Hodge and Robert Jenkins (District 2), Hunter Garrison (District 12), and Milton Watkins (District 18) and the staffs of their respective TSDHPT districts for their assistance and cooperation in the study.

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Sight-Distance Requirements at Lane-Closure Work Zones on Urban Freeways

STEPHEN H. RICHARDS AND CONRAD L. DUDEK

Findings of field studies conducted to evaluate the effects of sight distance to lane closures at urban freeway work zones are presented and discussed. The studies investigated the interaction of sight distance with traffic volume and various work-zone traffic-control features (e.g., advance signing and arrowboards). The studies were conducted at 15 maintenance work zones of freeways in Houston, Dallas, Fort Worth, San Antonio, and Corpus Christi, Texas. The studies revealed that, as sight distance to a lane closure decreases, more and more drivers are "trapped" in the closed lane at the taper area. At sites where the sight distance was less than 1000 ft, for example, up to 80 percent of the traffic in the closed lane did not leave the closed lane until reaching the immediate vicinity of the lane-closure taper. Sight distance becomes even more critical as traffic volumes increase. Based on the study findings, a minimum desirable sight distance of 1500 ft was recommended for lane-closure work zones on freeways. The studies also suggest that advance signing for lane closures is only partly effective. In the studies, only half of the affected drivers responded to the advance signing evaluated. Arrowboards were also studied and proved to be effective traffic-control devices for lane closures where sight distance is adequate, since they encourage early lane changing.

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

A series of field studies was conducted to evaluate current traffic-control practices at lane-closure work zones on urban freeways in Texas. The studies identified problem areas and provided input for the development of improved traffic-control practices.

PRELIMINARY STUDIES

Preliminary field studies were conducted at 15 lane-closure work zones on urban freeways in Dallas, San Antonio, Fort Worth, and Corpus Christi. In these studies, a research team documented the geometrics and traffic control used at each work site and measured the sight distances to the lane closure. All 15 work zones studied involved one- or two-lane closures on three-lane sections.

A field crew was also deployed at the work zones to manually collect volume and lane distribution data at points upstream of and at the beginning of the lane closure. These data, collected for several hours at each site, were used to determine the performance of the various traffic-control devices. The effectiveness of a control device was judged by its success in encouraging drivers in the closed lane to vacate the lane upstream of the taper area.

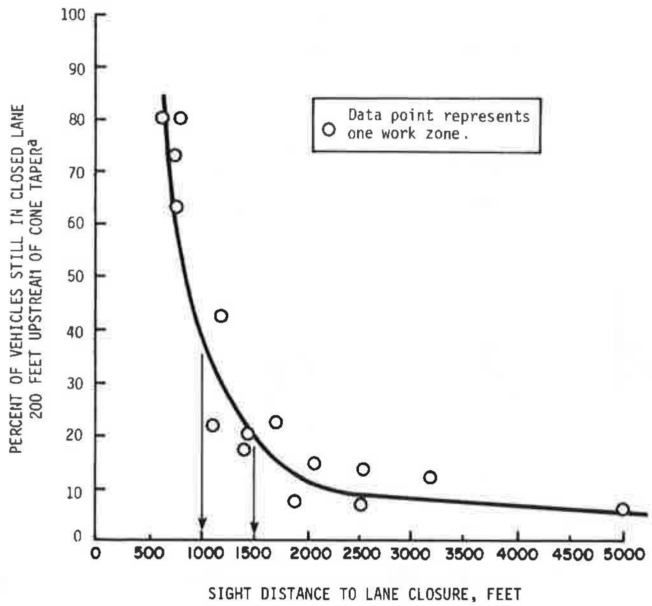
The data collected at the 15 work zones revealed that sight distance had a significant influence on driver behavior at lane-closure work zones. (Sight distance is defined as the distance from the beginning of the cone taper to the point where a driver can identify that his or her lane is closed, provided the line of sight is not obstructed by another vehicle.) This influence is shown in Figure 1, which plots the percentage of vehicles still in the closed lane 200 ft upstream of the cone taper versus sight distance. The figure indicates that as sight distance decreased more and more drivers were trapped in the closed lane until reaching the taper area, where these drivers had to "force" their way into an adjacent open travel lane.

As sight distance was restricted to less than about 1500 ft, the percentage of trapped drivers increased moderately. As the sight distance was reduced even more (to less than 1000 ft), the percentage of trapped drivers rapidly increased. At those work zones with a sight distance between 600 and 800 ft, for example, up to 80 percent of the traffic in the closed lane still occupied the closed lane 200 ft upstream of the cone taper.

