studies measured driver responses in work zones with and without arrow boards. The placement, size, and mode of the arrow board were also varied.

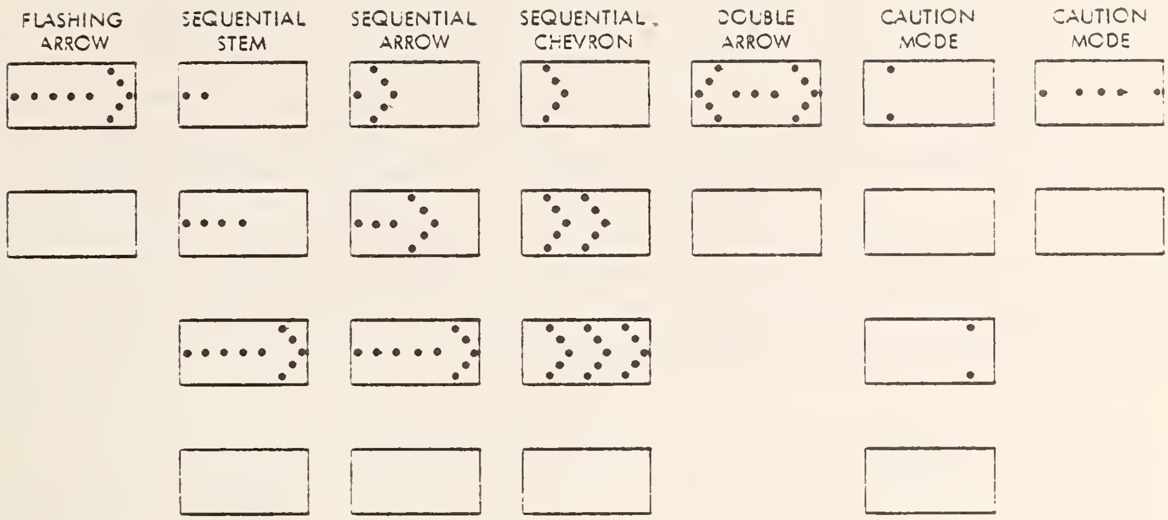

Figure 1 - Arrow Board Modes

To determine when the arrow board elicited a significant positive effect, the purpose of arrow boards was defined for three specific work zone situations. When a lane is closed, the arrow board should facilitate merging into the open lane(s). The effectiveness of the arrow board for this situation was determined by the location of lane changes and the safety of these lane changes. In diversion work zones (detours, crossovers, or bypass roadways), where traffic must move from its normal path but without a reduction in the number of lanes, drivers should remain in their own lane and follow the lane diversion without encroaching on adjacent lanes. The effects of the arrow board for this situation were measured by the number of unnecessary lane changes, by the number of encroachments on adjacent lanes and shoulders, and by the safety of the traffic operations. When work is being performed on the shoulder, drivers should remain in their own lane and not be lured into the work area or into following the work vehicle. Again, the effects of the arrow board were measured by the number of unnecessary lane changes, the number of encroachments on the shoulder or adjacent lanes, and the safety of the traffic operations. The safety of each of the work zone situations was determined by observing and classifying erratic maneuvers and conflicts.

The major results of the field studies were:

1. In lane closures, the presence of an arrow board produced lane-changing patterns that were closer to ideal. In other words, the arrow board encouraged drivers to leave the closed lane sooner and, consequently, fewer lane changes occurred close to the lane closure taper.

2. In traffic diversions, arrow boards produced some unnecessary lane changing; however, the number of these lane changes was small, particularly at night and for truck traffic. The arrow board did not have a clear effect on encroachments during the day, but encroachments tended to be lower at night. In traffic splits, where the traffic flow was separated, the arrow board caused vehicles to either remain in or move to the right lane, and decreased conflicts involving vehicles changing lanes near the split.

3. Arrow boards had little effect on traffic operations in moving shoulder closures on freeways. Conflicts due to slow-moving vehicles were greater when the caution-bar mode was used.

4. Placing the arrow board on the shoulder near the start of the taper generally produced a more satisfactory lane-changing pattern than placing the arrow board in the closed lane in the middle of the taper. However, the results of two tests, where the arrow board was placed on the shoulder upstream from the start of the taper, indicated that this placement may be even more effective than placement at the start of the taper.

5. The larger arrow board, 4 x 8 ft (1.2 x 2.4 m) was more effective than smaller arrow boards, particularly at night and during peak periods.

6. No differences were detected in the effect of various arrow board modes.

7. Slow-moving-vehicle conflict rates were normally increased when an arrow board was present. No clear trends were found relative to erratic maneuvers and conflicts associated with merging.

C. Interpretation of Results

Several major conclusions can be drawn from the results of each of the three phases of the research. First, arrow boards in lane closures are definitely effective in promoting earlier merging into the open lane(s). Second, the most effective placement of the arrow board is on the shoulder at, or upstream of, the start of the lane closure taper. Third, the 4 x 8 ft arrow board is more effective than smaller boards on all types of highways, and particularly at night and during peak periods. Fourth, although few significant differences in field-measured driver behavior could be attributed to the mode of the arrow board, the literature survey and human-factors studies indicate that the flashing-arrow mode is most effective in conveying its message to drivers. The case for uniformity would suggest a preference for the flashing-arrow mode for lane closures. Fifth, the arrow board is not generally beneficial in diversions, traffic splits, or shoulder-closure work zones. However, an arrow board may prove useful to correct detected operational problems in these work zones such as, (1) encroachments onto the shoulder in diversions, or (2) conflicts associated with lane changing near the gore of traffic splits.

Based on the interpretation of the results of all phases of the research, tentative guidelines for the application of arrow boards in work zones have been formulated. These guidelines are contained in Appendix B of this report Presented are design criteria for arrow boards and minimum recognition-distance requirements for various traffic conditions. The guidelines also rate arrow board effectiveness by type of site and operating conditions. These ratings can be used to choose arrow board sites in general, or to set priorities when the potential number of sites exceeds the available number of arrow boards. Appendix B also contains procedures for diagnosing unusual operating conditions at existing work zones that may indicate the need for an arrow board.

D. Further Research

Further research is needed to determine possible arrow board modes for use in diversions, traffic splits, and shoulder closure work zones. Also the placement of the arrow board in advance of the start of the taper should be tested at night.

II. INTRODUCTION

Safe and efficient work-zone traffic controls are more critical today than ever for two reasons. First, the public is increasingly demanding that work zones be safe for the driver and worker alike. Large court settlements have been the real consequence of these demands. Second, with the Interstate system nearly complete, highway monies are being shifted from building new facilities to improving the quality of service of existing facilities. Most of the Interstate mileage now requires maintenance, and the maintaining of other facilities that had been deferred during the construction of the Interstate system is now being carried out as well. Generally these maintenance operations must be performed in the presence of traffic.

The use of arrow boards (both trailer- and truck-mounted) has grown in recent years. Typically, these traffic control devices are used as supplementary devices to alert and guide the driver safely through a hazardous work zone. The arrow signal is used to attract attention to an aberrant situation in the roadway ahead which might violate a driver's expectancy of normal highway alignment. Most often, arrow boards are used for lane-closures;* however, they are sometimes also used where normal travel lanes are diverted laterally or where work is being done on the shoulder.

Because of a lack of national guidelines** arrow board use varies greatly. Some agencies specify arrow boards for use at lane closures only while others regularly use arrow boards at detours or at shoulder closures. A great many modes of operation are possible, including flashing arrow, sequential chevron, double arrow, and sequential arrow, and these are used interchangeably by some agencies. Others, however, specify only one mode. The placement of the arrow board relative to a lane-closure taper or a diversion also varies considerably. Some agencies specify that arrow boards "be positioned behind the required channelization in the center of the area closed" while others specify that they "be placed on the shoulder at the point where a lane-closing transition begins."

The purpose of this project was to develop objective criteria for the use and placement of arrow boards in work zones. These criteria determine those conditions that warrant arrow board use and specify where the arrow board should be placed to provide the safest and most efficient traffic movement possible.

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* See Appendix A for definition of terms.

** A section on arrow board use and design was adopted for the National Manual on Uniform Traffic Control Devices (MUTCD) in May 1977.

The project scope was confined to arrow boards; variable word message signs and portable flashing beacon signs were not included. The project considered the application of arrow boards to all types of work zones including lane closures, roadside or shoulder work, and diversions (detours, crossovers, or bypass roadways). Moving and stationary, long-term and short-term operations were studied. The locations included two-lane and multi-lane highways in rural and urban areas. Both day and night operations were investigated.

The research was conducted in three phases. In the first phase, a survey was undertaken of all available literature on arrow-board use and effectiveness, and 117 traffic control manuals from a cross-section of states, cities, counties, and utility companies were reviewed. Human factors investigations were conducted in the second phase to determine driver information requirements, expectancy, and understanding of arrow boards. The human factors investigations included two studies in which subjects viewed film clips of arrow boards and answered questions about their understanding of the particular arrow-board message.

The third phase of research was an intensive field study of driver responses to arrow boards in actual work zones in California and Illinois. Two types of field studies were conducted. Long-term construction projects were examined using tapeswitches attached to the pavement and connected to a 20-pen event recorder. Short-term construction and maintenance activities were studied with time-lapse photography. A 16-mm Bolex camera was mounted on the arrow-board trailer or maintenance vehicle to film approaching traffic. Twenty-six construction sites were studied, and 23 hours of maintenance activities were filmed.

This report is organized into seven sections. The first section is an executive summary of the results and conclusions of the research. Following Section II, which is an introductory section, Section III reports on the results of the literature search and the surveys of arrow board manufacturers and agencies that use arrow boards. Sections IV and V cover the human factors studies conducted on arrow board design and driver understanding of arrow boards. Section VI, "Arrow Board Field Studies," details and summarizes investigations related to construction-site and maintenance activities. Section VII provides conclusions formed from all phases of the research. Appendix A contains definitions of the major work-zone and arrow board terms used in this report. Appendix B gives recommendations for the use and placement of arrow boards in work zones. These recommendations were formulated based on all phases of the research. Appendix C contains the detailed results of the field studies, and Appendix D describes the rationale of the analysis of variance procedure used.

III. STATE OF THE ART OF ARROW BOARD USAGE

Three sources were examined to determine the state of the art of arrow board usage in work zones. The first was all available research on the effectiveness of arrow boards and principles of traffic control in other lane closure situations. The second source was 117 manuals on work zone traffic control from various states, counties, cities, and utilities. The third source of information was telephone calls to officials in various state and local governmental offices and utility offices.

A. Synthesis of Arrow Board Literature

A literature survey was conducted to determine the current status of arrow board usage for highway construction and maintenance activities. Because research dealing directly with arrow boards has been limited, lane drop studies were also surveyed.

1. Arrow Board Studies: Only four studies were found that measured the effects of arrow boards. One study by the California Department of Transportation[1/] tested 13 arrow boards ranging in size from 1 x 5 ft (0.3 x 1.5 m) to 4 x 8 ft (1.2 x 2.4 m) to determine the most effective size and operation for arrow boards. Testing was done by setting up the arrow boards on the median shoulder of a freeway, and displaying a merge-right pattern. All boards were mounted on trailers at a height of 8 ft (2.4 m) above the pavement with the right edge 1 ft (0.3 m) from the edge of the median lane. The median lane was not actually closed, and no construction or maintenance was underway. The measure of the arrow board effectiveness was the percent decrease in volume of the median lane at various distances from the sign. Also, radar speed measurements were taken 2,115 ft (630 m) upstream of the board.

The California study found that the larger arrow boards were more effective than the smaller boards during the daytime. At night, this relationship did not always hold due to the increased importance of light intensity and spacing between lenses. The study also found a sequencing pattern most effective during the day, but recommended a flashing pattern for nighttime operation. A "black-out" interval, with no lights activated, was recommended for the sequencing pattern to avoid confusion on the intended merge direction. The speed measurements revealed a drop in speed up to 5 mph due to the arrow boards, but the variance between boards was not significant. The study made no comparisons of the safety effects of the boards.

A study in Illinois[2/] of a bridge repair project tested the effect of two truck-mounted arrow boards on the capacity of the section where two lanes of traffic merged into one. One board was located approximately 1/2 mile (0.8 km) upstream of the merge point and the other was placed behind the barricades at the merge. The effect of the arrow boards was measured by determining whether vehicles merged farther upstream than they normally would without the boards. The study concluded that the arrow board trucks definitely promoted the earlier merging of traffic. This study also predicted that the more orderly merging of traffic effected by the arrow boards would reduce traffic accidents near the merge location. However, no data on the safety effects of the boards were collected. The ratio

$$\left(\frac{\text{percent vehicles in closed lane without arrow boards}}{\text{percent vehicles in closed lane with arrow boards}}\right)$$

was compared for both merge directions. The percentages were determined for three points, 4,700 ft (1,400 m) before merge, 2,100 ft (630 m) before merge, and at the point of merge. The ratio was consistently higher for the right lane closure, indicating that the arrow board trucks may be more effective in moving vehicles to the left than to the right, but the comparison was not statistically valid because of small samples for one merge direction.

A study by the Louisiana Department of Highways[3/] evaluated the effectiveness of various warning systems in controlling traffic flow through work zones. The warning systems varied according to sign size, sign height, sign legend, and presence or absence of a trailer-mounted arrow board (3.5 x 6.5 ft) (1 x 2 m) utilizing sequentially flashing chevrons. Systems were evaluated by measurement of spot speeds, traffic conflicts, and queuing of vehicles. The results showed that arrow boards significantly reduced speeds and queuing, but did not significantly change the number of "conflicts."* The study concluded, "present signing schemes requiring lane closures should be reinforced with some type of directional flashing signs."

An MRI study[4/] also examined the effects of arrow boards on work zone traffic operations. The arrow boards were tested in combination with several other speed control devices. The arrow board was located in the closed lane near the transition point. Speeds were measured at four locations in the zone. Erratic maneuvers and conflicts were measured in the taper area of the zone.

The MRI studies showed that an arrow board in the transition area of the zone reduced speed in this area by nearly 3 mph (4.8 km/hr). The arrow board also reduced erratic maneuvers by 25%, but increased the slow-moving

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* This study employed a very restrictive definition of a "conflict" which was a stop by a vehicle in the closed lane. This definition resulted in very low "conflicts" counts that may have affected the results of the study.

vehicle conflict rate by 20%. Since erratic maneuvers are actions of individual free-flowing vehicles, and the slow-moving conflicts are interactions between two or more vehicles, these results indicate the arrow board will likely increase slow-moving conflicts as traffic volumes increase.

Clearly, the references cited indicate that arrow boards can be of benefit in traffic control in work zones. The MRI study shows, however, that there may also be negative aspects of indiscriminate use of arrow boards.

2. Lane Drop Studies: The most frequent use of arrow boards is in construction zone lane closures. Therefore, literature on lane drops, not related to construction, was reviewed in hopes of drawing some useful comparisons between the two situations.

A study[5/] conducted with the UCLA Driving Simulator, attempted to measure a driver's performance in a lane drop situation. The emphasis of the study was on comparison of the left lane drop versus the right lane drop. A slightly larger number of failures to merge with traffic in the adjacent lane was found for the right lane drop, although the sample of failure statistics was small and, therefore, the results tentative. Another study[6/] found that accidents varied as to whether or not the lane was on the right or left. These two studies, in addition to the Illinois arrow board study, raise the possibility of definite differences in driver performance between the left and right merge maneuvers, possibly requiring different traffic control measures for optimum effectiveness.

A study[7/] to define operational problems at freeway lane drops developed eight basic design principles for the construction or remedial treatment of freeway lane drops, three of these apply to construction lane closures. They are: (a) provide continuous visibility; (b) minimize attention-dividing conditions; and (c) provide adequate transition cues. The importance of proper geometrics (and the corresponding continuous visibility) was also emphasized in a study by the Kentucky Department of Highways.[8/] The study observed that traffic control devices are not as effective as proper geometrics in reducing conflicts at the observed lane drops. The greatest potential benefit from the use of arrow boards may be at locations with restricted visibility where drivers need information from other sources regarding the route ahead. The need to minimize attention-dividing conditions, resulting in decreased driver confusion, is well established as is the necessity of adequate transition cues. Hopefully, arrow boards can play an important role in construction zones with regard to the latter.

A Federal Highway Administration study[9/] focused on driver expectancy to define signing problems and develop solutions. The study stated that driver confusion arises from expectancy violations, and the wide variation in lane drop signing is a major source of these expectancy violations.

Uniform signing treatments, consistently applied, are required. The principles set forth in this study indicate the need for uniform and consistent applications of arrow boards in work zones if they are to attain their potential to effectively guide traffic.

B. Usage Survey of State, Cities, Counties, and Utilities

1. Review of Manuals on Traffic Control: One hundred seventeen traffic control manuals from a wide assortment of states, cities, counties and utilities were reviewed. Of the 117 only 16 contained information on arrow board usage. The 16 manuals are shown in Table 1.

Of these 16 manuals, the only reference to arrow boards in five of them (11, 12, 13, 14, and 15) was the depiction of boards in diagrams of typical construction zone traffic control schemes. No specifications or standards for design, operation, or use were given. Two manuals (10 and 16) contained only very short descriptions of arrow boards and gave no standards or specifications for design and operation. The guidelines for use consisted of brief notes that arrow boards had been found effective for moving operations under high density conditions without using the advanced construction warning signs. This leaves only 9 out of 117 manuals that contained relatively complete standards and guidelines for arrow board design, operation, and use. (Possibly more agencies have added arrow board specifications to their manuals since the addition of an arrow board section to the national MUTCD in May 1977).

a. Size: Eight manuals contained specifications regarding the permissible size of arrow panels. Minimum acceptable sizes ranged from 2 x 4 ft (0.6 x 1.2 m) for five manuals (1, 3, 4, 8, 9) to 4 x 8 ft (1.2 x 2.4 m) for one (Manual 5). Manual 8 specified use of a 2 x 4 ft (0.6 x 1.2 m) panel only where the speed limit is less than 40 mph (65 kph) and a 3 x 5 ft (0.9 1.5 m) panel where the speed limit is 40 mph (65 kph) or greater.

b. Mounting Height: Specifications for mounting height, given in Table 2 are defined as the distance from the pavement surface to the bottom of the arrow board.

c. Legibility Distance: This refers to the distance at which the driver should be able to see and comprehend the arrow board (see Table 3).

d. Lens Size: Manuals 1 and 7 contained no standards for minimum acceptable lens diameter for use in arrow boards. Five inch (127 mm) lenses were specified in Manuals 10 and 11, and 4 inch (102 mm) lenses were specified in Manuals 2, 3, 4, 8 and 9.

TABLE 1

MANUALS CONTAINING INFORMATION ON ARROW BOARD USAGE

Manual Number	Document and Agency
1	"Manual on Uniform Traffic Control Devices for Streets and Highways," Federal Highway Administration, U.S. Department of Transportation
2	"Traffic Barricade Manual," Phoenix, Arizona, Traffic Engineering Department
3	"Manual of Warning Signs, Lights and Devices for Use in Performance of Work Upon County Highways, Contra" Costa County, California, Department of Public Works
4	"Manual of Warning Signs, Lights and Devices for Use in Performance of Work Upon Highways," California Department of Transportation
5	"Manual on Traffic Controls and Safe Practices for Street and Highway Construction, Maintenance and Utility Operations," Florida Department of Transportation
6	"Traffic Control Devices Used for Street and Highway Construction and Maintenance Operations," Georgia Department of Transportation
7	"Manual of Uniform Traffic Control Devices," Michigan Department of State Highways
8	"Manual of Uniform Traffic Control Devices, Appendix B," Minnesota Department of Highways
9	"Manual of Uniform Traffic Control Devices," New York State Department of Transportation
10	"Manual of Traffic Control for Construction and Maintenance Operations," Ohio Department of Transportation
11	"Handbook for Work Area Traffic Control," Publication 112, Pennsylvania Department of Transportation
12	"Work Area Protection Guide," Philadelphia Electric Company
13	"Handbook for Work Area Traffic Control," Pennsylvania Power and Light Company
14	"Typical Traffic Control for Work Area Protection," Virginia Department of Highways and Transportation
15	"Policy Manual," Commonwealth of Virginia, Department of Highways, Maintenance Division
16	"Traffic Control for Street and Highway Construction and Maintenance Operations," West Virginia Department of Highways, Traffic Engineering Division

TABLE 2

MOUNTING HEIGHT

Manual	Specifications
1, 5, and 6	None
2	8 ft
3	8 ft for high speed units
	6 ft for low speed units
4	7 ft for high speed open highway units
	6 ft for low speed open highway units
	4 ft for low speed city street units
7	7 ft for 4 x 8 ft panels
	4-1/2 ft for 3 x 5 ft panels
8	7 ft
9	4 ft

1 ft = 0.3 m

TABLE 3

MINIMUM LEGIBILITY DISTANCE FOR SUNNY DAY OR CLEAR NIGHT

Manual	Specifications
2, 5, 7, 8, and 9	None
1	1/2 mile for 2 x 4 ft panel
	3/4 mile for 2-1/2 x 4-1/2 ft panel
	1 mile for 4 x 8 ft panel
3 and 4	1/2 mile for low speed units
	1 mile for high speed units
6	1,000 ft

1 mile = 1.6 km
1 ft = 0.3 km

e. Lens Color: All manuals specified the exclusive use of yellow or amber lenses.

f. Lens Flash Rate: There was wide variation for the flash rate of lamps among manuals that included such a specification (Table 4).

TABLE 4

FLASH RATE

Manual	Specifications
3, 4, 5 and 8	None
1	Not less than 25 per min.
2 and 9	40 to 60 per min.
6	50 to 60 per min.
7	30 per min.

g. Number of Lenses: Only four manuals contained specifications on the number of lenses required for an arrow board. Manual 1 specified minimum requirements of 12 lamps for 2 x 4 ft (0.6 x 1.2 m) panels, 13 lamps for 2-1/2 x 4-1/2 ft (0.8 x 1.4 m) panels, and 15 lamps for 4 x 8 ft (1.2 x 2.4 m) panels. Manuals 3, 4, and 8 require a minimum of five lenses per chevron, and a minimum of three lenses to form a stem.

h. Spacing of Lenses: The only manual to mention lens spacing was Manual 8, which contained a brief note stating that arrow size shall substantially fill the board.

i. Light Intensity: Manuals 1, 2, 7, 8, and 9 contain a specification requiring the capability to dim the lamps of an arrow board for nighttime operation.

j. Power Source: Manuals 1, 5, and 9 do not specify a source of power for arrow board usage. A provision for an "electric source" is contained in Manuals 2, 6 and 8; and 3, 4 and 7 specify the capability to operate from a 12-volt direct current source.

k. Panel Surface: Manuals 1, 6, 8, and 9 contain a specification for the panel surface to be finished nonreflective black.

l. Display Configuration: Manual 9's only provision regarding display configuration is that the panel shall consist of flashing indications arranged to form an arrow. Manual 8 provides for a left and right arrow message. Seven manuals 1, 2, 3, 4, 5, 6, and 7 specify that arrow boards shall have the capability to show a left arrow, right arrow, and both simultaneously for diversion of traffic in both directions. In addition two manuals, 1 and 5, specify that arrow boards shall be capable of a general, nondirectional warning configuration. Manuals 1, 3, 4, 6, and 8 allow for sequentially flashing chevrons in lieu of the constant flashing arrow, Manuals 3, 4 and 8 also allow a sequential shaft on a flashing chevron.

m. Guidelines for Arrow Board Use: Guidelines for conditions under which arrow boards should be employed are painfully lacking. The two manuals previously mentioned (10 and 16) state that the panels had been found effective for moving operations under high density conditions without using the advance construction warning signs. Only three other manuals contain any guidelines for use. Manual 1 states the "...panel may be used for day or night closures, slow-moving maintenance or construction activities on the traveled way, or extremely hazardous high density and speed conditions." Manual 2 suggests the use of arrow boards where highway construction or maintenance activities demand channelization with a special emphasis on their use during hours of darkness. Manual 7 is somewhat more specific with its guidelines. The suggested criteria are:

(1) All urban freeways.

(2) All rural freeways (lanes closed more than 6 hours).

(3) On arterials with ADT in excess of 25,000.

(4) At other locations where field conditions justify.

n. Guidelines for Placement of Arrow Boards Within Work Zones: Information on the optimal placement of arrow panels is as lacking as information on their preferred use. Three manuals contained placement guidelines. Manual 2 states the "...arrow board in operation must be positioned behind the required channelization in the center of the area closed throughout the restricted period, except when used on a moving vehicle." Manual 3 specified that arrow boards "... be placed at the point of actual diversion of traffic." Manual 6 contains the guidelines that the "arrow shall be placed on the shoulder adjacent to the point where a lane closing transition begins." There is, obviously, wide disagreement about the arrow board placement that will result in the most efficient diversion of traffic.

2. Telephone Conversations with Various Users and Suppliers of Arrow Boards: Several officials in various state and local governmental offices, utility offices, and manufacturing firms were contacted by phone to determine the extent of arrow board use, the type and design of arrow boards used, and guidelines for the use and placement of arrow boards. A total of 31 agencies were contacted. Those contacted are shown in Table 5.

These agencies were chosen based on the information found in the manuals on work zone traffic controls. Also the American Public Works Association and the American Traffic Services Association were contacted to find good sources of information.

a. Local Governments: Two cities and one county were contacted. The level of arrow board use by these agencies does not approach the level of many state governments. Local officials felt that they did not have as many situations that might require an arrow board as state agencies. Uses mentioned included pavement marking operations and road work on high speed freeways.

b. State Governments: The traffic departments of 10 state transportation or highway agencies were contacted by telephone. Information on design specifications and guidelines for arrow board usage was requested. All 10 agencies sent additional information. Responses indicate that the amount of arrow board usage varies among the states. Maryland and Michigan have many in use and have complete specifications for their design and application. One state uses very few arrow boards and does not write specifications for their use.

Some highway departments are structured in a way which permits the field districts to operate as separate entities; generally receiving only advice and guidance from the central office. Because of this, some central office traffic departments were unable to provide the numbers of arrow boards in use; since the construction, maintenance and traffic sections of each field district would have to be contacted to determine the number of arrow boards in each section. Illinois, Minnesota and Ohio are examples. In Florida and Ohio, contractors supply their own arrow boards. This may be the case for most states.

Nominal sizes of arrow boards in use include: 2 x 4 ft (0.6 x 1.2 m), 3 x 6 ft (0.9 x 1.8 m) and 4 x 8 ft (1.2 x 2.4 m). The most prevalent sizes of arrow boards in use are 3 x 6 ft (0.9 x 1.8 m), and 4 x 8 ft (1.2 x 2.4 m). The 2 x 4 ft (0.6 x 1.2 m) and 3 x 6 ft (0.9 x 1.8 m) arrow boards are generally mounted on top of truck cabs. The 4 x 8 ft (1.2 x 2.4 m) model is attached to a trailer and has a mounting height of 7 ft (2.1 m).

In general, there is no preference for either the arrow or chevron modes, although the various forms of each mode are required. Exceptions are Maryland, Michigan and West Virginia which prefer only the arrow

TABLE 5

AGENCIES CONTACTED

1. Kansas City, Missouri, Department of Transportation
2. Baltimore County, Public Works Department
3. Washington, D.C.
4. Florida, Department of Transportation
5. Georgia, Department of Transportation
6. Illinois, Department of Transportation
7. Maryland, Department of Transportation
8. Michigan, Department of State Highways and Transportation
9. Minnesota, Department of Highways
10. Ohio, Department of Transportation
11. Pennsylvania, Department of Transportation
12. Virginia, Department of Highways and Transportation
13. West Virginia, Department of Highways
14. Bemis and Son, Inc.; Kalamazoo, Michigan
15. Bisi-Flash Rental; Dedham, Massachusetts
16. Casell Company, Inc.; Napa, California (Early Warner Sales and Rental; Kansas City distributor)
17. LNC Flashing Barricade; Canton, Massachusetts
18. R. E. Dietz Company; Syracuse, New York
19. Rhodes and Maine, Inc.; Anaheim, California
20. Royal Industries; Los Angeles, California
21. Warning Lites of Illinois, Inc.; Addison, Illinois
22. Work Area Protection Corporation; Addison, Illinois
23. Empco-Lite; Elgin, Illinois
24. Protection Services, Inc.; Harrisburg, Pennsylvania
25. Kansas City Gas Service Company
26. Kansas City Power and Light Company
27. Pennsylvania Power and Light Company
28. Philadelphia Electric Company
29. Mr. Mel Myer; Ex-Chairman; Standards Committee, ITE; Committee 45-9; "Portable Flashing Arrow Signs."
30. Mr. Bob Garrett, American Traffic Services Association
31. American Public Works Association

mode. Power source and electronics are not thought to be critical factors in the choice of arrow boards.

States that require light intensity adjustment, require both automatic and manual adjustments. Automatic light intensity adjustments are to occur when ambient light conditions reach 5 ft-candles (54 lux). The required range of voltages supplied to the arrow board lights for day and night operations are 12 volts and approximately 6 volts, respectively. The required flash rates ranged from 25 to 35 flashes per minute in Michigan to 55 to 60 flashes per minute in Georgia. All states require a 50% dwell time. Lens specifications, including spacing, appear to be similar.

Guidelines for arrow board usage indicate that they are used mostly for lane closures, followed by shoulder closures, moving operations, maintenance operations, and lane diversions.

c. Manufacturers/Rental Agencies: Thirteen manufacturers and/or rental agencies were contacted by telephone. Eight sent information as requested. Only three suppliers gave no information at all. Of those responding, all suppliers manufacture or rent the 4 x 8 ft (1.2 x 2.4 m) arrow board and only Protection Services, Inc., and Warning Lites of Illinois, Inc., do not have the 3 x 6 ft (0.9 x 1.8 m) arrow board. Rhodes and Maine Inc., Royal Industries, Work Area Protection Corporation and Empco-Lite Company supply the 2 x 4 ft (0.6 x 1.2 m) arrow board.

Most manufacturers offer arrow boards with either gasoline or diesel engines and the battery-powered mode for temporary operation.

The R. E. Dietz Company arrow boards only have the arrow mode but the other companies supply arrow boards with both the arrow and chevron modes.

The light intensity adjustments offered by the suppliers are equivalent to those required by the states. The lights of the Empco-Lite Company arrow boards have the capability of operating at 3 volts for night use, however.

The flash rates offered by suppliers are comparable to that required by the states. The Empco-Lite Company arrow boards have an adjustable flash rate which ranges from 20 to 80 flashes per minute; a slightly larger range than the others. All on-off flashing modes have a 50% dwell time. The sequential modes, which consist of three sequences, have dwell times of 75%, 50% and 25% for each sequence, respectively.

While the states present guidelines for arrow board usage, suppliers, in general, prefer not to offer any guidelines, for fear of legal problems which may arise.

d. Utility Companies: The four utility companies contacted do not use arrow boards; since most of their work is on city streets, they generally see no need for arrow boards.

e. Other: Mr. Mel Myer, ex-chairman of an Institute of Transportation Engineers (ITE) committee researching arrow boards was unable to give any pertinent information, since the committee was just starting work. Mr. Robert Garrett of the American Traffic Services Association and Mr. Jerome Franklin of the American Public Works Association were also contacted for advice on which agencies would be able to supply information for the survey.

The results of the arrow board usage survey indicate that the use of arrow boards is becoming more popular because of the belief that they are an effective traffic control device. The numbers of state-owned devices in the states we contacted, varies from approximately 10 in West Virginia to 100 in Michigan. The 3 x 6 ft (0.9 x 1.8 m) and 4 x 8 ft (1.2 x 2.4 m) arrow boards are the most popular. Arrow boards built to the design specifications required by the transportation and highway departments can easily be supplied by the manufacturers. In general, there is no preference for either the arrow or chevron modes. Guidelines for the use of arrow boards are similar among the states, except that some agencies require usage, while other agencies make it optional. States that indicated a guideline for placement generally mentioned a preferred placement near the start of the taper.

IV. HUMAN FACTORS CONSIDERATIONS IN ARROW BOARD DESIGN AND OPERATION

The state of the art review revealed a wide range of arrow board designs and criteria for the use and placement of arrow boards. This section will discuss the requirements for arrow boards from a human factors viewpoint. First, the development of performance criteria for arrow boards are discussed, and then these criteria are compared to arrow board design and operational characteristics.

A. Performance Criteria for Arrow Boards

As stated earlier in this report, the flashing arrow board is a traffic control device with high target value used primarily to divert drivers from a closed lane in a construction zone. The crucial issue, from a human factors viewpoint, is to insure that the arrow board displays its directional image well in advance of the hazardous lane closure, so that the driver can safely and effectively negotiate a merging maneuver into a parallel lane.

Viewed in this context, then, the sighting of an arrow board is subject to principles developed in Decision Sight Distance research. Decision Sight Distance (DSD) has been defined in concept as:

> "The distance at which a driver can detect a signal (hazard) in an environment of visual noise or clutter, recognize it (or its threat potential), select appropriate speed and path and perform the required action safely and efficiently."[10]

Since arrow boards, serve as warnings of the hazard ahead, their signal must be detectable from recommended distances derived from experimental research on DSD. One useful table of such design distances is found in a report by McGee, Moore, Knapp and Sanders[11] wherein, at an operating speed of approximately 55 mph (88 kph), DSD for the hazard should be approximately 1,000 ft (300 m). (Similar values for varying design speeds are shown in Table 6.) In essence, applying DSD to arrow board performance, it is evident that the flashing signal must be detectable and clearly recognized by 99% of drivers at an absolute minimum distance of 1/5 mile or 1,000 ft (300 m). To provide for high traffic densities which limit safe gaps for merging and occasional high speed drivers, an optimum performance standard is as follows:

TABLE 6

RECOMMENDED DECISION SIGHT DISTANCE[11/]

Design Speed (mph)	Times (Seconds)				Decision Sight Distance (ft)	
	Pre-Maneuver		Maneuver (Lane Change)	Summation	Computed	Rounded For Design
	Detection & Recognition	Decision & Response Initiation				
30	1.5 – 3	4.2 – 6.5	4.5	10.2 – 14	449 – 616	450 – 625
40	1.5 – 3	4.2 – 6.5	4.5	10.2 – 14	598 – 821	600 – 825
50	1.5 – 3	4.2 – 6.5	4.5	10.2 – 14	748 – 1027	750 – 1025
60	2 – 3	4.7 – 7.0	4.5	11.2 – 14.5	986 – 1276	1000 – 1275
70	2 – 3	3.7 – 7.0	4.0	10.7 – 14	1098 – 1437	1100 – 1450
80	2 – 3	4.7 – 7.0	4.0	10.7 – 14	1255 – 1643	1250 – 1650

1 mph = 1.61 kph
1 ft = 0.30 metre

- Detect presence of flashing lights at 1-1/2 mile (2.4 km)
- Recognize arrow symbol and direction of arrow at 1 mile (1.6 km)
- The above must be possible for 99% of the driving public
- The above should be possible in clear weather, both day and night conditions, urban and rural freeways.

The numbers 1,000 ft, 1-1/2 mile, and 1 mile are based on the decision sight distance concept of a hazard avoidance model.[11/] Insofar as the arrow board is the first target to be detected since its beacon is so powerful, these distances are specified as an approximation for detecting of the hazard (1-1/2 miles), then recognition (1 mile), then for absolute last minute identification (1,000 ft) before perturbation, conflicts, or collision occurs. For the arrow board to be visible in advance of the 1-1/2 mile point would simply be a flashing image to the driver which would create premature alarm and lane diversion. This range of distances for detection and recognition has been set to complement the driving decision-making processes necessary to negotiate hazards according to the model.

The requirement that the arrow board be visible for 99% of the driving public is based on the importance that virtually all drivers see and react to the arrow board. In traffic engineering, the 85 percentile has been frequently used as a criteria for roadway design, speed, and guide signing. Arrow boards provide a far more urgent message than, for example, guide signing. The arrow board is most likely in the lane of travel and is a prime source of warning and directional information to get drivers out of that lane. The 99% level simply reflects the urgency and importance of the arrow board function while acknowledging that it is unreasonable to expect to impact every single driver in the nation. Using these performance standards as a basis, the various design considerations may be examined.

B. Driver Detection and Recognition

In light of the above recommendation of a decision sight distance guideline, existing literature demonstrates that flashing warning lights have a high attention value well in excess of that required for detection.[12,13/] Many research studies in the applied psychological literature indicate the assets of flickering lights[14/] and brightness contrast in this original detection task.[15/] In fact, Swezey[16/] speaks of the crucial importance of brightness contrast of the target against its background--that it should be flashing lights against a flat black for maximum effectiveness. In this same vein, target size and luminance are addressed as a single detection task by recent researchers.[17,18/] Also, Benignus et al. (1976)[19/] demonstrated the superiority of steady rate signals on capturing the attention of subjects as the rate of on-off flashes increased. This agrees with the findings of Ruden et al. (1977).[13] When comparing these experimental findings with the design specifications of arrow boards in use, no drastic design changes appear necessary. Considering the design specifications of major arrow board manufacturers', the lens size, the flash rates,* etc., are all reasonable for signal detection well in advance of the prescribed minimum sight distance of 1,000 ft (300 m). Current arrow boards are more than adequate as detectable light sources for the optimum sight distances noted earlier. Also, although no research has been done on arrow recognition distances, informal observations by the authors suggest that arrows are recognizable from about 1 mile (1.6 km).

Some definition should be given to manufacturers' "visibility" specifications. They could be either detection of the signal lights themselves, or recognition of the arrow image as a signal. It is recommended that the latter be specified as the criterion, and a standard method needs to be established for testing conformance to the criterion.

Two points can be made about degrading of the boards' capabilities, as a function of placement and sight distance available. One, on a high speed controlled access facility where a lane closure is initiated by the flashing arrow, a sight distance of more than 1 to 2 miles (1.6 to 3 km) for the arrow board may actually constitute a hazard since this sighting is usually not a recognition of the arrow image[12,13] (cf. also field observations of arrow board operations at measured distances by the authors). In this regard, a bigger, more powerfully flashing target upgraded from those already available might inspire a real hazard too far in advance of proper assimilation of the intended message. Second, a point related to the high powered nature of the image displayed, involves arrow board usage on freeways versus arterial locations. No available literature directly documents the use of arrow boards on arterial highways. It seems intuitively obvious that in most urban arterial locations, other channelizing and traffic diverting devices would be much more cost-effective than an arrow board display in an already close up, slow-moving traffic stream. These questions of use of arrow boards in arterial situations are discussed further in the field studies section (Section VI).

C. Light Intensity/Glare

The arrow display of most arrow boards consists of as many as 10 bulbs of 8,800 candlepower each, giving an intensity of approximately 88,000 candlepower. This is quite intense enough to capture the attention of the driver, as shown in studies by ATSA,[20] Ruden,[13] and Hulbert and Burg,[12]

* For warning only (no symbolic message included) devices, flash rates in the 50 to 120 per minute range are optimum, but where an arrow must be recognized, slower rates, 40 to 50 per minute, are optimum.

and Goldblatt.[21] As mentioned previously, the power of the flashing image is such that a vehicle passing close up may be subjected to a glare condition, especially at night or in inclement weather.[12] Also, this much light completely eliminates any driver dark adaptation. This could pose a problem for drivers where it is quite dark, beyond the arrow board. Two simple design principles address this potential problem. One, lens hoods are found on arrow boards. Two, automatic dimmers are found on most arrow boards. The lens hoods recommended are the 360 degree type which encase the entire lens and not the 180 degree traffic light type found on some boards. The 360 degree lens hoods best cap dispersing light to passing drivers and, in turn, direct the flashes outward in a straight line perpendicular to the board.*

Since no empirical data were found directly documenting a glare problem with arrow boards, particularly at night, the authors conducted a brief field investigation of this phenomenon. In this investigation, photometer readings of the ambient conditions, the background of the board, and the lamps themselves were recorded. These readings were taken after dark on an unlighted, interstate highway. Various subjects were asked to drive toward the arrow board and tell when they experienced the following:

. Detection of the arrow board as a flashing signal

. Recognition of arrow image

. Beginning of image deterioration (glare or distortion)

. Any discomfort because of light intensity (glare)

Subjects reported experiencing the arrow board in the above sequence. First, detection consisted of reporting seeing a flashing set of lights. The second response, was the resolution of an arrow board image. It was not until very close proximity to the arrow board that a discomforting glare sensation occurred: from approximately 100 to 200 ft (30 to 60 m) up to parallel with the board.** This item is crucial, however, since motorists can be blinded in a split second,[22] and effect a dangerous swerving maneuver or completely lose their dark adaptation after going past the arrow board. It is reasonable

* Other techniques could be used but are probably not as cost-effective. One is focusing lenses, and the other is polarized lens. If an arrow is not recognizable at 1 mile, these same techniques could be used to improve arrow definition and hence, recognition distance.

** This was a conservative situation in that there was considerable other traffic creating ambient light before and after the arrow board.

to assume that the glare effect near the arrow board is enhanced in fog and other inclement conditions.[12] Since the effect occurs only close to the arrow board, it seems particularly imperative to use the 360 degrees lens hood on each lamp. This way, the driver will be protected from the then extraneous flashes as he parallels the arrow board. A final word might be said to advocate a further dimming potential of the boards. Current capabilities commence dimming of luminance as ambient conditions fall below 5 candlepower (54 lux). This could be upgraded to be more sensitive to inclement weather conditions and begin dimming with lesser diminution of daylight. Also, a further reduction of intensity (5 to 10%) at night would probably not degrade arrow board performance, and would have a small impact on glare reduction, but probably does not gain design or operational savings.

D. Angularity/Placement

The question of angularity of alignment with respect to the oncoming driver is in most cases simply addressed by the literature on general human factors visual display design principles. In general, a straightforward, direct image confronting the driver will best attract his attention and convey the intended message.[23] This means, then, that the arrow board is optimally placed head-on to the driver, perpendicular to the shoulder of the roadway. Slight deviation from this principle is appropriate only in a curved roadway section. This principle is consistent with the intent of the arrow board to move drivers out of a lane, not to change driver behavior in all lanes of travel.

The placement issue can be looked at from two dimensions: first, shoulder vs. lane placement; and second, beginning of construction zone taper vs. deeper into the zone. The shoulder vs. nonshoulder question is directly related to the meaning that the directional arrow board conveys. Since the empirical data (covered in Section V) and various literature sources indicate that the arrow board connotes lane closure, the board is most effectively placed directly in the lane that is being closed. The role of the arrow board on the shoulder to indicate some warning of hazards was discussed earlier, but a definite recommendation cannot be made without a more thorough experimental investigation. Placement of the arrow board at the beginning of the construction zone lane closure is the most effective position for the driver. This is documented by such reports as Graham, Paulsen, and Glennon.[4] Also some state highway traffic manuals advocate this placement. This placement is further supported by experimental evidence of Bruce and Morgan,[24] where the symmetry of the visual pattern of the construction zone is violated if an arrow board is placed deep in the zone. The primary function of the arrow board is the initial warning to the driver from afar that a hazard situation is ahead, and a lane shift is required. After the driver nears the zone, the other types of channelizing devices, such as cones and barricades, are directing the driver. Therefore, arrow board placement is most efficacious at or very near the beginning of the lane closure, since it is the first signal to be recognized and processed.

The implementation of arrow boards must be correct or their advantages will be lost. For example, as observed on local highways, a contractor placed an arrow board and other devices at exactly the distances specified by a state prepared plan. However, the arrow board was over the crest of a hill and could not be seen until drivers were within a few hundred feet of the zone. Guidelines for use of arrow boards must be carefully prepared and used by engineers and construction workers.

E. Ambient Light Conditions

Most factors of importance related to the use of arrow boards under varying ambient conditions have been alluded to in previous sections of this discussion. For example, the California study[1/] tested arrow board effectiveness in causing drivers to shift lanes and demonstrated the superiority of the flashing on-off arrow over the sequencing chevrons at night. It is also documented that flashing lights in general are a strong beacon attracting immediate attention at night,[12,13/] and fading to near indiscriminability in bright sunlight. Since most arrow board have automatic dimming features which can also revert to manual controls, the primary recommendation in this regard is to expand both the upper and lower limits of intensity capabilities so that the arrow board may be automatically or manually as sensitive as possible to changing ambience. As stated in the Hulbert and Burg report,[12/] "viewing conditions are often far less than optimum due to glare, fog, rain, etc., and moving or intermittent visual signals are several times more likely to be detected than nonmoving or steady signals under the same viewing conditions." As such, this information is adapted from research on barricade flashing lights and railroad grade crossing signal lights. No direct empirical evidence exists regarding signal detection of the arrow image under varying adverse ambient conditions, excepting the California study[1/] which was limited in scope.

