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16. Abstract

This report summarizes the research performed and documented in interim project reports to address visibility, spacing, and operational issues pertaining to lane control signals (LCSs) used for freeway traffic management in Texas. Chapters in this final report review the results of legibility studies of new and used LCSs; a TxDOT expert panel meeting to address LCS visibility, spacing, and mounting location issues; and an evaluation of yellow diagonal and downward arrows for freeway traffic management purposes. The final chapter summarizes the findings and recommendations resulting from this research effort.

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by

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IMPLEMENTATION RECOMMENDATIONS

As part of the early efforts on this project, several recommendations were developed for TxDOT's consideration. These are summarized below.

1. TxDOT should continue to use back panels (150 mm width per side appears adequate) on its LCS to increase conspicuity.

2. TxDOT should generally space LCS approximately 0.8 to 1.6 km apart when used continuously along the freeway.

3. TxDOT should employ positive guidance principles when selecting LCS locations to avoid information overload conditions.

4. TxDOT should strive to avoid LCS placements on horizontal curves because of parallax problems such installations create.

5. LCS should be cleaned and bulbs replaced (if fiberoptic technology) on a regular basis (i.e. 6 to 12 month intervals) to maintain adequate visibility.

More recently, data collected through this research effort indicates that the use of both the yellow diagonal and downward arrows for freeway traffic management purposes is perceived positively by TransGuide system operators and the motoring public. Furthermore, no evidence of operational problems or difficulties due to the use of either of these non-standard symbols has been collected through field studies in San Antonio. Similar statements can be made concerning the yellow X. Motorists in Fort Worth rated this symbol fairly highly once they saw it used in a freeway driving situation. Field studies suggest that the number of drivers exiting a closed lane when first encountering the yellow X symbol equals or exceeds those that would exit for the yellow diagonal arrow.

Based on the results of these study efforts, one cannot say for certain that the utilization of a yellow diagonal arrow in lieu of a yellow X results in improved freeway operations or the effectiveness of a motorist information component in a freeway traffic management system. In fact, the operations data collected to date it suggest that the two symbols are interchangeable. However, it is possible that the performance measures used in these studies were not sensitive to the operational differences that may exist between the two types of transition symbols. Two specific recommendations should consider with respect to these symbols are as follows.

6. The results of the motorist survey in Fort Worth still suggest one difficulty with the yellow X; it does not convey a strong inherent message to motorists about how they should respond. It appears that drivers are able to ascertain the intended meaning fairly easily once they see it used in a freeway driving situation. TxDOT should establish a

policy to allow the yellow X to be displayed only in conjunction with green arrows at a given LCS array.

7. If TxDOT wishes to use more complex LCS arrays in its traffic management efforts (arrays that included the display of red Xs, yellow symbols, and green arrows at a single location), TxDOT should pursue a change to the Manual Uniform Traffic Control Devices (MUTCD) to allow the use of the yellow diagonal arrow for freeway traffic management purposes.

Experiences regarding the yellow downward arrow at TransGuide do not indicate any problems with its continued use. Benefits accrued because of its utilization seem limited primarily to intangibles (better driver awareness of shoulder vehicle stalls, improved emergency response location abilities, etc.) at this time. TxDOT may wish to pursue a change to the MUTCD to allow this symbol to be used for freeway traffic management as well.

DISCLAIMER

The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Texas Department of Transportation (TxDOT) or the Federal Highway Administration (FHWA). This report is not intended to constitute a standard, specification, or regulation, nor is it intended for construction, bidding or permit purposes. The engineer in charge of the study was Dr. Gerald L. Ullman, P.E. #66876.

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The glance legibility studies conducted as part of this research required by the cooperation of several LCS manufacturers and vendors who provided, on loan at no charge, the LCS heads used for the studies. In particular, the authors appreciate the assistance provided by Corson Wyman and the Electro-Fiberoptics Corporation, Cynthia Hood of C.J. Hood Incorporated, and John Cunningham, formerly of FDS Incorporated.

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SUMMARY

This report documents the research performed to assess the effectiveness and applicability of yellow diagonal and downward arrows for freeway traffic management purposes. Motorist understanding and usefulness of the arrows were investigated through surveys of San Antonio motorists where these indications are being utilized as part of the TransGuide system. These results were compared to similar data obtained from motorists in Fort Worth, where TxDOT operates a traffic management system utilizing a yellow X. Interviews were conducted with operators of the TransGuide system to assess their opinions of the yellow arrow indications and identify any difficulties they have experienced in utilizing these symbols in their daily traffic management activities. Finally, a series of field studies were performed to assess how drivers respond to yellow diagonal arrows used to transition between a lane open (green arrow) and a lane closed (red X). These were considered in relation to driver response to a yellow X which is currently the MUTCD-accepted symbol for accomplishing this transition.

The results of the motorist surveys indicate that both the yellow diagonal and downward arrows are perceived positively in actual freeway driving situations. The ratings are very similar to those given for the yellow X by Fort Worth motorists. However, evidence again suggests that the yellow X does not possess a strong inherent meaning with motorists (as was noted by earlier laboratory research). However, once motorists can see the symbol used in an actual freeway driving context, they can deduce its intended message.

The TransGuide system operators indicated that no accidents had occurred that were attributable to either the yellow diagonal or downward arrows. Operators' impressions of the effectiveness of the yellow diagonal arrow are generally favorable. They agree that most drivers do appear to respond to the arrows, although there are always those that wait until the last minute to exit a given lane. Favorable operator responses were obtained about the effectiveness of the yellow downward arrow as well. As they noted, however, it is difficult to identify specific driving actions (speed reductions, reduced lane changing, etc.) from the closed-circuit television (CCTV) or other data to determine objectively how the indications are influencing drivers. An unexpected benefit obtained from the downward arrows is that emergency personnel can find incident and vehicle stall locations on the shoulders more quickly as they patrol the freeways because the arrow gives them advance warning about its location.

The operators felt that incidents in the vicinity of lane drops and additions were the most difficult to treat and manage with LCS (including the yellow arrow symbols). However, these difficulties are not due to the yellow indications themselves, but rather to the dilemma of trying to convey information upstream (where one type of roadway cross-section exists) about conditions downstream (where a different cross-section exists). There was some discussion among operators about the potential of having the arrows flash to increase their conspicuity. They felt that flashing changeable message sign (CMS) messages attracted more attention, and a flashing arrow might do the same. More extensive public information and driver training

regarding the intended meaning of the downward yellow arrow was recommended by a few of the operators.

Field study data from San Antonio showed very little difference in how drivers respond to a yellow diagonal arrow and a yellow X in a freeway driving environment under the conditions studied. Statistically, neither closed-lane volume distributions nor lane-changing frequencies were significantly different at any of the sites where both yellow indications were tested. However, the yellow indications at both San Antonio and Fort Worth locations were studied in an array consisting of only yellow symbols (arrows or Xs) and green arrows. In these type of LCS array configurations, past research has shown that the yellow X is commonly interpreted (as is the yellow diagonal arrow) as indicating the need to vacate the lane. Consequently, one would expect driver response to both symbols to be similar in these type of LCS arrays. A question that still remains is whether the yellow X could be displayed in conjunction with a red X and a green arrow at an array location and achieve the same results as would occur if a yellow diagonal arrow was displayed at that location. It is current TransGuide policy not to display these types of LCS arrays to motorists. Consequently, these more complex LCS arrays were not evaluated in the field studies.