Figure 1 also shows that the sight distances at the 15 randomly selected work zones varied considerably, from 650 to 5100 ft. Several of the work zones had relatively short sight distances. In fact, 4 of the work zones had sight distances of less than 1000 ft.

The preliminary field studies also provided insight into the effects of traffic volume on traffic operations at lane-closure work zones, as shown in Figure 2. (One of the 15 study sites was omitted from the evaluation because of inconsistencies resulting from the presence of an exit ramp near the taper area.) Figure 2 suggests that traffic volume did not significantly affect the percentage of closed-lane vehicles still in the closed lane very near the taper area when sight distance was greater than 1500 ft. At work zones where sight distance was less than 1500 ft, however, traffic volumes had a significant effect on occupancy of the closed lane near the taper area. As Figure 2 shows, the percentage of trapped vehicles increased very rapidly as traffic volume increased at work zones where the sight distance was less than 1500 ft.

Figure 1. Effect of sight distance to a closed lane on closed-lane occupancy.

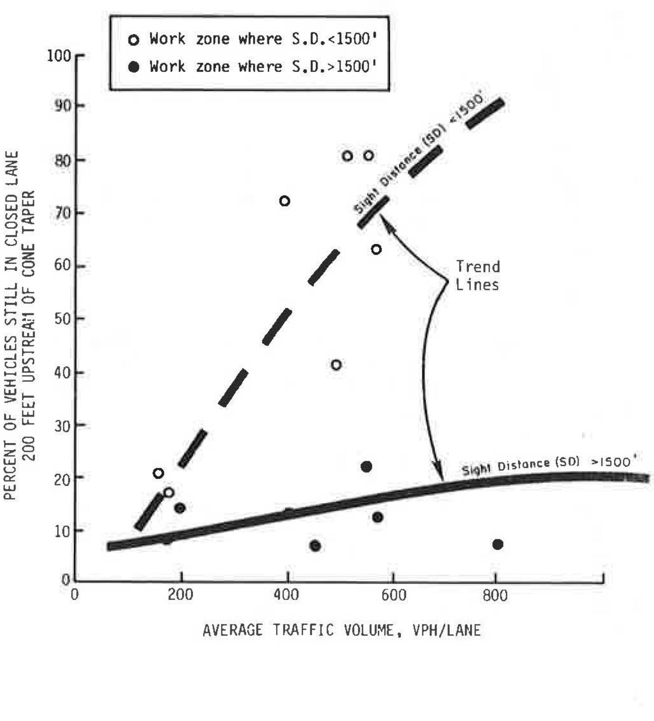


^{a}Percent $= \frac{B}{A}$ where:

A = The number of vehicles in the closed lane 200 feet upstream of the beginning of the cone taper, corrected for ramp traffic.

B = The number of vehicles in the closed lane before entering the work zone, corrected for ramp traffic.

Figure 2. Effect of traffic volume on lane occupancy at lane-closure work zone.



At work zones where sight distance was greater than 1500 ft, most drivers had enough warning time to find a gap in the adjacent open lane and merge comfortably into it, regardless of the volume level (150-800 vehicles/h/lane). At work zones where sight distance was less than 1500 ft, however, drivers could move quickly out of the closed lane only under very low-volume conditions (e.g., 200 vehicles/h/lane). As traffic volume increased, there were fewer gaps available in the adjacent lane and drivers had less time to find these gaps. Therefore, more drivers were trapped.

CONTROLLED FIELD STUDIES

The field studies previously discussed revealed that sight distance is a critical factor at lane-closure work zones. They also suggested that traffic volume becomes important when sight distance is less than about 1500 ft. It should be noted, however, that there were many differences among the work zones studied, especially in site geometrics and signing. The differences made it difficult to fully assess the effects of sight distance and, in particular, the interaction of sight distance with other traffic-control features (e.g., advance signing and arrowboards). To address these concerns, a series of "controlled" field studies was developed. By using the controlled study approach, conditions at the work zone could be regulated and the effects of individual traffic-control features determined.

Study Description

The controlled field studies were conducted at a median-barrier repair worksite on I-10 in Houston. The repair work was performed by a Texas State Department of Highways and Public Transportation (TSDHPT) District 12 maintenance crew, and it required closing the median lane on a three-lane section. A 600-ft cone taper was used to close the lane, along with advance signing and an arrow sign positioned behind the taper.