F. Arrow Board Height

Current mounting heights, usually specified by manufacturers at about 7 ft (2 m), whether on a trailer or truck appear adequate for arrow boards to meet the performance criteria recommended above. Further raising of the board would not prevent possible visual blockage by trucks, but would add to the expense of the device. Therefore, no changes are recommended, at least from a human factors viewpoint.

V. STUDIES OF DRIVER UNDERSTANDING AND EXPECTANCY OF ARROW BOARDS

Critical to the development and use of any traffic control device is the determination of the device's meaning to drivers. This section describes two studies and a small number of informal discussions with work zone drivers that reveal critical information on the messages that arrow boards are communicating to drivers.

Referring to Figure 1, which shows the different modes available on arrow boards, a process of deduction is required to determine, from current literature, what each may be telling the driver to do. Although various field studies have shown that the arrow board seems to tell drivers to "get out of your lane--merge ahead,"[1,2,3,4,25] only passing reference to the kind of arrow board most useful in doing this is found. This is most notable in the California study,[1] where the arrow board caused drivers to merge even though the device was not actually closing a lane, i.e., it was placed on the shoulder. No coherent superiority of flashing arrows over sequencing arrows over sequencing chevrons was truly shown, excepting a slight but significant degradation of the chevrons during nighttime operation.

To date, considerable emphasis has been placed on target potency, and this is well established. However, once a driver sees the arrow board, his subsequent behavior depends on what meaning he attaches to the arrow. It is particularly important, then, to determine if a meaning is attached to the arrow and which mode conveys a unitary message to the greatest number of drivers. To answer these questions, two small-scale studies and a small number of informal discussions with drivers in a work zone were performed.

A. Study of Driver Understanding of Arrow Boards

This study attempted to ferret out the driver's conceived meaning of arrow board modes and arrow board placement (i.e., on the shoulder or in the lane). Nine short film clips were made from a driver's eye view approaching an arrow board on the same stretch of roadway. Each of the nine clips represented a different mode of the arrow board in combination with a placement either in the lane or on the shoulder. Figure 2 shows the nine conditions along the abscissa of the summary graph. Each condition was presented twice in random order. The respondents were 20 employees of BioTechnology, Inc., consisting of 9 females and 11 males with an age range of 18 to 50 years (mean 29.7) and a mean driving experience of 13.8 years. After each film clip was shown, subjects were required to select one of four responses, A, B, C, or D, as shown in Figure 2. In addition, the subject was to indicate how confident he was in making this response on a scale of one to five, again as explained in Figure 2. Essentially, three hypotheses were tested:

- There is no difference in accuracy and confidence in interpreting different arrow modes.

- There is no difference in the meaning associated with flashing arrows, sequencing arrows, chevrons, and flashing lights.

- There is no difference in the meaning between arrow boards placed in a lane and those on the shoulder.

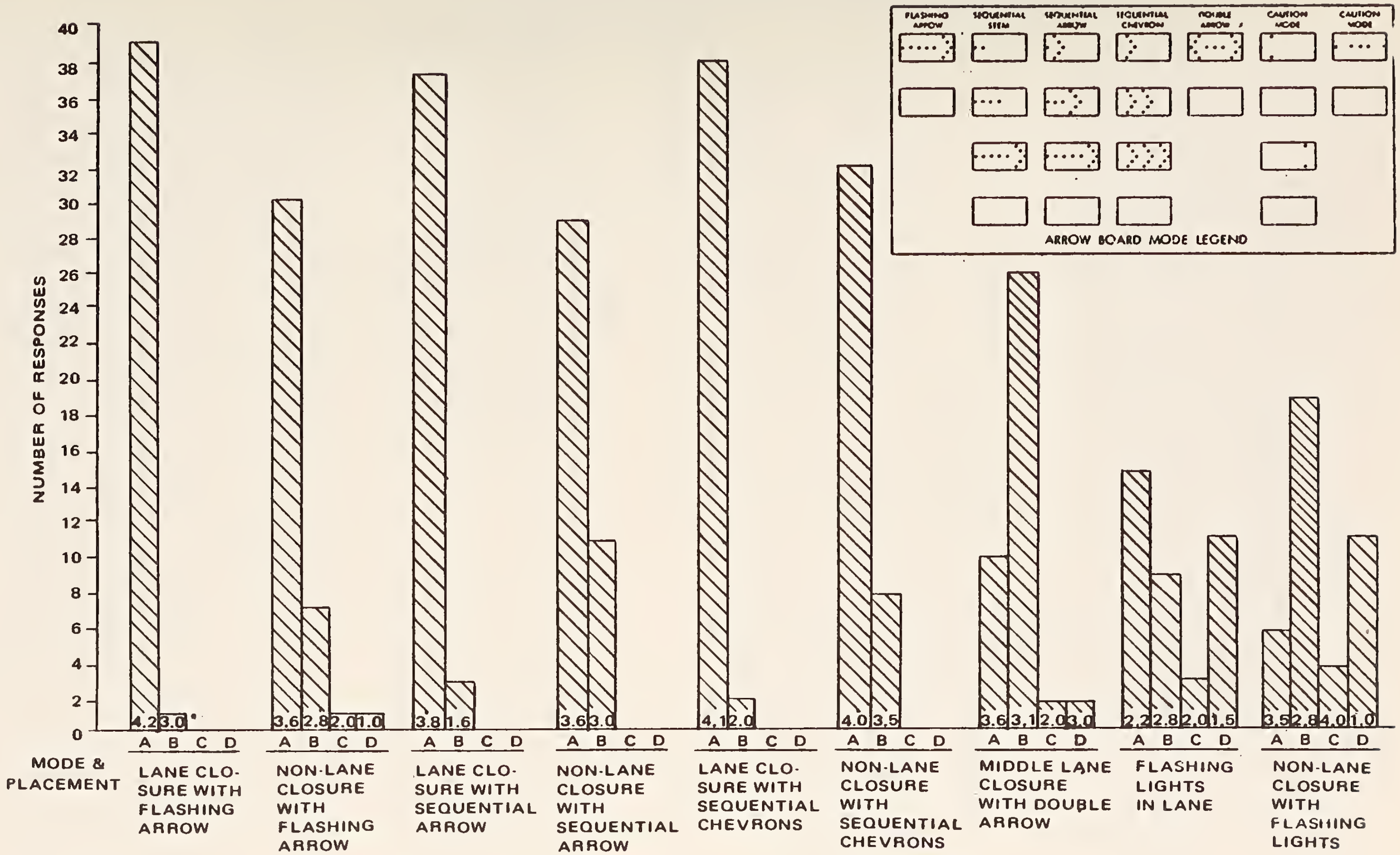
Figure 2 is a summary of the results obtained. The arrows and chevrons connote a lane closure ahead with high confidence for about 95% of the subjects. Mere flashing lights obviously stir more confusion than arouse meaning. Arrows and chevrons seem to indicate a lane closure for roughly 75% of the subjects, even when the arrow board is placed on the shoulder and merge would not actually be required. This is a reinforcement of the California findings.[1/] Here is empirical evidence that drivers mainly connote the flashing arrows or chevrons as meaning a lane closure ahead. Unanswered questions and problems remain, however. First, even simple inspection shows that no clear superiority of arrows over chevrons (or vice versa) has been determined. Second, respondents do not seem to be able to recognize when the lane is open or closed by virtue of arrow board placement. Third, the role of the caution or flashing lights mode needs in-depth examination in terms of its usefulness, considering the apparent confusion demonstrated.

The first consideration, establishing some rank order of effectiveness among flashing arrows, sequential arrows, and sequential chevrons in affecting the lane closure spurred the authors to perform a second study using a forced choice technique to single out a superior arrow mode. This study is discussed later.

The second and third considerations, shoulder placement and caution mode presentation, really dictate further refinement and replication of the study to make definitive conclusions. This was not within the scope of this phase of the project. However, the shortcomings of this study should be pointed out so that future efforts to clarify these points may be efficaciously accomplished.

B. Informal Discussions with Work Zone Drivers

These discussions were held to find out how drivers felt about arrow boards, and the meaning that was communicated to them by the arrow board mode. The arrow board mode was right sequential chevrons. The arrow board was located in the left lane on a four-lane divided arterial highway in a midwestern suburban area. The left lane of the highway was closed, but the actual closure was beyond a crest vertical curve and not visible to the approaching drivers. Those drivers that were stopped actually turned right into a shopping center parking lot about 300 ft (90 m) before passing the arrow board.



KEY:

A – MY LANE IS CLOSED AND I MUST CHANGE LANES AHEAD
B – MY LANE IS OPEN BUT I SHOULD SLOW DOWN AND WATCH FOR HAZARDS
C – MY LANE IS OPEN AND I DON'T HAVE TO CHANGE MY DRIVING AT ALL
D – OTHER (SPECIFY)

*NUMBERS INDICATE MEAN CONFIDENCE RATINGS GIVEN BY SUBJECTS ON A SCALE OF 1 THROUGH 5 WHERE 1 WAS A COMPLETE GUESS AND 5 WAS EXTREMELY CERTAIN.

Figure 2 - Summary of Results, Study of Driver Understanding

A total of 18 drivers discussed their interpretation of the arrow board message with the project staff. Sixteen of these drivers said they had seen the arrow board even though they were not continuing on the highway past the arrow board location. Thirteen of the 16 drivers who saw the board indicated that they felt it was telling them the left lane was closed and they must merge into the right lane. This result agrees with the results of the study of driver understanding. When asked about their preference between a chevron mode and an arrow mode, 11 of 17 drivers preferred the chevron, 5 preferred the arrow and 1 said they were equally effective. The preference of midwestern drivers for the chevrons was investigated further in the study of driver preferences.

C. Study of Driver Preferences for Arrow Board Modes

This study addressed the question of whether the three modes, i.e., flashing arrow, sequencing arrow, and sequencing chevrons, are essentially interchangeable in directing the driver to vacate his lane, or whether one mode is clearly superior and more effective in conveying this meaning. To this end, six short film clips were prepared to present two modes simultaneously, side-by-side, to have respondents choose one in a paired-comparison experimental model. Given three modes (six permutations), six pairs for comparison required testing.[26]

Trial	Left	Right
1	Sequential Arrow	Flashing Arrow
2	Sequential Arrow	Sequential Chevron
3	Flashing Arrow	Sequential Arrow
4	Flashing Arrow	Sequential Chevron
5	Sequential Chevron	Sequential Arrow
6	Sequential Chevron	Flashing Arrow

Consequently, two arrow boards, side-by-side, flashing the above pairs were filmed. The six short clips were then shown to a subject sample of 63 drivers at Midwest Research Institute and 46 drivers at the Office of Research, Federal Highway Administration. The response task for each clip was simply to indicate, by checking either left or right, which mode of the two presented best conveyed the meaning of lane closure. Table 7 shows the proportion of MRI drivers selecting each mode for each of the six cells. For example, in the first row of Table 7, 42 of 63 drivers or 67% preferred the flashing arrow over the sequential arrow, and reversing this, 19 of 63 drivers or 30% preferred the sequential arrow over the flashing arrow. Two of the 63 drivers or 3% did not select a preferred mode.

TABLE 7

SELECTION OF ARROW BOARD MODES IN SIX PAIRED COMPARISON TRIALS (%)[a/]

Trial Number	Preferred Mode	Percent Selecting	Comparison Mode	Percent Selecting	No Preference Percentage
1	Flashing Arrow	67	Sequential Arrow	30	3
2	Sequential Chevron	75	Sequential Arrow	25	0
3	Flashing Arrow	59	Sequential Arrow	41	0
4	Sequential Chevron	51	Flashing Arrow	49	0
5	Sequential Chevron	73	Sequential Arrow	27	0
6	Sequential Chevron	51	Flashing Arrow	49	0

a/ 63 Drivers - 44 male, 19 female.

The results are easily interpretable by simple inspection. It was judged appropriate to go no further in data analysis since this was a preliminary study with a sample not representative of the driving public. As can be seen, the flashing arrow and the sequential chevrons were clearly preferred over the sequential arrow. The flashing arrow and the sequential chevrons do not separate out significantly between themselves, however, indicating that these might be interchangeable in their use.

The six film clips were also shown to 46 employees of the Office of Research, Federal Highway Administration. Table 8 shows the results of this viewing.

Again, the flashing arrow and sequential chevron were clearly preferred over the sequential arrow. However, the FHWA sample also shows a clear preference for the flashing arrow over the sequential chevron. This may indicate a regional bias toward the sequential chevron with the MRI (Midwestern) drivers regarding the chevrons as interchangeable with the flashing arrow and the FHWA (Eastern) drivers preferring the flashing arrow. Discussions among the project staff reveal that it is likely that the sequential chevron is used more frequently in the Midwest than in the East. This is supported by the fact that the Commonwealth of Virginia no longer uses the sequential chevron mode.

TABLE 8

SELECTION OF ARROW BOARD MODES IN SIX PAIRED COMPARISON TRIALS (%)[a]

Trial Number	Preferred Mode	Percent Selecting	Comparison Mode	Percent Selecting	No Preference Percentage
1	Flashing Arrow	87	Sequential Arrow	13	0
2	Sequential Chevron	63	Sequential Arrow	37	0
3	Flashing Arrow	70	Sequential Arrow	30	0
4	Flashing Arrow	65	Sequential Chevron	35	0
5	Sequential Chevron	61	Sequential Arrow	39	0
6	Flashing Arrow	72	Sequential Chevron	28	0

a/ 46 Drivers - 29 male, 17 female.

Combining the two groups of drivers yields the results shown in Table 9. These data with evidence available from the literature suggests some reasons to advocate the flashing arrow over the chevrons. First, the California study[7] showed the superiority of a flashing mode at night in encouraging earlier merging. Second, human factors design principles suggests some target value advantage for a single on-off flashing operation rather than a multiflashing array.[18,27,28]

TABLE 9

SELECTION OF ARROW BOARD MODES IN SIX PAIRED COMPARISON TRIALS (%)[a/]

Trial Number	Preferred Mode	Percent Selecting	Comparison Mode	Percent Selecting	No Preference Percentage
1	Flashing Arrow	75	Sequential Arrow	23	2
2	Sequential Chevron	70	Sequential Arrow	30	0
3	Flashing Arrow	63	Sequential Arrow	37	0
4	Flashing Arrow	56	Sequential Chevron	44	0
5	Sequential Chevron	68	Sequential Arrow	32	0
6	Flashing Arrow	59	Sequential Chevron	41	0

a/ 109 Drivers - 73 male, 36 female.

VI. ARROW BOARD FIELD STUDIES

In this phase of the research, empirical data were collected in actual work zones in order to determine when there was a significant positive effect of using an arrow board at a site. To make this determination, it was first necessary to define the purpose of the arrow board in a specific work zone.

In general terms the purpose of an arrow board is to alert and guide drivers at lane closures, where normal travel lanes are diverted laterally, or where work is being done on the shoulder of the roadway. In a lane-closure situation, the drivers in the closed lane must merge into an open lane before continuing through the work zone. The purpose of an arrow board in this situation is to alert the drivers of the lane closure soon enough that they have time to make the required lane change safely. In a lateral diversion, where there is no lane closure, drivers should remain in their own lane and follow the diversion without encroaching on adjacent lanes. In situations where work is being done on the shoulder of the roadway, drivers should remain in their own lane and not be lured into following the work vehicle.

This phase of the research measured the effectiveness of arrow board performance in a variety of situations.

A. Measures of Effectiveness

The measures of effectiveness used in the field study included the proportion of vehicles in the closed or diverted lane at various distances from the transition point, speeds of vehicles nearing the transition point, encroachments onto the shoulder or adjacent lanes, erratic maneuvers, and conflicts. The volume of traffic in the zone was also recorded so that periods with similar flows could be compared. The following discussion specifies the various measures of effectiveness that were used for lane closures, diversions, and shoulder-work-only zones.

1. Lane Closures: When a lane is closed, the arrow board should facilitate merging into the open lane. The effectiveness of arrow boards for this purpose can be measured in terms of where vehicles make lane changes and how safely these lane changes are made.

Figure 3 is an illustrative plot of the decrease in lane volume versus the upstream distance from the point where a lane is closed. The curves shown represent hypothetical lane changing behavior for a typical lane closure work zone. In the area between lines A and C, many lane changes occur near the start of the taper. In this part of the work zone, drivers have a limited distance to merge into the open lane before reaching the actual lane

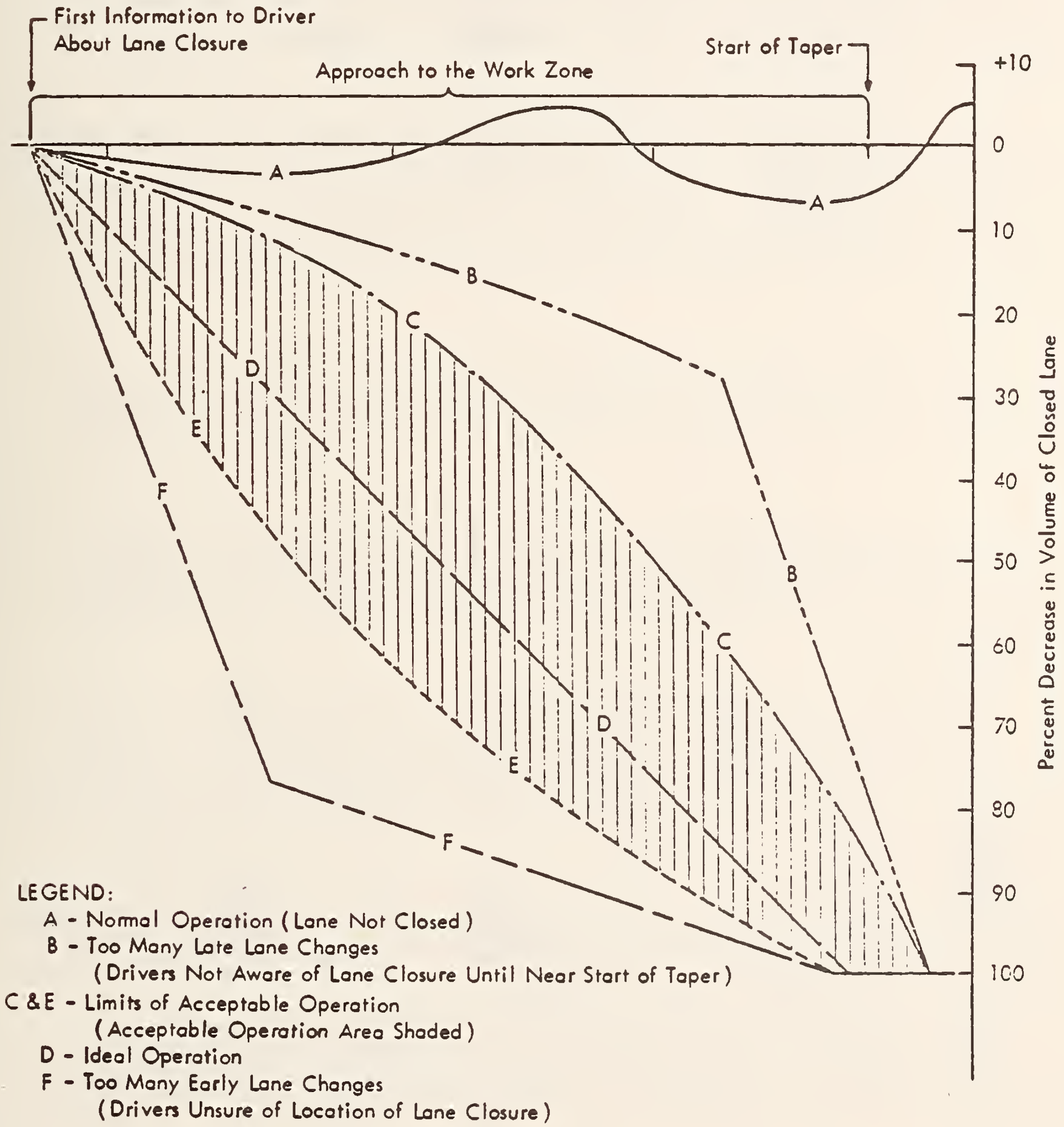


Figure 3 - Conceptual Lane Closure Operation

closure. In lane closures of this type, many vehicles may merge in the taper itself, leaving little room for driver error. The traffic flow and safety of the lane closure will be improved if lane changes are moved further upstream from the start of the taper and if the lane changes are distributed over a longer distance.

The shaded area in Figure 3 typifies ideal lane closures. It is best when lane changes take place rather uniformly throughout the approach area and where relatively few vehicles are in the closed lane near the start of the taper.

In the area between lines E and F in Figure 3, lane changes are too concentrated and are far from the lane closure. Drivers may be overreacting and making early lane changes, or the position of the lane closure may not be clear.

The effect of the arrow board was judged positive when the locations of lane changes were altered to more nearly satisfy the ideal lane closure operation described above. In other words in the analysis it is presumed that smoother traffic flow would ensue if lane changes were distributed over a longer distance thereby giving drivers more opportunities for merging into acceptable gaps.

The safety of the lane closure operation was determined using erratic maneuvers and conflicts. Diagrams of the various types of erratic maneuvers and conflicts are shown in Figure 4. They are each defined below.

An <u>erratic maneuver</u> occurs when an unimpeded vehicle brakes or suddenly swerves while approaching the transition (taper) area. (Unimpeded means there are no vehicles directly ahead or rapidly overtaking in an adjacent lane.)

In general, <u>a conflict</u> is defined as a situation in which a vehicle is required to take evasive action, to brake or swerve to avoid an impending collision with another vehicle ahead or alongside. A brake light indication, obvious braking, and swerving by the offended vehicle are indicators of a conflict.

A <u>lane-change conflict</u> is a situation in which a vehicle changes lanes into the path of another vehicle, causing the offended vehicle to brake or swerve to avoid collision.

A <u>slow-to-merge conflict</u> occurs when a vehicle slows or stops during its merge into the open lane, causing a vehicle in the open lane to brake or weave.

A <u>wrong-way lane-change conflict</u> occurs when a vehicle in an open lane approaching the transition area enters into a closed lane, and an offended vehicle brakes or takes evasive action to avoid collision with the wrong-way lane-change vehicle.

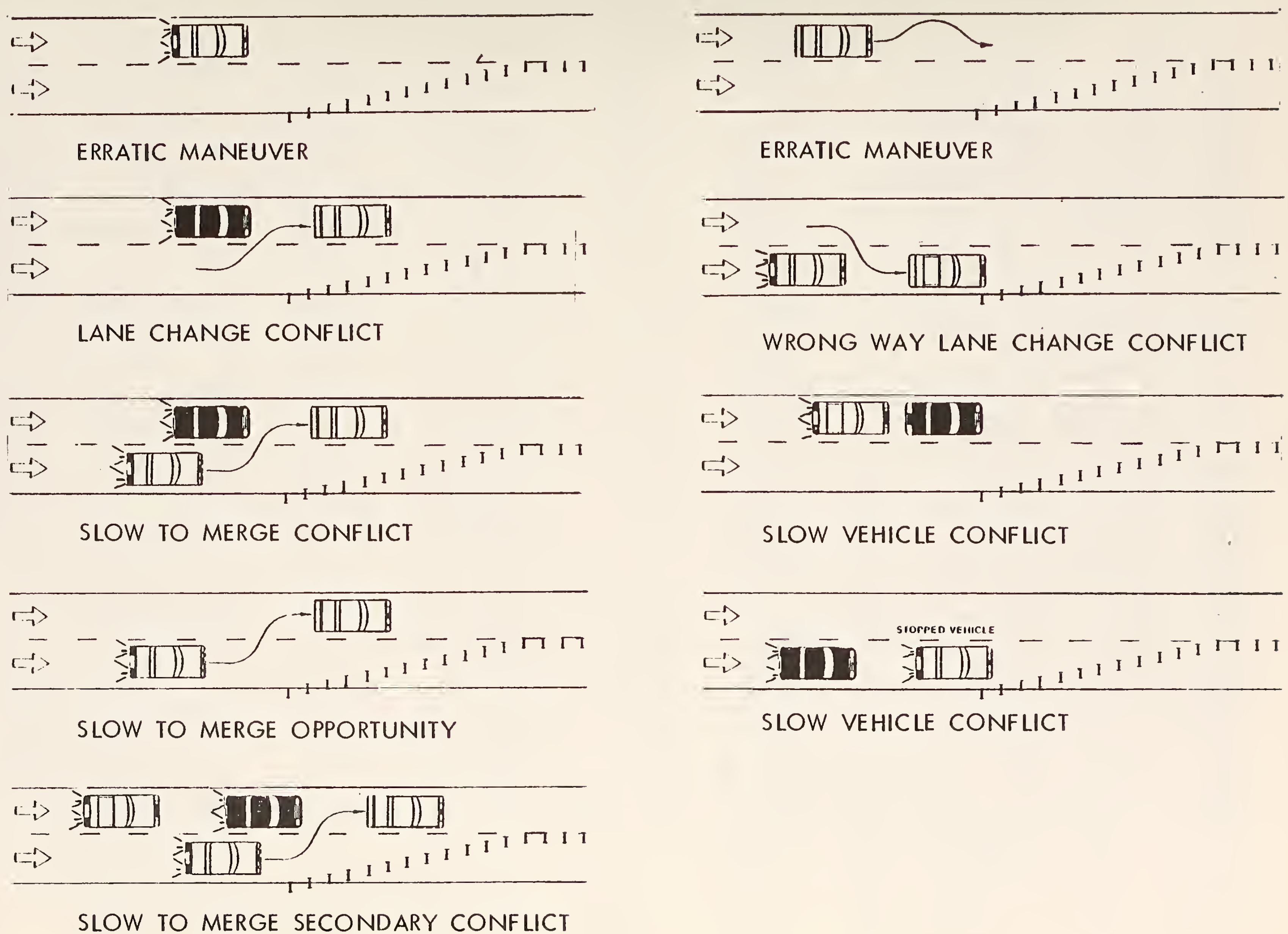


Figure 4 - Diagrams of Work Zone Erratic Maneuvers and Conflicts

A slow-moving vehicle conflict occurs when a vehicle swerves or brakes to avoid a slower vehicle in front.

A stop-in-closed-lane conflict occurs when a vehicle approaching the transition area is confronted with a stopped vehicle. The offended vehicle slows, stops, or swerves to avoid the stopped vehicle.

A secondary conflict is one that is initiated by an earlier traffic conflict. It occurs when two vehicles approach the transition area as a pair, and the lead vehicle of the pair becomes the offended vehicle in a traffic conflict and slows, stops, or swerves. The following vehicle then must take evasive action because of the action of the lead vehicle. Both the initiating and the resulting secondary conflicts are counted; the latter is attributed to the initiating conflict.

Conflicts are also classed according to severity. A routine conflict involves precautionary braking or lane changing when the risk of collision is small. For example, a freeway driver may feel threatened by a merging vehicle and change speed or position although the chance of contact is slight.

A moderate conflict is characterized by controlled braking or lane changing to avoid a situation with high collision potential. It would represent a close call, but the maneuver would be a clear case of controlled evasive action.

A serious conflict involves rapid deceleration or a severe swerve to avoid a collision. The driver has no time for a controlled maneuver. It would be a very near miss. Vehicle behavior indicating this condition would involve "fish-tailing," side-to-side rolling or rocking, skidding, or forward-lurching of a braking vehicle.

Also measured were the mean speed and variance of vehicles nearing the lane closure in the closed lane. This was done to determine how the arrow board affects the speed distribution of vehicles nearing a critical "merge or collide" situation where there is little time to merge into the open lane or stop before reaching the lane closure. During periods when traffic exceeded the capacity of the work-zone roadway, queues of vehicles formed. During these periods, the flow rate of vehicles passing through the work zone was the primary measure of effectiveness. The number of vehicles passing through the work zone was recorded during all study periods so that time periods with similar flows could be compared and so that other data could be converted to rates (e.g., per vehicle).

2. Diversions: These work zones involve moving traffic from its normal path without reducing the number of lanes. In these types of work zones, drivers should remain in their own lane and follow the lane diversion without encroaching on adjacent lanes.

For diversion work zones, the position of lane changes, erratic maneuvers, and conflicts were used as the measure of effectiveness. During periods when queues formed, the flow rate of vehicles passing through the work zone was the primary measure of effectiveness.

In addition, encroachments on adjacent lanes or the shoulder of the roadway were also used as measures of effectiveness in diversion work zones. Diagrams of shoulder and lane encroachments are shown in Figure 5. An encroachment is similar to a lane change in that the vehicle crosses a boundary of its lane (edge line, lane line, or centerline), but differs from a lane change because the lateral movement across the line is less than half the vehicle width.

3. Shoulder-work Only: When work is being done on the shoulder of the roadway, drivers should remain in their own lane and not be lured into the work area or into following the work vehicle. The measures of effectiveness for shoulder-work-only zones were lane changes, lane and shoulder encroachment and conflicts, and erratic maneuvers. The particular conflicts associated with maintenance vehicles are also shown in Figure 5.

B. Data Collection

In order to study the widest variety of work zone operations possible, two data collection methods were used. In long-term construction zones, lane volumes at various distances from the lane closure were determined by means of tapeswitches in the roadway connected to a 20-pen event recorder. Lane changes and encroachments in short-term construction and maintenance zones were studied by means of time-lapse photography. A 16-mm Bolex camera was mounted at the arrow board or on the maintenance vehicle for filming on-coming traffic. In all zones, an observer counted conflicts and erratic maneuvers occurring in the section of roadway from 800 ft before the start of the taper through the taper area. In long-term construction zones, an observer also counted encroachments.

The basic experimental plan was to study each work zone with and without an arrow board. The placement of the arrow board as well as the mode of the arrow board were also varied when possible. The basic study period with the arrow board present and its location remaining constant was called an "experiment." A series of experiments under various operating conditions was called a "test." In long-term construction zones, an experiment lasted 2 to 3 hours. For short-term construction and maintenance, an experiment lasted a maximum of 1 hour. Experiments were also described by time-of-day, area type, highway type, work-zone type, and direction of merge or diversion (left or right).

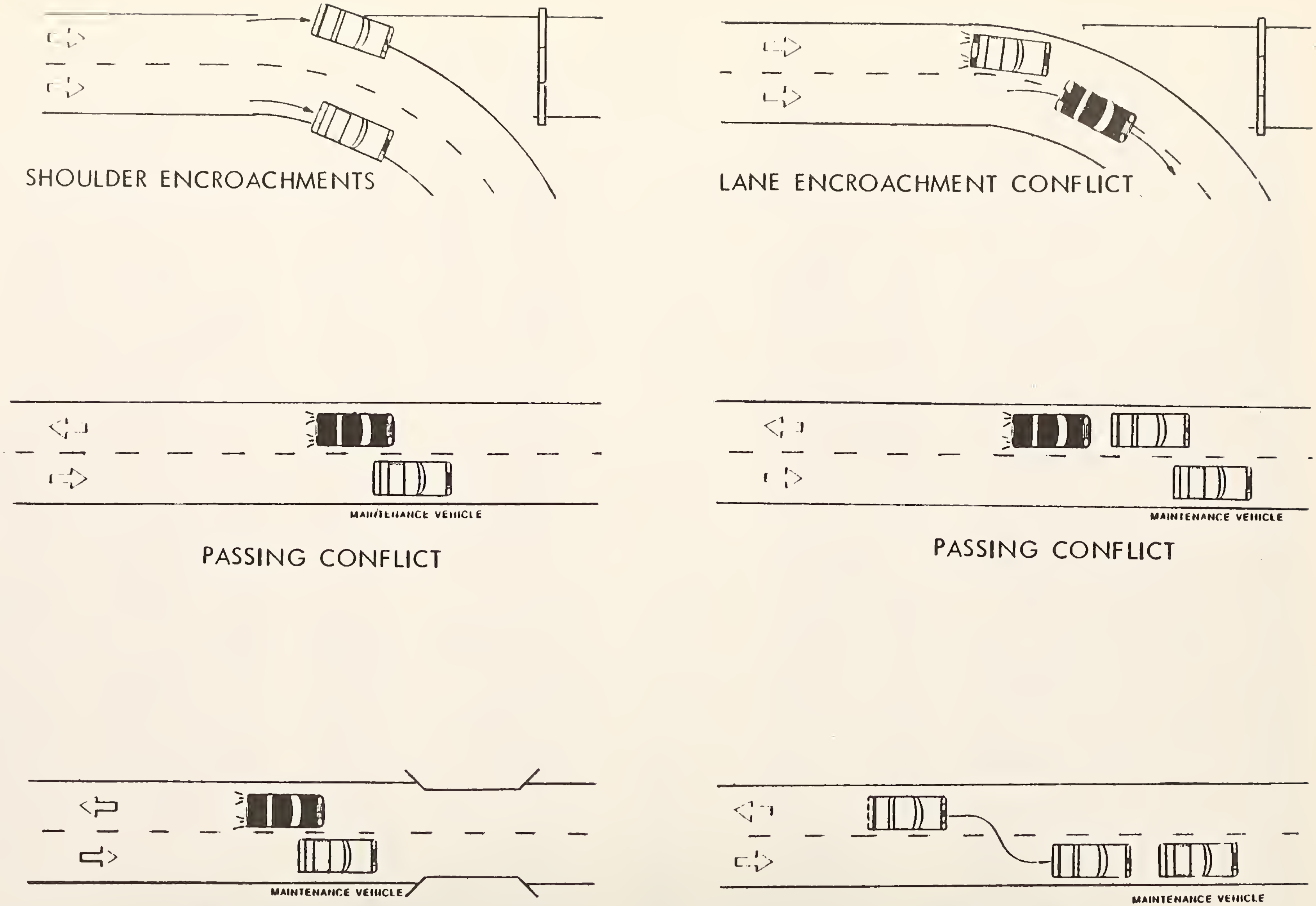


Figure 5 - Diagrams of Work Zone Encroachments and Maintenance Conflicts

1. Construction Operations: Data were collected at highway construction zones in California and Illinois from the end of March through August 9, 1978. The conditions of each experiment are shown in Table 10. In California, 25 experiments (15 long-term, 10 short-term) were performed using 11 construction sites. In Illinois, 62 experiments (43 long-term, 19 short-term) were performed using 17 construction sites. Typical construction activities included road widening, bridge-deck repair and waterproofing, shoulder underdrains, and overpass construction.

Studies of the effects of arrow boards at left- and right-lane closures and lane diversions were made in urban and rural locations, on controlled and uncontrolled access facilities, and during the day and night. There were no construction studies of arrow boards at shoulder closures.

In California, 16 of the 25 experiments were performed at lane-closure sites. In Illinois, 39 of the 62 experiments were performed at lane-closure sites. One site in California contained a lateral diversion in combination with a lane closure. This was a special case and is certainly not typical of the other lateral diversion locations which were studied. In Illinois, 23 of the 62 experiments were performed at lateral diversions.

Types of arrow board modes used included the flashing arrow, the sequential arrow, a double flashing arrow, a sequential chevron, and a sequential stem. Studies were also performed with no arrow board present. There were no studies performed using experimental display modes. Both 4 x 8 ft and smaller sized arrow boards were used. At lane closures, the arrow board locations included upstream of the taper, and beginning, middle and end of the taper. At lane diversions, arrow boards were located upstream of and at the point of diversion.

All of the construction projects were first reviewed by the project leader with the help of engineers and officials from the California and Illinois Department of Transportation and the Illinois State Toll Highway Authority. They helped to locate suitable construction projects, aided in gaining contractor approval, and provided other assistance. Before beginning any studies, the project staff met with the resident engineer and construction general contractor. At this time, they explained the study procedure and equipment to be used. The construction-zone traffic control device arrangement was not altered except when an arrow board was already present in the zone. Every zone but one was studied without an arrow board. The arrow board was not removed in that zone because of the perceived hazard that would be presented to drivers without an arrow board.

Before starting any work at a construction site, the project staff drove through the zone several times to become familiar with the arrangement of the devices and the operational characteristics of the zone. If traffic

TABLE 10

CONSTRUCTION SITE TESTS

						Arrow Board Conditions Tested									
							Placements				Modes				
State	Test	Experiments	Highway Type	Area Type	Work Zone Type and Direction	No Arrow Board	On Shoulder Near Start of Taper	In Closed Lane Near Middle of Taper	On Shoulder Upstream of Start of Taper	Other Placement	Flashing Arrow	Sequential Chevron	Sequential Arrow	Sequential Stem	Other
California	1	CC1-CC4	2-lane (with climbing lane)	Rural	Right Lane Closure	X	X	X			X		X		
California	2	CC5 and CC6	8-lane Interstate	Urban	2 Left Lanes Closed	X		X			X	X			
California	3	CC7-CC13	4-lane Interstate	Rural	Left and Right Closures	X	X	X			X	X			
California	4	CC14-CC16	8-lane Interstate	Urban	Right Lane Closure		X	X	X			X	X		
California	5	CC17-CC25	4-lane Divided Uncontrolled Access	Urban	Right Lane Closure and Left Diversion	X		X				X	X		
Illinois	6	IC1-IC6	4-lane Interstate	Rural	Left Diversion	X	X			X	X				
Illinois	7	IC7 and IC8	2-lane	Rural	Right Diversion	X				X	X				
Illinois	8	IC9-IC11	4-lane Interstate	Rural	Right Lane Closure	X	X		X			X			
Illinois	9	IC12-IC17	4-lane Interstate	Rural	Right Lane Closure	X	X	X			X				
Illinois	10	IC20-IC25	4-lane Undivided Uncontrolled Access	Urban	Right Lane Closure	X	X	X			X		X		
Illinois	11	IC26-IC29	4-lane Divided Uncontrolled Access	Urban	Left Lane Closure	X		X			X	X	X		
Illinois	12	IC30, IC33-IC35	4-lane Divided Uncontrolled Access	Rural	Right Diversion	X					X				
Illinois	13	IC31 and IC32	4-lane Undivided Uncontrolled Access	Rural	Right Lane Closure	X		X			X				
Illinois	14	IC36-IC38, IC45 and IC46	4-lane Undivided Uncontrolled Access	Urban	Right Diversion	X				X	X	X			
Illinois	15	IC39-IC44	4-lane Divided Uncontrolled Access	Rural	Right Lane Closure	X	X	X			X				
Illinois	16	IC47 and IC48	6-lane Interstate	Urban	Split Diversion	X				X					X
Illinois	17	IC49-IC51	6-lane Interstate	Urban	Left Lane Closure	X	X	X				X			
Illinois	18	IC52 and IC53	6-lane Interstate	Urban	Split Diversion	X				X					X
Illinois	19	IC54 and IC55	4-lane Interstate	Rural	Split Diversion					X					X
Illinois	20	IC56-IC60	4-lane Interstate	Rural	Left Lane Closure	X	X				X	X			
Illinois	21	IC61-IC64	4-lane Interstate	Rural	Left Lane Closure	X	X				X	X			

control plans were available, a set was obtained; but usually this was not the case so a field sketch was made. This procedure required two people one of whom pushed a Roll-a-Tape and gave distances, while the other drew a sketch of the zone. The sketch encompassed the area between the first advance warning sign and the "End Construction" sign. Along with the corresponding distances, the sketch included the number of lanes, pavement markings, signs, channelizing devices, barriers, ramps, intersecting roads, driveways, bridges, buildings, and any other important items. The number and locations of tapeswitches to be used in the study were added to the site sketch. Typical tapeswitch arrangements for lane closures and lateral diversions are shown in Figures 6 and 7, respectively.

Before being deployed, the tapeswitches were checked to make sure they functioned properly. This was necessary because the tapeswitches were to be reused for succeeding studies until they failed.

Tapeswitch deployment was usually done during daylight hours except where traffic was too heavy. The first step in deployment involved laying out the wire used to connect the switches to the event recorder. The wires and event recorder were generally located on the side of the road that contained the most switches. For example, at a right-lane closure (or diversion to the left), this would be the right side of the road. It required two people to uncoil the spools of 300 to 1,500 ft of three- or four-conductor wire. This task was usually accomplished within an hour.

Three people were needed to install the tapeswitches on the roadway. Two people placed and secured the switches while the third served as a flagman and alerted the other two in case of an emergency. All project staff wore fluorescent orange vests. Hard hats were required in California but were optional in Illinois. However, hard hats were more of a hindrance than a benefit because of the stooping and bending this job required.

The tapeswitches, which were 10 ft (3 m) in length, were installed when there was a sufficient gap in the flow of traffic. They were placed perpendicular to the roadway alignment. First the roadway at the switch location was swept with a broom to remove any dirt or gravel which could affect adhesion. Then a spray of tape primer was applied to the road. The switch was taped to the road surface with lengths of 2 in. duct tape. The tape primer enhanced the adherance of the switch and duct tape to the road surface. Originally the switches were inserted into a rubber protective cover that had a half-moon cross-section. Later it was determined that the switches could be installed without the rubber cover. When properly installed, the uncovered switches lasted about as long as the covered ones.

The lead wires of the tapeswitches were connected to the conductor wire which was in turn connected to a 48-volt dry cell battery and the 20-channel event recorder. Deployment usually took about 2 hours.

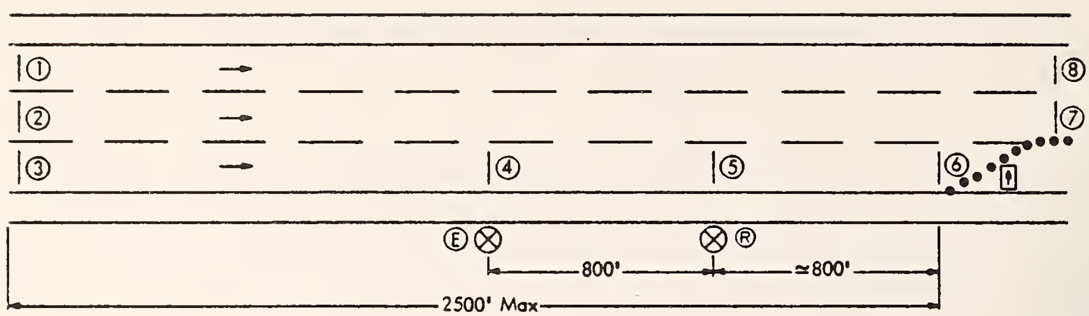


Figure 6 - Typical Data Collection Setup for a Construction Zone Closure

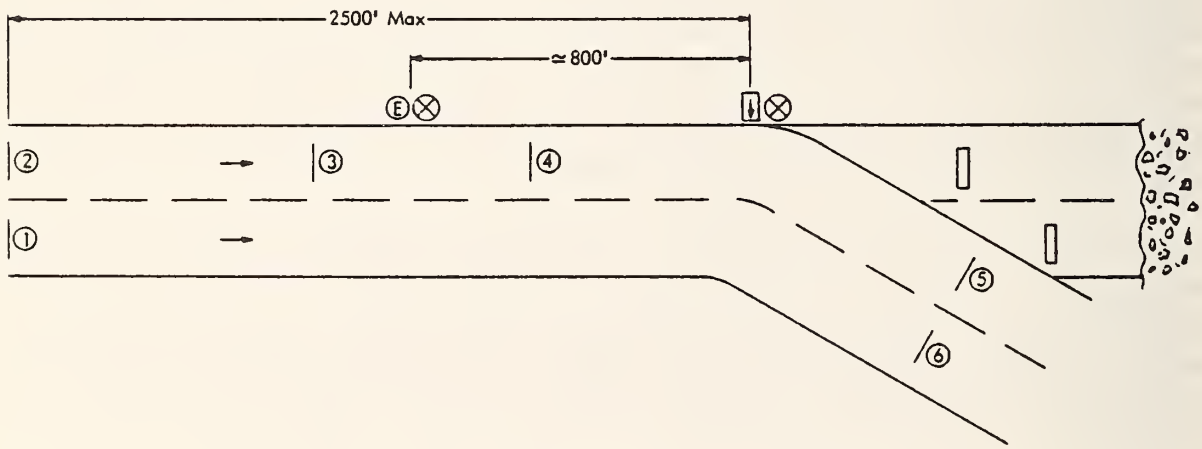


Figure 7 - Typical Data Collection Setup for a Construction Zone Diversion

Once the tapeswitches were in place and tested, data collection began. Each long-term urban experiment was conducted during the daylight peak and off-peak hours, and at night. Rural experiments were conducted during day and night hours. No studies were done on Saturdays or Sundays.

Each experiment lasted 2 to 3 hours. Erratic maneuvers, conflicts, encroachments, and spot speeds were counted and recorded in 15 min. increments during this period. Two people were needed to perform an experiment unless spot speeds were required; then an additional person was sometimes needed to operate a radar speed measuring unit.

The procedure used to collect data at a lane closure (Figure 6) varied only slightly from that used at a lateral diversion (Figure 7). In both cases, the conflict observer was located approximately 800 ft upstream of the start of the taper or point of diversion. This was a good location from which to observe traffic approach and proceed through the taper (or diversion). At distances farther upstream it becomes difficult under certain conditions to observe brake lights or weaves. Closer to the taper (or diversion) an observer might not be able to witness all of the conflicts taking place.