1. INTRODUCTION

Overhead freeway lane control signals (LCSs) are being installed in several major metropolitan areas in Texas. The purpose of these signals is to symbolically portray in real-time the status of the freeway on a lane-by-lane basis. LCS research conducted in the early 1990s identified several issues that bear directly upon the Department's design, installation, and operation efforts to utilize these signals. These issues included special LCS visibility needs and limitations unique to the freeway driving environment in Texas; a lack of guidance regarding the best placement of LCSs along a freeway; and the potential use of symbols not now in the MUTCD but that showed promise for enhancing driver comprehension of, and response to, freeway LCS systems.

Studies by the Texas Transportation Institute in 1992 and 1993 showed that a steady yellow X (to be used as a transition between a green arrow and a red X) lacked a consistent interpretation from motorists under different simulated driving scenes. Follow-up experiments of a diagonal yellow arrow (pointing toward the lane where motorists should move) indicated the need to exit a lane much more consistently (*1*). That study also raised concerns about the lack of an LCS symbol that could be used to convey the need to proceed with caution in a given lane, but not necessarily to exit that lane. A downward yellow arrow was suggested as such a symbol, and laboratory experiments indicated that intention to be in line with the interpretations of that symbol by many motorists. However, it was not possible to test the diagonal and downward yellow arrows in the field as part of that study.

That earlier research also involved some field testing in Fort Worth of the standard MUTCD LCS symbols; the steady red X, the steady yellow X, and the steady green arrow (*2*). Unfortunately, Researchers found that the visibility of some of the LCS were limited under bright, sunny conditions. Consequently, it was difficult to determine how effective LCS were in affecting motorist behavior. Researchers cited several possible reasons for the poor visibility, but these were not verified within the funding constraints of that earlier study.

Because of these issues, TxDOT funded SPR Study 0-1498 (Study of Visibility, Spacing, and Operations Issues of Freeway Lane Control Signals in Texas), performed by the Texas Transportation Institute at Texas A&M University between September 1993 and August 1996. This report summarizes the efforts and results of that three-year effort.

STUDY OBJECTIVES

1. Identify the extent, causes, and potential countermeasures for freeway LCS visibility limitations in Texas;

2. Determine spacing and location guidelines for freeway LCS in Texas;

3. Conduct operational studies to assess the effect of freeway LCS (including the non-standard yellow diagonal and downward arrows) on driver behavior, operations, and safety; and

4. Develop recommendations for the operation of freeway LCS, including possible changes to the MUTCD.

REPORT ORGANIZATION

Two interim reports have been prepared as part of this research project. These reports are as follows:

- FHWA/TX-94/1498-1, Visibility and Spacing of Lane Control Signals for Freeway Traffic Management, October 1994

- FHWA/TX-97/1498-2, Yellow Transition Lane Control Signal Symbols for Freeway Traffic Management, September 1996

This final report is a condensed version of these two reports, with the addition of LCS visibility data collected for a used LCS head obtained from the Fort Worth District of TxDOT. This report includes the results of that study as Appendix A and integrated into the chapter on LCS visibility.

Chapter 2 of this final report summarizes the results of legibility studies conducted during 1994 and 1995 on different commercially available LCS heads being marketed in the U.S. for freeway traffic management purposes. Chapter 3 summarizes the findings of an expert panel of TxDOT operations and engineering personnel convened to discuss LCS spacing and mounting concerns in a freeway driving environment. Chapter 4 summarizes the results of the evaluation of the yellow diagonal and downward arrows, suggested as potential new symbols to be incorporated into the MUTCD for freeway management use. Chapter 5 summarizes the major findings of the research project and provides recommendations regarding the design, purchase, and operation of LCS for freeway traffic management.

2. VISIBILITY OF FREEWAY LCS

INTRODUCTION

The effectiveness of LCS as a traffic management tool on Texas freeways depends on the ability of motorists to adequately detect and recognize the displays they encounter while driving. LCS displays must be visible enough to compete with the visual clutter present in this type of driving environment, yet not be so overbearing so as to overpower the other information sources that drivers need to access as well. This chapter describes the methodology and results of LCS legibility studies conducted to evaluate the visibility of commercially available LCS being used in freeway traffic management systems throughout Texas.

STUDY OBJECTIVES

The objectives of the legibility studies were as follows:

1. Determine the glance legibility distance of three commercially available LCS, identifying any differences in these distances as a function of symbol and color (i.e., red X, yellow X, green arrow, yellow downward arrow, yellow diagonal arrow), signal type (representing differences in design characteristics among the three signals evaluated), subject gender, and subject age, and
2. Determine the effect of dirt accumulation on the signal lenses and light bulb deterioration over time upon glance legibility, and to what extent the loss in legibility can be regained by cleaning the lenses and replacing the bulbs.

STUDY PROCEDURE

Description of the Glance Legibility Evaluation Measure

TTI researchers measured LCS visibility with a glance legibility study conducted in Texas during the middle of the day in late summer. LCS from three manufacturers were mounted side by side on an overhead sign structure at the TTI Proving Grounds. Initially, subjects were positioned as drivers in a TTI vehicle located a given distance away (460 meters) from the LCS head. Subjects then viewed a symbol presented to them on the LCS for a brief (1.5-second) interval. If the subject could not correctly identify the color *and* symbol displayed, he or she moved closer to the LCS. Researchers repeated the process until the subject correctly identified the color and symbol.

TTI researchers obtained a demographically balanced sample with regard to gender and age. The researchers based the selection of the participants used in the laboratory study on the age distribution of licensed Texas drivers. The education level of the participants was not expected to significantly affect distance measurements, and so was not considered in the subject selection process. Researchers randomized the sequence of the symbols and signals displayed to each subject so as to counterbalance any learning effects that might occur.

Design Characteristics of the Fiberoptic LCS

Commercial manufacturers provided three different fiberoptic LCS for legibility testing. All three signals could display the three standard MUTCD symbols used for freeway traffic management (i.e., red X, yellow X, and green arrow). In addition, one of the signals could display a yellow downward arrow (identical in shape to the green arrow) and a yellow diagonal arrow pointing downward to the left or the right. The actual symbols themselves measured 356 mm in height.

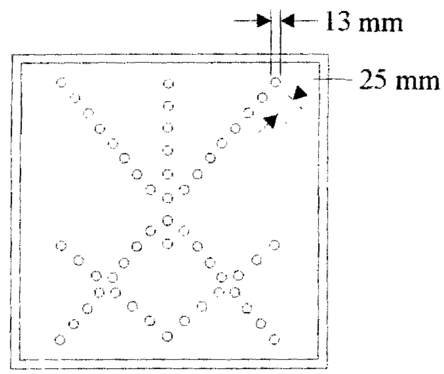
Figure 2-1 illustrates the layout of the pixels on each signal face. As can be seen from the figure, each symbol consists of either a single line of pixels (i.e., a single-stroke symbol) or two sets of pixels placed side by side (i.e., a double-stroke symbol). Signal #1 utilized a single-stroke arrangement for all of the symbols. Signal #2 utilized a double-stroke arrangement of pixels. Signal #3 utilized a double-stroke arrangement for the green arrow as well as for the red and yellow X, but a single stroke arrangement for both yellow arrows (downward and diagonal). The spacing between pixels was 25 mm on Signal #1, 38 mm on Signal #2, and 18 mm on Signal #3.