Figure 3 presents a site plan for the work zone. The figure shows that a set of four advance signs were used upstream of the taper area on each side of the affected travel lanes. (The SLOW sign has been deleted from the 1978 Manual on Uniform Traffic Control Devices. If it is used, it must be accompanied by an advisory speed sign.)

Figure 4 shows a plan-profile view of the work zone. Note in Figure 4 that a vertical curve at the Bunker Hill interchange limited sight distance to the lane closure. By moving the cone taper relative to this interchange, it was possible to control the sight distance. During the studies, two taper positions were evaluated (tapers 1 and 2 in the figure), which resulted in sight distances of 900 and 1600 ft, respectively.

A step-by-step description of the study approach is presented below:

1. Data were collected before the work zone was set up to determine normal traffic flow patterns.
2. The District 12 signing crew installed the advance signs. Data were collected with the signs in place (but no lane closure) in order to evaluate the effects of the advance signing.
3. The median lane was closed (with a cone taper and static arrow sign), and data were again collected. The taper was positioned to provide a 900-ft sight distance the first day of the studies and a 1600-ft sight distance the next.
4. Finally, the static arrow sign was replaced with a flashing arrowboard sign to determine the

Figure 3. Site layout.

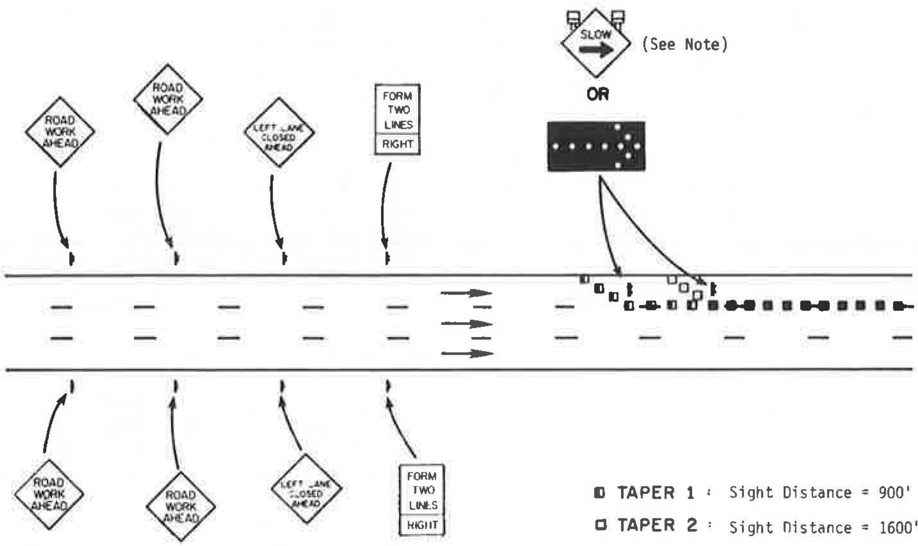
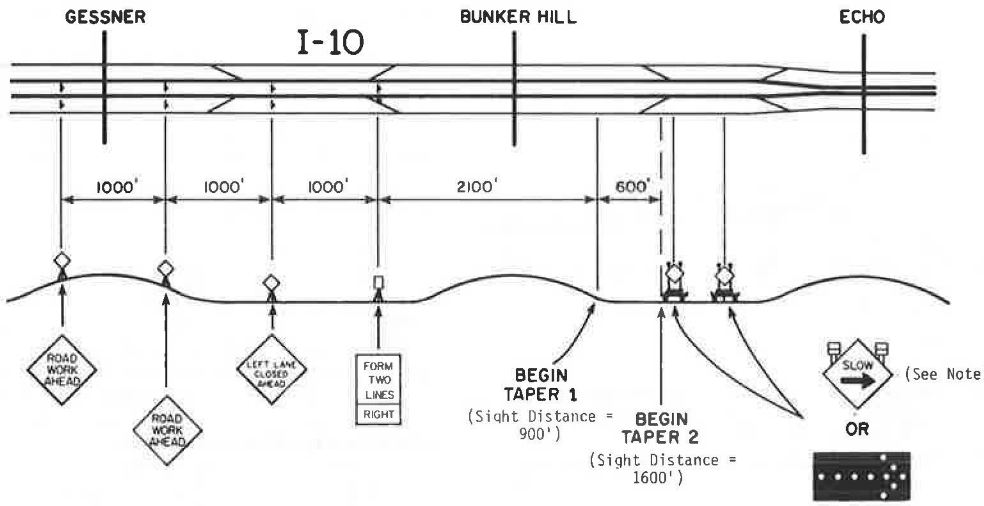


Figure 4. Plan-profile view of work zone.



effects of an arrowboard, if any. The arrowboard was evaluated under both sight-distance conditions.