At lane closures, the event recorder was located approximately 800 ft upstream of the conflict observer and was monitored by a second person. If traffic was not heavy, the conflict observer was also able to collect spot speed data. At other times a third person was required to collect spot speeds of vehicles approaching the transition area.

At lateral diversions, the conflict observer also monitored the event recorder. The second person was stationed by the point of diversion and observed vehicle actions which the conflict observer could not see. These included wrong-way lane changes, shoulder encroachments, lane encroachments, and the corresponding conflicts arising from such movements.

The observers either sat in lawn chairs or in the van used to carry the equipment. The van was used only if it could be parked where it would not interrupt the flow of traffic. The van was red and could not be mistaken for a police vehicle. The observers positioned themselves on the side of the road that gave them the best overall view of the area being studied. This was not necessarily the side where the event recorder was located. The observers used citizen band radios to communicate during each study. All observations and the study conditions were recorded on standardized forms.

Two types of traffic conditions exist, either non-queued or queued. When traffic is non-queued, the actions of any one vehicle do not always depend on those of others. (But this is not to say that there would not be any vehicle interactions under these conditions.) During periods of non-queued flow, all data were collected as described above.

When traffic flow nears capacity, queues of vehicles form. When this occurs, vehicles do not proceed unimpeded through the construction zone. During the time that a queue was present, normal conflict observation was terminated. During these periods almost every vehicle was braking so an objective determination of conflicts was not possible. The length of time that a queue existed was recorded. Wrong-way lane changes, stopped vehicles, and, of course, collisions were also recorded. The formation of many queues and the occurrence of these unsafe maneuvers were good indications that the traffic control procedures used to guide traffic through the construction zone were unsatisfactory and were confusing to the drivers.

Some construction operations were of such a short duration, or the traffic volumes were so large, that it was not possible to install tape-switches on the roadway. These construction zones were studied by means of time-lapse photography and are described in the following section on maintenance operations.

2. Maintenance Operations: Maintenance operations were also studied in California and Illinois. Maintenance zones and some short-term construction work zones were studied by positioning a 16-mm Bolex camera near the arrow board or on a moving maintenance vehicle. In stationary operations with no arrow board, the camera was placed where the arrow board would have been located. The camera film capacity was 100 feet which limited the duration of maintenance experiments to a maximum of 1 hour. Some experiments lasted less than 1 hour because the maintenance operations themselves were completed in less than an hour.

A total of 52 experiments were filmed. The conditions of each maintenance experiment are shown in Table 11. Fourteen maintenance experiments and 10 short-term construction experiments were filmed in California, and 9 maintenance experiments and 19 short-term construction experiments were filmed in Illinois. All maintenance experiments were filmed during the day. Two construction experiments were filmed at night and the remainder during the day.

The maintenance operations filmed were both moving and stationary and included sweeping (on shoulder), striping, pothole patching, mudjacking, and miscellaneous emergency lane closures. Maintenance operations were filmed on two-lane, multi-lane uncontrolled access and multi-lane controlled access highways. Left- and right-lane closures and left- and right-shoulder closures were tested, as was one center lane closure. Arrow-board modes that were tested included flashing arrow, sequential chevron, double arrow, and sequential arrow. Some of the maintenance experiments were filmed with no arrow board.

For filming moving operations, the photographer rode on the rear of the maintenance vehicle and filmed traffic as it approached the maintenance

TABLE 11

MAINTENANCE SITES TESTED

State	Experiment	Type of Maintenance Operation	Highway Type	Area Type	Work Zone Type	Arrow Board Conditions Tested: No Arrow Board	Placement: On Shoulder Near Start of Taper	Placement: In Closed Lane Near Middle of Taper	Placement: Blocking Closed Lane	Placement: Other Placement	Mode: Flashing Arrow	Mode: Sequential Chevron	Mode: Sequential Arrow	Mode: Sequential Stem	Mode: Other
California	CM1	Mudjacking-Stationary	8-lane Interstate	Rural	Right Lane Closure			X				X			
California	CM2	Mudjacking-Stationary	8-lane Interstate	Rural	2 Left Lanes Closed	X									
California	CM3	Stripping-Moving	8-lane Interstate	Urban	Left Lane Closure				X			X			X
California	CM4	Sweeping-Moving	8-lane Interstate	Urban	Right Shoulder Closure										X
California	CM5	Mudjacking-Stationary	8-lane Interstate	Rural	2 Right Lanes Closed			X				X			
California	CM6	Sweeping-Moving	8-lane Interstate	Urban	Right Shoulder Closure	X									
California	CM7	Bridge Repair-Stationary	8-lane Interstate	Urban	Right Lane Closure			X					X		
California	CM8	Sweeping-Moving	8-lane Interstate	Urban	Left and Right Shoulder Closure						X				
California	CM9	Sweeping-Moving	8-lane Interstate	Urban	Right Shoulder Closure						X				
California	CM10	Striping-Moving	4-lane Undivided Uncontrolled Access	Urban	Left Lane Closure				X		X				
California	CM11	Striping-Moving	4-lane Undivided Uncontrolled Access	Urban	Right Lane Closure				X		X				
California	CM12	Striping-Moving	4-lane Divided Uncontrolled Access	Urban	Right Lane Closure						X				
California	CM13	Mudjacking-Stationary	8-lane Interstate	Rural	2 Left Lanes Closed							X			
California	CM14	Sweeping-Moving	8-lane Interstate	Rural	Left Shoulder Closure	X									
Illinois	IM1	Striping-Moving	2-lane	Rural	Right Shoulder Closure	X									
Illinois	IM2	Striping-Moving	4-lane Interstate	Rural	Left Lane Closure				X			X	X		
Illinois	IM3	Pot Hole Patching Moving	6-lane Interstate	Urban	Center Lane Closure				X						X
Illinois	IM4-IM5	Catch Basin Repair Stationary	6-lane Interstate	Urban	Left Lane Closure	X	X				X				
Illinois	IM6	Pavement Patching Stationary	6-lane Interstate	Urban	2 Left Lanes Closed			X				X			
Illinois	IM7	Striping-Moving	6-lane Interstate	Rural	Left Lane Closure							X			
Illinois	IM8	Stationary	6-lane Interstate	Urban	Right Lane Closure		X					X			
Illinois	IM9	Stationary	6-lane Interstate	Urban	Right Lane Closure	X									

vehicle with particular emphasis on filming vehicles in the closed lane or the lane next to the shoulder closure. The camera was mounted on a Treck photographic shoulder pad strapped onto the photographer. The camera and mount are shown in Figure 8. This mounting allowed for vibration to be damped by the photographers body and facilitated aiming the camera, which had a side-mounted view finder. A 50-mm lens was used in all filming, and Kodak Triax Reversal film (ASA 200) was used.

The basic camera was altered to operate in a time-lapse mode at approximately 1 frame per second. To power the camera it was necessary to also carry a power inverter and a 12-volt battery. The photographer also wore a motorcycle helmet and, in some cases, a safety belt.

After the filming crew had located the maintenance vehicle, the driver of the maintenance vehicle was briefed on the study procedure and asked the direction he would be traveling. The driver was asked to continue the maintenance operation for an hour if possible. The photographer took a light reading based on the direction of travel and set the exposure reading on the camera. After the photographer was positioned on the maintenance vehicle, the driver was signaled to start the maintenance operation. As soon as the maintenance vehicle reached its normal position, the experiment began. The photographer marked the start of the study and 15-minute intervals throughout the study period by blacking out 5 to 10 frames of film.

Figure 8 - Camera Mounted on Shoulder Pad

An observer trailed the maintenance vehicle by about 800 ft to observe conflicts and erratic maneuvers near it. For sweeping operations, the observer followed the maintenance vehicle on foot and dressed as a maintenance worker. For higher speed operations, the conflicts observer either followed in the survey vehicle (a Chevrolet van) on the right shoulder or in another vehicle of the maintenance train. The conflicts observer and the photographer coordinated the study by communicating with walkie-talkies. When possible, the conflicts observer marked 15-min periods by waving at the camera or turning on the trailing vehicle's headlights.

In moving operations, the conflicts observer used a small tape recorder to dictate erratic maneuvers and conflicts. A film log was used to record details of the filming of each experiment.

Filming of stationary operations was similar to that of moving operations except that the camera was normally mounted on a tripod and positioned below the arrow board at a height of about 6 ft. The conflicts observer was stationed 800 ft upstream of the beginning of the taper and recorded erratic maneuvers and conflicts on the same data sheet that was used for construction operations.

C. Data Reduction

The data collected in the field included film, event recorder charts, dictation tapes, and completed forms used to record conflicts data, filming specifications, and general characteristics of each experiment. This section describes the procedures employed to reduce the raw data to a form useable for analysis.

1. Long-Term Construction Zone Data: The tapeswitch actuations were recorded on a paper chart. The first step in reducing the construction zone data was to place timing marks on the charts. The recorder ran at a speed of 1 ft of chart per min. The times when the chart started and finished were recorded on the chart in the field to ensure that the recorder ran at a constant speed. After the times were marked on the chart, volume counts at each switch location were made from the chart for 15-min periods. The tapeswitches were actuated by each axle of a vehicle so vehicles could be identified and separated as to trucks (three or more axles) and passenger vehicles.

The erratic maneuver, conflict, and encroachment data counts were also accumulated for 15 min periods corresponding to the flow counts. After these counts were determined, they were divided by the vehicle volume to obtain rates. For example if 10 erratic maneuvers were committed in one 15 min period and 200 vehicles were observed (counted) for the same period the erratic maneuver rate would be (10/200)(100) = 5.0% of observed vehicles committing erratic maneuvers. All volume, encroachment, conflict and erratic maneuver numbers and rates were recorded on a single form to facilitate further analysis of the data. This form also contained data about the site, such as switch locations, etc.

The speed data were collected in the construction zones by two methods. Data from radar were recorded directly in the field and reduced by determining the mean and variance of each 15-min speed sample. Speed data were obtained from tapeswitches by determining the time required for a vehicle to actuate two tapeswitches 100 ft (30 m) apart. As the switch volumes were being counted, free-flowing vehicles (those with headways of 5 sec or greater) were chosen for speed reading. In some zones a vehicle was measured at two or more locations as it traversed the zone. When a vehicle trace was chosen for speed reading, it was circled and numbered. The circled vehicle traces were measured by projecting the chart image on a rear-projection screen with an overhead opaque projector. The projector enlarged the image of the switch closures (vertical blips on the charts) four times, thus permitting more accurate determination of vehicle speeds. The tapeswitch speeds were also grouped into 15-min periods to correspond to the volume and conflicts data.

2. Maintenance and Short-Term Construction Zone Data: To determine how far away from the camera vehicles made lane changes, the film was projected onto a large rear-projection screen. A two-person crew read and recorded the width of the vehicle's image as it started to make a lane change, and (initially) the make and model of the vehicle. The vehicle type was recorded so that the actual width of the vehicle could be determined. However, the process of identifying each vehicle proved to be excessively time-consuming. For this reason, the film data reduction process was streamlined by placing vehicles of like widths into groups. Cars were divided into six groups with mean widths as follows:

a. Group I - mean width = 53.5 in.

b. Group II - mean width = 58.5 in.

c. Group III - mean width = 62.7 in.

d. Group IV - mean width = 66.7 in.

e. Group V - mean width = 72.0 in.

f. Group VI - mean width = 78.8 in.

Pickups and vans were classified as having a mean width of 80.0 in. and trucks as having a mean width of 96.0 inches.

Once all of the data were recorded, the distances were calculated by the following equation:

$$\frac{I}{D} = \frac{mf}{R}$$

where D = True dimension of a vehicle feature (the mean vehicle width of the group);

R = Range or distance from camera to vehicle;

f = Lens focal length;

I = Size of the projected image of D; and

m = Projection magnification.

Reforming this equation, we can write:

$$R = mfD/I.$$

If the condition of projection is unchanged, mf is constant and the distance to the photographed vehicle is equal to a constant multiplied by the ratio of the true size of a vehicle feature to its projected size.

A short calibration film was made with a vehicle of a known width at various distances from the camera. The mean value of mf computed from this calibration film was 15.41. This constant was used to convert the film readings into ranges (in feet). The ranges computed in this manner were within ± 5% of the true ranges of the calibration film.

As the lane-change image sizes were being measured, the lane volumes for each 15-min period were counted. The lane volumes were counted at the location of the camera (or as close as possible to the camera before the vehicle was out of view of the camera). A computer program was developed to convert these volumes and the ranges of each lane change into lane volumes at various ranges from the arrow board.

The conflict data recorded on tape were transcribed onto regular conflict count sheets. The vehicle volumes, erratic maneuvers, conflicts, and lane volume information were then put on a single form in preparation for the analysis of the data.

D. Data Analysis

All "tests" consisted of a set of experiments under various operating conditions. For example, Test 5, Experiments CC 17-25, are the nine possible combinations of the two 3-level factors. The three levels of "time" factors were night, day off-peak, and day peak; the three levels of the "arrow board" factor were: none; sequential chevron with large (4 x 8 ft) arrow board; and sequential arrow with small (2 x 5 ft) arrow board.

The construction experiments were grouped into 21 tests, and the maintenance experiments were grouped into 7 tests.

The responses consist of proportions, e.g., percentage of vehicles commiting erratic maneuvers or conflicts and the sequence of values of the percentage of total vehicles in the closed or diverted lane at decreasing distances from the arrow board. This sequence was used to describe differences in the spatial pattern of the volume proportion as well as differences in the initial lane volume proportion. Lane volume percentages were computed for passenger vehicles and trucks; however, they were analyzed together unless the percentage of trucks in the traffic stream varied between experiments.

In general, an appropriate analysis of variance (AOV) model was used to extract factor influences upon proportions or proportion sequences during each test. For various technical reasons, it was not desirable to treat these percentages directly as ordinary numbers in AOV calculations. The proportions themselves are not based on equal sample sizes; and even if they were, the numerical quantity--proportion--is not suitable for AOV due to heteroscedasticity. Therefore, the logit transformation[29/] was executed on these data and an appropriate AOV performed in the logit scale (via contrasts). The logit transformation was chosen in order to make the comparisons of erratic maneuvers, conflicts, or encroachments as compatible as possible with the analysis of the spatial sequence of closed or diverted lane proportions.

The analysis of the spatial proportions was complicated because the same physical vehicles traverse the test section. For example, a count of 200 vehicles in a lane at the first switch, 180 at the second, 150 at the third, etc., does not arise from a total volume of 200 + 180 + 150 +... vehicles but instead more closely corresponds to the "disappearance" of 20 cars between the first two switches, another "decay" of 30 cars between the second and third, etc. Note that these proportions are referenced to the closed lane only since this is the volume impacted by the arrow board. Closed lane volumes as a percentage of total volume are used, however, for clarity in tabular presentations of results.

The following example is given to illustrate the method of computing the percentage of vehicles in the closed lane or lane of interest. Assuming for some given period of time (usually 15 min periods were used), there were 200 passenger vehicles in the closed lane at the first switch, and the total number of passenger vehicles traveling through the zone was 300, then the percentage of vehicles in the closed lane would be (200/300)(100) = 66.7%. If there were 180 passenger vehicles at the second switch and 150 passenger vehicles at the third switch the corresponding percentages would be (180/300)(100) = 60.0% and (150/300)(100) = 50.0%.

Thus, it is the difference in lane change proportions between switches rather than the counts at switches that are the appropriate response for the AOV. This makes the AOV a "wear-curve" type of analysis,[30] with space represented as a factor with K-1 levels between the K switches. (Of course, it could have been that an apparent decay of 20 cars in an interval actually corresponds to 20 + k cars leaving and k cars entering, but such wrong-way lane changes were examined and found to be negligible.

A logit model was used to describe such data. Essentially a logit model states that in a given interval the cars that enter are subject to an interval-specific probability of leaving. A data set of R experiments x C intervals was therefore analyzed as a logit R x C table, i.e., non-parallel decay curves were detected by the R x C logit Chi-square value. Initial proportions (at the first switch) were compared like any other fractions. Additional discussion of the analysis method is given in Appendix D.

E. Summary of Individual Field Studies

This section contains a brief summary of each test and its results. Detailed results of each test and a diagram of each site are shown in Appendix C - Detailed Field-Study Results. All effects described in Appendix C were statistically significant with $P \leq 0.05$ unless noted otherwise. Although statistical determinations took place in a logit scale, descriptions of effects are given here in percentages. Although conflicts were classed by severity (routine, moderate, or serious), very few moderate or serious conflicts were observed. The low numbers of moderate or serious conflicts did not allow a formal analysis of the conflicts by severity. However, the observations of moderate or serious were used in a subjective manner to judge safety, and their occurrences are mentioned in the test results.

1. Test 1, Experiments CC1-4: This test was conducted on a 2-lane (with hill-climbing lanes), uncontrolled access, rural highway with the right lane closed. Two arrow board placements were tested: (a) on the shoulder near the start of the taper, and (b) in the closed lane near the middle of the taper. Both placements of the arrowboard were superior to no arrow board in getting drivers out of the right lane. However, there were fewer conflicts with the shoulder placement of the arrow board than either the closed lane placement or no arrow board. Speeds in the taper area of the zone did not vary between experiments, and no significant effects on right-lane volumes or conflicts could be attributed to change in the arrow board mode from flashing arrow to sequential arrow.

2. Test 2, Experiments CC5 and 6: Test 2 was conducted at night on an 8-lane urban freeway. Because of low volumes and tape switch failures, no usable data were obtained from this test.

3. Test 3, Experiments CC7-13: This test was conducted on a 4-lane rural Interstate highway at seven sites. Both left-lane and right-lane closures were tested. The arrow board placement was varied between (a) on the shoulder near the beginning of the taper, and (b) in the closed lane near the middle of the taper. The arrow board mode varied between the flashing arrow and sequential chevron.

The percentage of vehicles in the left lane when the left lane was closed was always very low. In the experiments with the right lane closed, the two arrow board placements were nearly identical in performance, and both were superior to no arrow board in moving vehicles from the right lane. Erratic maneuvers and conflicts were so rare during this test that no significant effects were found. However, one experiment did experience one serious lane change conflict and appeared to be more hazardous than the other experiments. In this experiment, the taper began near a horizontal curve and the arrow board was placed in the middle of the taper well into the curve. The problems arising during this experiment were probably due to poor placement of the lane closure taper.

4. Test 4, Experiments CC14-16: This test was conducted on an 8-lane urban freeway with the right lane closed. An arrow board was used in all experiments. The placement of the arrow board varied between (a) on the shoulder 965 ft (294 m) before the start of the taper, (b) on the shoulder at the start of the taper, and (c) in the closed lane in the middle of the taper. The modes tested were sequential arrow and sequential chevron.

The placement of the arrow board in advance of the start of the taper resulted in vehicles leaving the right lane sooner. Next best was placement at the start of the taper followed by closed-lane placement. There were significantly fewer lane-change conflicts with the placement in advance of the start of the taper, but slow-to-merge opportunities were less with placement at the start of the taper. No mode-specific effects were distinguishable.

5. Test 5, Experiments CC17-25: This test was conducted on a 4-lane, divided, uncontrolled access, urban highway with a right-lane closure and a diversion to the left. Two sizes of arrow board were tested, 4 x 8 ft (1.2 x 2.4 m) and 2.4 x 5 ft (0.7 x 1.5 m). For all experiments using an arrow board, it was placed in the closed lane behind the barricades.

In terms of moving cars out of the right lane, the larger board was superior to the smaller board and no board (which were indistinguishable) during the day-peak and night experiments. During the day off-peak experiments, both boards were superior to no arrow board. The small arrow board had higher erratic maneuver rates during the peak-hour and lower slow-moving conflict rates. This may have been due to larger average headways during the small arrow board peak-hour experiment.

6. Test 6, Experiments IC1-6: This test was conducted on a 4-lane, rural temporary Interstate highway with a left diversion. The arrow board was located at the point of diversion (shoulder placement) and in front of a type III barricade used to close the roadway. Day and night experiments were performed both with and without an arrow board. The flashing arrow mode was used for the arrow board experiments.

The results appear to indicate that a surprisingly high percentage of vehicles remained in the right lane with or without the arrow board. Overall, 81.6 percent of the cars and 86.0 percent of the trucks that were in the right lane at the beginning of the zone were also in the right lane at the point of diversion which was at the start of detour. Those vehicles that changed lanes did so within the last 600 ft (180 m) approaching the point of diversion. Results are mixed concerning which arrow board treatment caused more vehicles to remain in their lane. In the daytime, more cars stayed in their lane with no arrow board, and at night more stayed with the closed-lane placement. More trucks stayed in the right lane with the shoulder (point of diversion) placement in the day and with no arrow board at night. There were no arrow board effects on the erratic maneuver rate. Erratic maneuver rates were higher at night. The slow-vehicle conflict rate was lower (90 percent confidence level) with the shoulder placement than with no arrow board or when the arrow board was located in front of the type III barricade.

7. Test 7 - Experiments IC7 and 8: Test 7 was conducted on a 2-lane rural highway at a right diversion. Both experiments were performed during the day. A flashing arrow mode was used for one experiment, and the arrow board was located in front of the type III barricades used to close the through roadway. No arrow board was used for the other experiment.

The arrow board had no effect on vehicle speeds. However, the erratic maneuver rate was lower and the percentage of lane encroachments was higher when the arrow board was used.

8. Test 8 - Experiments IC9-11: This test was performed on a 4-lane rural Interstate highway at a right-lane closure. All experiments were performed during the day. Two experiments used an arrow board displaying the flashing arrow mode. The arrow board was located (a) on the shoulder at the beginning of the taper, and (b) on the shoulder 250 ft (76 m) upstream of the start of the taper. No arrow board was used in the third experiment.

The arrow board was effective in getting traffic to exit the closed lane sooner, with the best location for the arrow board being the upstream location. The no-arrow board experiment had the lowest slow-moving vehicle conflict rate, followed by the experiment with the arrow board located upstream of the taper.

9. Test 9 - Experiments IC12-17: This test was conducted on a 4-lane rural Interstate highway at a right-lane closure. Both day and night experiments were performed. For the four experiments performed with an arrow board, the flashing arrow mode was used. In two experiments, the arrow board was located on the shoulder at the beginning of the taper. For the other two experiments, the arrow board was located in the closed lane 500 ft (152 m) into the taper. A flagman was stationed at the beginning of the taper for the daytime experiments with the arrow board in the closed lane and with no arrowboard. The flagman's presence probably helped to reduce the percentage of vehicles in the right lane and also probably caused higher erratic maneuver rates and lower mean speeds. Therefore, more reliance should be placed on the results of the night experiments. These results clearly indicate that both arrow board placements reduced the percentage of vehicles in the right lane, and the shoulder placement near the start of the taper was superior to the placement in the closed lane well into the taper. The shoulder placement also reduced the erratic maneuver rate and slow-vehicle conflict rates in comparison to either no arrow board or placement in the closed lane.

10. Test 10, Experiments IC20-25: This test was conducted on a 4-lane, undivided, urban highway with the right lane closed. The arrow board placement was varied between (a) on the shoulder near the start of the taper, and (b) in the closed lane near the middle of the taper where flashing arrow and sequential arrow board modes were tested. During the day, the percentage of vehicles initially in the right lane was lowest with shoulder placement, followed by closed-lane placement, followed by no arrow-board. At night, all three conditions were the same. Also, the initial percentage of vehicles in the right lane was lower with the sequential arrow mode than with the flashing arrow. With either arrow board placement, vehicles left the right lane faster than with no arrow board. Erratic maneuvers were higher with shoulder placement, and slow-vehicle conflicts were higher with both arrow board placements. Slow-to-merge opportunities were higher with the closed-lane placement, and slow-to-merge conflicts were higher with the shoulder placement. At night lane-change conflicts were higher with an arrow board, but during the day they were lower with an arrow board. The analysis of conflict rates and the percentage of vehicles in the right lane at night were probably affected by event recorder problems on the night experiment with no arrow board.

11. Test 11 - Experiments IC26-29: This test was conducted on a 4-lane uncontrolled access urban highway with a left-lane closure. This road is divided by a raised concrete median which runs through the zone and ends in the taper. Day and night experiments were performed. The arrow board was located in the middle of the taper for experiments that used an arrow board. The flashing arrow, sequential stem, and sequential chevron modes were used.

For day operations, arrow boards regardless of mode were more effective in clearing the closed lane of traffic than when no arrow board was present. At night, arrow boards tended to increase confusion, as evidenced by the significant erratic maneuver and slow-vehicle conflict rates. The analysis of arrow board effects was further complicated by the fact that additional traffic entered the zone from a ramp located mid-way through the zone. Vehicles entering from the ramp were merging left while vehicles in the closed lane were merging right.

12. Test 12 - Experiments IC30,33-35: This test was performed on a 4-lane, limited access rural highway at a right diversion. Both day and night experiments were performed. The arrow board, when used, was located in the closed roadway behind the barricades. The flashing arrow, sequential chevron and sequential stem modes were used.

At night, there appeared to be no difference between modes on the lane change and lane encroachment patterns. During the day, the lane changes were more pronounced, and the arrow board had the most effect in producing these lane changes. The arrow board increased the erratic maneuver rate, especially at night. In general, the arrow board increased the number of lane changes, but the number of vehicles changing lanes was smaller at night.

13. Test 13 - Experiments IC31 and 32: This test was performed on a 4-lane undivided uncontrolled access, rural highway at a right-lane closure. Both experiments were conducted during the day. The arrow board was located near the middle of the taper in the closed lane. The flashing arrow mode was used for the experiment that was conducted with an arrow-board.

At this construction zone, vehicles started to exit the closed lane sooner when an arrow board was used. Since vehicles were leaving the closed lane sooner, there were fewer vehicle interactions occurring in the approach area of the zone. This observation can be substantiated by the fact that the percentage of slow-to-merge opportunities and conflicts were significantly less when an arrow board was used.

14. Test 14 - Experiments IC36-38, 45, 46: This test was conducted on a 4-lane, undivided, urban highway with a right diversion and the left lane closed. The arrow board was placed in the closed lane near the start of the taper. The flashing arrow and sequential chevron modes were tested during the day, and the flashing arrow mode was tested at night.

There were no significant arrow board effects on the pattern of left-lane percentages at night. Most vehicles left the closed lane between 400 and 200 ft (122 and 61 m) from the arrow board. More cars left with the flashing arrow mode, followed by the sequential chevron mode, followed by no arrow board. There were no significant differences in the erratic maneuver or conflict rates during the day experiments: however, at night, the erratic maneuver rate was lower with an arrow board than it was without an arrow board.

15. Test 15, Experiments IC39-44: Test 15 was conducted on a 4-lane, uncontrolled access, rural highway with the right lane closed. The arrow board placements varied between (2) on the shoulder near the start of the taper, and (b) in the closed lane near the middle of the taper. The flashing arrow mode was used at all times when an arrow board was present.

At night, cars left the closed lane faster with both of the arrow board placements than with no arrow board. During the day, the cars left faster with the closed-lane placement than with the shoulder placement or no arrow board. The speed of the vehicles was measured in the closed lane near the start of the taper. The mean speeds were higher with the shoulder placement during the day, but there were no significant differences in mean speeds at night. Slow-to-merge opportunity rates were higher with no arrow board. During the day, the closed lane placement had lower slow-to-merge opportunity rates than the shoulder placement. At night, the placements were equal.

16. Test 16, Experiments IC47 and 48: This test was conducted on a 6-lane urban Interstate highway with the right lane closed and the other two lanes split. Only the portion of the zone near the split was tested. It was tested with an arrow board with a double flashing arrow, and with an arrow sign. Both the arrow board and the arrow sign were located in the gore of the split.

The percentage of vehicles in the left lane was higher with the arrow sign than with the arrow board. In other words, with the arrow board, more vehicles stayed in the right lane. The only difference in operation was that more vehicles changed lanes near the split with the arrow sign.

17. Test 17, Experiments IC49-51: This test was conducted on a 6-lane urban freeway with the left lane closed. An arrow board was placed on the shoulder near the start of the taper and in the closed lane near the middle of the taper. The sequential chevron mode was used at all times when an arrow board was present.

The initial percentage of vehicles in the left lane (at 2,000 ft, or 610 m) was lowest with the shoulder placement. Also, the rate that vehicles departed the left lane was higher with the shoulder placement, although only marginally. The only significant conflict effect was that slow-moving vehicle conflict rates were higher with an arrow board than with no arrow board.

18. Test 18, Experiments IC52 and 53: This test was conducted on a 6-lane urban Interstate highway with the right lane closed and the remaining two lanes split. Only the portion of the work zone near the split was tested. It was tested with an arrow board with a double flashing arrow and with an arrow sign.

The only significant effect observed was that the rate of conflicts due to last second lane changes was lower with the arrow board.

19. Test 19, Experiments IC54 and 55: This test was conducted on a 4-lane rural Interstate highway with the two lanes split. An arrow board with the double flashing arrow was present during both experiments. One experiment was conducted during the day-peak and the other during the day off-peak. During both experiments, vehicles were moving from the left lane into the right lane. During the peak, about 5 % of the total vehicles moved from the left lane to the right lane, and during the off-peak about 6% made the same lane change. The percentage of cars in the left lane was higher during the peak hour experiment. No significant differences in erratic maneuver or conflict rates were observed.

20. Test 20, Experiments IC56-60: This test was conducted on a 4-lane rural Interstate highway with the left lane closed. The arrow board was located on the shoulder near the start of the taper. The modes tested were sequential chevron and flashing arrow.

The percentages of vehicles in the left lane were very low during all experiments. The rate of slow-vehicle conflicts was lower with an arrow board in the day but not at night. Also, during the day there were lower slow-vehicle conflict rates with the flashing arrow mode than with the sequential chevron mode.

21. Test 21, Experiments IC61-64: Test 21 was conducted on a rural 4-lane Interstate highway with the left lane closed. The arrow board was placed on the shoulder near the start of the taper. The arrow board modes were flashing arrow and sequential chevron. Vehicle speeds were measured by radar 1,500 ft (460 m) into the work area.

The percentage of cars in the left lane was very low during all experiments. There were no significant erratic maneuver or conflict effects. The speeds of cars were significantly lower statistically with an arrow board, although the reduction in mean speeds was only from 58.4 to 57.2 mph (87.7 to 91.5 Km/h). There were no arrow board effects on truck speeds.

22. Test 22- Experiments CM1 and CM7: These maintenance experiments were conducted on 8-lane Interstate highways with a stationary right-lane closure. Arrow boards were present in both experiments. The placement of the arrow board was varied between (a) shoulder near the start of the taper, and (b) in the closed lane near the end of the taper. One arrow board was a 4 x 8 ft (1.2 x 2.4 m) trailer-mounted board; the second was a 3 x 6 ft (0.9 x 1.8 m) vehicle-mounted board. The trailer-mounted board operated in the sequential chevron mode, and the vehicle-mounted board operated in the sequential arrow mode.

The larger board was more effective in getting cars out of the closed lane. With the smaller board cars stayed in the right lane longer and then left at a faster rate than with the larger board. Erratic maneuvers were marginally less ($p \leq 0.10$), slow-to-merge opportunities were significantly less and slow-to-merge conflicts were marginally less with the larger (trailer-mounted) board.

23. <u>Test 23 - Experiments CM3 and IM7</u>: These maintenance experiments studied moving striping operations on Interstate highways with the left lane closed. Experiment CM3 was conducted on an 8-lane urban Interstate and IM7 on a 6-lane rural Interstate. Both experiments employed arrow boards. It was not possible to observe conflicts in Experiment IM7.

The patterns of the lane changes in the two experiments were quite similiar except that CM3 had a lower initial percentage of cars in the left lane. In both experiments, nearly all vehicles had departed the left lane by 200 ft (61 m) from the striping operation. Conflicts on Experiment CM3 were very low; less than 1% of the vehicles committed any type of conflict.

24. <u>Test 24 - Experiments CM4, 6, 8, 9 and 14</u>: These maintenance experiments studied moving sweeping operations on 8-lane Interstate highways. Operations on both the left and right shoulders were studied. Modes studied were flashing arrow and caution bar. Two experiments did not have arrow boards. Rather, signs on the back of the sweepers read "Caution - Sudden Stops and Turns."

In all but one of the experiments, the pattern of lane changes that emerged was that a few vehicles changed lanes within 600 ft (183 m) of the maintenance vehicle. However, in the experiment when the sweeper was on the left shoulder and had no arrow board, there were very few lane changes out of the left lane. Slow-vehicle conflicts were greatest with the caution-bar mode on the right shoulder and very low in the left shoulder experiment with the sign only.

25. <u>Test 25 - Experiments CM5 and 13</u>: These maintenance experiments were stationary mudjacking operations on 8-lane Interstate highways. In CM5 the two right lanes were closed. In CM13, the two left lanes were closed. An arrow board located in the closed lane near the end of the first lane taper was tested in both experiments and both of them used the sequential chevron mode.

The lane-change patterns examined for both closed lanes in both experiments reveal that the left lane in CM13 was cleared faster than the right lane in CM5. However, the lane second from the left did not clear as readily as the lane second from the right. The slow-to-merge opportunity rate and the slow vehicle conflict rate were higher with the two left lanes closed than with the two right lanes closed.

26. <u>Test 26 - Experiment IM3</u>: This experiment was conducted on a 6-lane Interstate highway with the center lane closed. The maintenance operation being conducted was emergency pothole repair. An arrow board trailer with a double flashing arrow was used throughout the test. Also, traffic was queued throughout the 1-hour test so it was not possible to make conflict counts.

The lane change pattern shows that about 25 % of the vehicles were in the center lane at 800 ft (244 m) behind the arrow board trailer. About 60 % of the vehicles in the center lane merged into the right or left lane between 800 and 200 ft (244 and 61 m) behind the arrow board.

27. Test 27 - Experiments IM 4-6: These maintenance experiments were all conducted on stationary lane closure operations. Experiment IM6 involved closing two of three lanes. An arrow board was used in experiments IM4 and 6. During experiment IM4, traffic was queued for a total of 28 min of the hour tested. During IM5 and 6, traffic was queued during the entire hour of each experiment. Volumes were compared for 15-min periods to determine if the arrow board had any effect on the capacity of the work zone roadway. Unfortunately, the date film for IM4 was largely unusable, and volumes were readable for only one 15-min period. During this 15-min period with an arrow board, traffic was queued 8 min and 692 vehicles (579 cars and 113 trucks) moved through the zone. Without the arrow board, traffic was queued the entire hour and the average 15 min volume was 747 vehicles. During Experiment IM6, traffic was queued the entire hour and the average 15-min volume was 301 vehicles.

28. Test 28 - Experiments IM8 and 9: This maintenance test was conducted on a 6-lane Interstate highway with the right lane closed. During IM 8, a vehicle-mounted 3 x 6 ft (0.9 x 1.8 m) arrow board with sequential chevrons was located on the shoulder near the start of the taper. The middle chevron of this board was not operating. Experiment IM9 was without an arrow board. The lane change patterns and erratic maneuver and conflict rates of these two experiments did not differ in any way.

29. Unused Maintenance Experiments CM2, CM10-12, IM1, and IM2: There were conditions during all of these experiments that prevented a formal analysis of the film data. CM2 data film was overexposed, CM10, 11, and 12 were short-term striping operations that did not lend themselves to analysis. IM1 was a striping operation on a 2-lane road that could not be analyzed formally; and in IM2, a trailing maintenance vehicle blocked the camera's view of lane changes. Although these experiments did not produce quantitive results, information about typical arrow board uses was gained.

F. Summary of Results

As discussed previously, the three basic measures of effectiveness were: (1) lane-changing patterns; (2) erratic maneuvers; and (3) traffic conflicts. For summarizing the overall effects of arrow boards, however, the lane-changing patterns serve as the primary criteria.

The erratic maneuver results were mixed, with most tests showing no significant difference in rates with or without an arrow board. Two tests with lane closures indicated that the erratic maneuver rate at night was decreased by using a arrowboard.

Slow-moving vehicle conflicts were normally increased when an arrow board was present. However, the kinds of conflicts associated with merging (lane changes, slow-to-merge, and wrong-way lane changes) had mixed results. About half of the tests detected no difference in these conflict rates due to arrow boards. The other half of the tests were divided between those where the arrow board decreased the rate and those where the arrow board increased the rate.

The following paragraphs summarize the major results by the type of zone or arrow board size/mode.

1. Lane Closures: For each test conducted at a lane closure where there was a significant effect on the lane-changing pattern, the presence of an arrow board produced lane-changing patterns that were closer to the ideal. In other words, the arrow board encouraged drivers to leave the closed lane sooner and, consequently, fewer lane changes occurred near the start of the taper.

In rural areas, right-lane closures appear to be more critical (arrow boards are more effective) because of a much higher initial percentage of traffic in the right lane. On six and eight-lane urban freeways a double-lane closure on the left side is more critical than on the right side.

2. Traffic Diversions: In traffic diversions, arrow boards produced some unnecessary lane changing; however, the magnitude was small, particularly at night and for truck traffic. Encroachment rates during the day were greater with the arrow board for two tests and lower for one test. The two tests conducted at night revealed that encroachments were either unaffected or decreased by the use of an arrow board. Overall, no distinct benefits were observed by using arrow boards for traffic diversions.

3. Traffic Splits: The results of arrow board tests in traffic splits showed mixed effects. On one hand, conflicts arising from vehicles changing lanes near the split were reduced by the double flashing arrow. On the other hand, the arrow board caused more vehicles to either remain in or move to the right lane. Therefore, the overall effectiveness of the double flashing arrow used in a traffic split will depend on the volume-to-capacity ratios at a particular site.

4. Maintenance Operations: The use of the arrow board had little effect for shoulder sweeping operations on freeways. Slow-vehicle conflict rates were higher when the caution-bar was used.

5. Arrow Board Placement: The tests generally indicated that placing the arrow board on the shoulder near the start of the taper produced a more effective lane-changing pattern than placing the arrow board in the closed lane in the middle of the taper. In the two tests where the arrow board was placed on the shoulder upstream from the start of the taper, the results indicated that this placement may be even more effective than the placement at the start of the taper.

6. Arrow Board Size: The larger arrow board, 4 x 8 ft (1.2 x 2.4 m), was more effective than smaller ones, particularly at night and during peak periods. One maintenance test with a 3 x 6 ft. (0.9 x 1.8 m) arrow board failed to detect any effect on lane-changing pattern from the arrow board.

7. Arrow Board Mode: With one exception, no differences could be detected in the effect of the various arrow board modes. The sequential stem did increase conflict rates at night.

VII. CONCLUSIONS

1. In work zones with lane closures, arrow boards are effective in encouraging drivers to leave the closed lane sooner, thus reducing the number of vehicles in that lane near the start of the taper (page 62).*

2. Arrow boards are more effective in promoting lane changes when placed on the shoulder of the roadway either at the start of the taper or upstream of the start of the taper, rather than centered in the closed lane in the middle of the taper (page 63).

3. Although the field studies indicated that few statistically significant differences in driver behavior could be attributed to changes in the arrow board mode, the literature survey and human factors studies indicated that the flashing arrow is the most effective mode in conveying its message to drivers. Sequential modes must go through four pulses as opposed to two pulses for the flashing arrow. The four pulses have a greater tendency to have their meaning degraded if: (a) displayed at night; (b) blocked by large trucks; or (c) diffused under adverse weather conditions. The sequential-chevron mode was generally superior to the sequential-arrow or sequential-stem modes in promoting lane changing and driver understanding. The case for uniformity would suggest a preference for the flashing-arrow mode for lane closure situations. The sequential-chevron mode could be used for detours, crossovers, or bypass roadways (page 32).

4. The 4 x 8 ft (1.2 x 2.4 m) arrow board is much more effective in promoting lane changes than smaller boards, particularly during nighttime and day-peak operations (page 63).

5. Arrow boards are not generally effective in diversions (detours, crossovers, or bypass roadways). Human-factors laboratory studies revealed that drivers normally interpret the arrow board message to mean a lane closure ahead. Field study results indicate that arrow boards do cause some unnecessary lane changes in diversion work zones, although the number of these lane changes was not large. Arrow boards may be effective in decreasing encroachments onto adjacent lanes or onto the shoulder particularly at night (page 62).

6. When traffic is split into two flows and the double flashing-arrow mode is used, a higher proportion of traffic tends to shift to the right lane. An arrow board used in this situation also deters drivers from changing lanes near the gore of the split (page 62).

7. Where shoulder work is being done and a lane closure is not required, arrow boards may cause unnecessary lane changes. Also slow-vehicle conflicts are increased when the caution-bar mode is used (page 63).

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* Page numbers indicate the source of each conclusion.

8. The arrow board is optimally placed when it is head-on to the driver, on the shoulder of the roadway. Arrow board effectiveness is reduced where roadway curvature precludes a head-on viewing. This situation should be corrected by changing the position of lane closure taper or diversion (page 54).

9. Arrow boards are effective in moving-maintenance operations when a lane is closed. In field studies of striping operations with the left lane closed, nearly all vehicles departed the left lane by 200 ft (61 m) upstream of the striping operation (page 60).

10. In rural areas, right-lane closures are more critical because more vehicles are normally in the right lane (page 54).

11. Arrow boards tend to decrease vehicle speeds slightly, especially in the approach and taper areas of the work zone. However, tests of vehicle speeds 1,500 ft (460 m) into the work area did not reveal any practical speed differences due to the arrow board (page 59).

12. Slow-moving-vehicle conflict rates are normally increased when an arrow board is present. This effect may be linked to the decrease in vehicle speeds. Erratic maneuvers and conflicts associated with merging had mixed results (page 62).

13. Further research is needed to determine possible modes for use in diversions and in traffic splits (page 62).

14. Placement of the arrow board in advance of the start of the taper should be tested at night (page 55).

REFERENCES

1. McAllister, J. J., and D. L. Kramer, "Advance Warning Arrow Sign Study," California Department of Transportation, July 1974.

2. Bates, L., "The Effect of Arrow Board Trucks on Merging Traffic," Illinois Department of Transportation, Bureau of Traffic, January 1976.

3. Shah, S. C., and G. L. Ray, "Advance Traffic Control Warning Systems for Maintenance," Louisiana Department of Highways, Research and Development Section, July 1976.

4. Graham, J. L., R. J. Paulsen, and J. C. Glennon, "Accident and Speed Studies in Construction Zones," Report No. FHWA-RD-77-80, June 1977.

5. Wojcik, C. K., R. W. Allen, "Investigation of Novel Road Geometry: Lane Drop Study," California University, 1972.

6. Tye, E. J., "The Lane Drop Study," (Relating Roadway Elements to Accidents), California Division of Highways, October 1968.

7. Goodwin, D. N., "Operational Effects of Geometric Design at Freeway Lane Drops," Transportation Research Record, No. 541, pp. 26-30 (1975).

8. Cornette, Don, "Operational Characteristics of Lane Drops," Kentucky Department of Highways, August 1972.

9. Lunenfeld, H. and G. J. Alexander, "Signing Treatments for Interchange Lane Drops," Federal Highway Administration, June 1976.

10. Alexander, G. J., and H. Lunenfeld, "Positive Guidance in Traffic Control," Federal Highway Administration, April 1975.

11. McGee, H. W., W. Moore, B. G. Knapp, and J. Sanders, "Decision Sight Distance for Highway Design and Traffic Control Maneuvers," BioTechnology, Inc., January 1978.

12. Hulbert, S., and A. Burg, "A Human Factors Analysis of Barricades, Flashers, and Steady Burn Lights for Use at Construction and Maintenance Work Sites," ATSA Technical Committee, December 1974.

13. Ruden, R. J., et al., "Motorists' Requirements for Active Grade Crossing Warning Devices," MBA Associates, October 1977.

14. Remole, A., "Border Enhancement During Flicker Stimulation Effect of Retinal Location," Vision Research, Vol. 15 (12), pp. 1385-1388 (1975).

15. Tolhurst, D. J., and D. S. Dealy, "The Detection and Identification of Lines and Edges," Vision Research, Vol. 15 (12), pp. 1367-1372 (1975).

16. Swezey, R. W., "Brightness Contrasts Effects on Recall of Projected Highway Sign-Type Stimulus Material," Journal of Applied Psychology, Vol. 59 (3), pp. 408-410 (1974).

17. Osaka, N., "Target Size and Luminance in Apparent Brightness of the Peripheral Visual Field," Perceptual and Motor Skills, Vol. 41 (1), pp. 49-50 (1975).

18. Magnussen, S., and A. Glad, "Effects of Steady Surrounding Illumination on the Brightness and Darkness Enhancement of Flickering Lights," Vision Research, Vol. 15 (12), pp. 1413-1416 (1975).

19. Benignus, V. A., et al., "Monitoring Performance as a Function of Rate of Ready Signals," Perceptual and Motor Skills, Vol. 43 (3, Pt. 1), pp. 815-821 (1976).