The output lens on the end of the fiberoptic bundles also differed by signal type. For Signals #1 and #2, the output lenses were 15 and 13 mm, respectively. For Signal #3, the output lens was only 4 mm. Signal #3 utilized more pixels placed close together to generate a symbol (see Figure 2-1). However, all signals utilized two 50-watt, 10.8-volt halogen quartz lamps as the source of illumination.

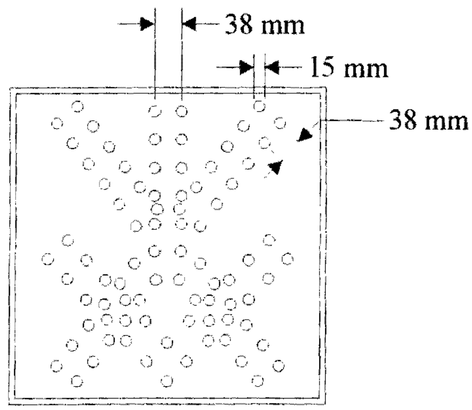
RESULTS

Legibility by Signal Type, Color, and Subject Age

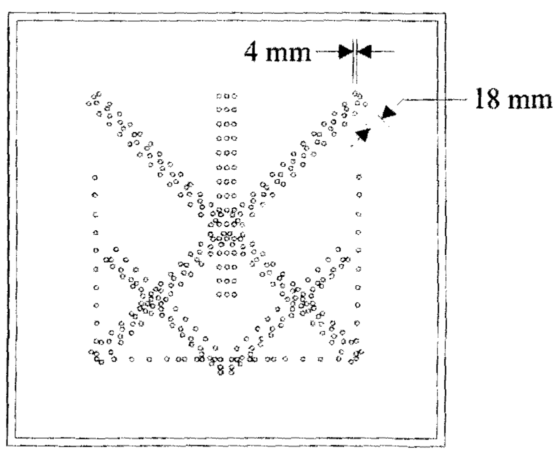
The results of the glance legibility studies demonstrated no significant differences in median legibility distances based on subject gender or ambient lighting condition (sunny or cloudy) (*3*). However, the data indicate a significant difference in legibility depending on the age of the subject. In particular, older drivers (those 65 years or older) had poorer glance legibility distance capabilities than their younger (i.e., those 45 years or younger) counterparts. As illustrated in Figure 2-2, median legibility distances for drivers older than 65 years viewing the red X, yellow X, and green arrow were 91 to 198 meters lower than for the 16- to 44-year-old age group. For the yellow diagonal and downward arrows displayed on Signal #3, older drivers had to be only 30 meters closer than younger drivers to properly identify the symbol.