During the two-day study, traffic volumes at the worksite varied somewhat. This made it possible to evaluate the effects of sight distance and the other factors (advance signing and use of a flashing arrowboard) under two volume conditions: 1000 and 3000 vehicles/h.

Data Collection

Sight distance to the lane closure was measured from a moving research vehicle by using a distance-measuring instrument (DMI) mounted in the vehicle. Several sight-distance measurements were taken, and an average sight distance was calculated for each taper location. Measurements affected by traffic interfering with the line of sight were rejected.

Lane distribution and volume data were collected at the lane closure and seven locations upstream of the closure. These data were manually counted in 5-min intervals by field crews stationed along the roadside.

The studies were conducted on two consecutive Sundays. Approximately 10 h of data (5 h/day) were collected, as follows:

Item	No. of Hours
Base date	1
Signs only	3
Signs and taper 1	2
Signs and taper 2	4

The lane distribution and volume data were reduced and analyzed to determine how much traffic was in the closed lane and when this traffic moved out of the lane in response to the signs and/or lane closure.

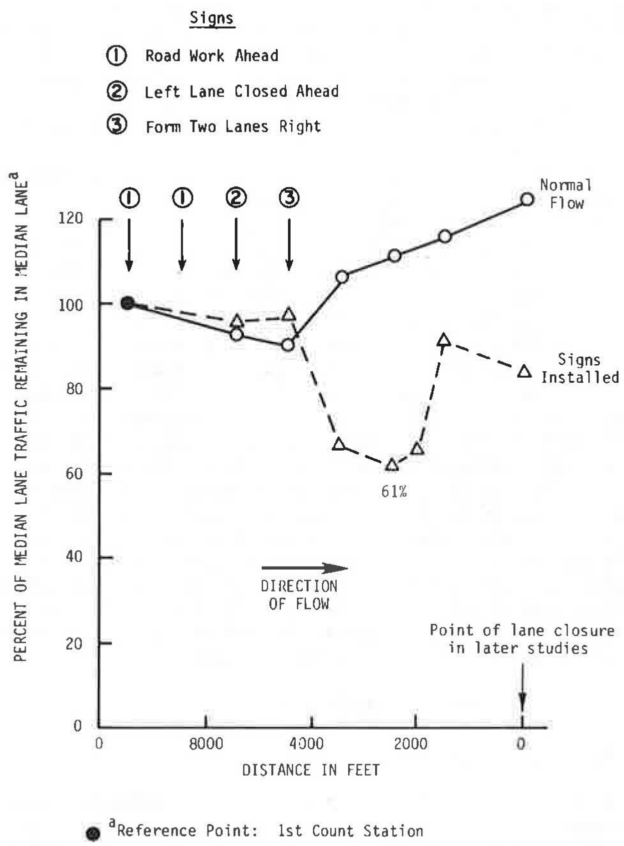
Findings

The controlled field studies confirmed that sight distance is an important factor at lane-closure work zones. The data gathered in the studies provided input for the development of sight-distance recommendations. The studies also revealed that the advance signing used by District 12 at the work zone (Figure 3) is only partly effective in encouraging drivers to vacate a lane. Thus, the need for adequate sight distance at lane-closure work zones is critical. As in the preliminary studies, the controlled studies revealed that traffic volume affects traffic operation more as sight distance is reduced. The studies also suggested that a flashing arrowboard, used behind the taper at lane-closure work zones, can enhance traffic operations. These findings are discussed in detail below.

Advance Signing

Figure 5 shows the effects of the work-zone advance signing on occupancy in the median lane. From the figure, only 39 percent (100 minus 61 percent) of the drivers observed in the median lane at the first count station vacated the median lane in response to the advance signing. All of these drivers moved out of the median lane within 2000 ft of the last sign in the series.