20. ATSA, "Field Evaluation of Barricade Warning Lights," ATSA Technical Subcommittee on Lights, May 1974.

21. Goldblatt, R. B., "Guidelines for Flashing Traffic Control Devices," KLD Associates, Inc., July 1976.

22. Rockwell, T. H., V. D. Bhise, and R. R. Safford, "Development of a Methodology for Evaluating Road Signs," June 1970.

23. Grether, W. F., and C. A. Baker, "Visual Presentation of Information," H. P. Van Cott and R. G. Kinkade (Eds.), In Human Engineering Guide to Equipment Design, McGraw-Hill Company, 1972.

24. Bruce, V. G., and M. J. Morgan, "Violation of Symmetry and Repetition in Visual Patterns," Perception, Vol. 4 (3), pp. 239-249 (1975).

25. Coppel, F., and P. Milliman, "Flashing Arrow-Bar Traffic Control Signs: A Report of Comparison Testing," Research Report No. R-163, Michigan Department of State Highways, November 1966.

26. Guilford, J. P., Psychometric Methods, New York: McGraw-Hill Company, pp. 154-177, 1954.

27. McCormic, E. J., Human Factors Engineering, New York: McGraw-Hill Company, pp. 53-63, 154-155, 1970.

28. Crawford, A., "The Perception of Light Signals: The Effect of Mixing Steady and Irrelevant Lights," Ergonomics, Vol. 6, pp. 287-294 (1963).

REFERENCES (Concluded)

29. Cox, D. R., The Analysis of Binary Data, Chapman and Hall, 1970.

30. Box, G. E. P., "Problems in the Analysis of Growth and Wear Curves," Biometrics, p. 362-389 (December 1950).

APPENDIX A

DEFINITION OF TERMS

General Definitions

Work Area or Work Site - That portion of the roadway where work is being done or is going to be done and is closed to traffic.

Work Zone - That portion or segment of a street or highway where a construction, maintenance or utility activity, or the traffic control devices for that activity, impact on traffic. The zone begins with the first information to the driver that he is approaching a work area and ends where traffic may resume its normal operation.

Arrow Board - A sign panel with a matrix of lights capable of either flashing or sequential displays.

Arrow Board Mode - The pattern of lights displayed on the arrow board. Alternatives include flashing arrow, sequential chevron, sequential arrow, sequential stem, and caution modes.

Work Zone Types

Roadside - Where the work activity is taking place adjacent to the traveled way (i.e., in medians, shoulders, or in the area adjoining the outer edge of the roadway).

Lane Closure - Where one or more lanes of a unidirectional traveled way are closed to traffic.

Crossover - Where traffic is channeled into one or more lanes of the roadway normally used for traffic in the opposite direction. On divided highways, a temporary or existing connection between the two directional roadways is used to channel traffic to the opposite side. On undivided roadways, traffic is channeled across the old centerline of the roadway so that both directions of traffic are using the same side of the roadway.

Bypass Roadway - Where a temporary road is built to carry traffic around the work area. The bypass roadway may be either one-way or two-way

Detour - Crossovers, bypass roadways or detours where traffic is diverted from its normal path, but the number of lanes is not reduced.

Shoulder Closure - A roadside work activity where the roadway shoulder is closed but the number of lanes is not reduced.

Areas Within Work Zones

Warning Area - Begins with the first information to the driver that he is approaching a work area. On high-speed expressways, the warning area may begin 1 to 2 miles upstream of the work areas.

Approach Area - Begins with the first information to the driver about the actual condition of the roadway ahead and the actions that will be required to travel through the work zone. Although no physical restrictions narrow the roadway in the approach area, there are often slowing and merging maneuvers as drivers adjust their speed and position based on their concept of the safe path through the zone.

Entering Transition - Begins at the point where the normal roadway is altered laterally by devices such as cones, barricades, or barriers in order to channelize traffic to the part of the roadway open through the work zone. In Figure 9, traffic must move from the right lane into the median lane.

Work Area - That portion where work is being done or is going to be done. The work area is completely closed to traffic.

Exiting Transition - The area downstream from the work area where traffic returns to the normal roadway. In Figure 9, the right lane is reopened in the exiting transition.

Types of Work Zone Operations

Long-term - A construction, maintenance, or utility activity that requires traffic control and that takes longer than one period of daylight to complete or that is performed during hours of darkness.

Short-term - A construction, maintenance, or utility activity that requires traffic control and that takes less than one period of daylight and is not performed during hours of darkness.

Stationary - A construction, maintenance, or utility activity that moves in a continuous fashion at less than 2 mph (3 km/h).

Moving - A construction, maintenance, or utility activity that moves in a continuous fashion at or greater than 2 mph (3 km/h).

Erratic Maneuver and Conflict Definitions

Erratic Maneuver - When an unimpeded vehicle brakes or suddenly swerves while approaching the transition (taper) area. (Unimpeded means there are no vehicles directly ahead or rapidly overtaking in an adjacent lane.)

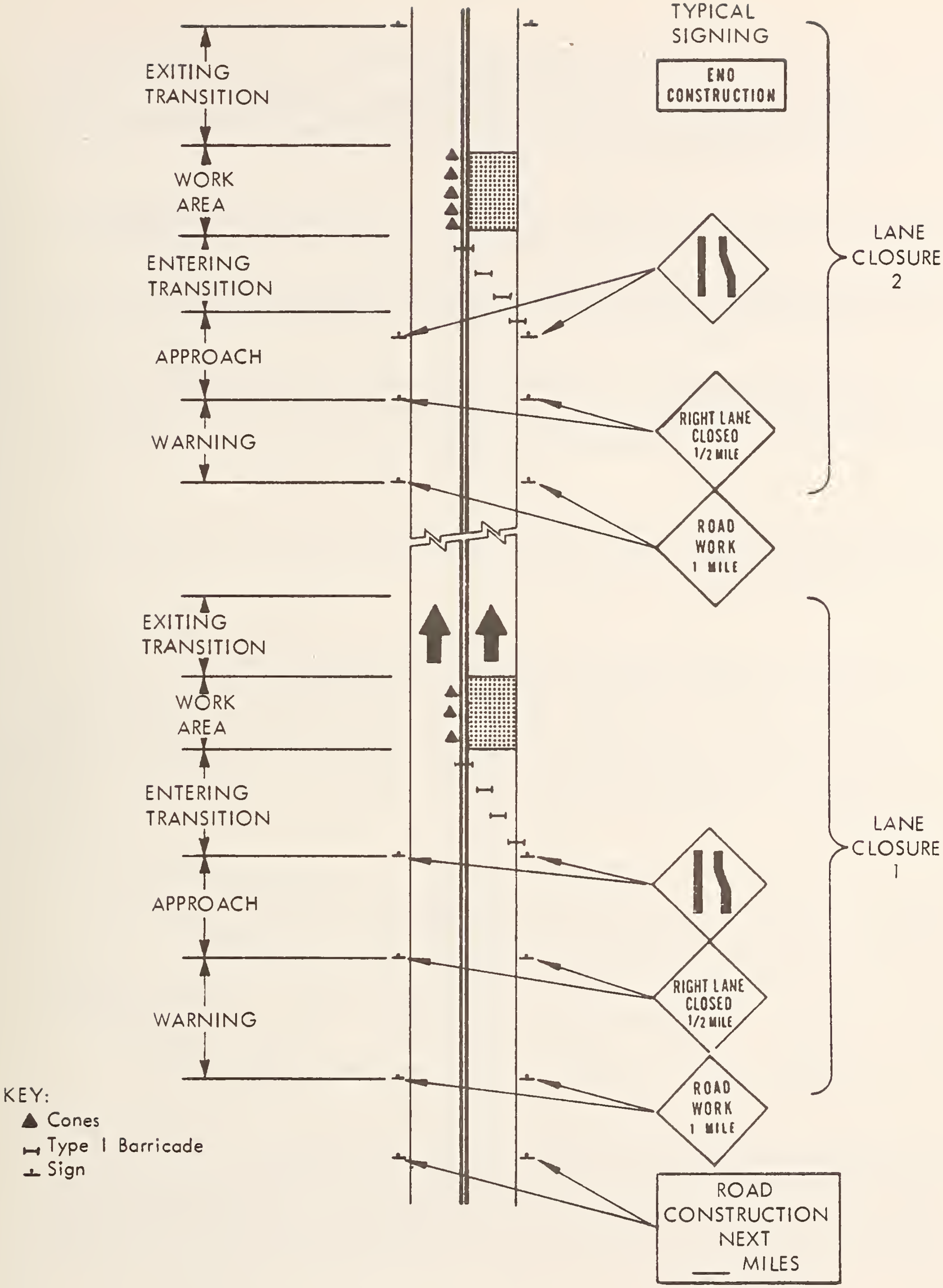


Figure 9 - Areas Within a Work Zone

Conflict - A situation in which a vehicle is required to take evasive action, to brake or swerve to avoid an impending collision with another vehicle ahead or alongside. A brake light indication, obvious braking, and swerving by the offended vehicle are indicators of a conflict.

Lane-Change Conflict - A vehicle changes lanes into the path of another vehicle, causing the offended vehicle to brake or swerve to avoid collision.

Slow-to-Merge Conflict - A vehicle slows or stops during its merge into the open lane, causing a vehicle in the open lane to brake or weave.

Wrong-Way Lane-Change Conflict - A vehicle in an open lane approaching the transition area enters into a closed lane, and an offended vehicle brakes or takes evasive action to avoid collision with the wrong-way lane-change vehicle.

Slow-Moving Vehicle Conflict - A vehicle approaching the transition area is confronted with a stopped vehicle. The offended vehicles slows, stops, or swerves to avoid the stopped vehicle.

Secondary Conflict - A conflict that is initiated by an earlier traffic conflict. It occurs when two vehicles approach the transition area as a pair, and the lead vehicle of the pair becomes the offended vehicle in a traffic conflict and slows, stops, or swerves. The following vehicle then must take evasive action because of the action of the lead vehicle. Both the initiating the resulting secondary conflicts are counted; the latter is attributed to the initiating conflict.

Conflicts are also classed according to severity. A routine conflict involves precautionary braking or lane changing when the risk of collision is small. For example, a freeway driver may feel threatened by a merging vehicle and change speed or position although the chance of contact is slight.

A moderate conflict is characterized by controlled braking or lane changing to avoid a situation with high collision potential. It would represent a close call, but the maneuver would be a clear case of controlled evasive action.

A serious conflict involves rapid deceleration or a severe swerve to avoid a collision. The driver has no time for a controlled maneuver. It would be a very near miss. Vehicle behavior indicating this condition would involve "fish-tailing," side-to-side rolling or rocking, skidding, or forward-lurching of a braking vehicle.

GUIDELINES FOR ARROW BOARD USE

This appendix contains guidelines for arrow board use including their design specifications, warrants for use, and placement details.

Arrow Board Specifications

Arrow boards are sign panels with a matrix of lights capable of either flashing or sequential displays. They are used for diverting traffic when construction or maintenance activities are on or near the traveled way.

Arrow boards are intended to supplement other traffic control devices. They will not solve difficult traffic problems by themselves, but they can be very effective when properly used to reinforce signs, barricades, cones and other traffic control devices.

Arrow boards are used for additional advanced warning and directional information where traffic must be shifted laterally along the roadway. They give drivers positive guidance about a roadway path diversion that they might otherwise not expect.

Arrow boards are generally used for lane closures, roadway diversions, and slow-moving maintenance and construction activities. They are particularly effective under high-speed or high-density traffic conditions. At night, they are effective where other traffic control devices cannot provide adequate advance warning of a roadway path diversion. During daylight, arrow boards are effective under high-density traffic conditions that might block the driver's advanced view of construction or maintenance activities ahead.

Arrow boards are rectangular, of solid construction, and finished with nonreflective black. For maintenance activities, the arrow boards are usually mounted overhead on a maintenance vehicle and are remotely controlled from the truck cab. For construction activities, the arrow board is often mounted on a trailer with a self-contained power source.

Arrow boards should be capable of either of the following displays: (1) left, right, and double flashing arrows; or (2) left and right sequential chevrons and double flashing arrows. Human factors research indicates that the flashing arrow and the sequential chevron are the only acceptable modes, with the flashing arrow preferred. For uniformity, the flashing arrow mode is recommended for all lane closures. All other arrow board modes such as sequential arrows or stems and nondirectional displays should not be used for construction and maintenance activities.

Other general specifications of arrow boards are as follows:

. Mounting Height:	7-8 ft (2.1-2.4 m)
. Panel Background:	Flat Black

- Lens Flash Rate: 30-60 flashes/min (50% dwell)
- Lens Size: 4-1/2 inch diameter (114 mm) PAR 36
- Lens Color: Amber
- Lens Hood: 360° (for close-up glare reduction)
- Bulb Intensity: 8,800 candle power (4 x 8 and 3 x 6 ft sizes)
- Intensity Adjustment: Automatic 50% reduction in intensity when ambient light falls below 5 foot candles
- Number of Lamps:

	Size of Arrow Boards		
	2 x 4' (0.6 x 1.2 m)	3 x 6' (0.9 x 1.8 m)	4 x 8' (1.2 x 2.4 m)
Flashing Arrow	12	13	15
Sequential Chevron	22	22	22

Arrow Board Use

Arrow boards can greatly improve traffic operations when used to supplement work-zone traffic controls or used with temporary or moving maintenance operations. The urgency for their use will vary depending on: (1) the type of highway; (2) the density of traffic; (3) the light condition, day or night; and (4) the kind of work zone or maintenance operation.

Table 12 gives some general guidance for deciding on arrow board use. This table, which rates arrow board need by type of site and operating conditions, can be used to choose arrow-board sites in general or to set priorities when the potential number of sites exceeds the available number of arrow boards.

In Table 12, a rating of 0 (zero) indicates sites where arrow boards generally should not be used because they could cause adverse effects. For a rating of 1, arrow boards can most often be disregarded unless an operational diagnosis at the site indicates a need. For example a damaged barricade in the transition area of a diversion work zone would indicate shoulder encroachments that could possibly be prevented by use of an arrow board. Shoulder encroachments for shoulder or roadside work zones could possibly be prevented by an arrow board also. Because an arrow board in a shoulder or roadside work zone causes unnecessary lane changing they should not be used under high density conditions. For ratings of 2 through 4, arrow boards should always be considered with preferences given to sites with the higher ratings. With a rating of 4, arrow boards should almost always be used.

TABLE 12

ARROW BOARD NEED

Type of Highway	Highway Operational Conditions*		Type of Work Zone: Right Lane Closure	Left Lane Closure	Diversion to Left	Diversion to Right	Shoulder or Roadside Work
Urban Freeway	High Density	Day	4	4	1	1	0
		Night	4	4	1	1	0
	Moderate to Low Density	Day	3	3	1	1	1
		Night	4	4	1	1	1
Rural Multilane		Day	3	2	1	1	1
		Night	4	3	1	1	1
Rural 2-Lane		Day	**	**	0	1	0
		Night	**	**	0	1	0
Urban Multilane Arterial	High Density	Day	3	3	1	1	0
		Night	3	3	1	1	0
	Moderate to Low Density	Day	3	2	1	1	1
		Night	3	3	1	1	1
Urban 2-Lane Arterial	High Density	Day	**	**	0	1	0
		Night	**	**	0	1	0
	Moderate to Low Density	Day	**	**	0	1	0
		Night	**	**	0	1	0

* If operating under more than one condition, higher rating takes precedence.

** Do not use under alternating traffic conditions. (Two lanes reduced to one lane with alternating two-way-traffic.)

Legend

4 Priority Need
3 Highly Needed
2 Moderately Needed
1 Do not use unless diagnosed as needed.
0 Do not use

Table 12 serves as a reasonable guide for initial decisions on arrow board use. Sometimes, however, unusual operating conditions at a site without an arrow board will indicate need. This is particularly true for the conditions rated "1" in Table 12. Arrow boards are not generally effective in diversions because they promote unnecessary merging. However, if an operational diagnosis of a diversion work zone reveals that vehicles are either encroaching on the shoulder of the roadway or actually striking delineation devices in the diversion, an arrow board may be warranted, particularly at night or where traffic volumes are low and unnecessary lane changes are not generally hazardous. Other operational problems such as vehicles stopped for lane changes, erratic maneuvers or conflicts indicate a need for traffic control improvements.

When traffic control improvements are needed, the proper application of existing traffic controls should be checked first. Lane closure tapers that are either on highway curves, or just downstream of crest vertical curves, or near cross-over diversions should be modified if possible. If deficient traffic operations exist even with the proper application of primary traffic control devices, then use of an arrow board should be considered.

Arrow Board Size and Recognition Distance

Although arrow boards can usually be detected at great distances, the most important criterion is recognition distance. This is the distance between the arrow board and the upstream point where drivers can first discern and understand the directional message. Recognition distances are a function of the geometric and environmental conditions at the roadway site and the legibility of the arrow board. Recognition distance requirements for desired arrow board operations are a function of the speed and/or density of traffic.

Table 13 shows the minimum recognition distance requirements for various traffic conditions based on the decision-sight-distance concept.[11/] Also shown are the arrow board sizes needed to meet the recognition distance requirement and that have been shown to be effective. If an arrow board is needed at a site under both high and low density traffic operations, the larger recognition distance and board size must be used. Also the recognition distance requirement establishes the minimum sight distance requirement for the site. If sight restrictions will not allow the minimum recognition distance requirement, the layout of the work zone should be altered to furnish the required sight distance.

Arrow Board Placement

The placement of arrow boards can be very critical to traffic operation. Of particular importance is a placement that ensures the required

TABLE 13

ARROW BOARD SIZE AND RECOGNITION DISTANCE

Recognition Distance (ft)	Urban Streets (20-35 mph)	Arterial (40-50 mph)	Freeway and Other (55 mph)
Recommended	725	1,025	1,175
Minimum	525	750	900
Arrow Board Size (ft)			
Recommended	3 x 6	4 x 8	4 x 8
Minimum	2 x 4	3 x 6	3 x 6

1 ft = 0.3 m
1 mph = 1.61 kph

recognition distances specified in Table 13. Arrow boards should also be placed correctly in relation to the lane closure taper or diversion.

For stationary lane closures, the arrow board should be placed on the shoulder or adjacent to the traveled lanes on the same side as the lane closure, as shown in Figure 10. Field studies at two sites during daylight hours indicate that the most effective placement is about 100 to 500 feet upstream from the beginning of the taper, and in most field tests placement at the start of the taper was superior to placement in the middle of the taper. Placement of the arrow board should be varied as needed to achieve the required recognition distances. Also, care must be taken in the placement to avoid driver confusion in the vicinity of ramps, median crossovers, and side road intersections.

In diversions where arrow board need has been determined, the arrow board should be placed behind the barricades closing the roadway. This placement is shown in Figure 11. A placement on the shoulder at the start of the diversion is acceptable, although not as effective in preventing vehicles from driving into the closed roadway.

For moving-maintenance activities where a lane is closed, the arrow board should be placed at the rear of the activity in the closed lane as shown in Figure 12. In these operations, it is preferable that the arrow board be placed on a vehicle separate from the maintenance vehicle itself. The arrow board should always remain upstream of the maintenance vehicle where adequate recognition distance is available. In other words, in areas of restricted sight distance, the arrow board vehicle should remain in a stationary position upstream of the maintenance vehicle until the separation between the vehicles is greater than the required recognition distance given in Table 13 at which time the arrow board vehicle should close up the gap. The vehicle carrying the arrow board should also be equipped with a sign stating "Road Work Ahead."

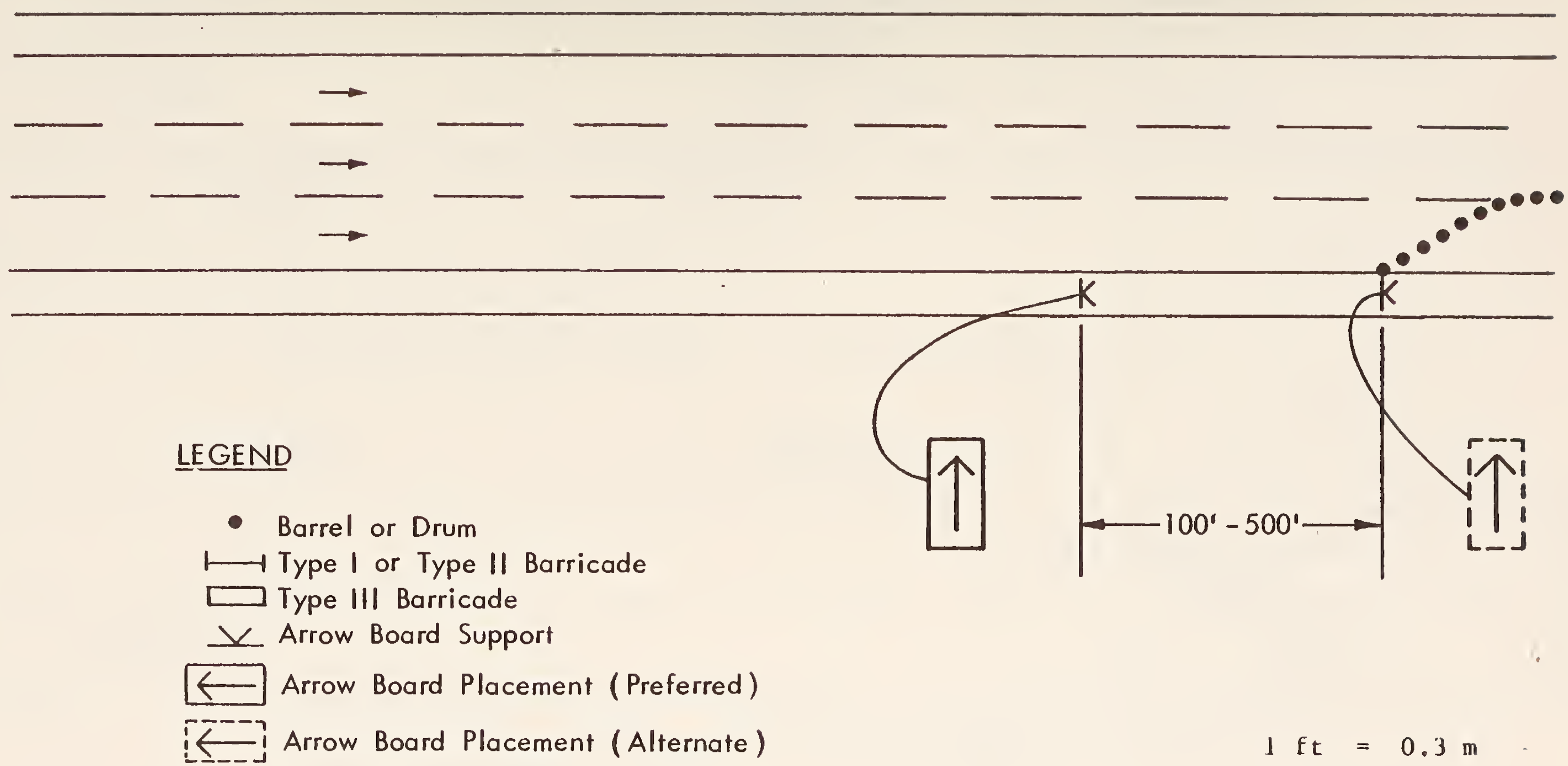


Figure 10 - Arrow Board Placement at Lane Closures

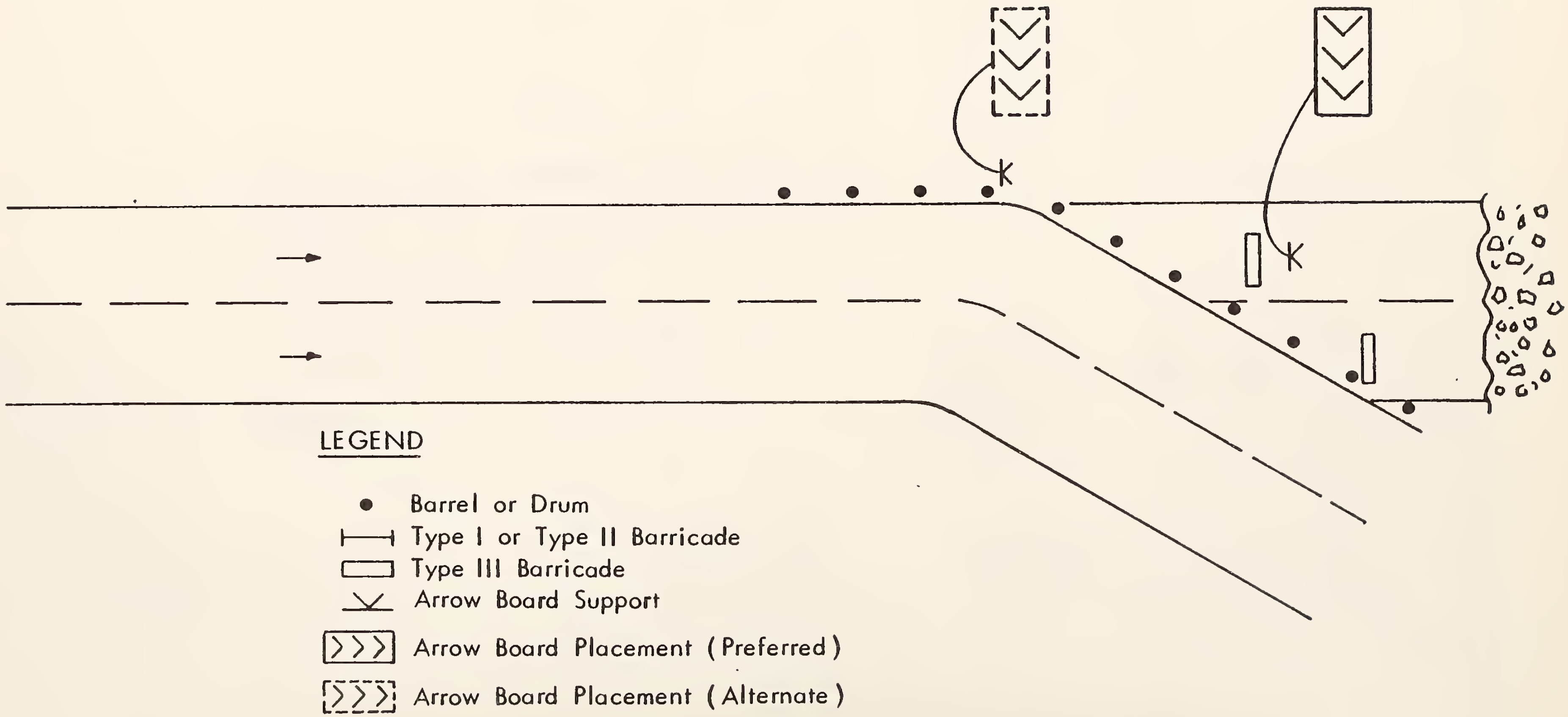
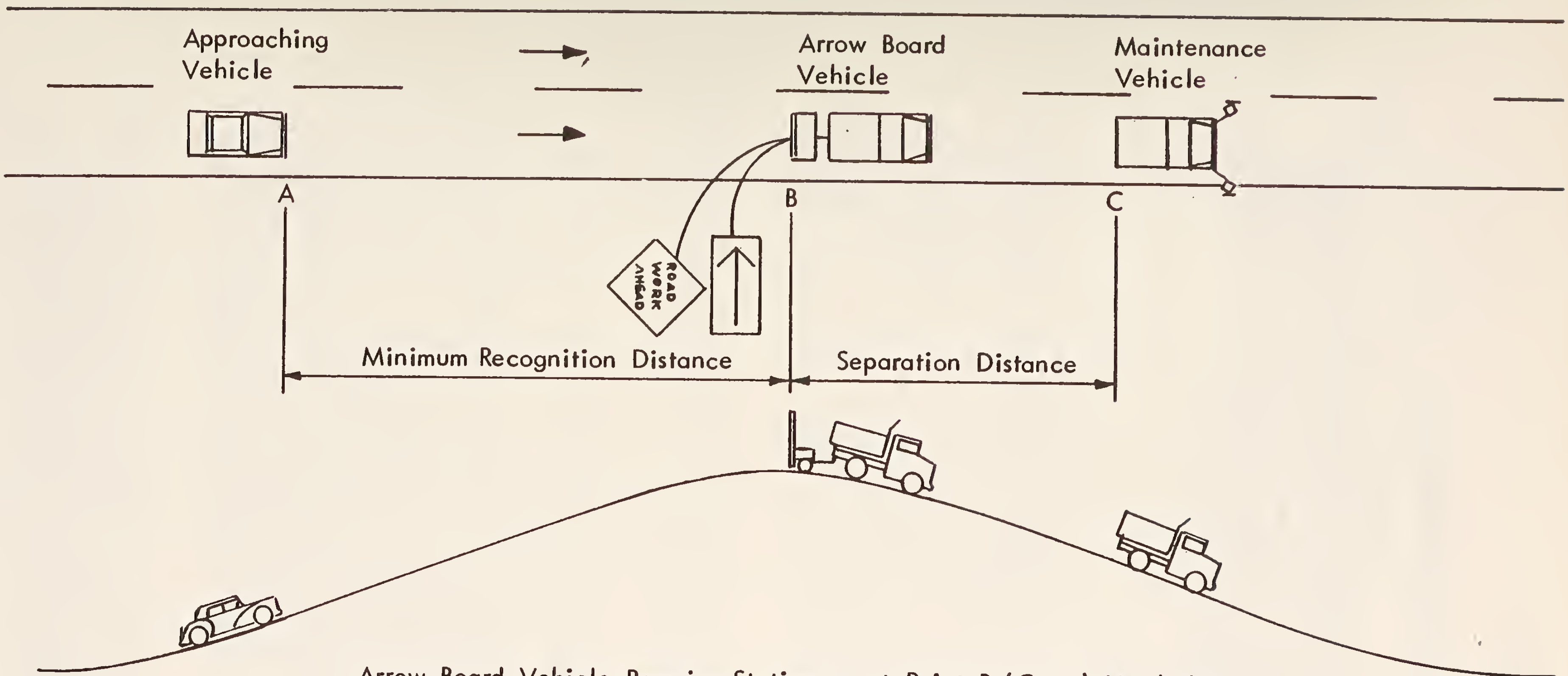


Figure 11 - Arrow Board Placement in Diversions



Arrow Board Vehicle Remains Stationary at Point B (Crest) Until the Separation Distance, BC, Exceeds the Minimum Required Recognition Distance, AB, Given in Table 13

Figure 12 - Arrow Board Placement Following Maintenance Operations

APPENDIX C

DETAILED FIELD-STUDY RESULTS

This appendix presents the detailed results of each of 28 tests conducted in actual work zones. All effects described, unless otherwise noted, were statistically significant at a level of $p \leq 0.05$. Although statistical determinations take place in a logit scale,29/ for convenience all illustrative descriptions in the text use percentages.

Test 1, Experiments CC 1-4

This test was conducted on a 2-lane (with hill-climbing lanes), uncontrolled access, rural highway with the right lane closed. Figure 13 is a diagram of the location. During Experiments CC 1 and CC 2, the arrow board was located on the shoulder near the beginning of the lane-closure taper. During Experiment CC 3, the arrow board was located in the closed lane near the middle of the taper. In these three experiments, the arrow board mode was alternated every 15 minutes from the flashing arrow to the sequential arrow. Experiment CC 4 was conducted without an arrow board. All experiments were conducted during daylight. The arrow board used in Experiments CC 1-3 was 4 x 8 ft (1.2 x 2.4 m).

Lane volumes were tested at three spots (Switches 4, 5 and 6) 1340, 500, and 100 ft (408, 152 and 30 m) from the start of the taper. Speeds were recorded using switch pairs 1-3, 2-4, and 7-8.

Experiment CC 1 was shortened by rain and therefore was combined with CC 2, which had identical experimental conditions.

Table 14 shows the percentage of vehicles traveling in the right lane at various distances from the start of the taper. In terms of the initial (far upstream) percentage of vehicles in the right lane, the proportion is less with the arrow board on the shoulder or with no arrow board than with the arrow board in the closed lane. In terms of the pattern of the decrease in the percentage of vehicles in the right lane, both placements are superior to no arrow board in removing cars from the right lane. The two placements are statistically indistinguishable in this pattern although the shoulder placement yields 3 to 5 percent fewer right-lane vehicles than the closed-lane placement at each of the three switches. There were no significant effects due to the arrow board mode.

The analysis of the speed data was hampered by the lack of initial speeds for Experiment CC 4. However, speeds determined between switches 7 and 8 in the taper did not vary significantly among the four experiments. Vehicles did slow from the first speed reading to the second in Experiments CC 2 and 3.

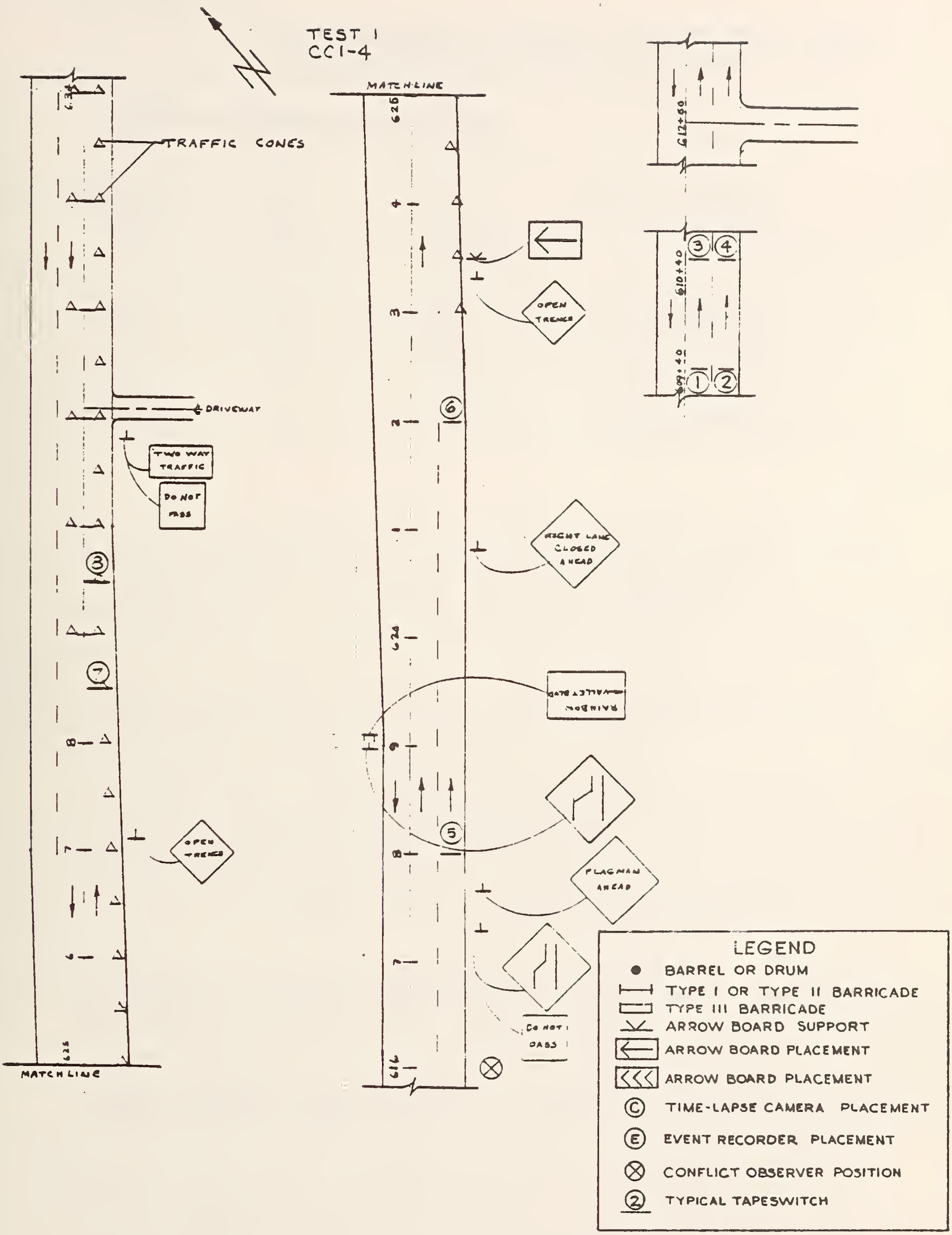


Figure 13 - Test 1 Site Diagram

TABLE 14

TEST 1 - PERCENTAGE OF VEHICLES IN THE RIGHT LANE
(Rural, 2-lane highway with hill climbing lane)

Experiment	Mode	Distance From Beginning of Taper 1,340 ft	500 ft	100 ft
CC 1 and CC 2	Sequential Arrow	63.0	53.5	36.6
CC 1 and CC 2	Flashing Arrow	65.8	54.3	36.3
CC 1 and CC 2	ALL	64.5	53.9	36.4
CC 3	Sequential Arrow	68.4	60.2	42.1
CC 3	Flashing Arrow	66.9	58.9	41.8
CC 3	ALL	67.5	59.4	41.9
CC 4	No Arrow Board	63.4	61.4	53.6

1 ft = 0.3 m

Erratic maneuvers were highest with the combination of the closed-lane placement and the sequential arrow mode. Under these conditions 4.3 percent of the vehicles committed erratic maneuvers versus 0.15 to 1.05 percent otherwise.

The shoulder-placement experiment (CC 2) had fewer conflicts, in general, than either the closed-lane or no-arrow-board experiments. Lane-change conflicts were 0.47 percent with the shoulder placement versus 2.43 percent with the closed-lane placement and 2.58 percent with no arrow board. The shoulder placement also had significantly fewer slow-to-merge opportunities, slow-to-merge conflicts, and slow-moving-vehicle secondary conflicts. The conflict counts may have been affected by a different observer being used on Experiment CC 2 than on Experiments CC 1, 3, or 4. There were no significant effects on the conflict rates due to the mode changes.

In summary, both placements of the arrow board were superior to no arrow board in getting drivers out of the right lane. However, the shoulder placement of the arrow board resulted in fewer conflicts than the closed-lane placement or no arrow board. Speeds in the taper area of the zone did not vary between experiments, and no significant effects on lane volumes or conflicts could be attributed to the change in the arrow board mode from flashing arrow to sequential arrow.

Test 2, Experiments CC 5-6

Test 2 was conducted at night on an 8-lane urban freeway. Because of low volumes and many tapeswitch failures, no useable data were obtained from this test.

Test 3, Experiments CC 7-13

This test was conducted on a rural, 4-lane, Interstate highway at seven sites. During Experiments CC 7, 8, and 9, the left lane was closed; during CC 10-13, the right lane was closed. The 4 x 8 ft (1.2 x 2.4 m) arrow board was located on the shoulder near the beginning of the taper for Experiments CC 7, 8, 10 and 11 and in the closed lane near the end of the taper for Experiments CC 9 and 13. There was no arrow board for Experiment CC 12. For Experiments CC 7-11, the arrow board mode was varied between the flashing arrow and sequential chevron modes. All experiments were conducted during the day.

Table 15 shows the percentage of vehicles traveling in the closed lane for each of the experiments. The percentage at some distances was not observed or was beyond a range that could be accurately determined.

The percentage of vehicles in the left lane when it was closed was always very low, indicating that there were never very many vehicles traveling in the left lane. Therefore, the right-lane closure experiments (CC 10-13) were analyzed separately. A plot of the distribution of lane changes for CC 10-13 is shown in Figure 14.

For these four experiments, the initial proportion of vehicles in the closed right lane was highest with no arrow board (66.3 percent). With the arrow board, the initial proportion of vehicles in the right lane varied from 19.5 to 36.0 percent. The pattern of lane changes in the experiments showed that with an arrow board 2.5 to 4.5 percent of the vehicles were in the right lane 200 ft (61 m) before the start of the taper. When there was no arrow board, 13.2 percent of the vehicles were in the right lane at this location in the zone. The two placements were nearly identical in lane-change patterns, and both were superior in performance to the no-arrow-board experiments.

Erratic maneuvers and conflicts were so rare during this test that no significant effects were found. However, Experiment CC 13 did experience one serious lane-change conflict, had the highest erratic maneuver rate of the experiments in this test, and appeared to be more hazardous than the other experiments. In this experiment, the taper was started near a horizontal curve and the arrow board was placed in the middle of the taper (well into the curve). The problems experienced were probably due to poor placement of the lane-closure taper.

TABLE 15

TEST 3 - PERCENTAGE OF VEHICLES IN THE CLOSED LANE
(Rural, 4 lane Interstate highway)

Experiment	Placement	Lane Closed	Distance from Start of Taper (ft) 2000	1750	1500	1400	1250	1150	1000	900	800	650	600	400	200
CC7	Start of Taper	Left	3.8	3.8	3.8	--*	3.8	--	3.2	--	1.9	--	0.6	0.6	0.0
CC8	Start of Taper	Left	9.5	9.5	9.5	--	9.5	--	8.9	--	7.2	--	6.3	4.9	2.3
CC9	End of Taper	Left	--	--	--	4.9	--	4.6	--	3.0	--	1.1	--	0.8	0.0
CC10	Start of Taper	Right	19.5	14.0	10.0	--	7.2	--	4.9	--	4.0	--	2.9	2.6	2.3
CC11	Start of Taper	Right	36.0	29.0	24.5	--	19.8	--	15.8	--	13.0	--	9.0	6.5	4.5
CC12	No Arrow Board	Right	66.3	67.0	66.7	--	64.1	--	60.0	--	49.8	--	37.4	22.7	13.2
CC13	End of Taper	Right	--	--	--	23.6	--	22.0	--	17.6	--	11.5	--	9.9	4.4

* Dashes indicate percentages not computed for that distance.

1 ft = 0.3 m

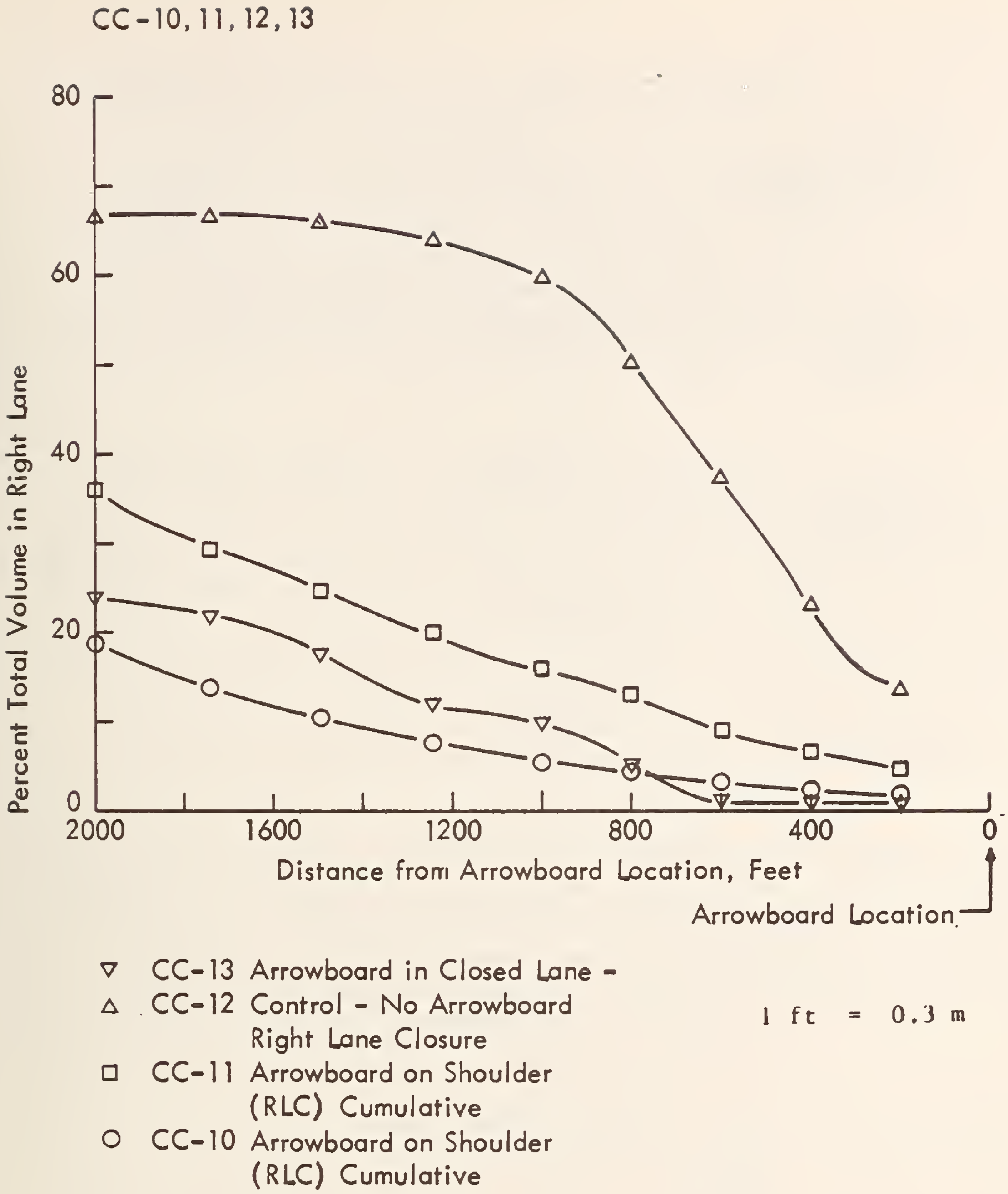


Figure 14 - Test 3 - Distribution of Lane Changes for Right Lane Closures

Test 4, Experiments CC 14-16

This test was conducted on an 8-lane, urban, Interstate highway with the right lane closed. Figure 15 is a diagram of the location. A 4 x 8 ft (1.2 x 2.4 m) arrow board was used in each of the three experiments. The placement of the arrow board varied between being (a) on the shoulder 965 ft (294 m) before the start of the taper (CC 14), (b) on the shoulder at the start of the taper (CC 15), and (c) in the closed lane in the middle of the taper (CC 16). During Experiment CC 14 the arrow board operated in the sequential chevron mode, and during Experiments CC 15 and 16, the arrow board operated in the sequential arrow mode. All experiments were filmed during daylight.