Signal #1



Signal #2



Signal #3

FIGURE 2-1. Pixel Layout of the Three LCS Heads Evaluated

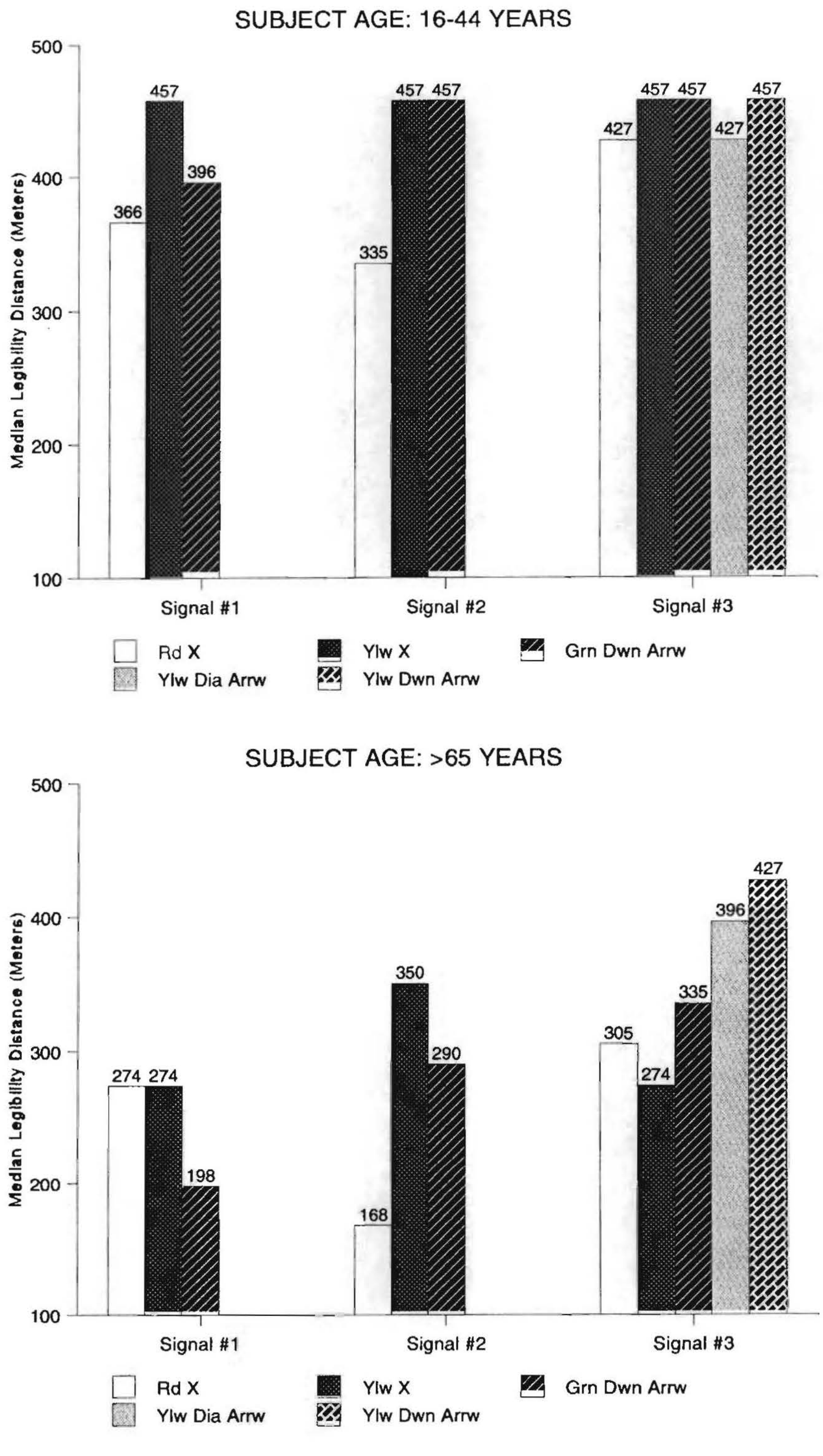


FIGURE 2-2. Median Glance Legibility Distances of LCS by Age of Subject

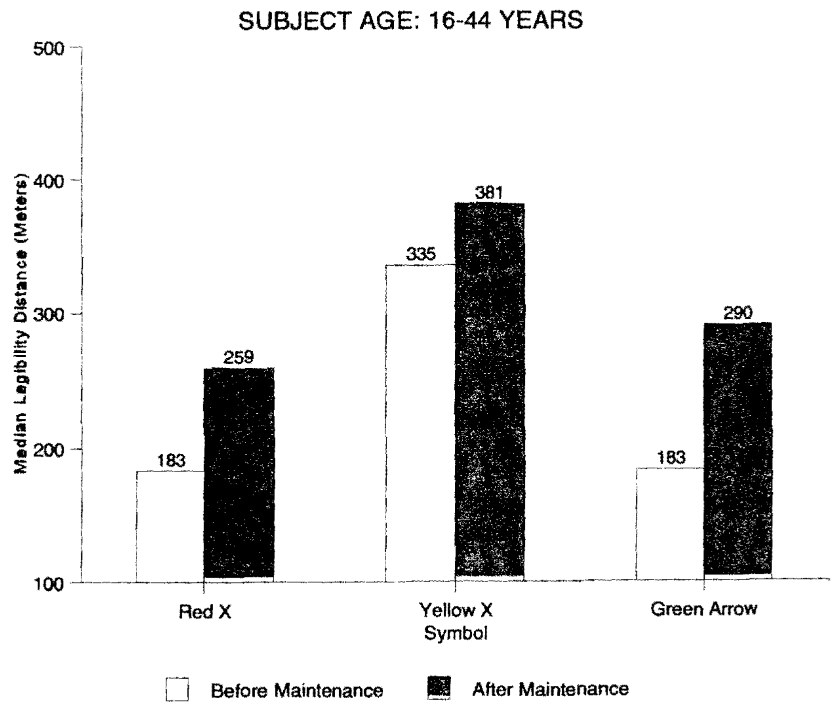
Other studies have shown that the static sign legibility distance of an older driver is 65-75 percent of the legibility distance of a 18- to 24-year-old driver (*4*). For the data presented in Figure 2-2, it appears that this percentage holds for the light-emitting fiberoptic LCS displays as well, with a few notable exceptions. Specifically, older driver legibility distances for the red X on Signal #2 and the green arrow on Signal #1 were only 50 percent of the legibility distance of younger drivers. Comments from the older drivers indicated that the double-stroke pixel arrangement along with the larger pixel lenses on Signal #2 caused irradiation effects, such that those drivers could not identify the actual shape of the red "glow" until they were closer to the signal. For Signal #1, the actual hue of the green arrow appeared to be slightly more "blue" than for the other signals. At least one other study has reported that older drivers have more trouble seeing blue and purple hues than younger drivers (*5*). However, researchers could not absolutely determine the actual cause of the poorer legibility.

It is also interesting to note that the older driver median legibility distance of the yellow diagonal and downward arrows on Signal #3 was as much as 93 percent of those of the younger drivers. These particular symbols were created with only a single line of closely spaced, small pixels. Apparently, the yellow color and rather thin lines of this arrangement were very advantageous to older driver vision in this particular study.

Effect of LCS Age, Road Grime Accumulation, and Pixel Lens Cleaning

An LCS head originally installed on I-35W in Fort Worth, Texas, in 1989 was obtained from the Texas Department of Transportation (TxDOT) for glance legibility testing. The signal manufacturer was the same as for Signal #2, but the actual design of the LCS head was similar to Signal #1 (i.e., single-stroke symbols created with the pixels, and pixel lenses measuring approximately 13 mm in diameter). At the time of testing, the signal had been in place over the freeway for approximately six years. Furthermore, TxDOT reported that it had last cleaned the pixel lenses and replaced light bulbs in that signal 18 months prior to testing. Appendix A describes the detailed evaluation of this signal head. A summary of the results are provided below.

Figure 2-3 presents the median glance legibility distances for the red X, yellow X, and green downward arrow for the used LCS in its "as is" condition (before maintenance) and after the pixel lenses were cleaned and all light bulbs were replaced (after maintenance). The legibility distances before maintenance ranged between 183 and 335 meters for the under-45 age category, depending on the symbol. For the over-65 age category, legibility distances for these same symbols were only 107 to 274 meters. After maintenance, visibility distances increased significantly for both age categories. The median legibility distances for younger drivers ranged between 259 and 381 meters; for older drivers, the median legibility distance ranged between 213 and 335 meters.



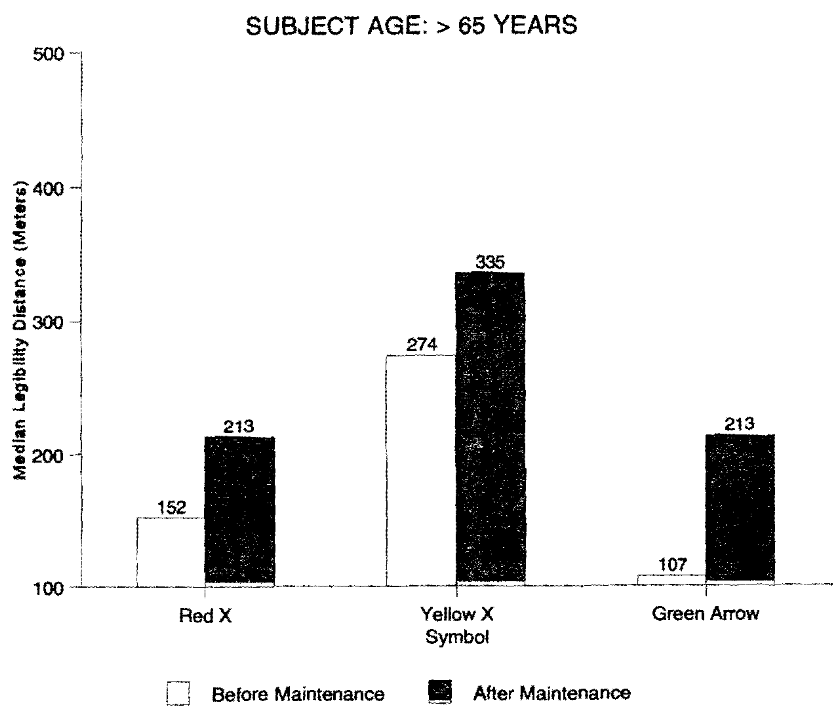


FIGURE 2-3. Effect of Maintenance and Signal Head Age on LCS Legibility

Although median legibility distances of this particular LCS in a new condition were not available for this study, comparing the values in Figure 2-3 with those in Figure 2-4 for Signals #1 and #2 do provide some indication of the relative effect of age, dirt accumulation, and regular maintenance on LCS visibility. In general, the combined effect of age and dirt accumulation significantly reduced the visibility of the green arrow and red X for both younger and older drivers. The data in Figure 2-3 before maintenance for these symbols are less than one-half of those for new LCS (see Figure 2-2). Interestingly, the effect of dirt and signal age was not as significant for the yellow X display. The legibility distances before LCS maintenance for both younger and older drivers for that indication are three-fourths or more of those shown for a new LCS.

Figure 2-3 also illustrates that after LCS maintenance regular cleaning and bulb replacement restored a significant amount of legibility distance to the red X and green arrow. However, it does appear that some permanent loss in symbol legibility does occur over time. After LCS maintenance, the legibility distances for both younger and older drivers were two-thirds to three-fourths of those shown for new LCS. This effect apparently does not hold for the yellow X, though. In Figure 2-3, the yellow X legibility distance after LCS maintenance for younger drivers is nearly that of a "new" LCS. For older drivers, the yellow X legibility distance after maintenance actually exceeds the "new" LCS distance.