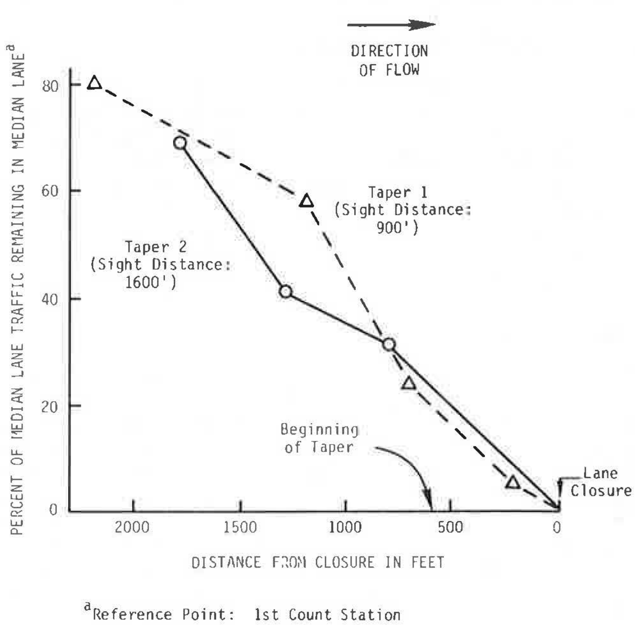
Figure 5. Effectiveness of advance signing used by TSDHPT District 12.



The advance signing was evaluated before the median lane was actually closed. From Figure 5 it is seen that many drivers started moving back into the median lane approximately 2500 ft beyond the last sign. This point coincided with the crest of the vertical curve at the Bunker Hill interchange, and drivers could see that the median lane was clear for at least 2 miles ahead. There was also an entrance ramp just beyond the Bunker Hill interchange. Many of the ramp drivers, not having seen the advance signing, quickly made their way into the median lane.

Based on the data in Figure 5, it is apparent that advance signing alone will not encourage all drivers to vacate a closed lane. Many drivers apparently wait until they can identify that a lane is actually closed before they attempt a lane change. For this reason, adequate lane-closure sight distance should be provided, regardless of advance signing. Figure 5 also suggests that advance signing can be placed too far upstream of a lane closure, since drivers will begin moving back into the closed lane if they travel some distance without observing the lane closure. These studies, however, did not address the issue of sign placement relative to the point of lane closure in depth.

Figure 6. Effect of sight distance on median-lane occupancy.



Sight Distance

Figure 6 shows the percentage of median-lane traffic still in the median lane at various distances from the lane closure for taper 1 (sight distance = 900 ft) and taper 2 (sight distance = 1600 ft). It can be seen that many drivers apparently vacated the median lane sooner when the sight distance was 1600 ft than when it was 900 ft. Under both conditions, however, the same approximate percentage of median-lane drivers still occupied the lane near the taper area. This trend, shown in Figure 6, is further illustrated in the table below, which gives the percentages of median-lane traffic still in the median lane at 1000, 500, and 200 ft upstream of the cone taper:

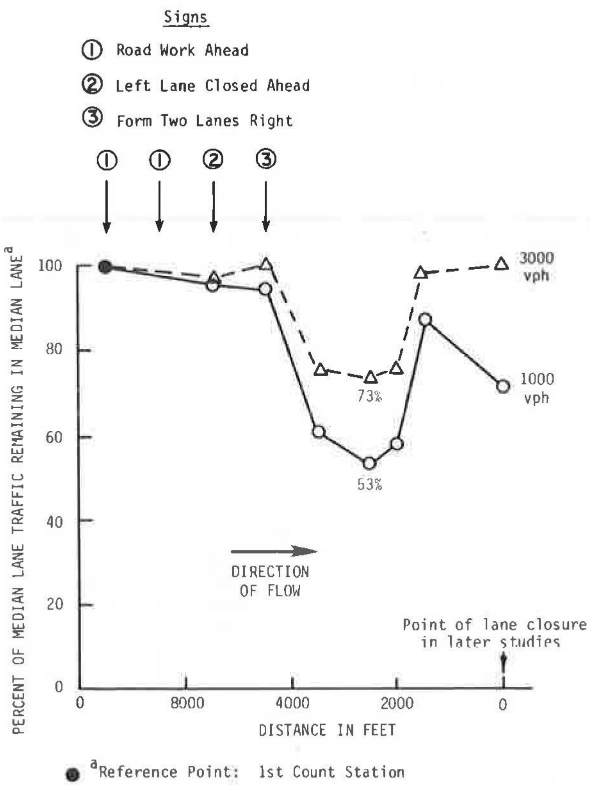
Sight Distance to Lane Closure (ft)	Distance Upstream of Cone Taper (ft)	Median-Lane Traffic Still in Median Lane (%)
900	1000	67
	500	51
	200	31
1600	1000	58
	500	37
	200	31

The table indicates that 31 percent of the median-lane traffic still occupied the median lane 200 ft upstream of the cone taper under both sight-distance conditions.