Table 16 shows the percentage of vehicles traveling in the right lane at various distances from the start of the taper. Some readings are not shown because the camera was located at the arrow board location in each experiment, so the percentage of vehicles in the closed lane at some distances was not observed or was beyond a range that could be accurately determined. Figure 16 is a plot of the lane change distribution for the three experiments. The results clearly indicate that cars left the right lane sooner when placement was on the shoulder upstream of the start of the taper. Second best was when placement was at the start of the taper, followed by closed-lane placement. The rate that lane changes occurred was similar for all three experiments.

The only significant effects on conflicts were that lane-change conflict rates were lower with the placement upstream of the taper (0.1 percent) than with placement at the start of the taper (0.4 percent) or in the middle of the taper (0.5 percent) and slow-to-merge opportunity rates were lower with placement at the start of the taper (0.2 percent) than with placement upstream of the taper (0.5 percent) or in the middle of the taper (0.5 percent).

No mode-specific effects were distinguishable.

Test 5, Experiments CC 17-25

This test was conducted on a 4-lane, divided uncontrolled access, urban highway with a right-lane closure and diversion to the left. A diagram of the site is shown in Figure 17. Two sizes of arrow board were tested. A 4 x 8 ft (1.2 x 2.4 m) board was used during Experiments CC 19-21, and a 2.4 x 5 ft (0.7 x 1.5 m) board was tested during Experiments CC 23-25. No arrow board was used during Experiments CC 17, 18 and 22. For all experiments using an arrow board, it was placed in the right lane behind the barricades. The larger arrow board was operated in the sequential chevron mode, and the smaller arrow board, in the sequential arrow mode. Experiments CC 17, 21, and 25 were conducted at night, Experiments CC 18, 20, and 24 during daylight peak hour and Experiments CC 19, 22, and 23 during daylight off-peak hour.

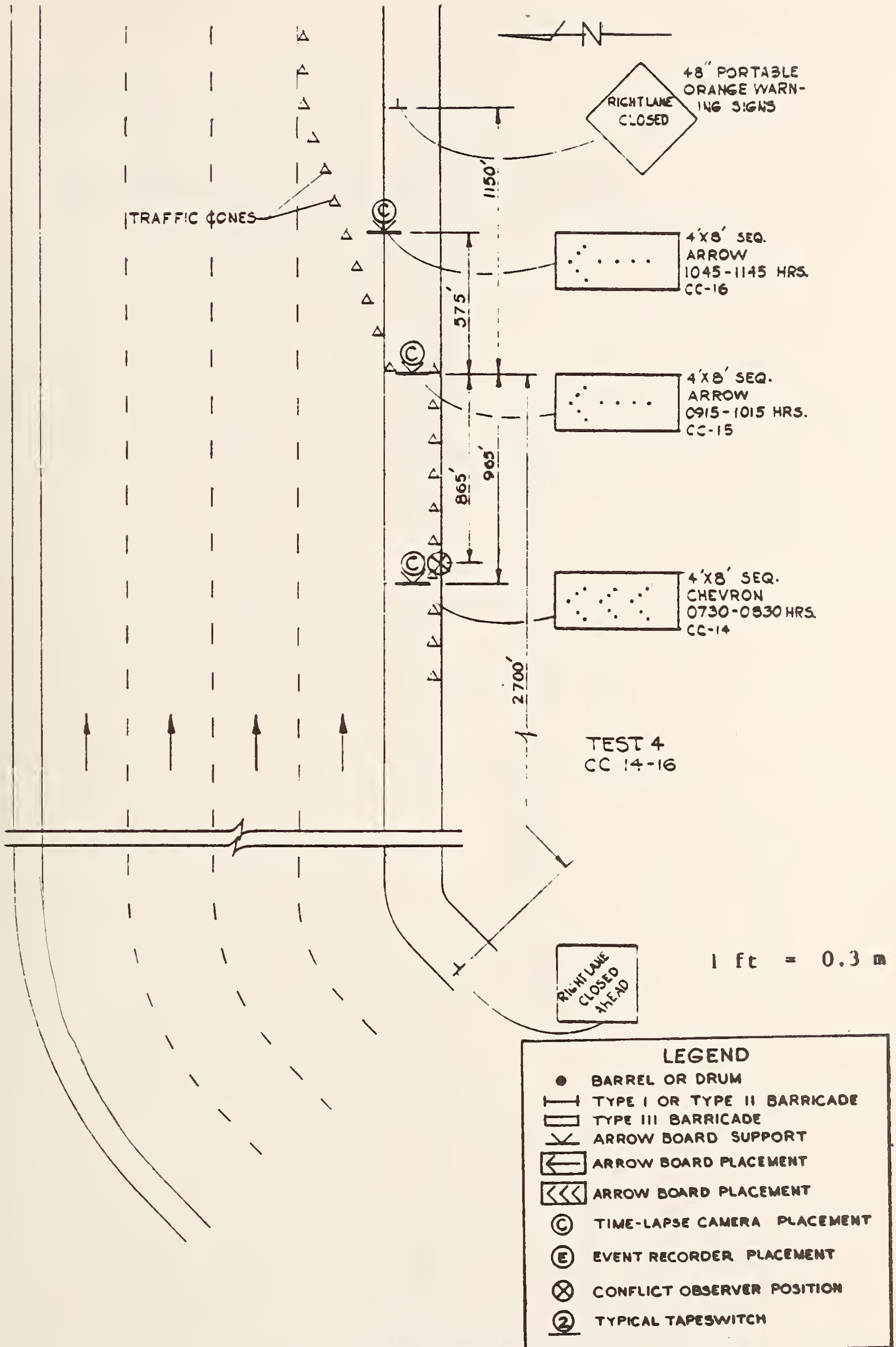


Figure 15 - Test 4 Site Diagram

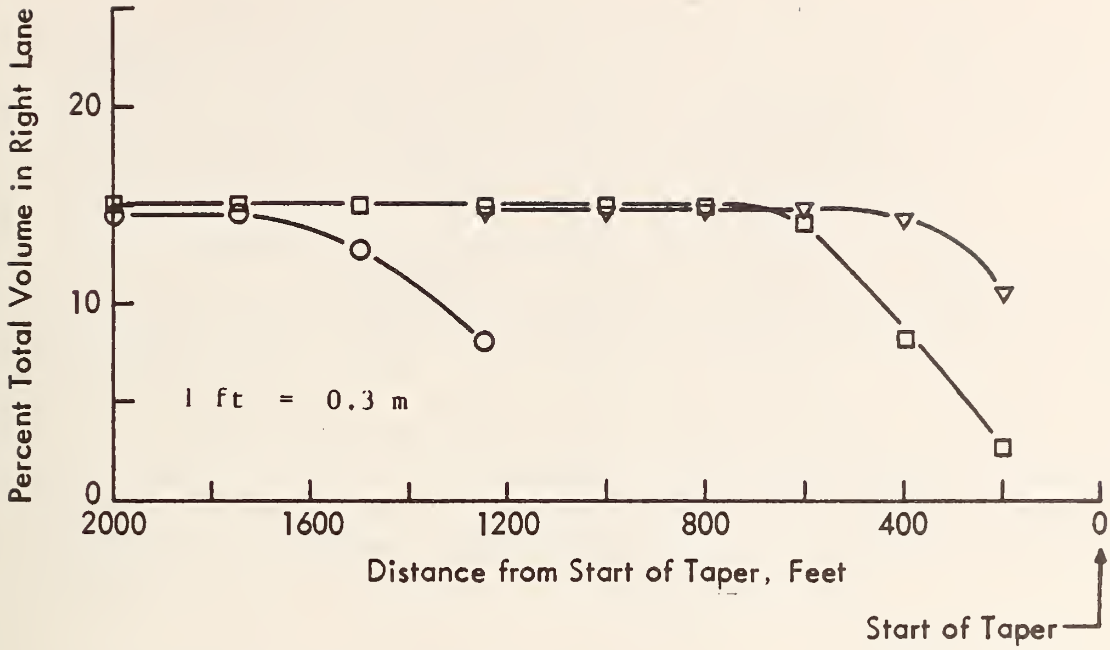
TABLE 16

TEST 4 - PERCENTAGE OF VEHICLES IN THE RIGHT LANE
(Urban, 8-lane Interstate highway)

Experiment	Placement	Distance from Beginning of Taper (ft)								
		2000	1750	1500	1250	1000	800	600	400	200
CC 14	On shoulder 965 ft before the start of the taper	14.5	14.5	12.9	8.1	--	--	--	--	--
CC 15	On shoulder at the start of the taper	15.0	15.0	15.0	15.0	15.0	14.9	14.0	8.2	2.8
CC 16	In closed lane near middle of taper	--*	--	--	14.8	14.8	14.8	14.7	14.4	10.6

* Dashes indicate percentages not computed for that distance.
1 ft = 0.3 m

Daytime
CC-14, 15, 16



○ CC-14 Right Lane Closure, Arrowboard Upstream from Start of Taper

□ CC-15 Right Lane Closure, Arrowboard at Start of Taper

▽ CC-16 Right Lane Closure, Arrowboard in Taper

Figure 16 - Test 4 - Lane Change Distribution

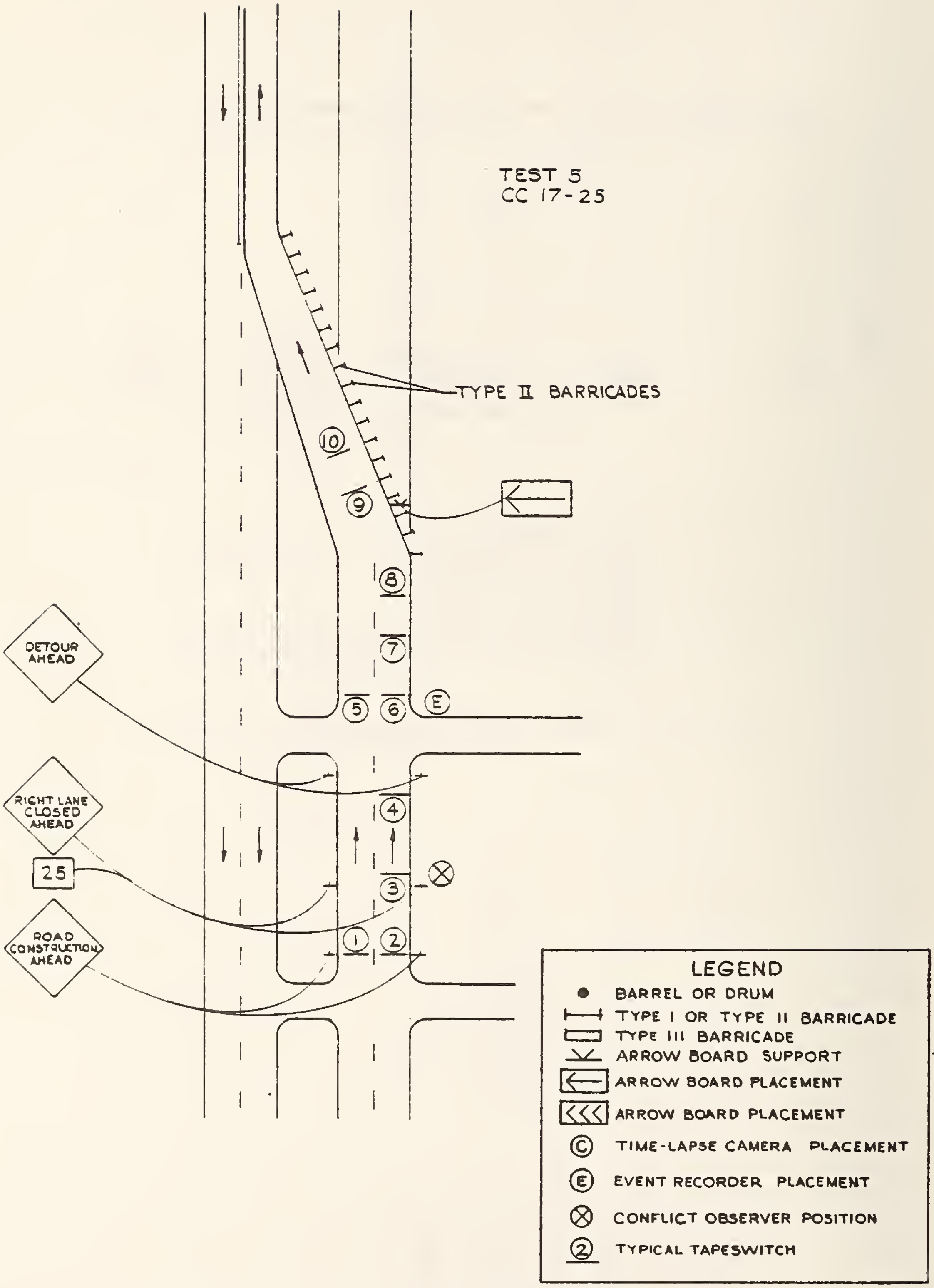


Figure 17 - Test 5 Site Diagram

The percentage of vehicles traveling in the right lane at various distances from the start of the taper are shown in Table 17. This table is arranged to facilitate comparison of the two sizes of arrow board and no arrow board. The percentages at this site were affected by the intersection of Sigsbee Road in the middle of the study section. Vehicles were both leaving and entering the study section at this intersection.

In terms of moving cars out of the right lane, the larger board was superior to the smaller board and no arrow board (which were indistinguishable) during the night and day peak experiments. During the day off-peak experiments, with arrow boards were superior to no arrow board.

The erratic maneuver rate was significantly higher for the small arrow board during the day peak-hour experiment; however, this effect was offset by a lower rate of slow-vehicle conflicts during the same experiment. These offsetting effects could have been due to larger average headways during the small arrow board, peak-hour experiment.

Overall, the small arrow board performance was superior to no arrow board during the day off-peak hour; however, the small arrow board did not perform as well as the large arrow board at night or during the day peak hour.

Test 6 - Experiments IC 1-6

Test 6 was conducted on a rural 4-lane, temporary Interstate highway at a left diversion. Figure 18 is a diagram of the location. During Experiments IC1 and 2, the arrow board was located on the shoulder of the roadway at the start of the detour. During Experiments IC5 and 6, the arrow board was located in the right lane in front of the barricades that closed the road. The flashing arrow mode was used during these four experiments. There was no arrow board present during Experiments IC3 and 4. Experiments IC1, 4, and 5 were conducted during the day, and Experiments IC2, 3, and 6 were conducted at night. The size of the arrow board used was 4 x 8 ft (1.2 x 2.4 m).

Two observers were present during each experiment. The conflict and erratic maneuver observer was stationed 800 ft (244 m) upstream of the start of the diversion, and the encroachment observer was stationed at the start of the diversion.

Lane volumes on the approach to the work zone were measured at four locations, switches 2, 3, and 4 which were 1,800, 1,200 and 600 ft (549, 366 and 183 m) before the start of the diversion, and switch 6 at the start of the diversion.

TABLE 17

TEST 5 - PERCENTAGE OF VEHICLES IN THE RIGHT LANE
(Urban, 4-lane uncontrolled access highway)

Experiment	Arrow Board Size	Time	Distance from Beginning of Taper (ft)					
			1,000	800	600	375	200	100
CC 17	No Arrow Board	Night	63.7	63.2	62.0	55.6	58.1	57.3
CC 21	4 x 8 ft	Night	53.1	54.3	52.2	46.5	50.2	43.3
CC 25	2.4 x 5 ft	Night	62.0	62.4	59.8	57.6	55.0	47.6
CC 18	No Arrow Board	Day, Peak	43.5	42.7	40.6	41.2	42.9	35.3
CC 20	4 x 8 ft	Day, Peak	37.6	38.3	36.9	26.6	27.5	21.7
CC 24	2.4 x 5 ft	Day, Peak	50.0	49.7	53.2	50.6	49.1	36.9
CC 22	No Arrow Board	Day, Off Peak	49.6	50.2	49.7	44.7	39.9	36.7
CC 19	4 x 8 ft	Day, Off Peak	44.2	44.7	41.7	35.5	37.8	29.5
CC 23	2.4 x 5 ft	Day, Off Peak	43.1	44.3	41.3	32.7	32.8	24.6

1 ft = 0.3 m

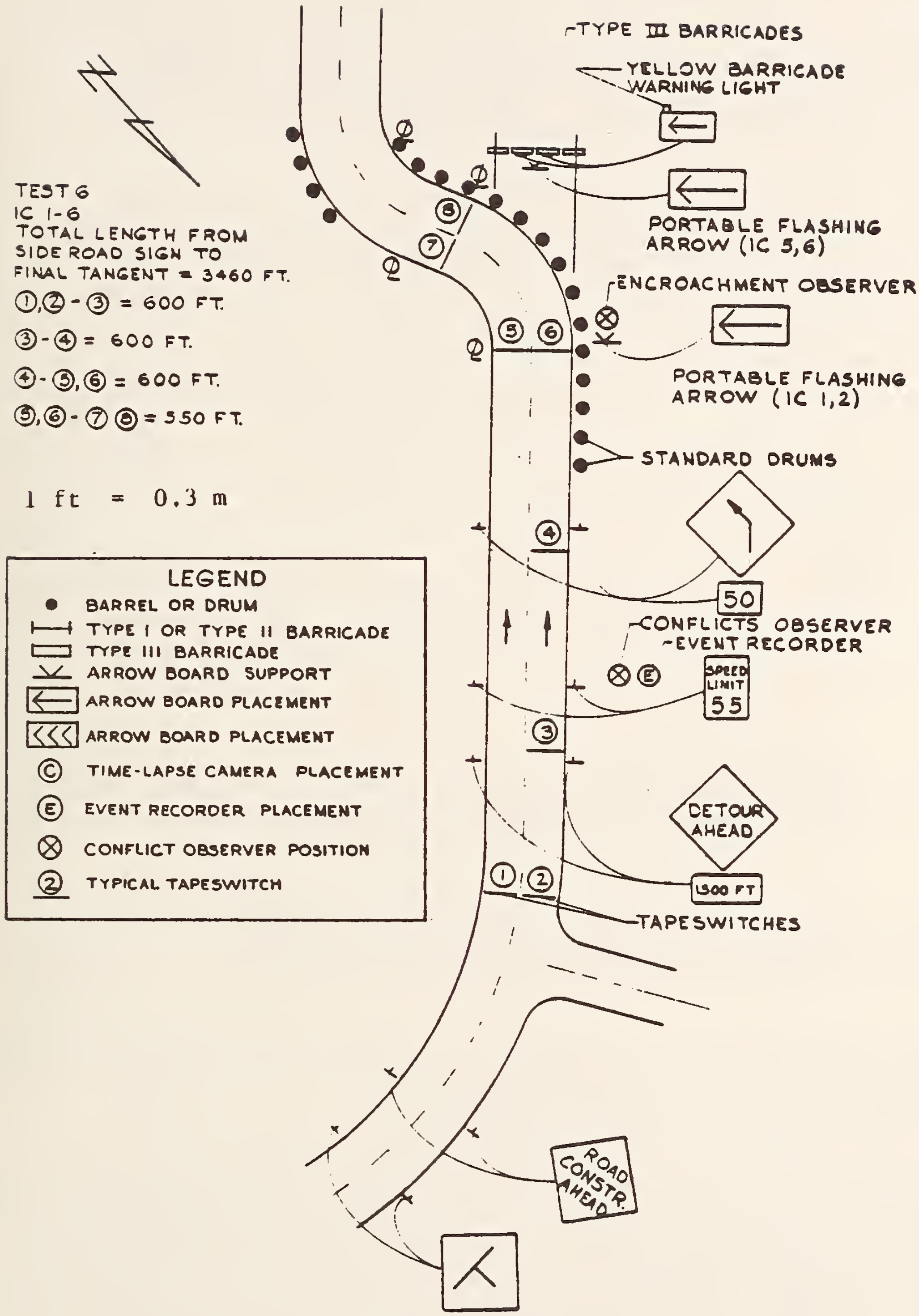


Figure 18 - Test 6 Site Diagram

Table 18 shows the percentage of vehicles in the right lane on the approach to the zone. Figure 19 shows the daytime lane change distribution and Figure 20 shows the nighttime lane change distribution. Trucks are shown separately because the percentage of trucks in the traffic stream differed from experiment to experiment. Also, the pattern of trucks moving from the right lane is also different from the pattern for cars. In general, the percentage of trucks in the traffic stream was higher during the night, and trucks did not leave the right lane to the extent that cars did.

For cars, the initial percentage in the right lane (Switch No. 2) was lowest for no arrow board, higher for shoulder placement, and highest for closed lane placement. Most cars did not leave the right lane until they were within 600 ft (183 m) of the start of the diversion. Also, more cars left the right lane at night than during the day and more cars left the right lane during the day with shoulder placement. At night more cars left the lane with shoulder placement or no arrow board than with the closed-lane placement.

The initial percentages of trucks in the right lane were very high (86.6 to 100 percent). They were highest with the closed lane placement, lower with no arrow board, and lowest with the shoulder placement. Practically no trucks left the right lane until they were within 600 ft of the diversion. At night, the percentages of trucks leaving the right lane were similar for all of the experiments. During the day, only 1.4 percent of the trucks left the lane during the shoulder placement, 6.6 percent left with no arrow board, and 14.7 percent left with the closed-lane placement.

Thus, more cars stayed in the right lane with no arrow board in the day and with the closed-lane placement at night. More trucks stayed in the right lane with the shoulder placement in the day and with no arrow board at night.

There were no arrow board effects on the erratic maneuver rate. Erratic maneuver rates were significantly higher at night (9.4 percent versus 5.5 percent).

The slow-moving-vehicle conflict rate was significantly (confidence 90 percent) lower with shoulder placement than with no arrow board. It was also lower than with the closed-lane placement.

Encroachments were divided into left lane encroaching on right lane and right lane encroaching on left lane. No shoulder encroachments were observed. The left-lane encroachments on the right lane were significantly lower with the shoulder placement (4.0 percent) than with the closed-lane placement (5.5 percent), which was in turn significantly lower than the no-arrow-board experiment (7.0 percent). The right-lane encroachments on the left lane were significantly lower with the shoulder placement (17.6 percent) than with no arrow board (25.2 percent) or closed-lane placement (25.7 percent).

TABLE 18

TEST 6 - PERCENTAGE OF VEHICLES IN THE RIGHT LANE
(Rural, 4 lane temporary Interstate highway)

Experiment	Time of Day	Placement	Vehicle Type	Distance from Start of Diversion (ft) 1,800	1,200	600	0
IC1	Day	On shoulder at start of detour	Cars	83.0	80.3	75.8	67.3
IC1	Day	On shoulder at start of detour	Trucks	90.8	86.1	85.0	84.3
IC2	Night	On shoulder at start of detour	Cars	78.3	76.2	74.8	54.3
IC2	Night	On shoulder at start of detour	Trucks	86.6	86.6	84.1	67.9
IC3	Night	No arrow board	Cars	90.1	83.1	84.5	57.4
IC3	Night	No arrow board	Trucks	93.8	95.4	94.6	90.2
IC4	Day	No arrow board	Cars	73.8	70.3	70.8	67.0
IC4	Day	No arrow board	Trucks	91.1	90.4	94.1	88.1
IC5	Day	In closed lane in front of barricades	Cars	88.6	88.9	84.5	75.9
IC5	Day	In closed lane in front of barricades	Trucks	95.6	95.0	93.8	80.0
IC6	Night	In closed lane in front of barricades	Cars	96.8	97.4	93.6	77.6
IC6	Night	In closed lane in front of barricades	Trucks	100.0	100.0	100.0	76.1

1 ft = 0.3 m

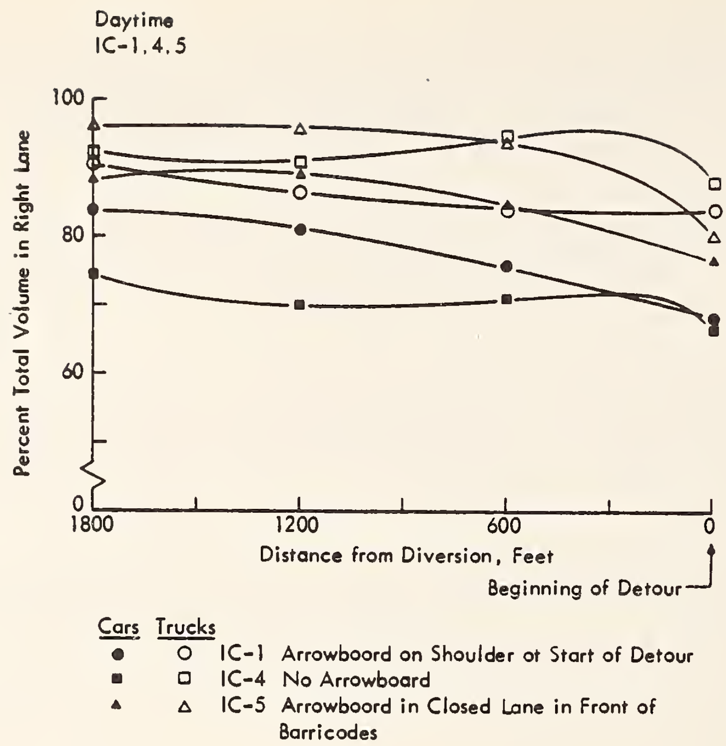


Figure 19 - Test 6 - Daytime Lane Change Distribution

1 ft = 0.3 m

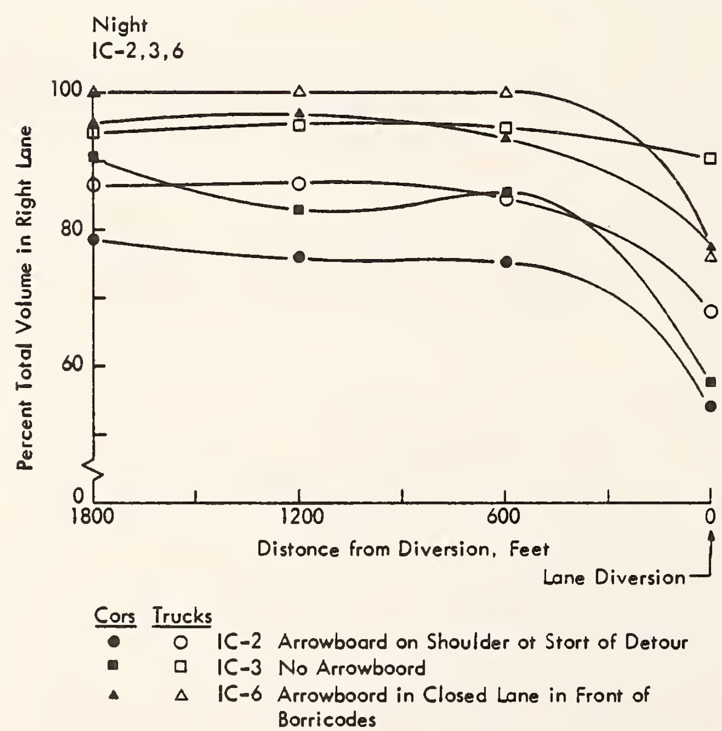


Figure 20 - Test 6 - Night Lane Change Distribution

In summary, the results seem to indicate that a surprising high percentage of vehicles remained in the right lane with or without the arrow board. Overall, 81.6 percent of the cars and 86.0 percent of the trucks that were in the right lane at Switch No. 2 remained there at Switch No. 6. Those vehicles that did leave the right lane usually waited until they were within 600 ft of the detour before they changed lanes. Results are mixed concerning the arrow board treatment that caused more vehicles to remain in their lane. More cars stayed in their lane with no arrow board in the day and with the closed-lane placement at night. More trucks stayed with the shoulder placement in the day and with no arrow board at night.

Slow-vehicle conflict rates and encroachment rates from the right lane onto the left lane, or the left lane onto the right lane, were lower with the shoulder placement.

Test 7 - Experiments IC 7-8

Test 7 was conducted on a rural, 2-lane road. The zone type was a right diversion. The site diagram is shown in Figure 21. During IC7, an arrow board displaying a right arrow was located in front of the barricades. During IC8, there was no arrow board. Both experiments were conducted during the day.

Two conflict observers were used in this test, and their positions are shown in Figure 21. In addition to the erratic maneuver and conflicts observations, speeds were measured in two areas of the zone between switches 1 and 2, and switches 3 and 4.

Although there was a speed drop of about 14 mph (22 kph), between switches 1 and 2 and switches 3 and 4, the magnitude of the difference and the speeds themselves did not vary according to the presence of an arrow board. With an arrow board, mean speed between switches 1 and 2 was 53.8 mph (86.6 kph) and the mean speed between switches 3 and 4 was 40.0 mph (64.4 kph). Without an arrow board, the mean speed between switches 1 and 2 was 53.9 mph (86.7 kph); between switches 3 and 4 it was 40.4 mph (65.0 kph).

Both observers counted erratic maneuvers and conflicts. Observer No. 2 also recorded centerline encroachments by vehicles traversing the detour. Erratic maneuvers were significantly lower with an arrow board. For observer no. 1, the erratic maneuvers were 4.87 percent with an arrow board and 10.04 percent without an arrow board. For observer no. 2, erratic maneuvers were 52.1 percent with an arrow board and 64.9 percent without. There was no significant difference in slow-moving-vehicle conflicts counted by either observer.

The lane encroachments counted by observer no. 2 were significantly greater with an arrow board (29.93 percent versus 20.08 percent).

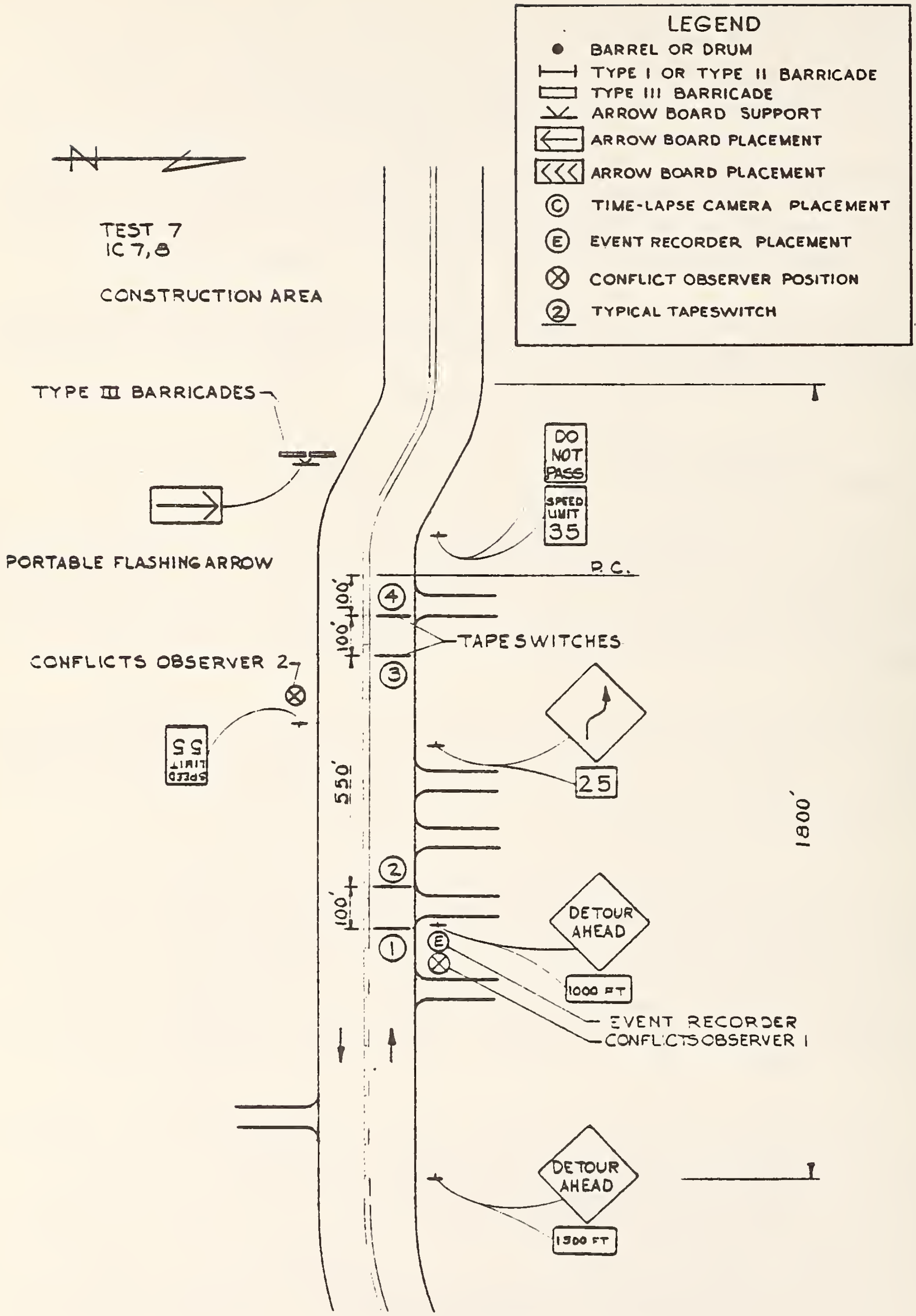


Figure 21 - Test 7 Site Diagram

In summary, the arrow board did not affect the mean speed of vehicles traversing the zone. The presence of an arrow board did decrease erratic maneuvers in the zone but also increased the percentage of centerline encroachments.

Test 8, Experiments IC 9-11

This test was conducted on a rural, 4-lane, Interstate highway at a right-lane closure. Three day experiments were performed. A 4 x 8 ft (1.2 x 2.4 m) arrow board displaying the flashing arrow mode was used during two experiments. The arrow board was located on the shoulder near the beginning of the taper (IC 9) and on the shoulder 250 ft (76 m) upstream of the taper (IC 10). Traffic volume data were collected by means of a time-lapse camera. The camera locations are noted in Figure 22, which contains the Test 8 site diagram. Erratic maneuvers and traffic conflicts were collected in 15-minute increments. Each experiment was performed for 1 hour. A horizontal curve, curving to the left, was in the construction zone. The start of the taper was located approximately at the point of curvature (PC) of this curve.

The percentages of vehicles in the right (closed) lane are contained in Table 19. Figure 23 shows the lane change distribution. Although the initial percentage of vehicles in the right lane was least with no arrow board present, the experiment with the arrow board located 250 ft (76 m) upstream of the taper had the fastest rate of vehicles departing the closed lane. The other arrow board experiment had the second fastest rate of departure.

The percentages of commercial vehicles were approximately equal for all experiments. There were no significant erratic maneuver rates. With the no-arrow-board experiment, the slow-vehicle conflict rate was less than the corresponding rate of the experiment 250 ft (76 m) upstream of the taper location, which was in turn less than the other arrow board experiment. There were no other significant traffic conflict rates.

In conclusion, the closed lane of traffic was cleared more effectively when an arrow board was present. However, the arrow board experiments had significantly higher slow-vehicle conflict rates.

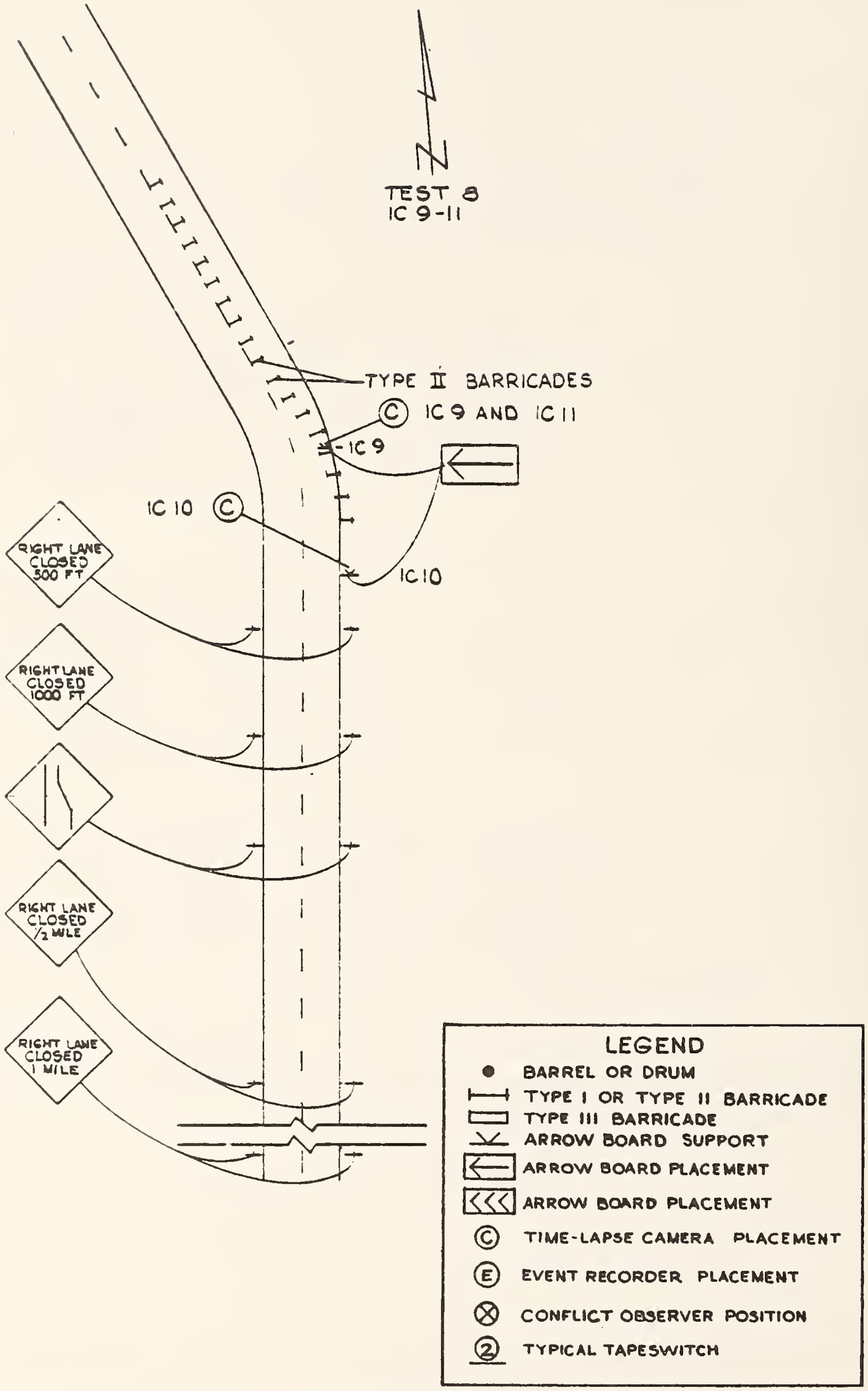
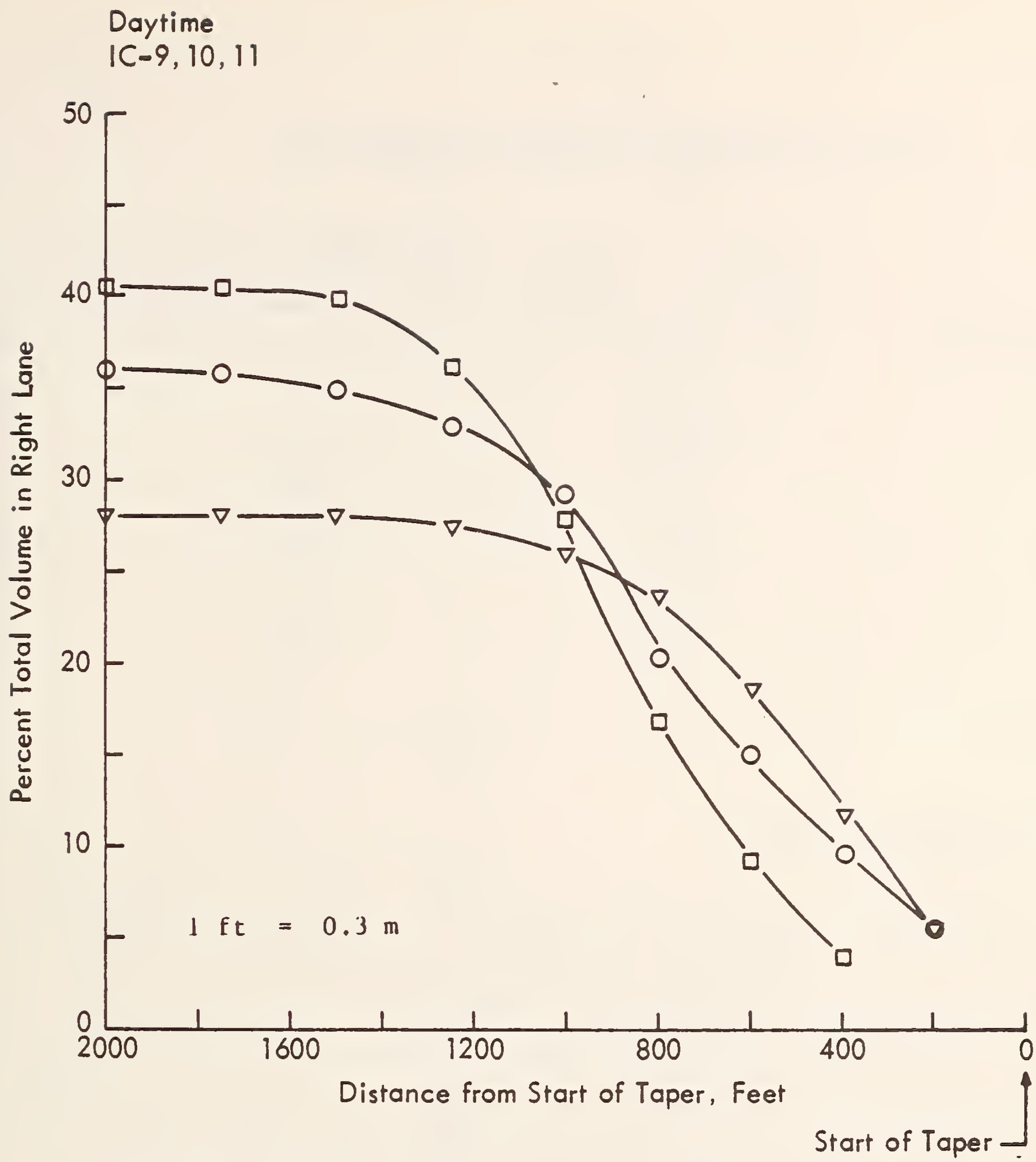


Figure 22 - Test 8 Site Diagram



○ IC-9 Right Lane Closure, Arrowboard at Start of Taper

□ IC-10 Right Lane Closure, Arrowboard Upstream of Start of Taper

▽ IC-11 Right Lane Closure, No Arrowboard

Figure 23 - Test 8 - Lane Change Distribution

TABLE 19

TEST 8 - PERCENTAGE OF VEHICLES IN RIGHT LANE
(Rural, 4-lane Interstate highway)

Distance from Start of Taper	Experiment: Arrow Board on Shoulder Near Start of Taper (IC 9)	Arrow Board on Shoulder 250 ft Upstream of Taper (IC 10)	No Arrow Board (IC 11)
2,000 ft	35.9%	40.4%	28.1%
1,750 ft	35.9%	40.4%	28.1%
1,500 ft	35.0%	39.9%	28.1%
1,250 ft	32.9%	36.1%	27.6%
1,000 ft	29.1%	27.9%	26.0%
800 ft	20.1%	16.8%	23.6%
600 ft	15.0%	9.1%	18.7%
400 ft	9.4%	3.9%	11.8%
200 ft	5.6%	-	5.6%

1 ft = 0.3 m

Test 9 - Experiments IC 12-17

This test was conducted on a 4-lane, rural, interstate highway with the right lane closed. Figure 24 is a diagram of the location. In Experiments IC12 and 13, the arrow board was located on the shoulder near the beginning of the taper. In Experiments IC14 and 16, the arrow board was located in the closed lane 500 ft (152 m) into the taper. Experiments IC15 and 17 were conducted without an arrow board. The arrow board mode used was always a flashing arrow. Experiments IC12, 16 and 17 were conducted at night; 13, 14, and 15 were conducted during the day. There was a flagman near the start of the taper during the entire period of experiment IC14 and during seven of the nine 15-minute periods of IC15. The size of the arrow board was 4 x 8 ft (1.2 x 2.4 m).