SUMMARY

The following list highlights the major findings of these studies:

- Two of the three LCS tested exhibited differences in median legibility distances between symbols. Specifically, the legibility distance tended to be the greatest for the yellow indications (X, downward arrow, diagonal arrow), somewhat less for the green arrow, and shortest for the red X. In contrast, the legibility distances for all of the symbols displayed on the third signal were much more uniform.

- Significant differences were evident in the median legibility distances achieved by younger drivers (those less than 44 years) and older drivers (those greater than 65 years). In general, older drivers achieved legibility distances that were 50 to 75 percent of those achieved by younger drivers.

- Older drivers had a particularly difficult time viewing the red X on the signal that used a double-stroke arrangement of 15-mm pixels spaced 38 mm apart. Irradiation from this design significantly blurred the X, such that the median legibility distance for older drivers was only 168 meters. In contrast, the median older driver in this study could see the red X on the other two signals from a distance of 274 to 305 meters.

- Older drivers also had some difficulty seeing the green arrow on the signal using the single-stroke arrangement of 13-mm pixels spaced 25 mm apart. Researchers surmise that a more bluish green tint of this signal is what created the viewing difficulties for older drivers.

- Older drivers could see the single-stroke arrangement of 4-mm pixels used to create the yellow downward and yellow diagonal arrows very well. In fact, the median legibility distances for these symbols by older drivers were greater than the double-stroke arrangement used for the yellow X on that signal.

- Dirt accumulation and light bulb degradation over time appear to be fairly significant for LCS mounted on urban freeways. Data from this study suggest that median legibility distances after approximately 18 months of LCS use may be reduced by as much as 60 percent, depending on the symbol. Generally speaking, the yellow X was not as significantly affected by dirt as was the red X and the green arrow.

- Legibility studies showed that maintenance of the LCS (wiping dirt from the pixel lens and replacing light bulbs) restored a significant portion of legibility. After maintenance, median legibility distances were at least 70 percent of those estimated for new LCS.

3. SPACING AND MOUNTING OF LCSs ON FREEWAYS

OVERVIEW

TTI researchers invited an expert panel, consisting of personnel employed by TxDOT Districts and Divisions throughout the state, to Fort Worth in August 1994 to participate in a brainstorming session to explore problems and potential solutions relating to the use of lane control signals for freeway traffic management. The individuals invited to participate represented several of the urban areas in Texas that have or will be installing LCS on freeways within their jurisdiction. The Traffic Operations Division of TxDOT was also represented on the panel.

The panel discussed four major topic areas during the day-long meeting. These topics included the following:

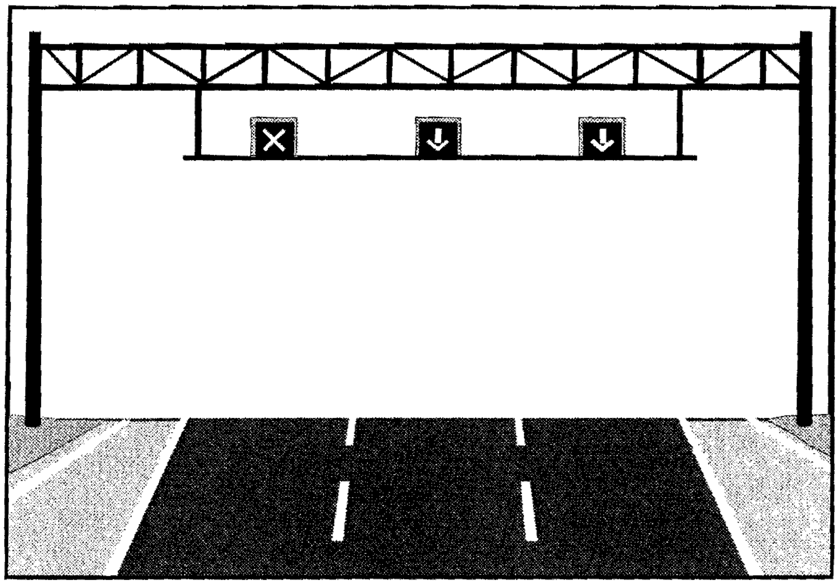
- visibility,
- spacing,
- mounting location, and
- LCS applications in unusual geometric situations.

MEETING RESULTS

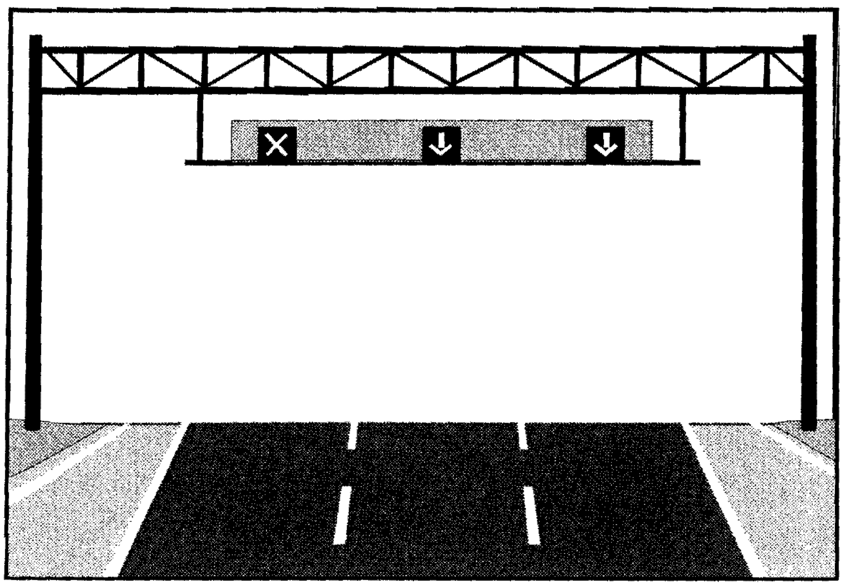
LCS Visibility

Panelists agreed that the existing brightness of the LCS signals in Fort Worth was generally adequate. The panelists did note that visibility was more of a problem for the east-west freeways in the morning due to sun interference. With the sun at their backs, panelists noted that the LCS indications tended to "wash out." Conversely, when facing the sun, panelists had difficulty seeing the LCS because of the extreme sun glare. These types of problems are consistent with those reported elsewhere in the literature (*6*). However, the panel had concerns that increasing the LCS brightness to combat sunlight glare during certain hours of the day for those east-west signals would cause the signals to be too bright and overpowering during other hours of the day and when oriented in a different direction.

Several panelists indicated that they felt the contrast between the signal symbol and the background was not adequate. The Fort Worth District personnel did acknowledge that they were considering upgrading their sign specifications as well as some simple countermeasures to combat this contrast deficiency. As one idea, the Fort Worth District was considering installing back plates on its LCS mounted on overhead sign structures. Two types of back panels under consideration are illustrated in Figure 3-1. The first consists of a 150- to 200-m border mounted around each individual display (Figure 3-1a), whereas the second is a louvered panel installed across the length of the sign structure behind the signals (Figure 3-1b).



(a) individual back plates



(b) louvered back panel

FIGURE 3-1. Proposed Back Plate/Back Panel Configurations in Fort Worth

Another suggestion discussed at the meeting was the improvement in face plate materials that resist fading from the sun. The flat black paint used on the faces of the LCS installed in Fort Worth has faded dramatically over the six years they have been in place. Other methods of covering the face plate (i.e., a plastic material or a higher quality paint) need to be considered to help reduce sun fading and maintain adequate contrast for a longer period of time.