The data presented in Figure 6 and the table above were collected while the advance signing used by District 12 was in place upstream of the lane closure and a static arrow sign was positioned behind the cone taper. The data represent two volume conditions at the site: 1000 and 3000 vehicles/h.

The results of the controlled sight-distance studies were fairly consistent with those of the preliminary studies. They indicate that sight distances in the 900- to 1600-ft range are tolerable, but that many motorists will still be trapped in the

Figure 7. Effect of traffic volume on median-lane occupancy.



closed lane at the taper area. Thus, greater sight distances are desirable.

Traffic Volumes

Data were collected under the two volume conditions of 1000 and 3000 vehicles/h when only the advance signs were present. Figure 7 summarizes these data and reveals that traffic volume had a significant effect on driver response to the advance lane-closure signing. The figure shows that 47 percent (100 minus 53 percent) of the median-lane drivers changed lanes when the flow rate was 1000 vehicles/h. When the flow rate was 3000 vehicles/h, however, only 27 percent (100 minus 73 percent) changed lanes.

These numbers (47 versus 27 percent) suggest that as traffic volumes increase drivers are less likely to respond to advance signing for a lane closure. As volume increases, there are fewer available gaps in the traffic stream. Apparently, many drivers are unable or simply hesitant to find one of these infrequent gaps in order to merge out of a lane signed for closure.

The effects of traffic volume on median-lane occupancy in the taper area were also studied (sight distance to the lane closure = 1600 ft):

Traffic Volume (vehicles/h)	Median-Lane Traffic Still in Median Lane 200 ft Upstream of Cone Taper (%)
1000	17
3000	20

As the table indicates, 17 percent of the original median-lane traffic still occupied the median lane 200 ft from the taper when the flow rate was 1000 vehicles/h. As volume at the site increased to 3000 vehicles/h, the percentage of trapped vehicles increased to 20. The difference (17 versus 20 percent) is statistically significant at the 95 percent confidence level and suggests that, at the sight distances evaluated, traffic volume had an effect on driver response to the lane closure. More drivers were trapped as volumes increased.

Flashing Arrowboard

The effects of flashing arrowboards at the lane closure were also studied. The flashing arrowboard was positioned behind the cone taper in place of the static arrow sign (Figure 3). The use of the arrowboard at this site did not increase sight distance to the lane closure since the closure was purposely positioned just downstream of a hilltop. The arrowboard did, however, greatly enhance the conspicuity of the closure.

Figures 8 and 9 present the results of the arrowboard studies, showing the percentage of drivers remaining in the median lane versus distance from the lane closure for sight distances of 900 and 1600 ft, respectively. In the figures, the effects of the arrowboard are compared with those produced by the static arrow sign. Figure 8 indicates that the arrowboard had little added effect when the sight distance was only 900 ft. Traffic simply did not have time to respond, even though the arrowboard probably made the closure more conspicuous. The arrowboard did not have a significant effect when the sight distance was increased to 1600 ft, however. Figure 9 shows that 40 percent of the median-lane traffic still occupied the lane 1000 ft from the taper when the static arrow sign was used. When the arrowboard was used, this was reduced to only 23 percent. Thus, if sight distance is adequate at a lane-closure work zone (e.g., >1500 ft), the studies suggest that the use of an arrowboard encourages better driver response to the closure.

CONCLUSIONS AND RECOMMENDATIONS

Advance Signing

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

Importance of Sight Distance

The field studies revealed that many drivers (20-50 percent, depending on volume conditions) wait until sighting the lane closure before attempting to merge out of the closed lane(s). Therefore, adequate sight distance to the lane closure must be provided to ensure safe and efficient traffic flow. As traffic volume increases, more and more drivers will be trapped at the lane closure if adequate sight distance is not provided.

Implementation

Based on the study results, it is recommended that a minimum sight distance of 1500 ft be provided at work-zone lane closures on urban freeways. If the sight distance is at least 1500 ft, the number of drivers trapped at the taper area will be minimized and thus safety and traffic flow will be enhanced. It is also recommended that an arrowboard, such as that shown in Figure 10, be positioned behind the cone taper at all freeway lane closures, regardless of sight distance, to help encourage traffic to merge out of the closed lane(s).