Lane volumes were measured at four locations in the zone (switches 2, 3, 4 and 5) 1500, 1000, 500 and 50 ft (457, 305, 152 and 15 m) from the start of the taper.

Table 20 shows the percentage of vehicles traveling in the right lane at each of the four locations. Although Table 20 lists the percentages separately for cars and trucks, statistically both kinds of vehicles responded to the experimental treatments in the same manner.

In terms of initial percentages of vehicles in the right lane at switch no. 2 in the daytime studies, there was a higher percentage when the arrow board was on the shoulder near the beginning of the taper. At night, the initial percentages were higher when there was no arrow board or the arrow board was in the closed lane. The daytime percentages may have been

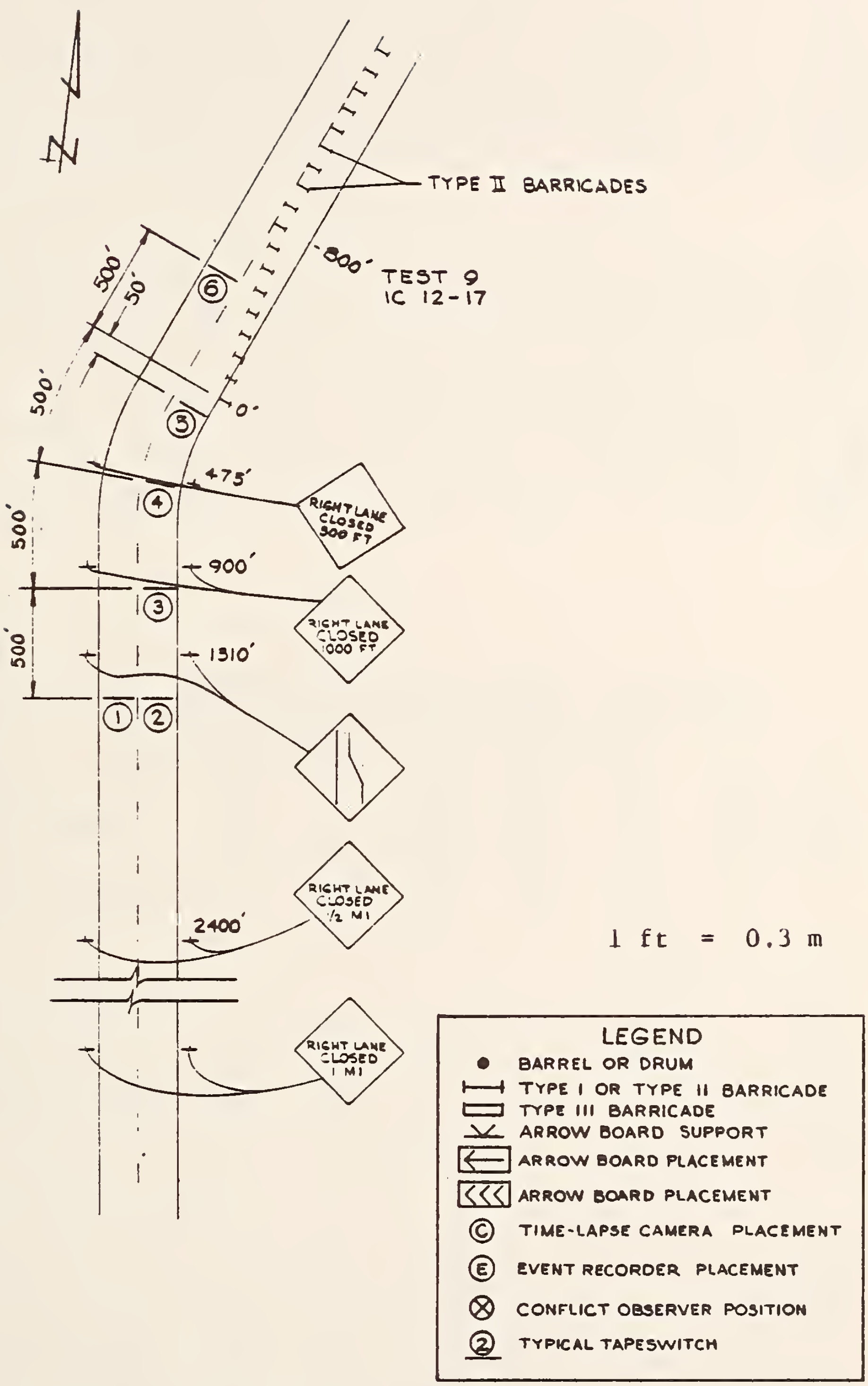


Figure 24 - Test 9 Site Diagram

TABLE 20

TEST 9 - PERCENTAGE OF VEHICLES IN THE RIGHT LANE
(Rural, 4-lane Interstate highway)

Experiment	Vehicle Type	Placement	Distance from Beginning of Taper (ft) 1500	1000	500	50
IC 12	Cars	On shoulder near start of taper	44.8	36.2	14.7	4.9
IC 12	Trucks	On shoulder near start of taper	29.4	32.5	23.0	11.9
IC 13	Cars	On shoulder near start of taper	81.6	78.1	13.1	5.1
IC 13	Trucks	On shoulder near start of taper	82.1	52.6	18.0	1.3
IC 14	Cars	In closed lane 500 ft into taper	35.6	29.7	10.0	3.3
IC 14	Trucks	In closed lane 500 ft into taper	34.6	30.1	10.9	2.6
IC 15	Cars	No arrow board	51.7	39.4	12.7	3.5
IC 15	Trucks	No arrow board	51.3	38.3	8.7	0.9
IC 16	Cars	In closed lane 500 ft into taper	72.3	51.8	17.5	13.9
IC 16	Trucks	In closed lane 500 ft into taper	56.6	38.2	18.4	10.5
IC 17	Cars	No arrow board	92.0	76.0	32.0	36.0
IC 17	Trucks	No arrow board	83.3	66.7	46.7	26.7

1 ft = 0.3 m

affected by the presence of a flagman in the taper during the no-arrow-board and closed-lane experiments.

In terms of the pattern of the percentages of vehicles in the right lane, during the day the percentages at the first two lacations (switches 2 and 3) were higher for the shoulder placement. All of the arrow board treatments are identical at the last two locations (switches 4 and 5). Again these results may have been affected by the presence of a flagman in the taper. At night, the placement of the arrow board on the shoulder is most effective in reducing the percentage of vehicles in the right lane, and both arrow board placements are superior to no arrow board in getting vehicles to move from the right lane.

Analysis of mean speeds of vehicles in the closed lane near the start of the taper revealed that, on the average, both arrow board placements reduce the mean speeds from those measured when there was no arrow board. If the results are examined in relation to time of day, however, the effect on mean speeds is that only the closed-lane placement reduces speed in the daytime and only the closed-lane placement reduces speed in the daytime and only the shoulder placement reduces speeds at night. The mean speeds for each condition are shown in Table 21.

TABLE 21

Test 9 - Mean Speeds of Vehicles in the Closed Lane Near the Start of the Taper
(Rural, 4-lane Interstate highway)

Arrow Board Placement	Time of Day	Mean Speed (mph)
On the shoulder near the start of the taper	day	52.6
On the shoulder near the start of the taper	night	44.5
On the shoulder near the start of the taper	all	49.3
In closed lane 500 ft into the taper	day	49.9
"	night	48.4
"	all	49.2
No arrow board	day	53.7
"	night	50.0
"	all	51.8

1 mph = 1.61 kph
1 ft = 0.3 m

The erratic maneuver rate was lower with the presence of an arrow board. The placement on the shoulder reduced the erratic maneuver rate during both day and night, while placement in the closed lane only reduced the rate at night. The erratic maneuver rates for each arrow board treatment and the time of day are shown in Table 22.

TABLE 22

Test 9 - Erratic Maneuver Rates
(Rural, 4-lane Interstate highway)

Arrow Board Placement	Time of Day	Erratic Maneuver Rate (Percentage of Vehicles)
On the shoulder near the start of taper	day	0.0%
On the shoulder near the start of taper	night	1.0%
In closed lane 500 ft into taper	day	3.5%
In closed lane 500 ft into taper	night	1.9%
No arrow board	day	3.0%
No arrow board	night	5.5%

1 ft = 0.3 m

Slow-moving-vehicle conflicts rates were lower for the shoulder placement during the day than with no arrow board, while the closed lane placement had higher slow-moving-vehicle conflict rates. At night, both the shoulder placement and no arrow board rates were very low (0.7 and 0 percent), while the closed-lane placement rate was nearly equal to the daytime rates. The slow-moving conflict rates for each arrow board treatment and the time of day is shown in Table 23.

TABLE 23

Test 9 - Slow-Moving Vehicle Conflict Rates
(Rural, 4-lane Interstate highway)

Placement	Time of Day	Conflict Rate (Percentage of Vehicles)
On the shoulder near the start of the taper	day	1.1
On the shoulder near the start of the taper	night	0.7
In the closed lane 500 ft into the taper	day	7.7
In the closed lane 500 ft into the taper	night	7.0
No arrow board	day	5.8
No arrow board	night	0.0

1 ft = 0.3 m

Slow-moving-vehicle secondary conflict rates did not exhibit any statistically significant effects, but they appear to be a "proper" subset of the slow-moving-vehicle conflict rates.

In summary, the results seem to vary based on the time of day, with shoulder placement normally superior at night and closed-lane placement in general, superior during the day. Much of the difference in effects might have been due to the presence of a flagman in the taper for the daytime experiments that involved the arrow board in the closed lane and no arrow board. The flagman's presence probably helped to reduce the percentage of vehicles in the right lane and also probably caused higher erratic maneuver rates and lower mean speeds. Therefore, more reliance should be placed on the results of the night experiments which clearly indicate that both arrow board placements reduce the percentage of vehicles in the right lane. The shoulder placement near the start of the taper is superior to placement in the closed lane well into the taper. The shoulder placement also reduces the erratic maneuver and slow-moving vehicle conflict rates relative to no arrow board or placement in the closed lane in general.

Test 10 - Experiments IC 20-25

This test was conducted on an urban, 4-lane, undivided, uncontrolled access highway at a right-lane closure. Experiments were performed both with and without a 4 x 8 ft (1.2 x 2.4 m) arrow board during the day and night. The flashing arrow and sequential arrow modes were used during each arrow board experiment. The arrow board was placed near the beginning of the taper on the shoulder and near the middle of the taper on the closed lane. Figure 25 contains the site diagram.

Traffic volume data were collected by means of a series of tapeswitches installed along the test section of the construction zone. Erratic maneuvers and traffic conflicts were collected in 15-minute increments.

Table 24 contains the percentages of vehicles in the right (closed) lane at various distances from the beginning of the taper. Figure 26 shows the daytime lane change distribution and Figure 27 shows the night time lane change distribution. The percentages of traffic volume at the first (switch number 2) tapeswitch do differ. The first two experiments are significantly low. In terms of lane departure patterns, the experiments are indistinguishable between the first tapeswitch and the start of the taper. Five of the six experiments are also homogeneous at the tapeswitch in the middle of the taper. However, during the day experiment with the arrow board located at the beginning of the taper (IC 21), practically every vehicle departed the closed lane by the middle of the taper.

Some of the differences in the erratic maneuver and conflict rates were significant. Erratic maneuver rates were higher with the arrow board located at the beginning of the taper. The flashing arrow mode produced a higher rate than the sequential arrow mode but only for one experiment (IC 20). The night erratic maneuver rate was higher than the day rate.

Slow-vehicle conflict rates were highest at night and also when an arrow board was used. Slow-to-merge opportunity and conflict rates were higher at night. The flashing arrow mode produced a greater slow-to-merge opportunity rate than the sequential arrow mode. The slow-to-merge opportunity rates were highest when the arrow board was located in the middle of the taper. However, the slow-to-merge conflict rates were greatest with the arrow board located at the beginning of the taper. The lane-change conflict rates with arrow boards were greater at night than without an arrow board. However, during the day the no-arrow-board rates were the highest. There were some significant slow-for-left-turn conflict rates at an intersection in the zone (intersection between switches 3 and 4). These may or may not be attributable to the construction zone.

In summary, there was not much difference in the lane departure patterns of the various experiments. Erratic maneuver and conflict rates

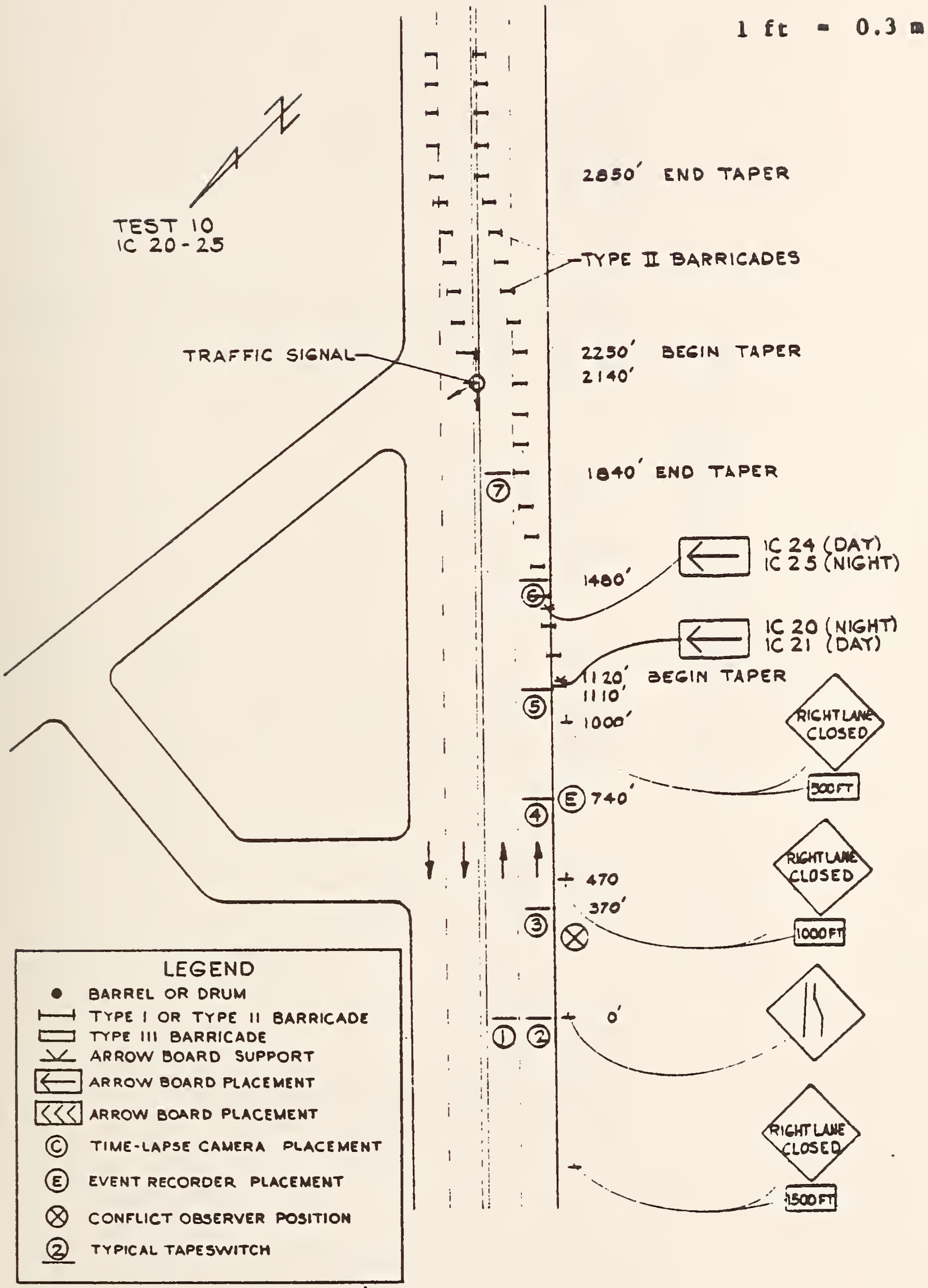


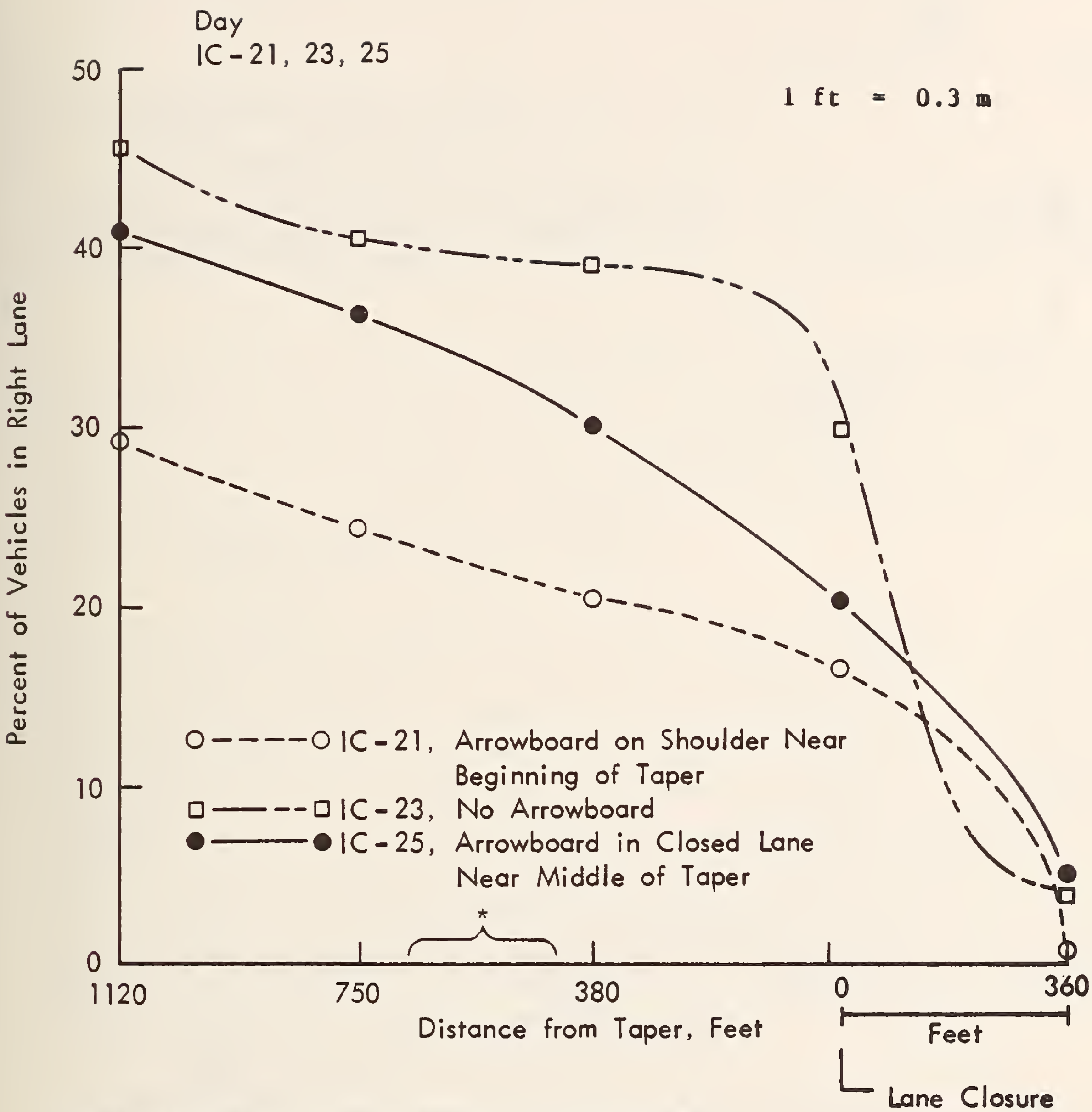
Figure 25 - Test 10 Site Diagram

TABLE 24

TEST 10 - PERCENTAGE OF VEHICLES IN RIGHT LANE
(Urban, 4-lane uncontrolled access highway)

			Distance from Beginning of Taper				
Experiment	Arrow Board Location	Time of Day	1,120 ft (Switch 2)	750 ft (Switch 3)	380 ft (Switch 4)	10 ft (Switch 5)	-360 ft (Switch 6)
IC 20	Beginning of taper	Night	36.7%	30.7%	23.5%	15.9%	4.8%
IC 21	Beginning of taper	Day	29.2%	24.7%	20.3%	16.7%	0.5%
IC 22	None	Night	41.0%	32.0%	26.2%	22.1%	*
IC 23	None	Day	45.7%	40.4%	39.1%	29.8%	4.0%
IC 24	Middle of taper	Night	42.2%	37.7%	31.8%	22.7%	5.3%
IC 25	Middle of taper	Day	41.0%	35.7%	30.2%	20.4%	4.7%

* Missing
1 ft = 0.3 m



*Some Vehicles Exit the System by Turning Left

Figure 26 - Test 10 - Daytime Lane Change Distribution

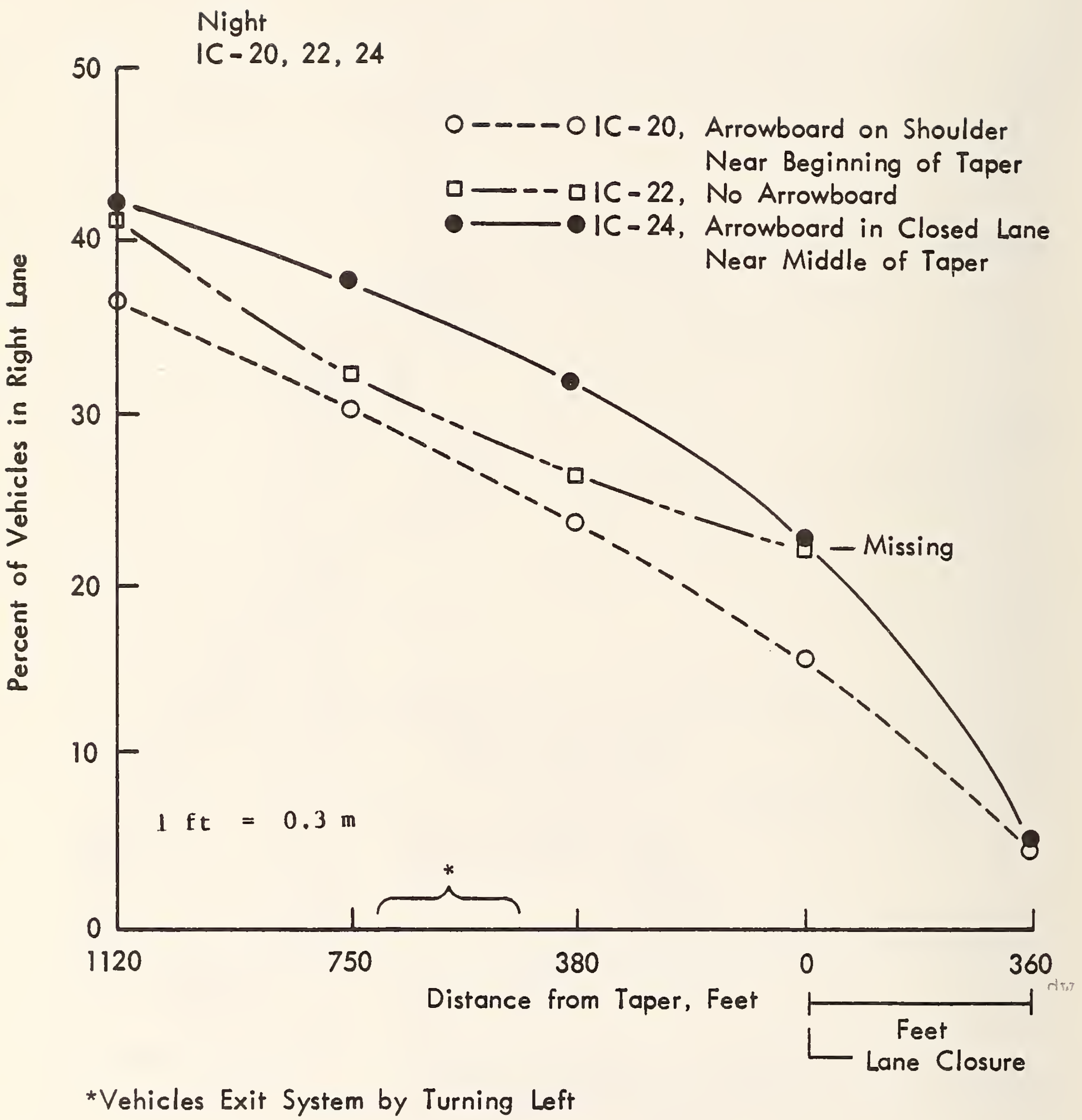


Figure 27 - Test 10 - Night Lane Change Distribution

were higher at night. There was not much difference in the rates between the flashing arrow and the sequential arrow modes. There was not much difference in the rates relative to arrow board placement. However, arrow board usage generally produced greater rates than when no arrow board was used.

Test 11 - Experiments IC 26-29

This test was conducted on a 4-lane, uncontrolled access, urban highway at a left-lane closure. This road is divided by a raised, concrete median which runs through the zone and ends in the lane taper. A diagram of this work zone is presented in Figure 28.

Experiments IC 26 (night) and IC 27 (day) were performed using a 4 x 8 ft (1.2 x 2.4 m) arrow board. The flashing arrow, sequential stem and sequential chevron modes were alternately displayed for 30 minutes during each 2-1/2 hr experiment. The arrow board was located in the closed lane near the middle of the taper. Experiments IC 28 (night) and IC 29 (day) were done without an arrow board. The day and night experiments were performed at about the same times of the day.

Lane volume data were recorded at four positions upstream of the start of the taper: 956 ft, 656 ft, 356 ft, and 56 ft (29 m, 200 m, 109 m, and 17 m) and in the taper of 260 ft (79 m) from the start. Table 25 includes the percentages of vehicles traveling in the left (closed) lane at various distances from the start of the taper. Figure 29 shows the daytime lane change distribution and Figure 30 shows the nighttime lane change distribution. The left lane was cleared sooner and more thoroughly in day experiments than at night. There were no significant differences in lane departure patterns between the flashing arrow, sequential stem, and sequential chevron modes. In daylight operations, the arrow board was more effective in clearing the closed lane than when no arrow board was present. At night, there was no significant difference in the lane departure distributions whether an arrow board was or was not present.

Erratic maneuver and traffic conflict rates were analyzed. Erratic maneuver rates and slow-vehicle conflict rates were significantly greater at night. The slow-to-merge opportunity, conflict and secondary rates were the only other types showing any significant results, and these were interactions of the arrow board/no arrow board, mode, and day/night effects. The presence of an arrow board increased all slow-to-merge rates. The sequential stem mode promoted the highest night rates of slow-to-merge opportunities and secondary conflicts. However, the day slow-to-merge opportunity rate was the lowest of all modes.

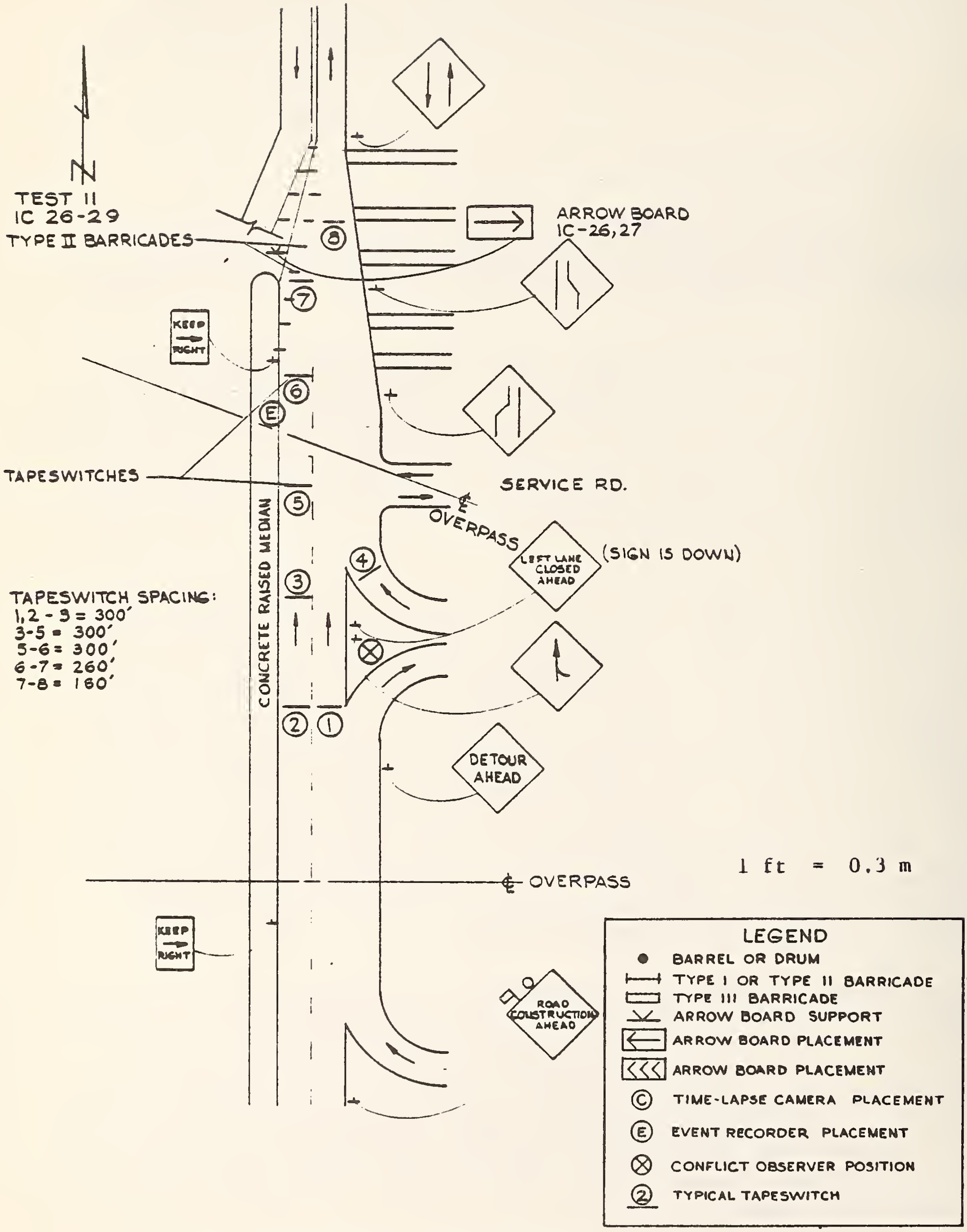
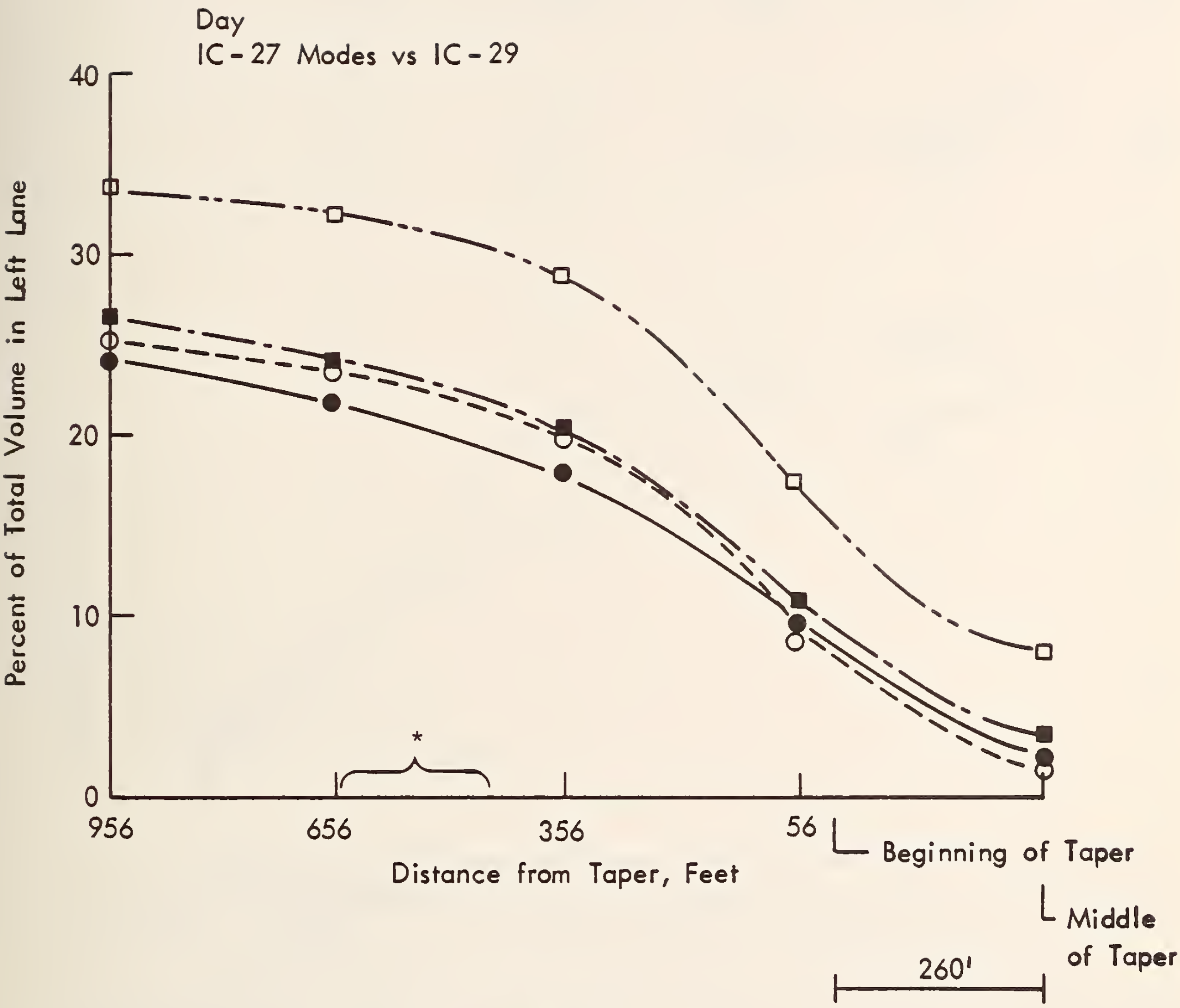


Figure 28 - Test 11 Site Diagram

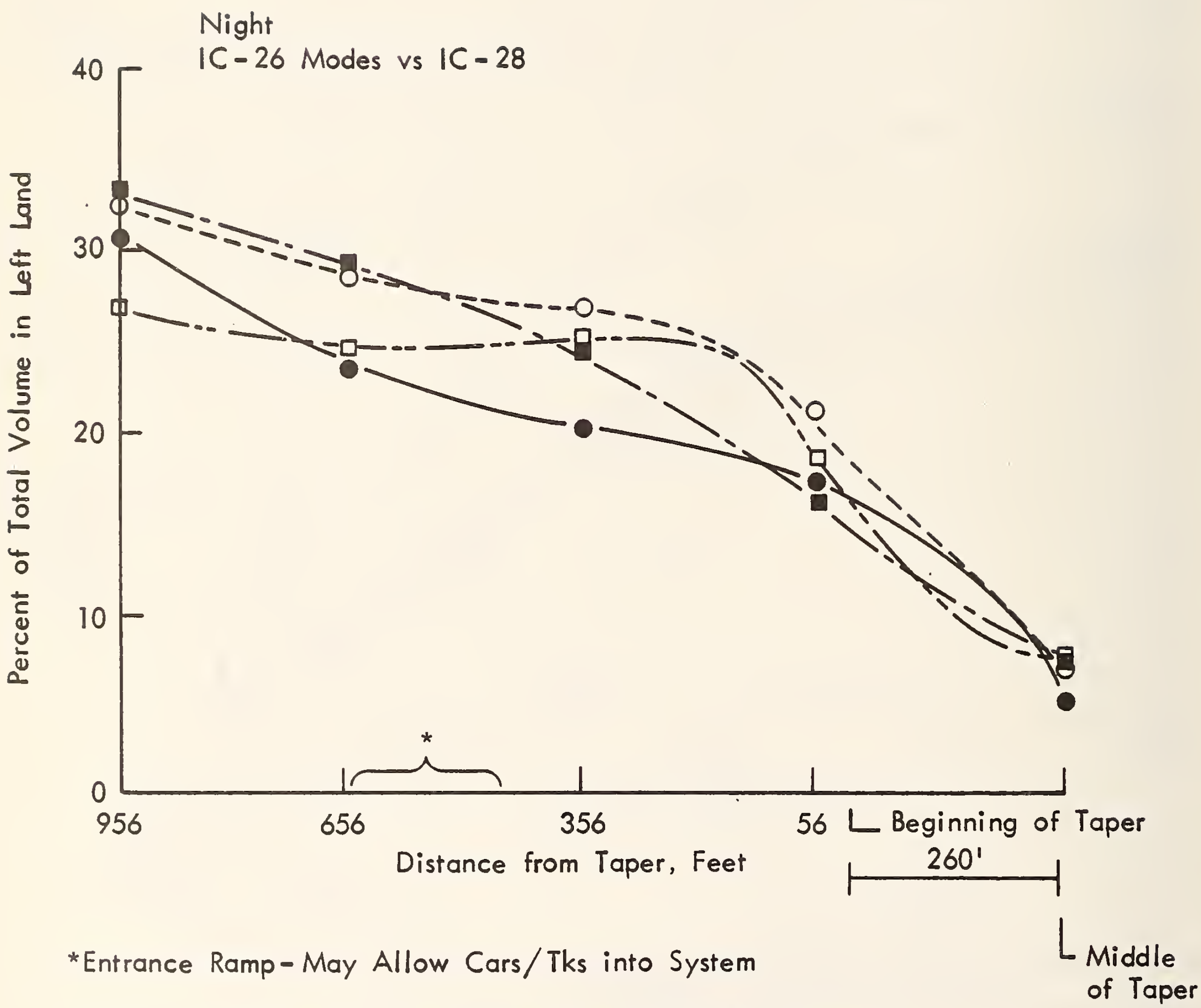


*Entrance Ramp - May Allow Vehicles into System

IC-27, Arrowboard in Closed Lane Near Middle of Taper
Modes:
- ● ——— ● Flashing Arrow
- ○ - - - - ○ Sequential Stem
- ■ —— — ■ Sequential Chevron
- □ —— - - □ No Arrowboard, IC-29

1 ft = 0.3 m

Figure 29 - Test 11 - Daytime Lane Change Distribution



*Entrance Ramp - May Allow Cars/Tks into System

IC-26, Arrowboard in Closed Lane Near Middle of Taper
Modes:
●———● Flashing Arrow
○- - - -○ Sequential Stem
■—— —■ Sequential Chevron
□——- - □ No Arrowboard, IC-28

1 ft = 0.3 m

Figure 30 - Test 11 - Night Lane Change Distribution

TABLE 25

TEST 11 - PERCENTAGE OF VEHICLES IN LEFT LANE
(Urban, 4-lane uncontrolled access highway)

Experiment	Distance from Start of Taper (ft)				
	956	656	356	56	-260
Night IC 26					
FA	30.0%	23.1%	20.4%	16.8%	5.4%
SS	32.0	28.4	26.9	20.9	7.1
SC	32.8	28.7	25.1	16.5	7.5
All	31.6	26.7	24.0	18.0	6.7
Day IC 27					
FA	24.4	22.0	18.2	9.7	2.5
SS	25.2	23.4	20.2	8.8	1.6
SC	26.4	23.7	20.1	11.5	2.7
All	25.2	23.0	19.5	9.8	2.2
Night IC 28	26.3	24.5	25.2	18.5	7.9
Day IC 29	33.5	32.2	29.1	17.5	8.0

1 ft = 0.3 m
FA = Flashing Arrow Mode
SS = Sequential Stem Mode
SC = Sequential Chevron Mode

For day operation, arrow boards, regardless of mode, were more effective in clearing the closed lane of traffic than when no arrow board was present. At night, arrow boards tended to increase confusion, as evidenced by the significant erratic maneuver and slow-vehicle conflict rates. The analysis of arrow board effects was further complicated by the fact that additional traffic enters the zone by means of a ramp located mid-way through the zone (see Figure 28). Vehicles entering from the ramp were merging left while vehicles in the closed lane were merging right.

Test 12 - Experiments IC 30-33-35

This test was conducted on a 4-lane, limited access, rural highway at a right diversion. Figure 31 is a diagram of the location. A 4 x 8 ft (1.2 x 2.4 m) arrow board, located in the closed roadway behind the barricade, was used in Experiments IC 30 and 35. No arrow board was used in

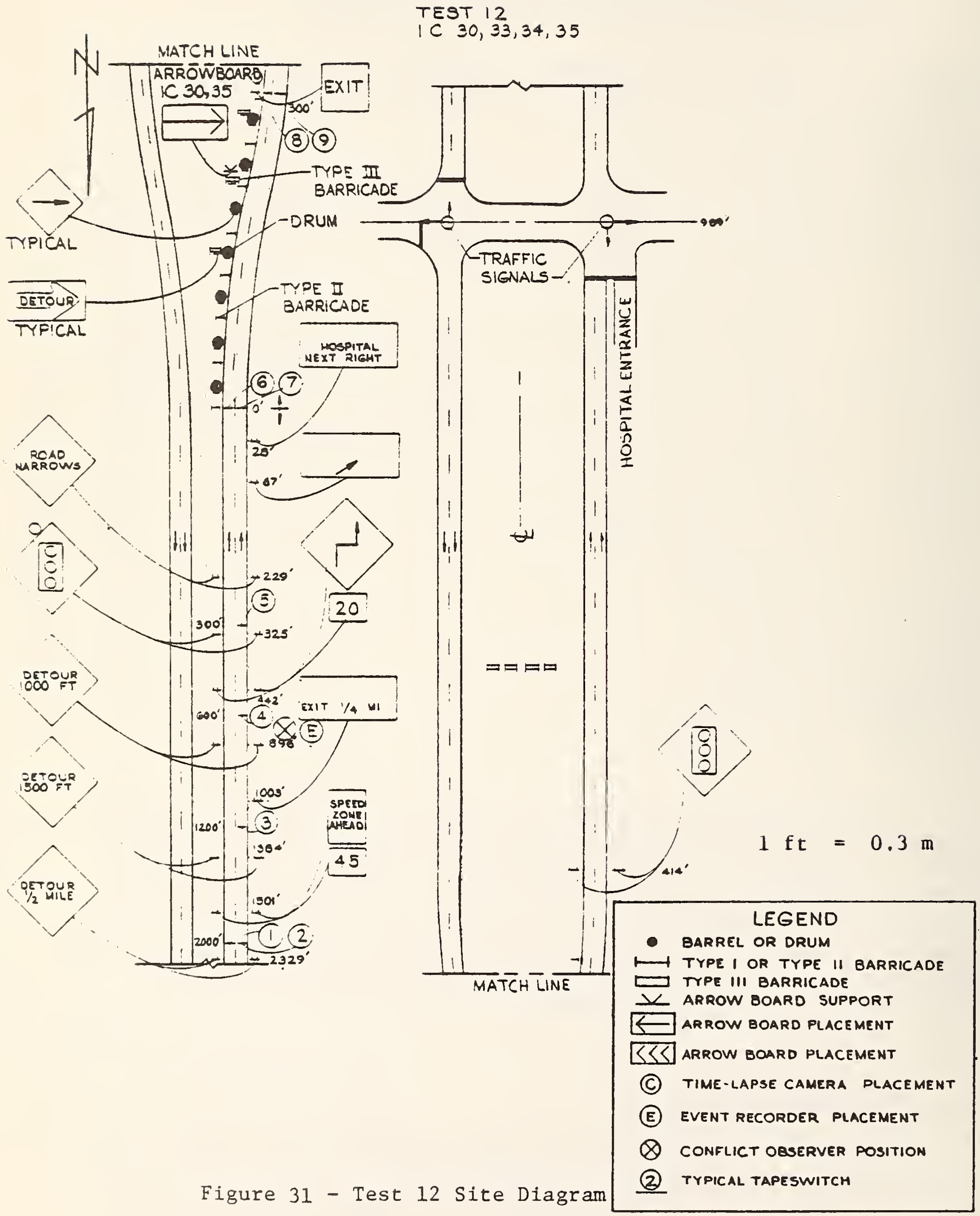


Figure 31 - Test 12 Site Diagram

Experiments IC 33 and 34. When the arrow board was used, the mode was alternated from flashing arrow to sequential chevron to sequential stem. Experiments IC 30 and 34 were conducted during the day, and Experiments IC 33 and 35 were conducted at night.