One panel member pointed out that the common fiberoptic LCS that have a narrow cone of vision (typically 20° centered on the optical axis) may not be appropriate for all freeway applications. This is particularly true for very wide freeways and those having a more rolling alignment. The concern centers around a driver's ability to see the LCS indications over all travel lanes. Laboratory research (*1*) and field experience have both demonstrated the importance of having the entire LCS array visible to drivers so that they can evaluate the overall display and move to an appropriate lane if necessary. This can become a problem when trying to view the LCS on a wide urban freeway.

A panel member suggested exploring the possible advantages of using LCS that have wider cones of vision, particularly for wide freeways and freeways carrying a large amount of heavy truck traffic. Another panel member cautioned that this could create difficulties for maintenance crews in the future if different LCS heads having different specifications were mixed within the overall system. One member suggested that it may be possible to develop a LCS head that could be "focused" to the correct cone of vision. In this way, each signal head could be configured specifically to the needs of a particular location. Those locations having long tangent approaches to the signals could be focused with a more narrow cone of vision to maximize visibility distance. Conversely, signals at those locations where sight distance is restricted could be configured to a wider cone of vision so that drivers have the maximum amount of time possible to see the symbols before passing underneath the structure supporting the LCS.

LCS Spacing and Mounting Locations

Another area of concern about freeway LCS relates to the need for, and appropriate specification of, spacing criteria. Although some panel members felt that consistency in LCS spacing promotes driver expectancy of lane status information and thus the potential utilization of the LCS, other members felt that it is far more important to focus on where to, or not to, install the signals (rather than attempt to strive for uniform spacing). Early on in the discussion, the point was made that cost considerations currently control most LCS location decisions. Designers commonly use existing overhead sign structures, overhead bridge structures, etc., for LCS installations, and these limit the flexibility that the Department has in where the LCS are provided. At least one member noted difficulties in utilizing an LCS currently in operation in his jurisdiction because most of the lane-blocking incidents in the vicinity occur just upstream of the LCS installations, rendering them useless in notifying approaching motorists of the lane blocked conditions at that location.

After some discussion, the panel agreed in principle that LCS spaced somewhere between 0.8 and 1.6 kilometers apart appear to function adequately in urban areas. It was noted that most of the LCS viewed along the Fort Worth freeways are spaced about this far apart, and appear to present lane status information to motorists at a reasonable rate. Also, the limited short-term memory span of drivers (30 seconds to 2 minutes [*7*]) suggests that this range of spacings is beneficial to information retention, because drivers encounter LCS displays every 30 to 60 seconds at normal operating speeds. However, the actual location of LCS should be based on the following criteria:

- ramp spacing,
- location of other major driving decision points,
- available sight distance, and
- location of other information sources (guide signs, changeable message signs, etc.).

A problem cited by the panel with respect to LCS spacing was in determining how these signals should fit into the overall information package presented to motorists as they traverse a section of roadway. Specifically, the panel expressed concern about the placement of LCS on overhead sign structures where a large number of sign panels are already installed. The latest edition of positive guidance principles from FHWA indicates that a roadway information system begins to reach an overload condition when it contains more than five information sources (*8*). These information sources are not only limited to the LCS and other signing installed on the roadway but include pavement markings, geometric features, and even certain structural elements. As a rule of thumb, it is recommended that LCS not be mounted on overhead sign bridges supporting two or more guide sign panels.

A final concern noted by panel members with regard to LCS spacing and mounting location involved the use of overhead bridge structures as LCS supports when the structure is skewed relative to the freeway alignment. It is not known whether an adverse visual effect is caused by mounting the heads next to the structure and thereby creating an offset between heads as depicted in Figure 3-2.

One panel member suggested the use of a cantilever support arm extending out from the bridge structure. As shown in Figure 3-3, a design of this type would maintain uniformity in the LCS displays. However, this design would only be appropriate for structures having a moderate degree of skew; more oblique skews would necessitate the use of a different support structure.

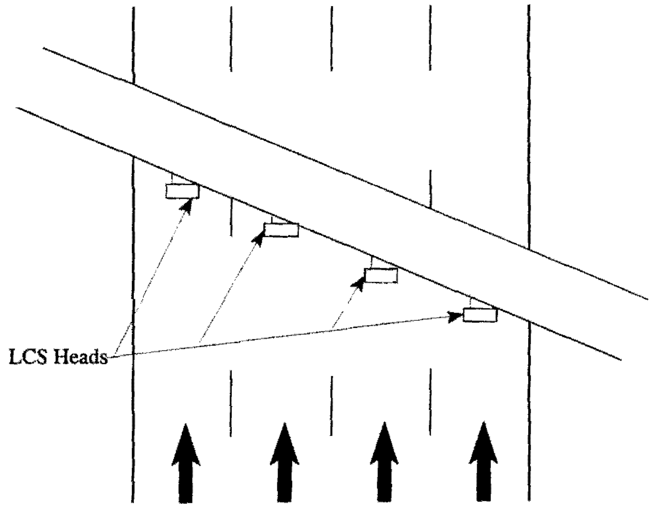


FIGURE 3-2. LCS Mountings on Skewed Bridge Structure

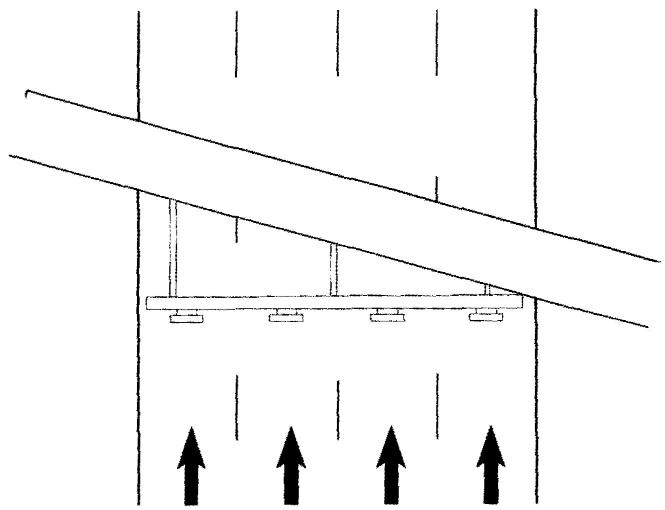


FIGURE 3-3. Cantilever LCS Mountings on Skewed Bridge Structure

LCS Use at Unusual Geometric Situations

A considerable amount of panel discussion centered around the use of LCS over auxiliary lanes and lane drop locations. Placing LCS over the exit lane could lead to driver confusion, particularly during conditions when all but one of the freeway main lanes are blocked. In this situation, drivers may perceive a green arrow over the exit lane and over the remaining open through lane as indicating that two lanes are open on the freeway downstream. This incorrect perception could then lead to increased erratic maneuvers at the exit lane gore area as drivers fooled by the LCS display attempt to get back into the freeway traffic flow. In general, it was the opinion of the panel that LCS should not be placed over exit only lanes.