Figure 8. Effect of arrowboard when sight distance is 900 ft.

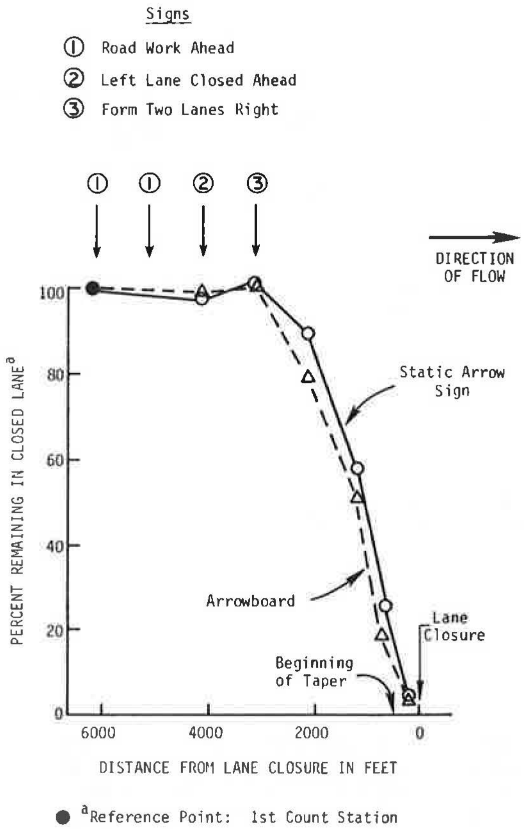


Figure 9. Effect of arrowboard when sight distance is 1600 ft.

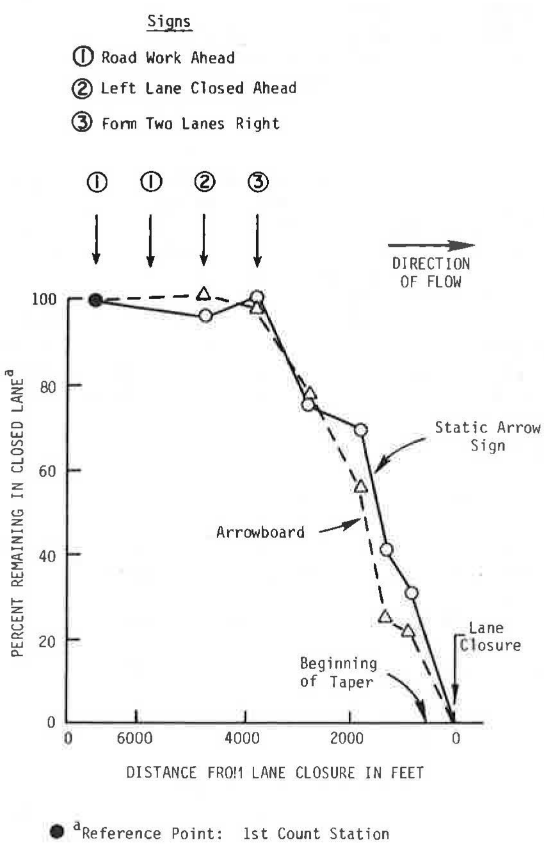


Figure 10. Typical arrowboard recommended for use at work-zone lane closures.

If it is not possible to provide a sight distance of at least 1500 ft, an additional arrowboard should be placed upstream of the cone taper for median and shoulder lane closures (1). This additional arrowboard should be positioned so that drivers are warned of the lane closure at least 1500 ft upstream of the cone taper. The advance arrowboard will encourage more drivers to vacate the closed lane before they see the closure itself. Even if an advance arrowboard is used, the sight distance to a lane closure should not be less than 1000 ft (absolute minimum).

Field Procedure for Checking Sight Distance

The following field procedure is recommended for checking sight distance to lane closures at work zones on urban freeways to ensure that a minimum sight distance of 1500 ft is provided.

Two vehicles are required to check sight distance (e.g., the job foreman's vehicle and the sign truck that is used to deploy traffic-control devices). Prior to installation of the lane-closure taper, the two vehicles stop together on the roadside or shoulder well upstream of the planned taper area. Driver 1 (sign truck driver) enters the roadway first and proceeds toward the taper area in the lane to be closed. As driver 1 pulls away, he or she begins counting lane stripes. After counting 38 stripes, driver 1 signals driver 2 to follow, either by radio or by flashing the vehicle lights. (A normal stripe-dash combination is 40 ft long; therefore, 38 stripes x 40 ft/stripe = 1520 ft.)