The percentage of vehicles traveling in the right lane at various distances from the detour is shown in Table 26. The arrow board did increase the percentage of vehicles that moved into the right lanes as they approached the detour both at night and during the day. However, in general, more vehicles moved into the right lane during the day than at night.

TABLE 26

TEST 12 - PERCENTAGE OF VEHICLES IN RIGHT LANE
(Rural, 4-lane limited access highway)

		Distance from Start of Detour (ft)				
Experiment	Mode	2,000	1,200	600	300	Start of Detour
IC 30	Flashing Arrow	67.5%	69.2%	64.5%	72.3%	71.9%
IC 30	Sequential Chevron	62.4	67.4	62.4	74.7	72.3
IC 30	Sequential Stem	59.7	59.3	55.4	58.9	67.7
IC 30	All	63.2	65.3	60.8	68.6	70.6
IC 34	All	64.4	66.2	64.8	67.7	65.2
IC 35	Flashing Arrow	66.9	65.3	69.2	69.5	73.4
IC 35	Sequential Chevron	69.8	70.5	72.0	72.0	74.1
IC 35	Sequential Stem	80.8	81.6	85.0	81.6	83.3
IC 35	All	70.2	55.8	72.8	72.3	75.2
IC 33	All	69.6	70.6	70.8	72.8	72.3

1 ft = 0.3 m

During the day fewer vehicles moved into the right lane with the flashing arrow mode than the other two modes. During the day there were fewer vehicles in the right lane with the sequential stem mode.

The arrow board increased the erratic maneuver rate, especially at night. At night the percentage of vehicles committing erratic maneuvers was 11.17 percent with an arrow board and 1.2 percent without an arrow board. During the day the erratic maneuver rate was 4.0 percent with arrow boards and 1.1 percent without arrow boards. The rate of encroachments from the left lane into the right lane was higher with the arrow board during the day (7.7 percent with an arrow board versus 2.1 percent without) but not at night.

Overall, the effect of the arrow board at this location was negative. The arrow board increased the number of lane changes and increased the erratic maneuver rate.

Test 13 - Experiments IC 31-32

This test was performed on a 4-lane, undivided, uncontrolled access, rural highway at a right lane closure. A diagram of the site is shown in Figure 32. Both experiments were performed during the day, and each was conducted for 1 hr. Lane-change data were collected by means of a time-lapse camera located in the closed lane near the middle of the taper. During Experiment IC 31, a 4 x 8 ft (1.2 x 2.4 m) arrow board displaying the flashing arrow mode was located near the middle of the taper in the closed lane. Experiment IC 32 was conducted without an arrow board. The experiments were performed between 0945 hrs and 1245 hrs of the same day.

Lane volume data were recorded from 2,000 ft (610 m) to 200 ft (61 m) upstream of the camera location. Erratic maneuvers and traffic conflicts were recorded in 15 min increments.

Table 27 includes percentages of vehicles traveling in the right (closed) lane at various distances from the camera location. Figure 33 shows the lane change distribution. Since the passenger car/commercial vehicle distributions were equal for both experiments, the analysis was performed using the total number of vehicles. In terms of initial percentages of vehicles in the right lane at 2,000 ft (610 m), the percentage was less with the flashing arrow present. In both experiments, the respective lane percentages remained the same at 2,000 ft, 1,750 ft, and 1,500 ft (610 m, 533 m, and 457 m) and the right lane was virtually empty at 200 ft (61 m) from the camera. Using the arrow board, traffic started leaving the closed lane between the 1,250 ft (381 m) and 1,000 ft (305 m) positions, and the rate of departure was more or less steady until the 500 ft (152 m) position when most of the vehicles had exited the lane. Without an arrow board, the vehicles started to leave the closed lane later, between the 1,000 ft (305 m) and 800 ft (244 m) positions, and the rate of departure was faster. At the 400 ft (122 m) position, the percentages of vehicles remaining in the closed lane were about the same.

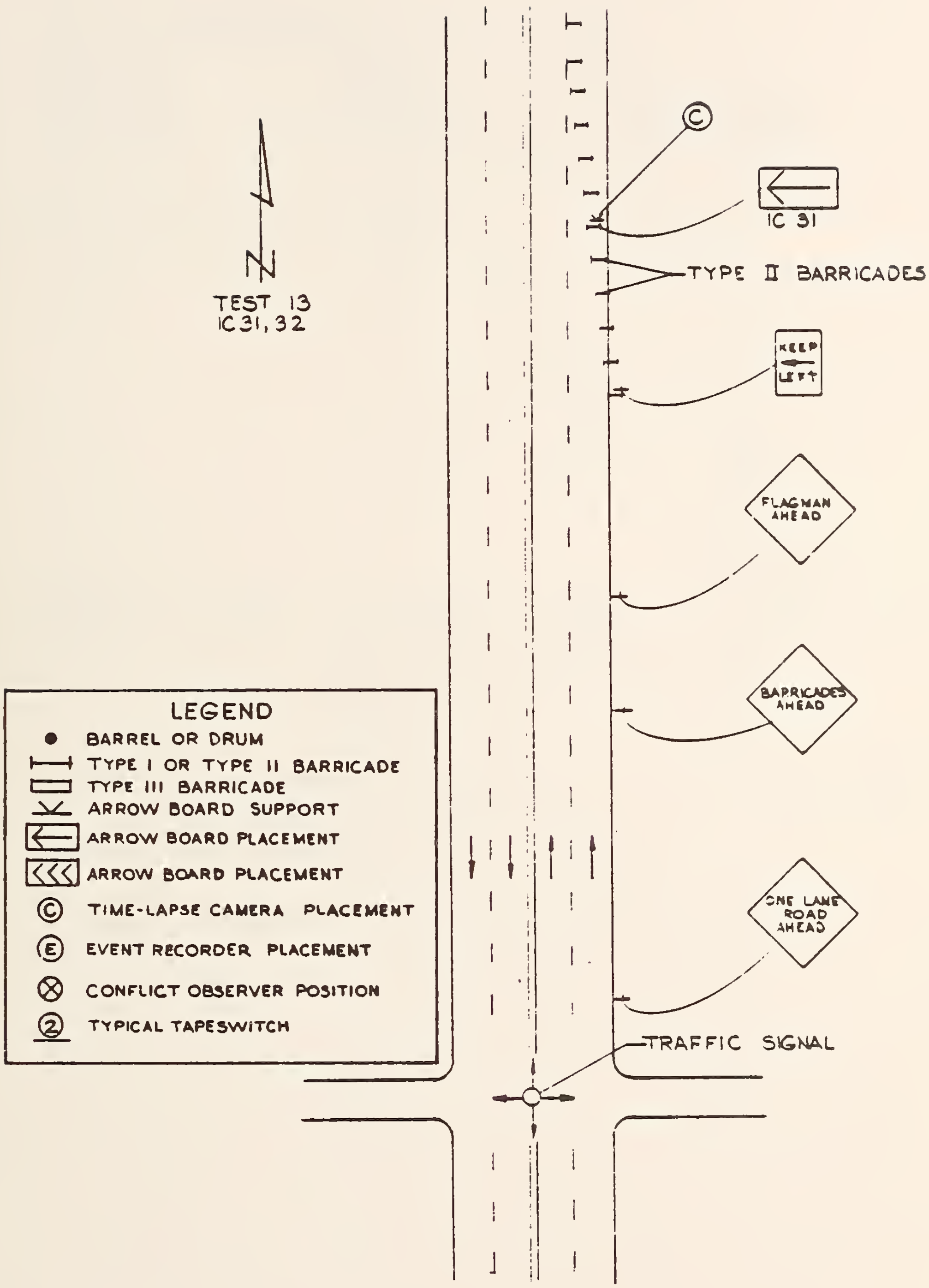


Figure 32 - Test 13 Site Diagram

TABLE 27

TEST 13 - PERCENTAGE OF VEHICLES IN RIGHT LANE
(Rural, 4-lane uncontrolled access highway)

Distance From Camera (ft)	Experiment: Flashing Arrow IC 31 (%)	Experiment: No Arrow Board IC 32 (%)
2,000	22.7	38.4
1,750	22.7	38.4
1,500	22.7	38.4
1,250	21.5	38.1
1,000	17.3	37.3
800	9.4	32.0
600	3.5	17.9
400	1.6	2.7
200	0.2	0.3

1 ft = 0.3 m

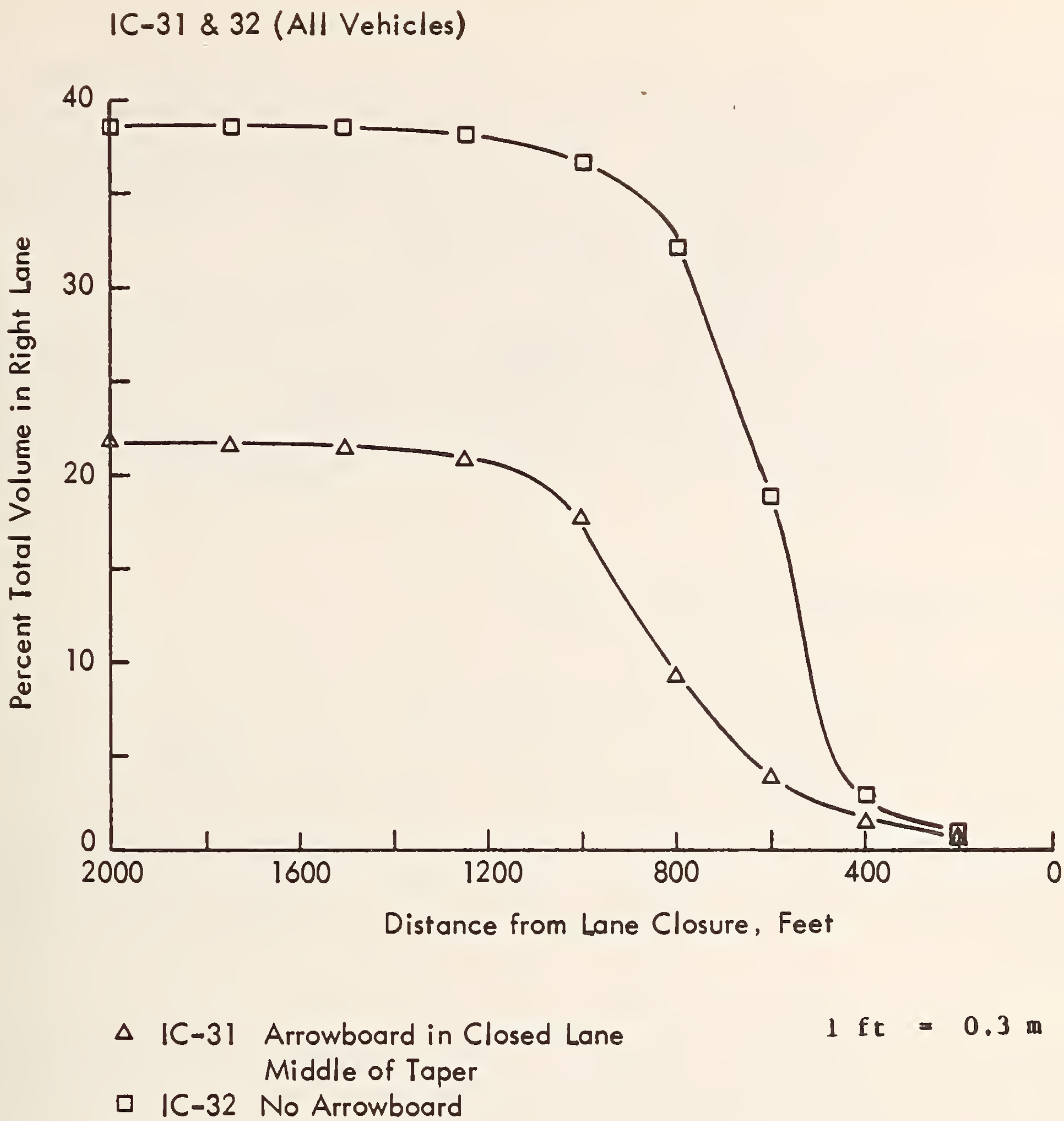


Figure 33 - Test 13 - Lane Change Distribution

Both the slow-to-merge opportunity and conflict rates were significantly greater when no arrow board was present (95 and 90 percent confidence levels, respectively). There were no significant differences between the rates of slow-vehicle conflicts, slow-vehicle secondary conflicts, lane-change conflicts, lane-change secondary conflicts, and the wrong-way lane-change opportunities of both experiments.

At this construction zone, vehicles started to exit the closed lane sooner when an arrow board was being used. Since vehicles were leaving the closed lane sooner, there were less vehicle interactions occurring in this portion of the zone. This is substantiated by the fact that the percentages of slow-to-merge opportunities and conflicts were significantly less when an arrow board was used.

Test 14 - Experiments IC 36-38, 45-46

This test was conducted on a 4-lane, undivided, urban highway with a right diversion and the left lane closed. A diagram of the site is shown in Figure 34. An arrow board was tested during experiments IC 36, 37 and 45. During these experiments, the arrow board was placed in the closed lane near the start of the taper. The flashing arrow mode was used during Experiments IC 36 and 45, and the sequential chevron mode was used in Experiment IC 37. Experiments IC 36-38 were conducted during the day, and Experiments IC 45-46 were conducted at night. All experiments were filmed.

The percentage of vehicles in the left lane at various distances from the arrow board are shown in Table 28. The signalized intersection was 725 ft (221 m) from the start of the detour and was probably responsible for the increased percentage between 800 and 600 ft (244 and 183 m) in Experiments IC 36 and 37. There was no significant difference in the pattern of lane changes at night. During the day very few lane changes took place until the interval between 400 and 200 ft (122 and 61 m). In this interval, the flashing arrow was most effective in removing cars. Both arrow board modes were more effective than no arrow board.

The only significant effect on conflicts or erratic maneuvers was that arrow boards reduced the erratic maneuver rate at night.

Test 15 - Experiments IC 39-44

Test 15 was conducted on a 4-lane, divided, uncontrolled access, rural highway with a right lane closure. Both day and night experiments were performed using a 4 x 8 ft (1.2 x 2.4 m) arrow board displaying the flashing arrow mode and also without an arrow board. The arrow board was

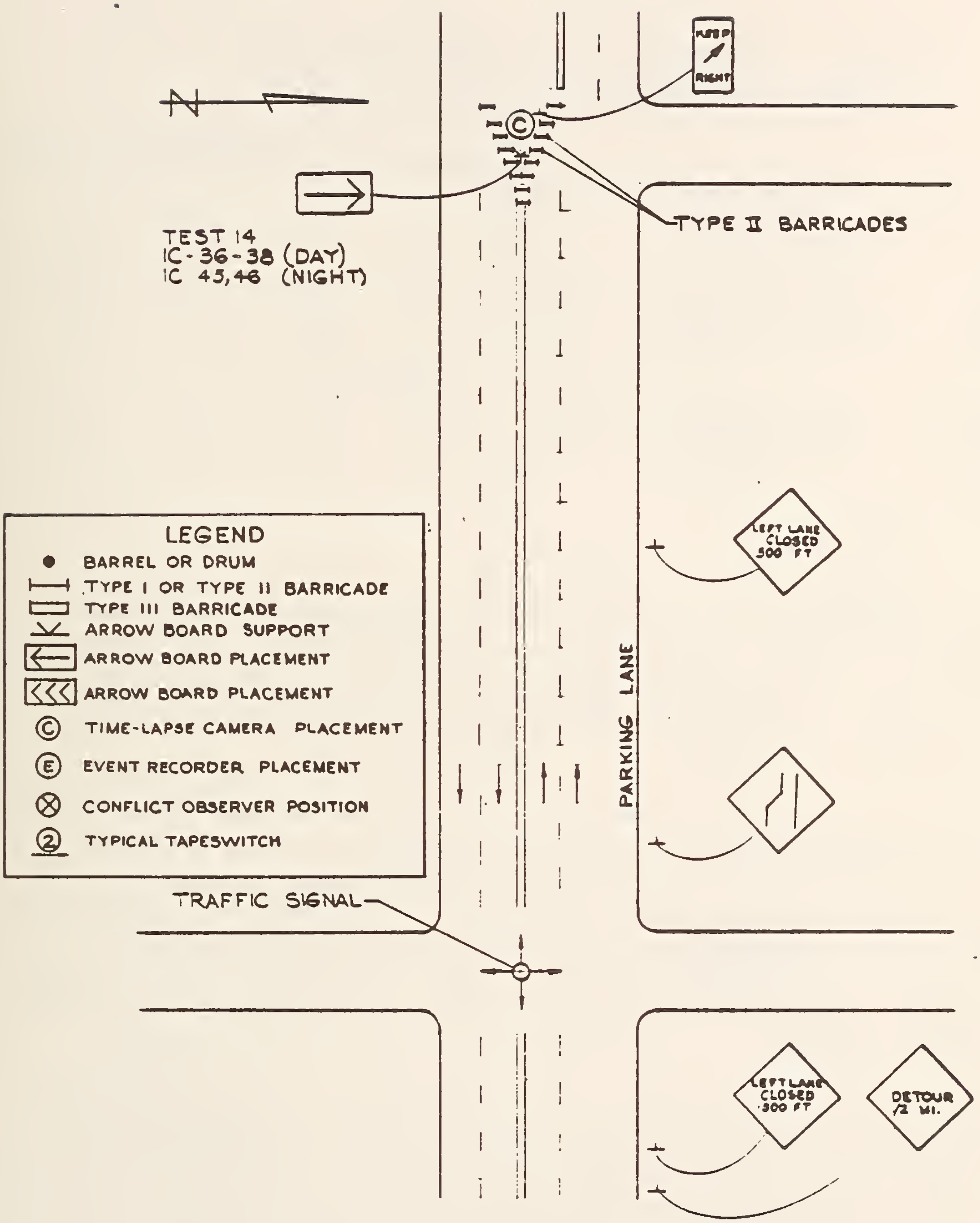


Figure 34 - Test 14 Site Diagram

located on the shoulder near the beginning of the taper and in the closed lane near the middle of the taper. Figure 35 contains the Test 15 site diagram.

TABLE 28

TEST 14 - PERCENTAGE OF VEHICLES IN LEFT LANE
(Urban, 4-lane uncontrolled access highway)

Experiment and Time	Arrow Board Mode	Distance from Start of Detour (ft)					
		1,250	1,000	800	600	400	200
IC 36 Day	Flashing Arrow	39.7%	39.5%	39.5%	41.2%	39.7%	16.0%
IC 37 Day	Sequential Chevron	34.9	34.7	34.5	36.1	32.2	17.8
IC 38 Day	No Arrow Board	33.2	33.2	32.8	32.4	31.4	20.5
IC 45 Night	Flashing Arrow	19.4	19.4	16.1	12.1	5.7	0.8
IC 46 Night	No Arrow Board	8.3	5.6	5.6	2.8	2.8	0.0

1 ft = 0.3 m

Each experiment was conducted for 2-1/2 hr. Traffic volume data were collected by a series of tapeswitches installed along the test section of the construction zone. Erratic maneuvers and traffic conflicts were collected in 15 min increments. Spot speeds were collected in the closed lane near the start of the taper.

Due to an equipment malfunction, initial lane volumes could not be determined for each experiment. However, lane departure rates could be determined. At night, cars left the closed lane at a faster rate with both of the arrow board placements than with no arrow board present. During the day, the cars left faster with the closed-lane placement than with the shoulder placement or with no arrow board. Mean speeds were higher with the shoulder placement during the day, but there were no significant differences in mean speeds at night.

There were no significant erratic maneuver or traffic conflict rates. Slow-to-merge opportunity rates were higher with no arrow board present. During the day, the closed lane placement had lower slow-to-merge opportunity rates than the shoulder placement. At night, there was no difference in the slow-to-merge opportunity rates of the arrow board placements.

In summary, the flashing arrow mode was more effective both during the day and night at causing vehicles to depart the closed lane than when no arrow board was present. During the day, the shoulder-placement experiments had higher mean speeds, but at night mean speeds were approximately equal. Slow-to-merge opportunity rates were greatest when no arrow board was present.

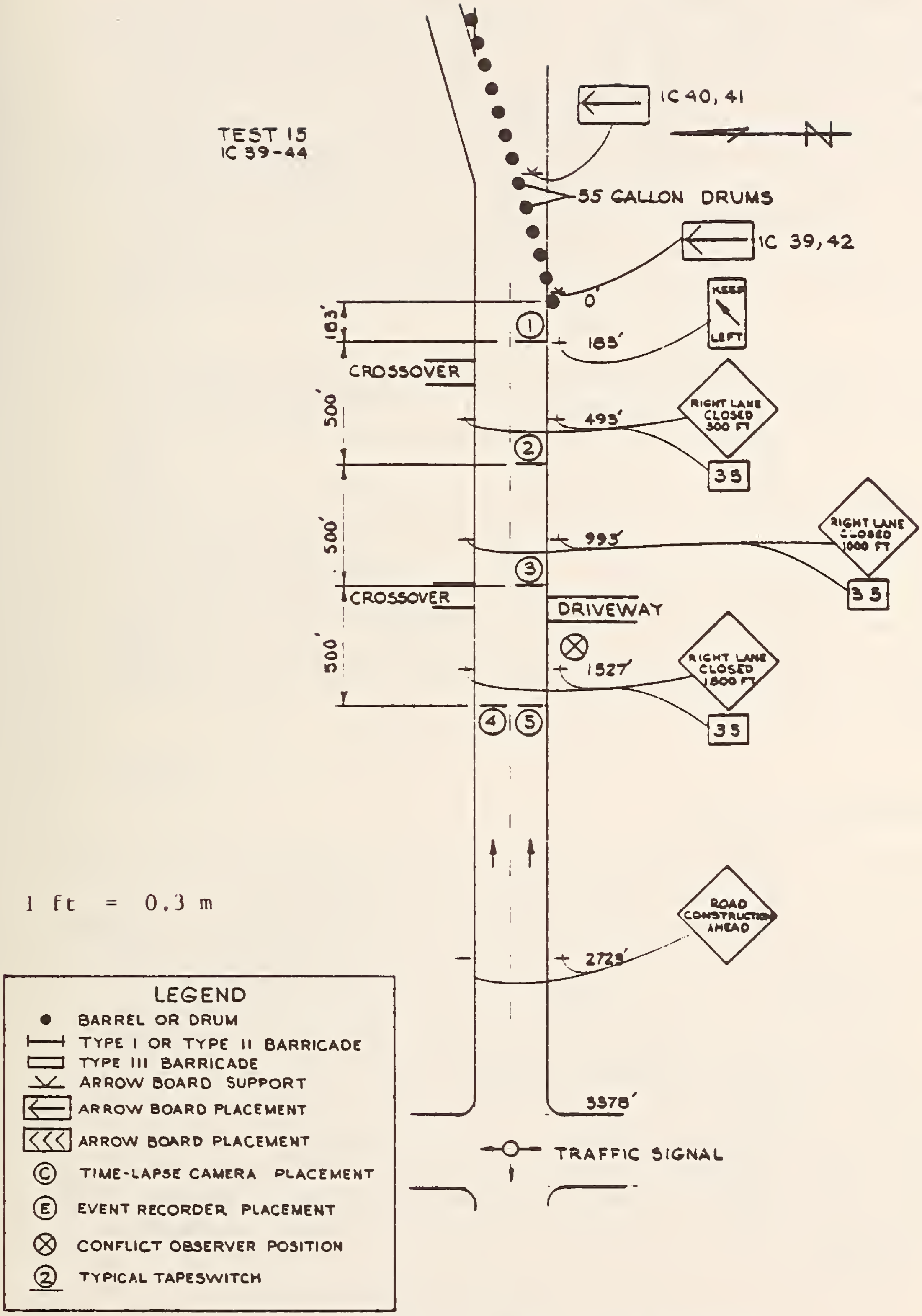


Figure 35 - Test 15 Site Diagram

Test 16 - Experiments IC 47-48

This test was performed on a 6-lane, urban, Interstate highway. Of the three lanes where this test was conducted, the right lane was closed. Traffic on the other two lanes was split to avoid the bridge deck repair work. A diagram of the test site is contained in Figure 36. Both experiments were conducted during the day. Lane-change data were collected by means of a time-lapse camera located near the gore area where the two lanes were split. Each experiment was conducted for 1 hr. During Experiment IC 47, a 48 in. (1.2 m) double arrow, construction, warning sign was located immediately upstream of the camera. For Experiment IC 48, a 4 x 8 ft 1.2 x 2.4 m) arrow board displaying a double flashing arrow replaced the double arrow sign.

Lane volume data were recorded at distances ranging from 2,000 ft (610 m) to 200 ft (61 m) upstream of the camera. Erratic maneuvers and traffic conflicts were recorded in 15 min increments for each experiment.

Table 29 contains the percentages of vehicles in the left lane for both experiments. The initial percentage of vehicles in the left lane was higher with the double arrow sign than with the double flashing arrow. In other words, more vehicles stayed in the right lane while the double flashing arrow was in use. The percentage of vehicles making last second lane changes was significantly higher while the double arrow sign was in use. There were no significant differences between the erratic maneuver rates and traffic conflict rates of the two experiments.

Test 17 - Experiments IC 49-51

This test was conducted on a 6-lane, urban freeway during the day. The 4 x 8 ft (1.2 x 2.4 m) arrow board displaying the sequential chevron mode was placed in the closed lane halfway through the 1,200 ft (366 m) taper during Experiment IC 49 and on the shoulder at the beginning of the taper during Experiment IC 50. Experiment IC 51 was performed without an arrow board. The portion of the construction zone which was studied was located on a long horizontal tangent that had a slight vertical downgrade. These roadway characteristics provided excellent sight distance for vehicles entering the zone. Traffic movements were recorded by means of a time-laspe camera located in the middle of the taper. Each experiment was conducted for 1 hr. Lane volume data were recorded from 2,000 ft (610 m) to 200 ft (61 m) upstream of the camera. Erratic maneuvers and traffic conflicts were collected in 15 min increments during the studies. Figure 37 contains the Test 17 site diagram.

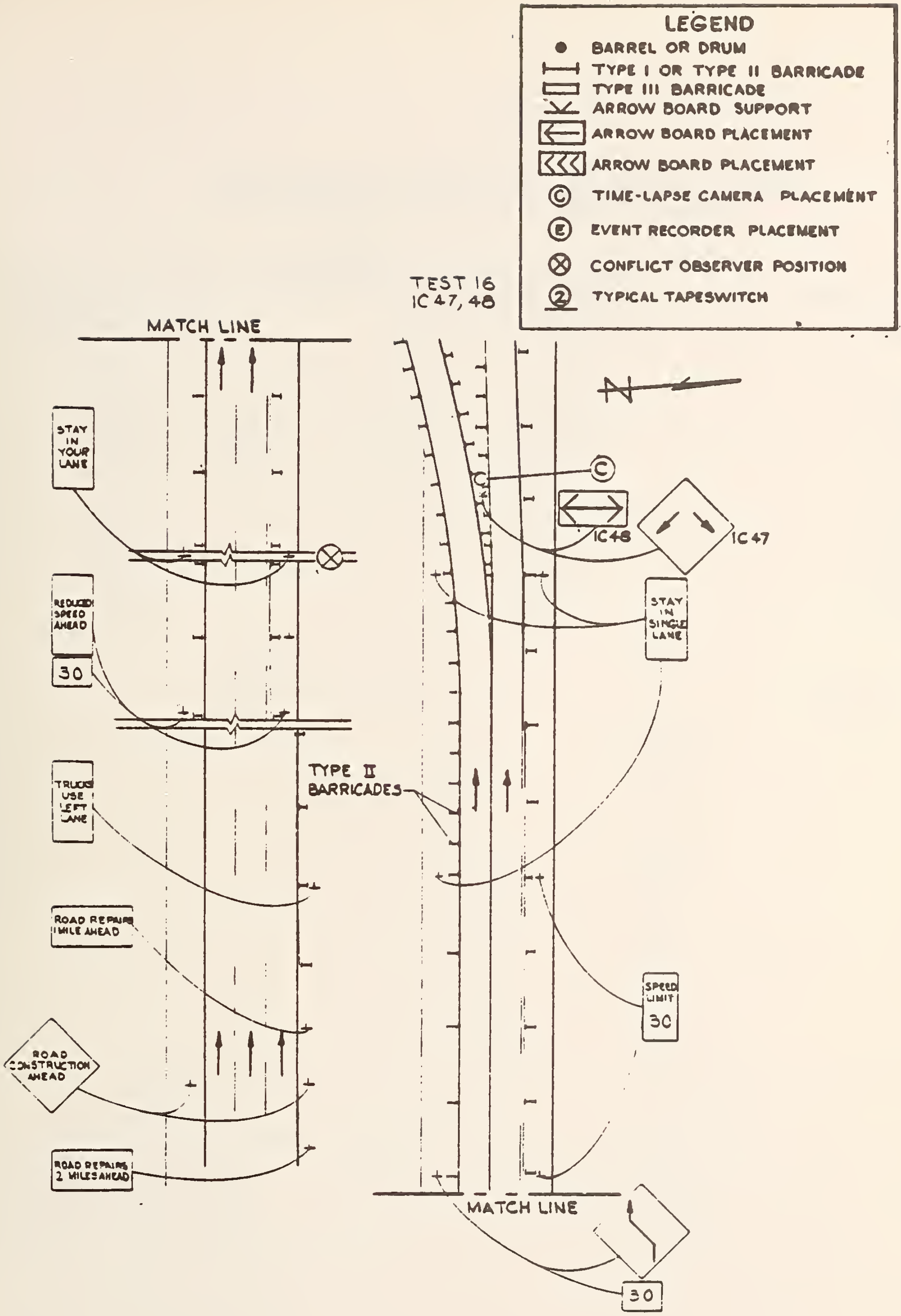


Figure 36 - Test 16 Site Diagram

TABLE 29

TEST 16 - PERCENTAGE OF VEHICLES IN LEFT LANE
(Urban, 6-lane Interstate highway)

Distance from Camera	Experiment: Double Arrow Sign (IC 47)	Experiment: Double Flashing Arrow (IC 48)
2,000 ft	56.2%	43.6%
1,750 ft	56.2%	43.6%
1,500 ft	56.2%	43.6%
1,250 ft	56.2%	43.6%
1,000 ft	55.9%	43.3%
800 ft	55.4%	43.3%
600 ft	55.2%	43.6%
400 ft	55.1%	43.6%
200 ft	54.8%	43.2%

1 ft = 0.3 m

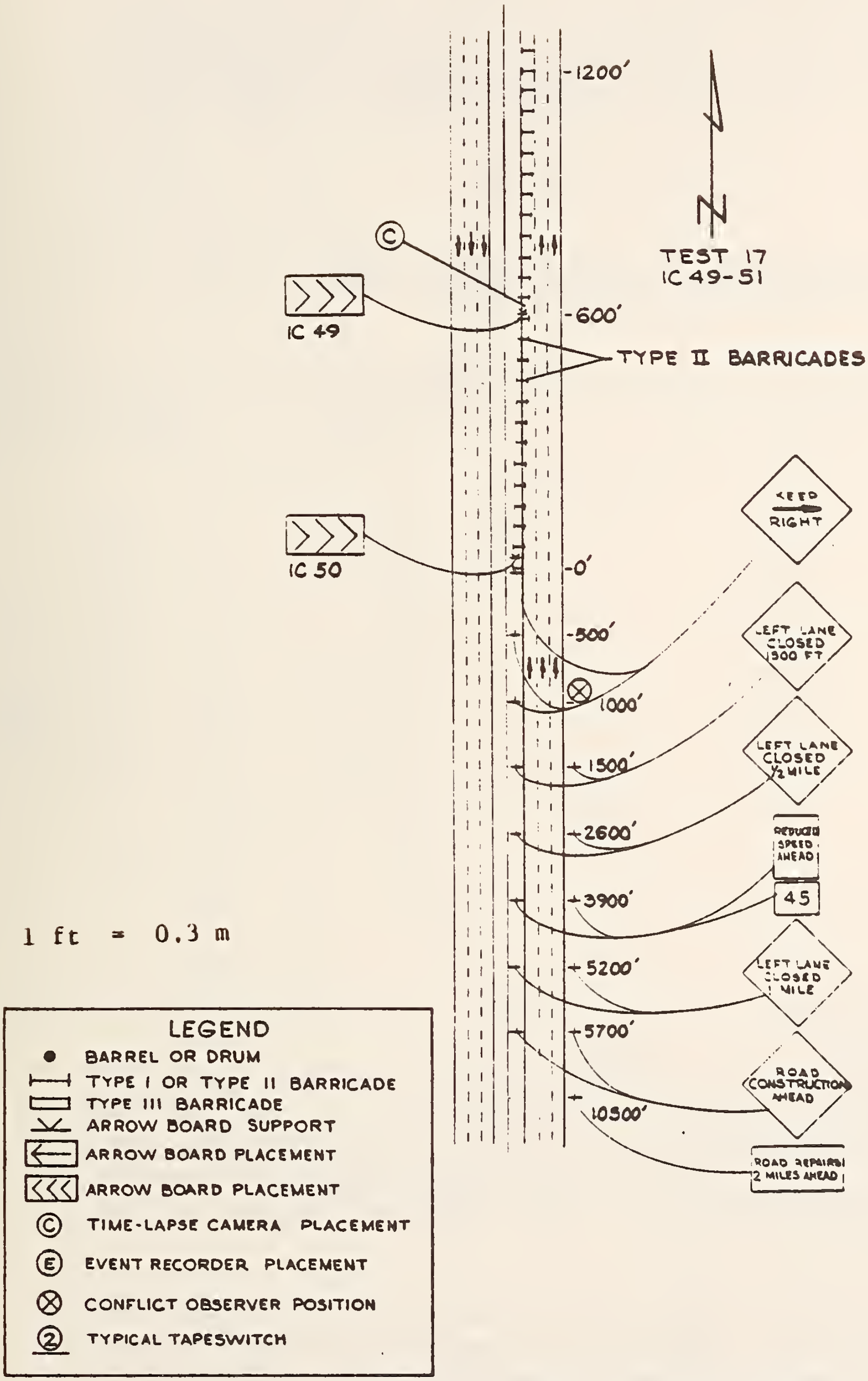


Figure 37 - Test 17 Site Diagram

The initial percentage of vehicles in the closed (left) lane at 2,000 ft (610 m) was lowest with the arrow board at the beginning of the taper on the shoulder. The rate at which vehicles departed the closed lane was greatest, although only marginally, with the arrow board located at the beginning of the taper, also. Percentages of vehicles in the closed (left) lane are contained in Table 30. There were no significant erratic maneuver effects. The slow-vehicle conflict rates were higher with arrow boards than without an arrow board. No other traffic conflict rates were significant.

TABLE 30

TEST 17 - PERCENTAGE OF VEHICLES IN LEFT LANE
(Urban, 6-lane Interstate highway)

Distance from Camera	Experiment		
	Sequential Chevron (IC 49)	Sequential Chevron (IC 50)	No Arrow Board (IC 51)
2,000 ft	10.8%	5.8%	11.1%
1,750 ft	10.4%	5.5%	10.8%
1,500 ft	10.4%	4.9%	10.2%
1,250 ft	9.6%	4.6%	9.7%
1,000 ft	8.4%	3.8%	8.7%
800 ft	5.3%	2.9%	7.2%
600 ft[a/]	3.6%	2.2%	5.1%
400 ft	2.2%	1.4%	3.0%
200 ft	1.0%	0.7%	1.1%

a/ Start of taper.
1 ft = 0.3 m

Test 18 - Experiments IC 52-53

This test was performed on a 6-lane, urban freeway during the day. The right lane in the construction zone was closed upstream of the test section of highway. The two remaining lanes were split in order to bypass the bridge deck reconstruction. The existing on-ramp was closed, and a temporary ramp was built upstream from the original ramp. Figure 38 contains the Test 18 site diagram.

Traffic movements were filmed from the gore area of the lane split using a time-lapse camera. Each experiment was conducted for 1 hr. A 4 x 8 ft (1.2 x 2.4 m) double flashing arrow was used during Experiment IC 52 and a 48 in. (1.2 m) double arrow, construction, warning sign was used during

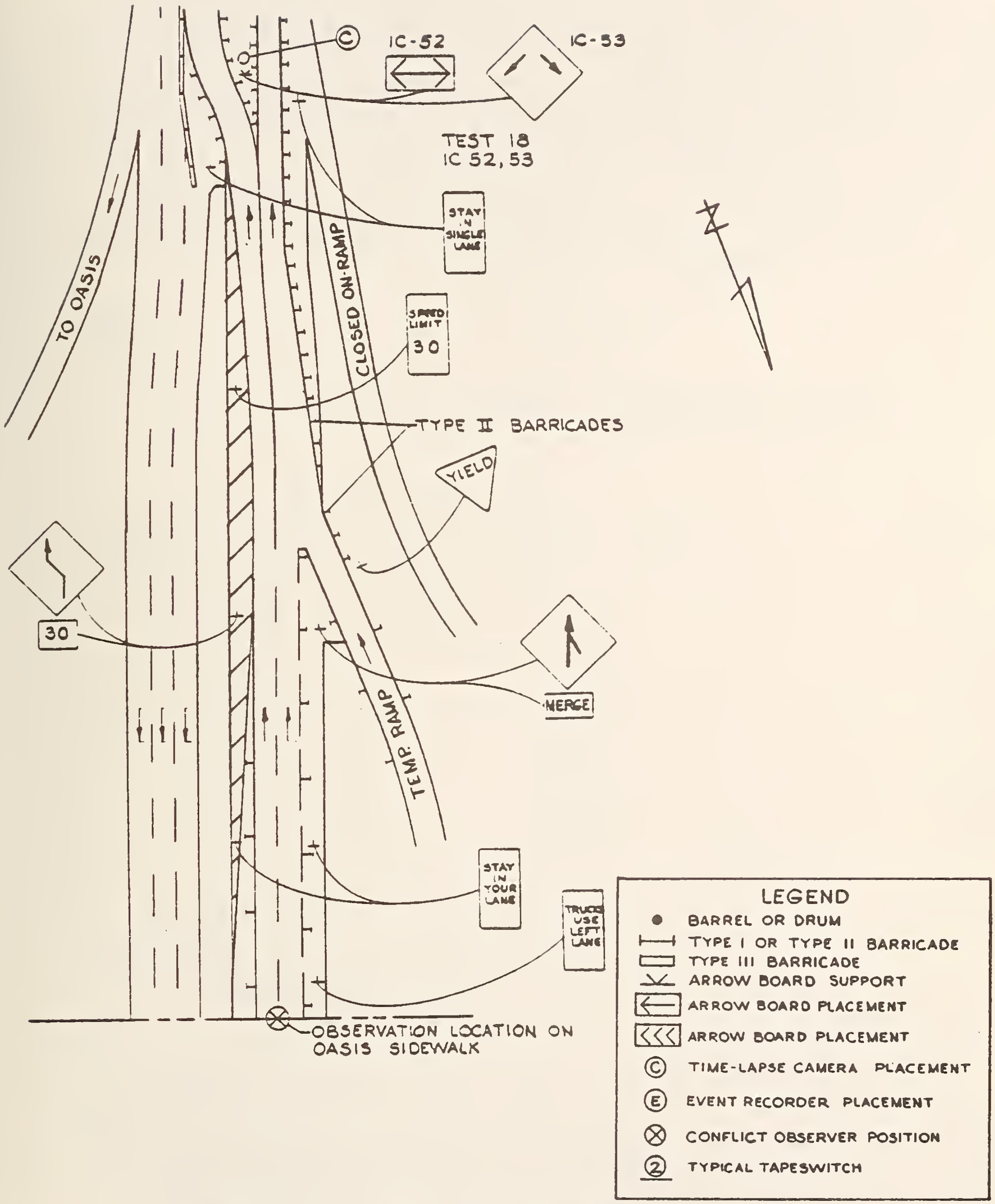


Figure 38 - Test 18 Site Diagram

Experiment IC 53. For both experiments, the warning devices were placed immediately upstream of the camera location. Erratic maneuvers and traffic conflicts were collected in 15 min increments.

There were no differences between the double flashing arrow and double arrow sign for either the initial lane distribution at 2,000 ft (610 m) or throughout the remainder of the test section. Percentages of vehicles in the left lane are contained in Table 31. The difference in erratic maneuver rates for both experiments was not significant. The last-second lane change rate was significantly less while the double flashing arrow was in use. No other differences in traffic conflict rates were significant. It appears that the double flashing arrow, when used where lanes of traffic are split, provides a clear indication that drivers may proceed through the construction zone without having to change lanes.

TABLE 31

TEST 18 - PERCENTAGE OF VEHICLES IN LEFT LANE
(Urban, 6-lane Interstate highway)

Distance from Camera	Experiment: Double Flashing Arrow (IC 52)	Experiment: Double Arrow Sign (IC 53)
2,000 ft	49.6%	49.3%
1,750 ft	49.6%	49.3%
1,500 ft	49.7%	49.4%
1,250 ft	49.7%	49.4%
1,000 ft	49.8%	49.5%
800 ft	49.7%	50.0%
600 ft	49.6%	50.4%
400 ft	50.0%	51.2%
200 ft	50.8%	51.7%

1 ft = 0.3 m

Test 19 - Experiments IC 54-55

This test was conducted on a rural, 4-lane, Interstate highway. The two test lanes were split to avoid bridge deck reconstruction. Two day experiments were performed during peak (IC 54) and off-peak (IC 55) periods. A 4 x 8 ft (1.2 x 2.4 m) double flashing arrow was used for both experiments and was located in the gore area of the lane split. A time-lapse camera, which was located immediately downstream of the arrow board, was used to film traffic movements. Each experiment was conducted for 1 hr. Figure 39 contains the Test 19 site diagram.

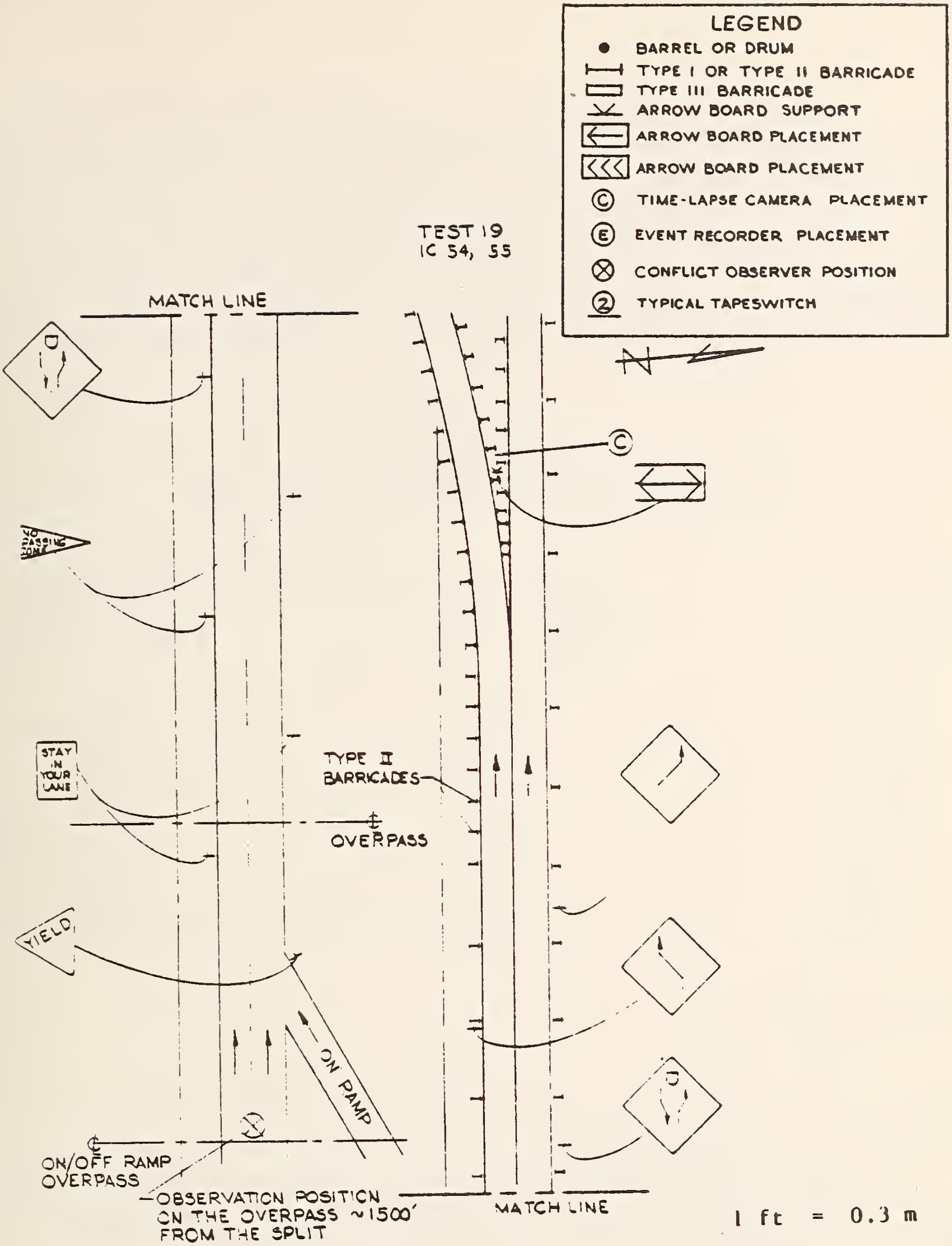


Figure 39 - Test 19 Site Diagram

During both experiments, vehicles were moving from the left lane into the right lane. During the peak period about 5 percent of the total vehicles moved from the left lane to the right lane. During the off-peak period, about 6 percent made the same lane change. The percentage of cars in the left lane was higher during the peak period experiments. Table 32 contains the percentages of vehicles in the left lane. No significant difference in erratic maneuver or conflict rates were observed. Any driver confusion have been created by what appeared to be an excess of signing.