The panel was in less agreement as to whether LCS should be displayed over all lanes upstream of a major freeway-to-freeway bifurcation. Many bifurcations involve splitting away two or more lanes. Placing LCS only over through lanes upstream of the bifurcation limits the information that can be displayed to just the through travel lanes. Often, incidents occur on one of the exiting lanes connecting the two freeways, and it would be desirable to inform motorists of the lane blocked condition upstream of the interchange as well. However, the same argument exists concerning the possible driver misinterpretation of green arrows over lanes that are to exit. The panel discussed whether LCS displays should be placed immediately after the bifurcation, but reached no consensus on this issue.

The final special situation discussed involved the installation and use of LCS during the actual freeway reconstruction process. Generally speaking, LCS are intended to provide real-time lane status information. Consequently, some means of monitoring traffic conditions and lane status must be in place in order to utilize the LCS. However, the Fort Worth District chose to install LCS at selected locations early on in its reconstruction of I-20 on the west side of the city. Rather than use the LCS in real-time to indicate lane status, traffic engineers have configured the LCS displays to coincide with the long-term lane closures required for the project. In this way, the LCS reinforce the complement of advance warning signs for the lane closures. TxDOT officials in Fort Worth believe that the early implementation of LCS for this purpose is worthwhile. However, panelists expressed some concerns as to whether this reduces the credibility of the signals in terms of the real-time information presented to motorists via LCS on other freeways in the system.

Concluding Remarks

One final topic discussed by the panel during the meeting was the importance of knowing and understanding the appropriate target audience for which the LCS are intended and designing the LCS system for that audience. In general, panel members identified three types of drivers, each potentially having a very different need for, and response to, LCS:

Unfamiliar drivers (maybe older drivers as well) -- those who hardly ever travel on the freeway system and who would not even be expected to be looking for lane status information via LCS.

For these drivers, it is essential that LCS displays and the operation of the system be designed to maximize quick and common driver understanding, because there will be little opportunity to teach or train these drivers about what certain symbols, arrays, or sequences are intended to convey.

Occasional drivers -- those who drive on the freeway on occasion, but not on a regular enough basis to be totally familiar with the specific freeway section they are on to know about downstream bottlenecks, lane drops, etc. These individuals may be looking for lane status information, but may become confused at certain locations if the information system (i.e., LCS) is not designed properly or is not consistent with previous locations.

Repeat drivers -- those who travel the section of freeway on a regular basis and who are familiar with the various geometric features present, available alternative routes in the corridor, and available traffic information (including LCS displays). These individuals will likely learn over time what various displays mean in terms of expected delays, congestion, etc., and may become particularly responsive to those displays. Conversely, inconsistent utilization of the LCS from location to location or from one incident to the next will likely decrease the credibility of the displays with this driving group and reduce the overall effectiveness of the real-time information system.

4. EVALUATION OF YELLOW TRANSITION SYMBOLS

TxDOT received permission from FHWA in 1994 to experiment with both the yellow diagonal and the downward arrows. As part of the approval process, the agency required a plan to evaluate the use of the experimental devices. The plan approved by FHWA to evaluate the LCS consisted of three main components described below.

- *Motorist Surveys* -- Motorists coming into regular contact with the LCS were to be surveyed to assess their level of understanding of the diagonal and downward yellow arrows, their perceptions of the usefulness of LCS, and any problems or deficiencies in how the LCS are being used.

- *System Operator Interviews* -- Researchers were to conduct interviews of the traffic management control center operators who deployed the yellow diagonal arrow and downward arrow during actual lane blockage conditions. Operator perceptions and experiences with the symbols would be identified. Situations in which the use of either the downward or diagonal yellow arrows was seen as particularly useful were of interest, as were any special situations in which the operators found it somewhat difficult to apply the yellow arrows effectively.

- *Field Evaluations* -- Comparisons of traffic approaching the yellow diagonal arrow and the yellow X as transition symbols from a green arrow to a red X were to be conducted where possible. Both single-lane and multiple-lane blockages existing in the peak and off-peak periods were of interest. Particular measures of effectiveness included the distribution of traffic across available freeway lanes, volumes exiting and entering the freeway to determine what effect alternative LCS displays have upon upstream diversion rates, and any erratic maneuvers occurring at the upstream end of the freeway queue.

A summary of the evaluation results are presented in this chapter.

MOTORIST SURVEYS OF YELLOW SYMBOLS

TTI conducted surveys of motorists' exposure to the yellow arrows (diagonal and downward) in San Antonio and to the yellow X in Fort Worth. Details of these surveys are provided in TTI Research Report 1498-2 (*9*). The following sections highlight the major findings from those surveys.

Researchers first asked survey participants whether they had actually encountered the yellow symbols being used in their cities (the yellow arrows in San Antonio, the yellow X in Fort Worth) during their normal freeway travels. The researchers then queried motorists as to whether the yellow symbol of interest was helpful to them when driving the freeways and whether the symbol was confusing to them. Survey responses were generally very positive for all of the symbols. Interestingly, the degree to which the subjects rated the symbols as helpful depended on whether they had actually seen them used while driving on freeways. However, subject ratings of whether the symbols were confusing were not dependent upon previous subject exposure to the symbols for either the yellow downward or diagonal arrows but were for the yellow X. Figures 4-1 through 4-3 present the percentage of subjects rating the yellow downward arrow, yellow diagonal arrow, and yellow X as helpful and confusing.

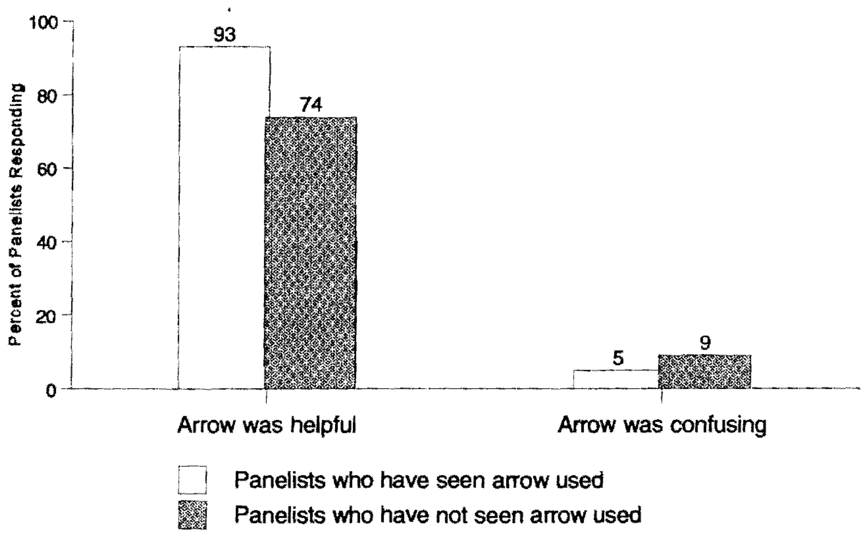


FIGURE 4-1. Effect of Seeing Yellow Downward Arrow in Freeway Context Upon Subject Assessments of Helpfulness and Clarity