Driver 2 enters the roadway and follows driver 1, keeping the same approximate spacing (1500 ft). When driver 1 reaches the planned taper area, he or she pulls off the roadway. Driver 2 should be able to see vehicle 1 at the point where it pulls off the road. If so, it is likely that, once the lane is closed, sight distance to the closure will be 1500 ft or greater.

This procedure will give only a rough estimate of sight distance. After a lane is closed, the job foreman or another member of the work crew should drive through the work zone and check the sight distance to the lane closure. To do this, he or she drives in the closed lane and counts lane stripes from the point where the closure is sighted to the beginning of the taper. A minimum of 38 stripes should be counted to ensure that the minimum sight distance of 1500 ft is provided. If fewer stripes are counted, the taper should be relocated to provide greater sight distance or an advance warning arrowboard should be used at the site.

ACKNOWLEDGMENT

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The direction of the research was guided by a Technical Advisory Committee. The contributions of the committee members are gratefully acknowledged.

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Transit Bus Maintenance in Small and Medium-Sized Communities

GARY L. ROBERTS AND LESTER A. HOEL

The findings of a study of bus maintenance practices used by 13 small and medium-sized public transit systems in Virginia are presented. Bus maintenance activities are discussed according to two basic maintenance approaches: (a) municipal fleet, in which the buses in a fleet of all vehicles operated by a political jurisdiction are maintained, and (b) transit only, in which the transit buses of a publicly owned transit system are maintained. An overview of the current condition of bus maintenance is provided by comparing maintenance practices of the municipal-fleet and transit-only systems. The main factors that affect the performance of transit bus maintenance are identified and classified. These factors, such as inadequate personnel assignment and low maintenance priority for transit buses, serve as the basis for proposed guidelines to improve transit bus maintenance and to provide adequate protection of taxpayer investment statewide.

It is generally acknowledged that the maintenance of transit vehicles accounts for approximately 20 percent of total transit operating expenses (1) and, with the increasing complexity of the advanced-design buses (ADBs) currently being purchased, it is quite likely that this proportion will become even larger. The changing characteristics of the new buses were noted in a recent congressional report (2), which stated that "the ADB does not embody any serious attempt to simplify and make [buses] more durable, but rather may be another manifestation of our love affair with complex technology. Like new autos, new buses emphasize features related to style and comfort--often at the expense of durability, maintainability, and fuel economy."

In addition to facing the increased costs occasioned by the technical complexity of the ADB, transit bus systems are expected to lose the federal funds that they have come to rely heavily on for operating assistance. From its beginning in 1975, federal funding for operating assistance increased from $300 million to more than $1.1 billion in 1980. Because the costs of operating transit vehicles have increased significantly in the past two decades (1), this federal assistance is being used as a subsidy that enables transit fares to be kept artificially low (3,4). The loss of this subsidy will necessitate decreases in the operating budget, which will adversely affect bus maintenance.

When combined, this increasing technical complexity and decreasing federal operating assistance make a strong argument that the adequacy of transit bus maintenance in the future is uncertain. Thus, it is essential that the federal, state, and local agencies responsible for the administration and funding of public transit bus systems give high priority to efforts to assist the operating properties to increase the effectiveness and productivity of their vehicle maintenance.

The research reported here was undertaken to develop information that would be useful to state and local agencies in Virginia in developing and implementing the needed assistance programs.

OBJECTIVES AND SCOPE

The objectives of this research were (a) to document the current condition of transit bus maintenance and the maintenance practices used by the small and medium-sized transit systems in Virginia and (b) to propose guidelines for maintenance practices to improve transit bus maintenance statewide.

The small and medium-sized transit systems studied included all fixed-route transit bus systems except the Washington Metropolitan Area Transit Authority, which operates in Northern Virginia.

METHODOLOGY

The study comprised the following tasks:

1. A direct mail questionnaire survey of maintenance management personnel at 13 Virginia operating properties,
2. Site visits to each of these operating properties, and
3. An analysis of the information obtained from the survey and site visits.

QUESTIONNAIRE SURVEY

A questionnaire was mailed to maintenance management personnel at each of the 13 Virginia properties participating in the study to obtain information on