TABLE 32

TEST 19 - PERCENTAGE OF VEHICLES IN LEFT LANE
(Rural, 4-lane Interstate highway)

	Experiment	
Distance from Camera	Double Flashing Arrow (IC 54)	Double Flashing Arrow (IC 55)
2,000 ft	47.9%	38.1%
1,750 ft	47.7%	37.2%
1,500 ft	47.6%	36.4%
1,250 ft	47.1%	35.6%
1,000 ft	45.3%	34.9%
800 ft	43.7%	33.2%
600 ft	43.3%	32.4%
400 ft	43.2%	32.2%
200 ft	43.2%	31.9%

1 ft = 0.3 m

Test 20 - Experiments IC 56-60

This test was performed on a rural, 4-lane, Interstate highway at a left lane closure. When the 4 x 8 ft (1.2 x 2.4 m) arrow board was used, it was placed on the shoulder near the beginning of the taper. There were three day experiments (IC 56, no arrow board; 57, sequential chevron; and 58, flashing arrow) and two night experiments (59, flashing arrow; and 60, no arrow board). From about 0700 hr to 1730 hr a flagman with a "slow" paddle was stationed at the start of the taper. The advance signing was slightly different during this time period, also (see Figure 40). Each experiment was conducted for 2 hr.

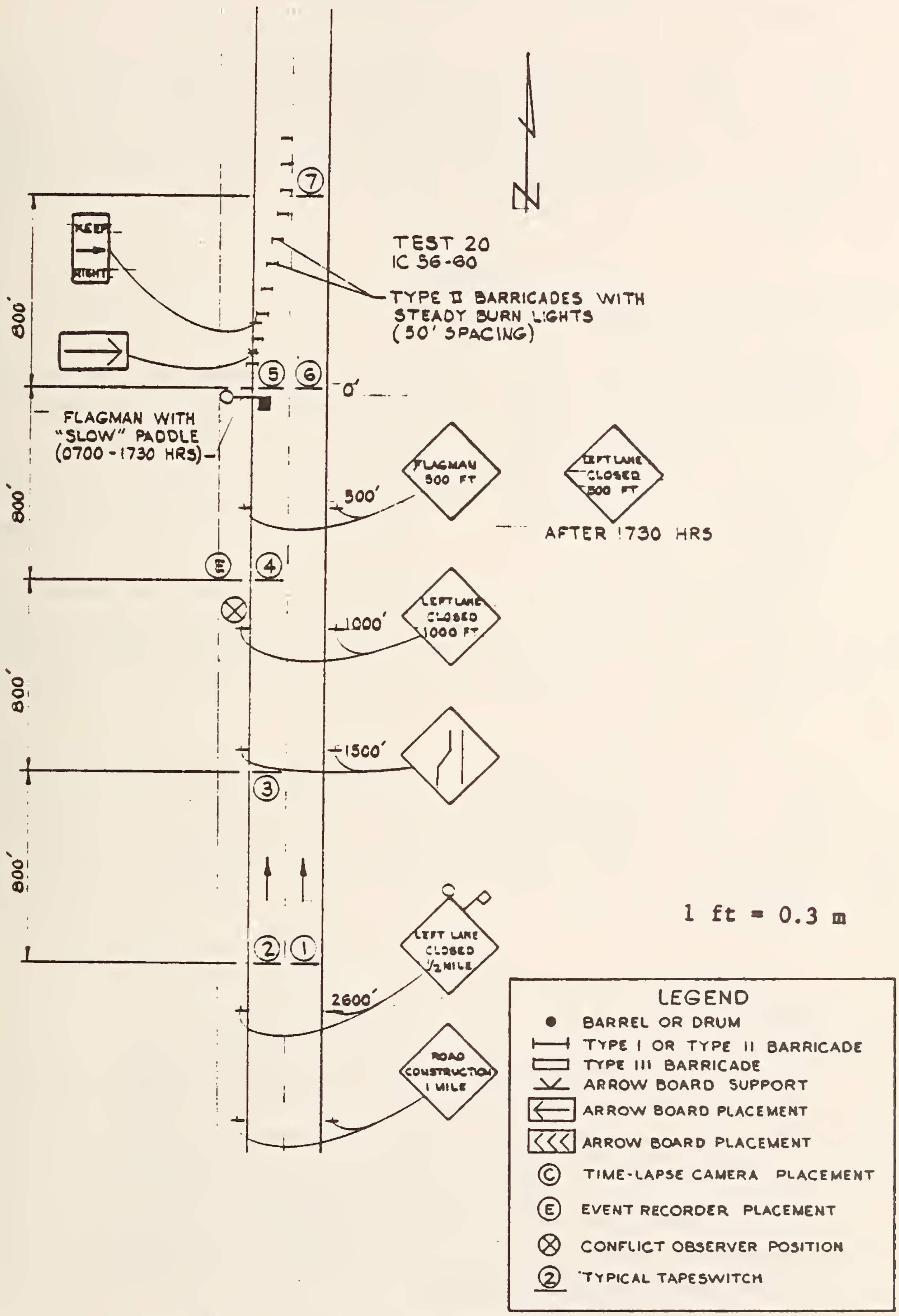


Figure 40 - Test 20 Site Diagram

Traffic volume data were collected by means of tapeswitches. However, traffic volumes in the left (closed) lane were too low to perform a meaningful lane change distributional analysis.

Erratic maneuver and traffic conflict data were collected in 15 min increments. There were no significant erratic maneuver rates. The daytime slow-vehicle conflict rate for arrow boards was less than for no arrow board. However, there was no difference in the night rates. Also, the slow-vehicle conflict rate for the flashing arrow mode was less than that of the sequential chevron mode.

Test 21 - Experiments IC 61-64

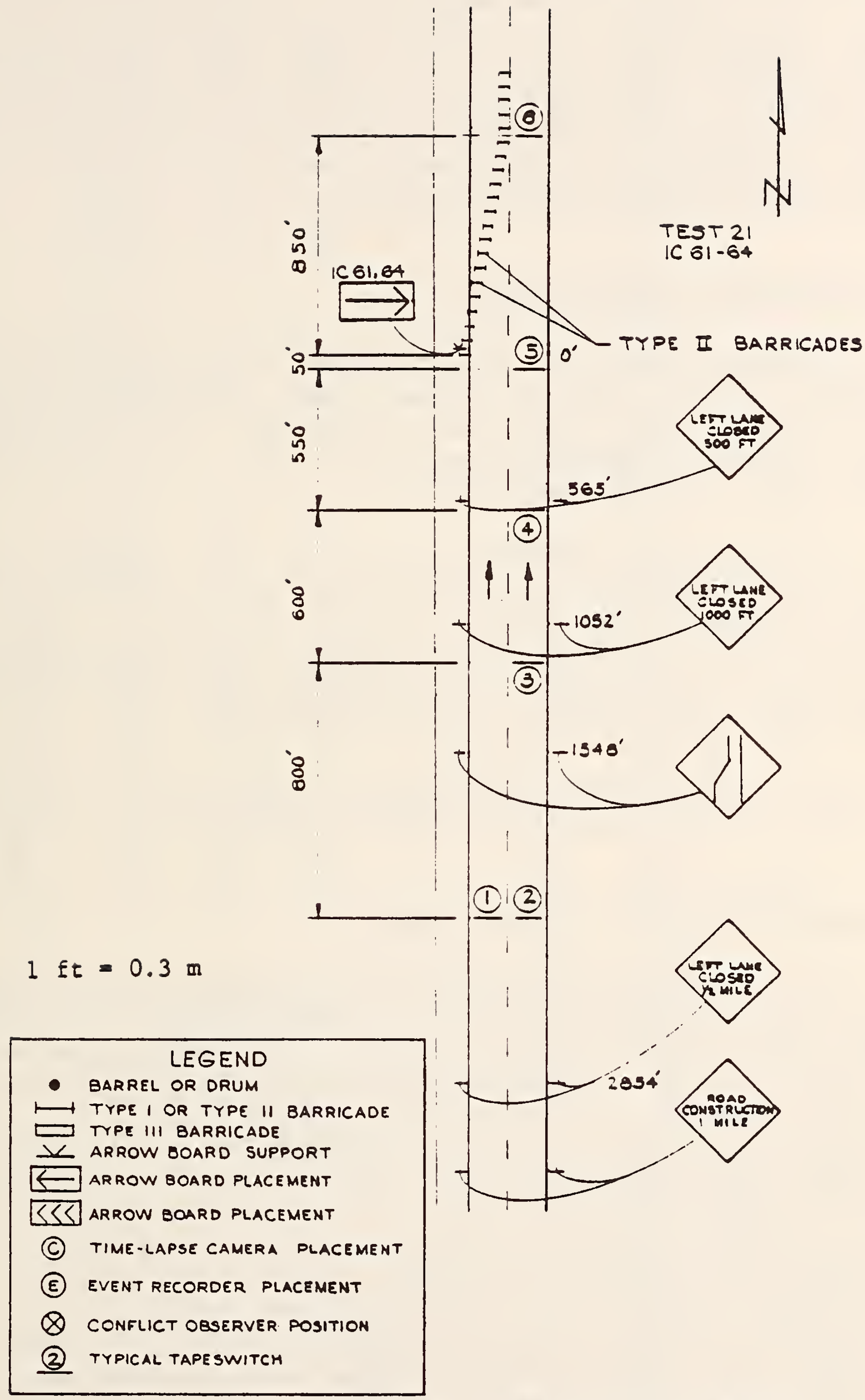
Test 21 was conducted on a rural, 4-lane, Interstate highway at a left lane closure. Experiments were conducted both during the day and night; with and without a 4 x 8 ft (1.2 x 2.4 m) arrow board. The flashing arrow and sequential chevron modes were used during each of the two arrow board experiments. The arrow board, when used, was located on the shoulder near the start of the taper. Figure 41 contains the Test 21 site diagram.

Each experiment was conducted for 2-1/2 hr. Traffic volumes were recorded by means of tapeswithces installed along the test section of the construction zone. Erratic maneuvers and traffic conflicts were collected in 15 min increments. Spot speeds were recorded 1,500 ft (460 m) into the work zone.

The percentage of vehicles in the left lane was very low during all experiments. There were no significant erratic maneuver or conflict effects. Both car and truck speeds were greater during the day. Car speeds were lower with an arrow board present although the reduction was only from 58.4 mph to 57.2 mph (94.0 kph to 92.1 kph). Arrow boards had no effect on truck speeds, however.

Test 22 - Experiments CM 1 and 7

These maintenance experiments were conducted on 8-lane Interstate highways with stationary right-lane closures. Arrow boards were present in both experiments. In Experiment CM 1 the arrow board was located on the shoulder near the start of the taper and operated in the sequential chevron mode. In Experiment CM 7 the arrow board was located in the closed lane near the end of the taper and operated in the sequential arrow mode. The arrow board in Experiment CM 1 was 4 x 8 ft (1.2 x 2.4 m), and the arrow board in CM 7 was a vehicle-mounted, 3 x 6 ft (0.9 x 9.8 m) board. Both experiments were filmed during the day.



1 ft = 0.3 m

Figure 41 - Test 21 Site Diagram

The percentage of vehicles in the right lane at various distances from the arrow board are shown in Table 33. The larger arrow board encourages vehicles to leave the right lane sooner and the percentage of vehicles leaving in each interval is more consistent than with the smaller board. The experiment with the 4 x 8 ft (1.2 x 2.4 m) arrow board had a significantly lower slow-to-merge opportunity rate. Also the rate of erratic maneuvers and slow-to-merge conflicts were marginally less ($p \leq 0.10$) with the larger size board. Undoubtedly the larger board placed near the start of the taper resulted in much better traffic operations.

Test 23 - Experiments CM 3 and IM 7

These maintenance experiments studied moving striping operations on Interstate highways with the left lane closed. Experiment CM 3 was conducted on a 8-lane, urban, interstate and Experiment IM 7 on a 6-lane, rural, interstate. Both experiments employed arrow boards. It was not possible to observe conflicts in Experiment IM 7.

The percentage of vehicles in the left lane is shown in Table 34. As might be expected the percentage of vehicles in the left lane is higher for the 6-lane highway. The pattern of vehicle departures is quite similar except for the fact that the percentage leaving in any interval was usually slightly higher for IM 7 since it had a higher percentage of vehicles in the left lane at the initial (2,000 ft or 610 m) reading.

The conflict rates on Experiment CM 3 were very low; less than 1 percent of the vehicles committed any type of conflict.

Test 24 - Experiments CM 4, 6, 8, 9 and 14

These maintenance experiments studied moving, shoulder-sweeping operations on 8-lane Interstate highways. Experiments CM 4 and 14 did not use arrow boards, rather, signs on the back of the sweepers read "Caution-Sudden Stops and Turns." The caution-bar mode was used during Experiment CM 4, and the flashing-arrow mode was used during Experiment CM 9. The sweeper operated on the right shoulder during Experiments CM 4, 6 and 9 and on the left shoulder during Experiment CM 14. Both the mode and shoulder of the roadway were varied in Experiment CM 8. During the first 15-min period the sweeper operated on the left shoulder and the flashing arrow mode was used. During the second 15-min period the sweeper moved across the roadway to the right shoulder. This 15-min period was not used. For the third and fourth 15-min periods the sweeper operated on the right shoulder. The flashing-arrow mode was used during the third period, and the caution-bar mode was used during the fourth period. All experiments were filmed during the day.

TABLE 33

TEST 22 - PERCENTAGE OF VEHICLES IN THE RIGHT LANE

			Distance from Start of Taper						
Experiment	Size	Mode	1250 ft	1000 ft	800 ft	750 ft	500 ft	300 ft	100 ft
CM 1	4 x 8 ft	Sequential Chevron	14.9	13.6	12.1	--	9.2	6.4	2.2
CM 7	3 x 6 ft	Sequential Arrow	16.5	16.2	--	14.9	10.2	2.1	0.2

1 ft = 0.3 m

TABLE 34

TEST 23 - PERCENTAGE OF VEHICLES IN THE LEFT LANE

		Distance from Maintenance Vehicle								
Experiment	Number of One-Way Lanes	2000 ft	1750 ft	1500 ft	1250 ft	1000 ft	800 ft	600 ft	400 ft	200 ft
CM 3	4	15.1	14.7	14.2	13.4	12.1	8.6	5.1	2.5	0.9
IM 7	3	22.6	21.5	20.3	19.7	18.5	15.1	11.7	6.3	0.8

1 ft = 0.3 m

Table 35 shows the percentage of vehicles in the right lane when the sweeper was on the right shoulder. In all of the experiments a few vehicles vacated the right lane in the interval between 600 ft (193 m) and the sweeper. There were no significant lane change effects due to the arrow board use or the various modes. The rate of slow-moving vehicle conflicts was higher during one trial when the caution-bar mode was used.

Table 36 shows the percentage of vehicles in the left lane when the sweeper was on the left shoulder. The percentage of vehicles in the left lane was lower when the flashing arrow was used. During this experiment some vehicles actually entered the left lane in the interval between 800 and 600 ft (244 and 183 m), and there was a decrease in the percentage between 400 and 200 ft (122 and 61 m). When the sign was used, the percentages remained constant. There were fewer slow-moving vehicle conflicts when the sign was used.

In summary, there was little difference in the pattern of lane changes when the sweeper was on the right shoulder. When the sweeper was on the left shoulder, more cars remained in the left lane when the sign "Caution--Sudden Stops and Turns,"was used than when an arrow board was used.

Test 25 - Experiments CM 5 and 13

These maintenance experiments were stationary mudjacking operations on 8-lane Interstate highways. In Experiment CM 5 the two right lanes were closed. In CM 13 the two left lanes were closed. An arrow board, located in the closed lane near the end of the first lane taper, was tested in both experiments. The arrow board operated in the sequential chevron mode during both experiments. Both experiments were filmed during the day.

Table 37 shows the percentage of vehicles in the closed lanes for each experiment. Lane 1 was the rightmost lane and Lane 4 was the leftmost lane. Lane 4 in CM 13 was cleared fasted than Lane 1 in CM 5. Table 37 also shows an increase in the percentages of vehicles in the second closed lane in both experiments as vhicles began to leave the first closed lane. Lane 3 did not clear as readily as the Lane 2. In CM 13, 12.4 percent of the vehicles were still in the Lane 3 at the start of the lane closure taper. Only 0.6 percent of the vehicles were in Lane 2 at the start of the lane closure taper.

The slow clearing of Lane 3 was reflected in the slow-to-merge opportunity rate and the slow-vehicle conflict rate which were higher in Experiment CM 13 than in Experiment CM 5. In summary it appears that closing two left lanes of four lanes is more hazardous than closing the two right lanes.

TABLE 35

TEST 24 - PERCENTAGE OF VEHICLES IN RIGHT LANE WHEN SWEEPER WAS ON RIGHT SHOULDER

	15-Minute		Distance from Sweeper (ft)				
Experiment	Period	Mode	1000	800	600	400	200
CM 4	All	Caution-bar	34.8%	34.5%	34.3%	33.5%	31.6%
CM 6	All	Sign Only	30.9	31.0	30.7	30.4	29.4
CM 8	3	Flashing Arrow	31.5	31.8	31.5	30.7	30.1
CM 8	4	Caution-bar	36.1	36.4	35.9	35.2	30.2
CM 9	All	Flashing Arrow	31.7	31.4	31.2	30.3	28.6

1 ft = 0.3 m

TABLE 36

TEST 24 - PERCENTAGE OF VEHICLES IN LEFT LANE WHEN SWEEPER WAS ON LEFT SHOULDER

	15-Minute		Distance from Sweeper (ft)				
Experiment	Period	Mode	1000	800	600	400	200
CM 8	1	Flashing Arrow	4.7%	4.7%	5.4%	5.1%	3.0%
CM 14	All	Sign Only	15.5	15.2	15.2	15.0	15.1

1 ft = 0.3 m

TABLE 37

TEST 25 - PERCENTAGE OF VEHICLES IN CLOSED LANES

Experiment and Zone Type	Lane*	Distance from Start of Second Lane Taper (ft) 200	400	600	800	1000	1250	1500	1750	2000
CM 5 - Two	1	0.1%	0.9%	2.9%	3.2%	3.3%	3.4%	3.5%	4.3%	5.8%
Right Lanes Closed	2	0.6	3.9	4.2	5.8	7.8	9.4	11.0	10.8	10.0
CM 13-Two Left	4	0.0	0.4	1.7	1.9	2.3	4.6	7.1	8.1	11.6
Lanes Closed	3	12.4	16.2	20.6	24.2	28.0	28.9	27.2	26.5	26.2

* Lane 1 = right most lane
Lane 4 = left most lane

1 ft = 0.3 m

Test 26 - Experiment IM 3

This experiment was conducted on a 6-lane Interstate highway with the center lane closed. The moving maintenance operation being performed was emergency pothole repair. An arrow board trailer with a double flashing arrow was used throughout this test. The arrow board trailer was positioned approximately 400 ft (122 m) upstream of the maintenance truck and workers. Traffic was queued throughout the 1-hr test so it was not possible to count erratic maneuvers or conflicts.

The lane-change pattern for all vehicles in shown in Table 38. About 25 percent of the vehicles were in the center lane at 800 ft (244 m) behind the arrow board trailer. About 60 percent of the vehicles in the center lane merged into the right or left lane between 800 and 200 ft (244 and 61 m) behind the arrow board trailer.

TABLE 38

TEST 26 - PERCENTAGE OF VEHICLES IN CENTER LANE

		Distance from Arrow Baord Trailer (ft)					
Experiment	Mode	1250	1000	800	600	400	200
IM 3	Double Flashing Arrow	24.8	24.6	24.4	23.6	20.4	10.7

1 ft = 0.3 m

Test 27 - Experiments IM 4-6

These maintenance experiments were all conducted on 6-lane, urban, Interstate highways with stationary lane closures. A diagram of the site for IM 4 and 5 is shown in Figure 42. Experiment IM 6 involved closing two of three lanes. A 4 x 8 ft (1.2 x 2.4 m) arrow board was used in Experiments IM 4 and 6. During Experiment IM 4, traffic was queued for a total of 28 min of the hr tested. During IM 5 and 6 traffic was queued during the entire hr of both experiments.

Volumes were compared for 15-min periods to determine if the arrow board had any effect on the capacity of the work zone roadway. These volumes are shown in Table 39. Unfortunately, the data film for IM 4 was

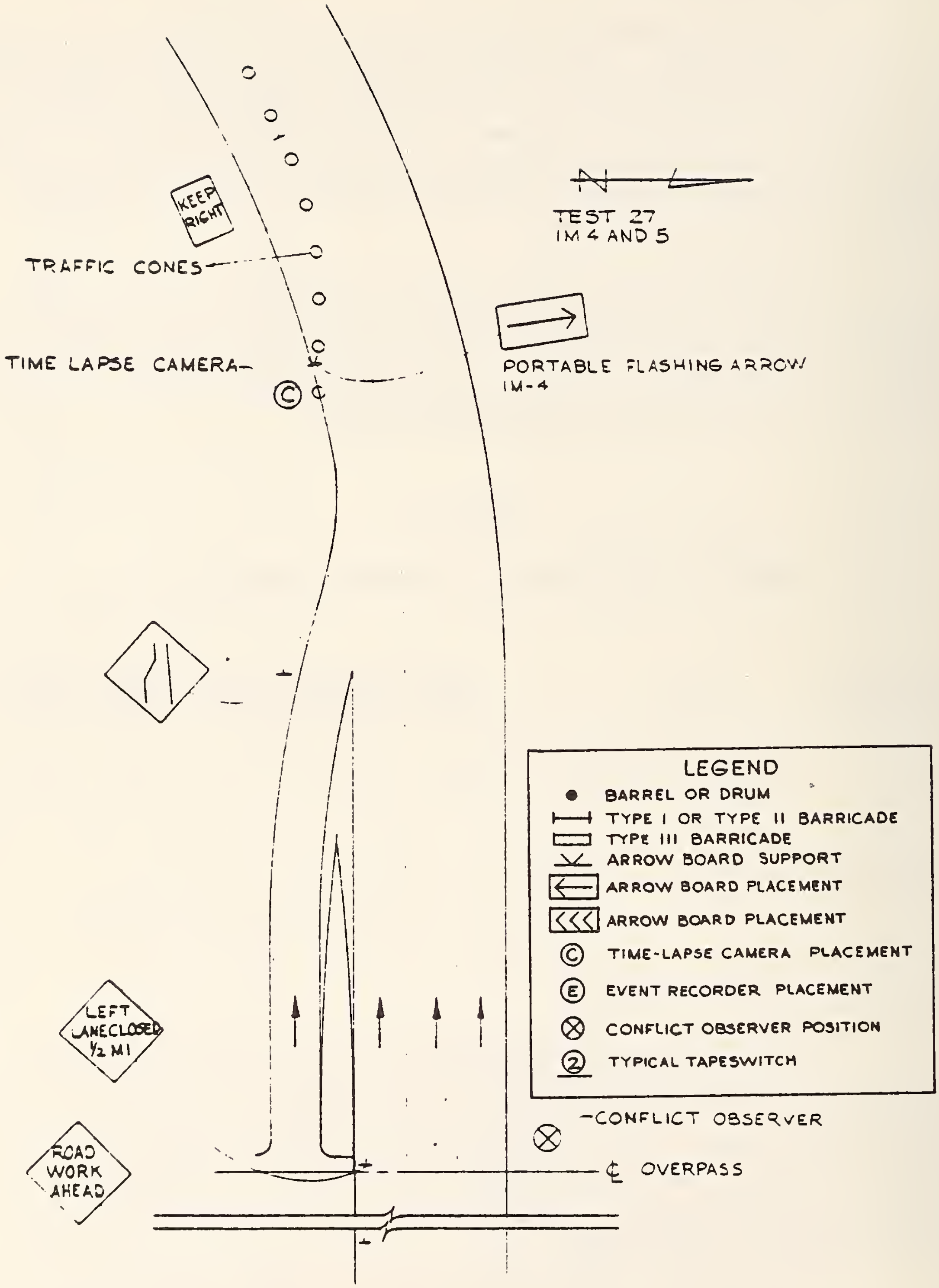


Figure 42 - IM 4 and 5 Site Diagram

TABLE 39

TEST 27 - 15-MINUTE TRAFFIC VOLUMES BY LANE AT START OF TAPER

Experiment	Time Period	Lane 1 Cars	Lane 1 Trucks	Lane 2 Cars	Lane 2 Trucks	Lane 3 Cars	Lane 3 Trucks	Total Cars	Total Trucks	All
IM 4	1	148	49	258	50	173	14	579	113	692
IM 5	1	173	74	218	49	269	13	660	136	796
IM 5	2	134	64	200	61	254	28	588	153	741
IM 5	3	156	53	190	58	249	17	595	128	723
IM 5	4	162	65	217	35	239	9	618	109	727
IM 6	1	82	30	81	7	82	4	245	41	286
IM 6	2	93	33	89	4	93	0	275	37	312
IM 6	3	41	0	121	5	107	32	269	37	306

Lane 1 = Right Lane

largely unusable, and volumes were readable for only one 15-min period. During this 15-min period with an arrow board, traffic was queued 8 min and 692 vehicles (579 cars and 113 trucks) moved through the zone. Without the arrow board, traffic was queued the entire hr and the average 15-min volume was 747 vehicles. Since the traffic demand during Experiment IM 4 was not large enough to produce queues, it is not possible to determine if the arrow board had any effect on work zone capacity.

During Experiment IM 6, traffic was queued the entire hr and the average 15-min volume was 301 vehicles. Of course this figure is much less than 50 percent of the IM 4 or IM 5 volumes because some vehicles were required to merge twice.

Test 28 - Experiments IM 8-9

This maintenance test was conducted on a 6-lane Interstate highway with the right lane closed. During Experiment IM 8, a vehicle mounted 3 x 6 ft (0.9 x 1.8 m) arrow board with sequential chevrons was located on the shoulder near the start of the taper. The middle chevron of this board was not operating. Experiment IM 9 was without an arrow board. Both tests were conducted during the day.

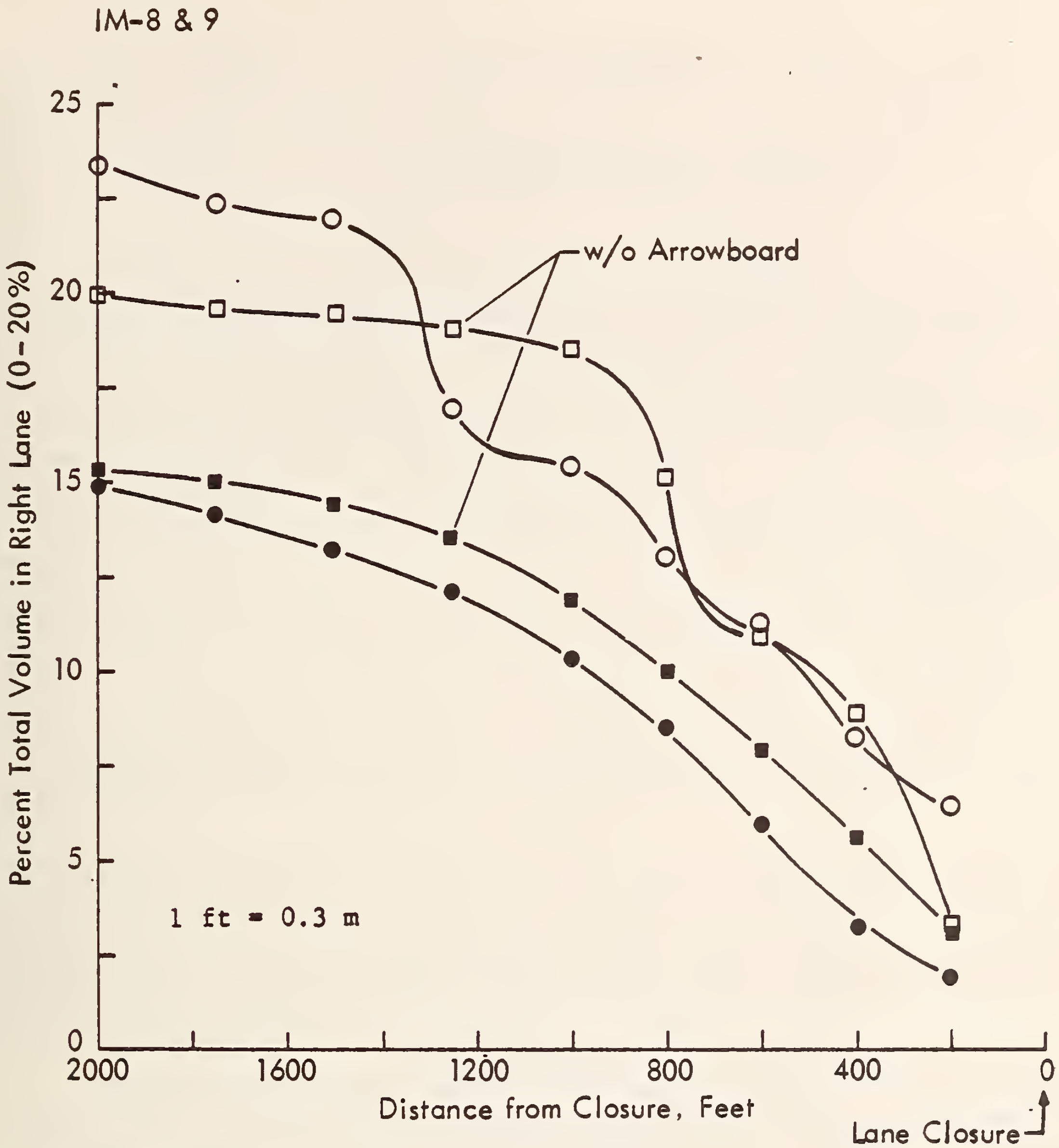
Table 40 shows the percentages of vehicles in the right lane. Figure 43 shows the lane change distribution. The lane-change patterns and erratic maneuver and conflict rates of these two experiments did not differ in any way. This test points out the criticality of the arrow board being in fully operable condition.

TABLE 40

TEST 28 - PERCENTAGE OF VEHICLES IN THE RIGHT LANE

Experiment	Mode	Distance from start of taper (ft) 200	400	600	800	1,000	1,250	1,500	1,750	2,000
IM 8	Sequential Chevron (middle chevron not openable)	2.7	4.1	6.8	9.2	11.1	12.4	14.5	15.4	16.4
IM 9	No Arrow Board	3.2	5.9	8.3	10.8	12.9	14.3	14.9	15.6	16.0

1 ft = 0.3 m



Cars	Trucks		
●	○	IM-8	Sequential Chevron - Middle Chevron Inoperable Small Arrowboard at Beginning of Taper
■	□	IM-9	w/o Arrowboard

Total volume of cars or/ total volume of trucks was used for calculations.

Figure 43 - Test 28 - Lane Change Distribution

APPENDIX D

ANALYSIS OF VARIANCE RATIONALE

This appendix describes the statistical approach that was used to determine significant effects of arrow board use. In particular, the appendix addresses the use of logit transformations of the data and the use of "wear-curve" type analysis of variance through consideration of orthogonal contrasts. The discussion focuses on the statistical methods used to evaluate the rate at which vehicles vacate a closed lane. However, the appendix also identifies the variations in the statistical methods that were employed to analyze the percentage of vehicles in the closed lane, traffic conflicts and vehicle speeds.

The appendix is organized by first presenting the response measures used, then discussing the reasoning behind use of a "wear-curve" type analysis and the resulting need for logit transformation of the percentages of vehicles leaving a lane in a given interval of highway. Finally, an example of the analysis of variance is given using lane counts from Test 1 (Experiments CC 1-4) discussed in the text.

The primary objective of the data analysis is to examine the patterns of observed lane occupancy as traffic in the closed lane approaches the lane closure taper. Specifically, the analysis considers the percentage of vehicles exiting the lane in a given interval a known distance from the lane closure taper. In these analyses only the closed lane is considered, because theoretically the effect of the arrow board is to cause vehicles in the closed lane to exit the lane in a pattern potentially distinguishable from the case where no board is present. In summary, the primary AOV examines percentages (in effect) of exiting vehicles to initial volume in the closed lane.

The analysis of the percentage of vehicles exiting the closed lane is complicated because the same physical vehicles traverse the test section. For example, a count of 200 vehicles in a lane at the first switch, 180 at the second, 150 at the third, etc., does not arise from a total volume of 200 + 180 + 150 + ... vehicles but instead more closely corresponds to the "disappearance" of 20 cars between the first two switches, another "decay" of 30 cars between the second and third, etc. Thus, it is the difference in lane change proportions between switches rather than the counts at switches that are the appropriate response for the AOV. This makes the AOV a "wear-curve" type of analysis,30/ with space represented as a factor with K-1 intervals between the K switches.

Although the closed lane "interval percentages" are the primary statistical response, the total volume may also be useful to some extent in assessing arrow board influences. For this reason, a secondary set of AOV's was performed on the "lane percentages;" i.e., upon the ratios (initial number of vehicles in the closed lane)/(total volume).

Thus, two kinds of percentages were statistically analyzed:

- Interval percentages; i.e., the spatial response to the arrow board in terms of vehicles exiting the closed lane;

- Lane percentages; i.e., the (initial) level of closed lane occupancy in terms of total volume.

For convenience in displaying results, however, driver behavior is graphically shown or tabulated in the text as the spatial sequence of lane percentages. In other words, interval percentages and lane percentages are shown "simultaneously," as it were, in the displays of the data.

Prior to the analysis of variance, a logit transformation of the data is performed. The need for the logit transformation does not arise from the structure of the analysis, but rather from the nature of the response (the percentage of vehicles exiting the closed lane) itself. Percentages themselves are not a good response variable for AOV because: (1) treated literally, the analysis will not realize that percentages outside the interval 0-100 are impossible; and (2) the variance of a percentage is not constant, but itself depends upon the percentage. In addition, the percentages are not based upon equal sample sizes since different numbers of vehicles were present in each interval.

These properties result in the use of the logit transformation,[29/] specifically, $y = \ln \frac{(N_L)}{(N_R)}$, where N_L is the number of vehicles leaving the lane during an interval and N_R is the number of vehicles remaining.

However, the AOV itself is not executed in the usual fashion (via computations of sums of squares) because each different comparison has its own particular error term due to the variation in interval sample sizes. Therefore, the mean percentage of vehicles leaving the closed lane in any given experiment should be computed as a weighted average. The logit transformation provides for this situation (which is in part why it was used) by calculating weights W associated with each logit, where

$$W = \frac{N_R \, N_L}{\left(N_R + N_L \right)} \quad .$$

Thus, the original data is treated as a set of logit values (Y_i's) and associated weights (W_i's). Means for each experiment and interval are computed as:

$$\frac{\Sigma Y_i W_i}{\Sigma W_i}$$

The weighted means of the interval percentages associated with an experiment or a particular interval are used to compute F-ratios for the main effects and interactions of the analysis factors. A typical AOV employed two factors: "experiment" (arrow board presence and placement) and "interval" (switch pair). The AOV of logit-transformed data cannot be performed in the conventional manner using sums of squares, and was therefore performed by evaluation of contrasts. Significance tests for each main effects or interactions were executed via an appropriate contrast, where for any contrast

$L = \Sigma \lambda_i X_i$, the variance is given by $V(L) = \frac{(\lambda_i^2)}{W_i}$.

For example, one useful contrast that was evaluated for many experiments was the mean response with an arrow board versus the (mean) response under "control" or no-arrow-board conditions.

Initial percentages or conflict proportions were also analyzed in the same way, except that the factor "interval" does not exist. Speeds were treated by AOV, except that of course no logit transformation is required.

Each test, of course, required an individual set of contrasts for analysis, since the number of lanes, placement of switches and other site conditions vary, but in every case the general analysis method is the same. (Sometimes, in case of small number of trials, individual t - tests were performed between specific experiment pairs, in addition to AOV contrasts.)

An example of the logit-transformed AOV using the lane count data from Test 1 (Experiments CC 1-4) follows. The example covers the AOV of interval percentages, because the other analyses are essentially equivalent but simpler since the "interval" factor does not exist.

The total volume of vehicles observed and the volume in the closed lane at various switches are shown in Table 41. Experiments CC 1 and CC 2 were combined due to the short duration of CC 1.

These volumes are first translated into the percentages of vehicles leaving the closed lane in the interval between Switch No. 3 and Switch No. 6 and the interval between Switch No. 6 and Switch No. 8. For example the first such "interval" percentage for CC 1-2 is (420 - 357) x 100/420. The interval percentages are shown in Table 42.

TABLE 41

LANE VOLUMES TEST 1 (EXPERIMENTS CC 1-4)

Experiment	Total Volume	Closed at Switch No. 3	Lane at Switch No. 6	Volume at Switch No. 8
CC1 - 2	1491	420	357	244
CC3	1154	542	447	299
CC4	774	333	293	205

TABLE 42

INTERVAL PERCENTAGES - TEST 1 (EXPERIMENTS CC 1-4)

	Interval Percentages	
Experiment	Interval 1 (Switch No. 3 to Switch No. 6)	Interval 2 (Switch No. 6 to Switch No. 8)
CC 1-2	15.0	31.7
CC 3	17.5	33.1
CC 4	12.0	30.0

This set of 6 percentages is the data set treated by the analysis of variance. However, each percentage must first be modified by the logit transform discussed above. For example, the transformation for the 15 percent of vehicles leaving the closed lane in the first interval is:

$$Y_i = \ln \frac{N_L}{N_R} = \ln \frac{(63)}{357} = -1.735$$

Each of the y's must also be weighted by using

$$W_i = \frac{N_R N_L}{\left(N_R + N_L\right)}$$

So for the first interval in Experiment CC 1-2

$$W_i = (63)(357)/420 = 53.6$$

The complete set of logit values and associated weights are shown in Table 43.

TABLE 43

TRANSFORMED INTERVAL PERCENTAGES AND WEIGHTS

Experiment	Interval 1	Interval 2
CC 1-2	Y = -1.735 W = 53.6	Y = -0.770 W = 77.2
CC 3	Y = -1.549 W = 78.3	Y = -0.703 W = 99.0
CC 4	Y = -1.991 W = 35.2	Y = -0.846 W = 61.6

The means for each experiment and interval are then computed using the weights. For example the mean value of y for Interval 1 is (53.6) (-1.735) + (78.3) (-1.549) + (35.2) (-1.991) = -284.3659/167.1 = -1.702.

The means and weights for each experiment and interval are shown in Table 44.

TABLE 44

MEANS AND WEIGHTS FOR TEST 1

Factor	Mean Y	W
Interval 1	-1.702	167.1
Interval 2	-0.762	237.8
Experiment CC 1-2	-1.165	130.8
Experiment CC 3	-1.077	177.3
Experiment CC 4	-1.262	96.8
All Data	-1.163	404.9

The tests of significance for main effects and interactions are executed by evaluation of appropriate contrasts. For example, to see whether or not the arrow board had an effect in Test 1, on the average, versus no arrow board, one would use:

$$L = 1/2\ (-1.737 - 1.549) - (-1.991) = -0.349,\ V(L) = \frac{1}{(4)(53.6)} + \frac{1}{(4)(78.3)} + \frac{1}{35.2} = 0.0363;\ \sigma_L = 0.190$$

The F-statistic for mean arrow board effect is thus $(0.349/0.190)^2 = 3.39$ (significant at about $\alpha = 0.05$).

Of course, other contrasts for comparing the experiments are also possible. In particular, the orthogonal contrasts for polynomial breakdown were always computed for all data sets. Other contrasts, such as the one just presented, were constructed individually according to the nature of the data set under consideration. Analogous tests for "interval" effects and "interval-experiment" interactions were also conducted.

The set of AOV results (with orthogonal contrasts) for this example are shown in Table 45.

TABLE 45

ANALYSIS OF LANE CHANGE PERCENTAGES

Source	F-Ratio	Significant
Interval Effect (I)	86.79	Yes
Experiment Effects (E)		
E_L (linear term)	0.12	No
E_Q (quadratic term)	0.44	No
E(arrow board versus no arrow board)	3.39	Yes
Interactions		
I x E_L	0.42	No
I x E_Q	1.04	No

These results indicate that the percentage of vehicles leaving in Interval 1 was statistically significantly different from the percentage of vehicles leaving in Interval 2, and that the pattern of vehicles leaving the closed lane was significantly affected by the presence of an arrow board. No other effects or interactions were significant. The interpretation of the example analysis results are discussed in Appendix C.

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FEDERALLY COORDINATED PROGRAM OF HIGHWAY RESEARCH AND DEVELOPMENT (FCP)

The Offices of Research and Development of the Federal Highway Administration are responsible for a broad program of research with resources including its own staff, contract programs, and a Federal-Aid program which is conducted by or through the State highway departments and which also finances the National Cooperative Highway Research Program managed by the Transportation Research Board. The Federally Coordinated Program of Highway Research and Development (FCP) is a carefully selected group of projects aimed at urgent, national problems, which concentrates these resources on these problems to obtain timely solutions. Virtually all of the available funds and staff resources are a part of the FCP, together with as much of the Federal-aid research funds of the States and the NCHRP resources as the States agree to devote to these projects.*

FCP Category Descriptions

1. Improved Highway Design and Operation for Safety

Safety R&D addresses problems connected with the responsibilities of the Federal Highway Administration under the Highway Safety Act and includes investigation of appropriate design standards, roadside hardware, signing, and physical and scientific data for the formulation of improved safety regulations.

2. Reduction of Traffic Congestion and Improved Operational Efficiency

Traffic R&D is concerned with increasing the operational efficiency of existing highways by advancing technology, by improving designs for existing as well as new facilities, and by keeping the demand-capacity relationship in better balance through traffic management techniques such as bus and carpool preferential treatment, motorist information, and rerouting of traffic.

3. Environmental Considerations in Highway Design, Location, Construction, and Operation

Environmental R&D is directed toward identifying and evaluating highway elements which affect the quality of the human environment. The ultimate goals are reduction of adverse highway and traffic impacts, and protection and enhancement of the environment.

4. Improved Materials Utilization and Durability

Materials R&D is concerned with expanding the knowledge of materials properties and technology to fully utilize available naturally occurring materials, to develop extender or substitute materials for materials in short supply, and to devise procedures for converting industrial and other wastes into useful highway products. These activities are all directed toward the common goals of lowering the cost of highway construction and extending the period of maintenance-free operation.

5. Improved Design to Reduce Costs, Extend Life Expectancy, and Insure Structural Safety

Structural R&D is concerned with furthering the latest technological advances in structural designs, fabrication processes, and construction techniques, to provide safe, efficient highways at reasonable cost.

6. Prototype Development and Implementation of Research

This category is concerned with developing and transferring research and technology into practice, or, as it has been commonly identified, "technology transfer."

7. Improved Technology for Highway Maintenance

Maintenance R&D objectives include the development and application of new technology to improve management, to augment the utilization of resources, and to increase operational efficiency and safety in the maintenance of highway facilities.

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* The complete 7-volume official statement of the FCP is available from the National Technical Information Service (NTIS), Springfield, Virginia 22161 (Order No. PB 242057, price $45 postpaid). Single copies of the introductory volume are obtainable without charge from Program Analysis (HRD-2), Offices of Research and Development, Federal Highway Administration, Washington, D.C. 20590.