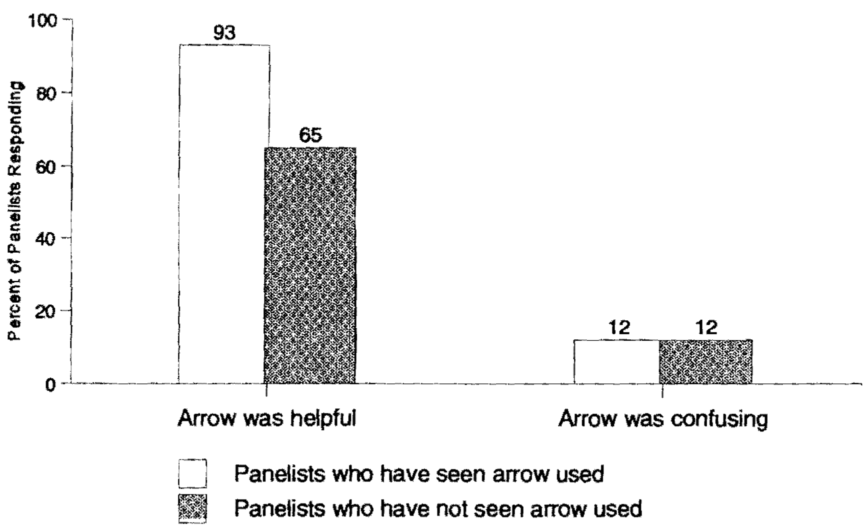


FIGURE 4-2. Effect of Seeing Yellow Diagonal Arrow in Freeway Context Upon Subject Assessments of Helpfulness and Clarity

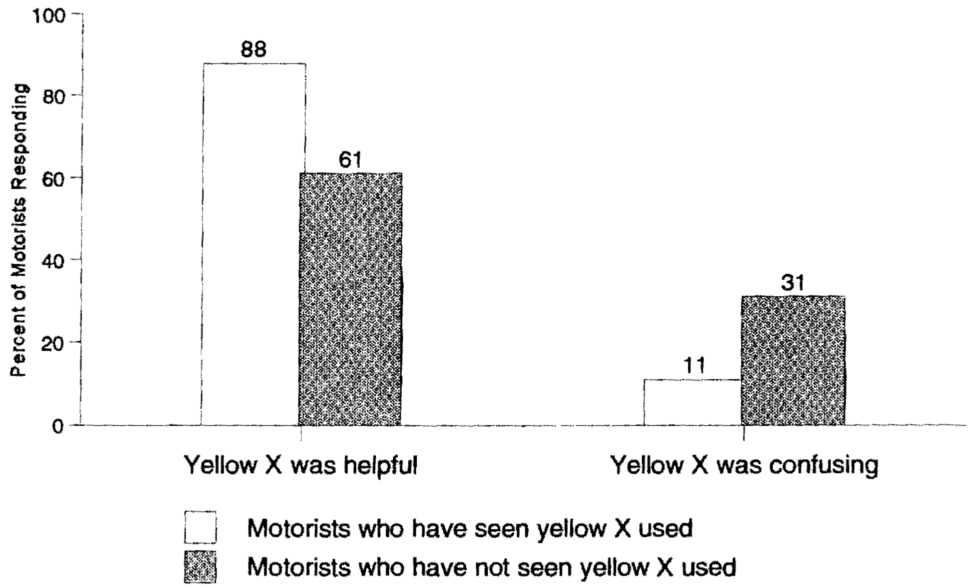


FIGURE 4-3. Effect of Seeing Yellow X in Freeway Context Upon Subjects Assessment of Helpfulness and Clarity

Subjects were asked to describe in detail any confusing situations they had encountered with respect to the LCS in their respective cities. Some of the common situations included the following:

- "Did not know what the symbol meant,"
- "Wasn't sure what lane the arrow meant"
- "Arrow said to change lanes but there was no accident downstream,"
- "Arrows on sequential signs conflicted with each other,"
- "Wasn't sure whether to change lanes or exit the freeway,"
- "Arrows conflicted with message on CMS,"
- "Saw the arrow blink - what does that mean,"
- "Too many arrows to comprehend at some locations,"
- "Did not know what roadway the symbol referred to,"
- "Poor visibility,"
- "Arrow was on for no reason,"
- "Arrow was located too far upstream of congestion,"
- "Arrow was not located far enough upstream of congestion."

A greater percentage of subjects in San Antonio identified a confusing situation involving the yellow diagonal arrow than did the Fort Worth subjects about the yellow X. However, the subjects from each city were recruited in very different ways (the San Antonio subjects were recruited specifically to assess the TransGuide system [including the LCS]). This may have made those subjects more inclined to provide feedback to this question as compared to subjects from

Fort Worth. Also, the freeway geometrics in San Antonio, where the yellow diagonal arrows are being used, are much more complex than on the freeways in Fort Worth where the yellow X is being used. This also may contribute to the higher number of confusing instances reported by San Antonio subjects.

TRANSGUIDE OPERATOR EXPERIENCES WITH THE YELLOW ARROWS

As part of the evaluation plan to assess the effectiveness and practicality of the non-standard yellow diagonal and downward arrow LCS symbols for freeway traffic management, TTI researchers interviewed system operators of TransGuide in March 1996. The purpose of the meeting was to obtain operator impressions of the effectiveness of the two types of yellow arrow indications for communicating with motorists and to identify any particular problems they may have encountered due to these symbols when attempting to apply the LCS to a particular roadway event.

With respect to the use of the yellow arrows, the operators could not think of a specific instance where they noticed driver behavioral problems that would suggest that drivers were confused by either the diagonal or downward yellow arrows. They indicated that no accidents had occurred that were attributable to the yellow arrows, either.

Operators' impressions of the effectiveness of the yellow diagonal arrow were generally favorable. They agreed that most drivers do appear to respond to the arrows, although there are always those that wait to the last minute to exit a given lane. The operators also felt that during daylight hours it may be more difficult for drivers to notice the arrows (the symbols are much more visible at night or in cloudy conditions).

The operators also noted that the presence of, and information provided on, CMSs in conjunction with the LCS significantly affects driver responses. The operators cited one particular incident in which glass was scattered on two inside travel lanes, and they had diagonal arrows displayed upstream telling drivers to move to the right. They also had a message on a CMS that said "Debris on Roadway - Merge Right." Drivers initially merged to the right, but when they could not see a problem in the left lanes they moved back into those lanes and ran over the glass. Operators eventually modified the message to read "Glass on Roadway - Merge Right." Drivers moved out of the left lanes and stayed out of them until the LCS and CMS indicated that the lanes were open to traffic. The operators agreed that the CMSs and LCSs must be operated as a system.

Favorable operator responses were obtained about the effectiveness of the yellow downward arrow as well. As they noted, however, it is difficult to identify specific driving actions (speed reductions, reduced lane changing, etc.) from the CCTV or other data to determine objectively how the indications are influencing drivers. However, emergency and service personnel had mentioned to Trans Guide operators an unexpected benefit from using the downward arrows. It seems that they appreciate the use of the downward arrow indications because it helps them to pinpoint incident and vehicle stall locations on the shoulders as they patrol the freeways.

Generally speaking, the operators felt that incidents in the vicinity of lane drops and additions were the most difficult to treat and manage with LCS. However, these difficulties are not due to the yellow arrow indications themselves, but rather to the dilemma of trying to convey information upstream, where one type of roadway cross-section exists, about conditions downstream where a different cross-section exists. Another type of difficulty encountered by operators occurs at the boundaries of TransGuide operations, when an incident is located outbound beyond the limits of TransGuide surveillance. Operators want to provide information on the upstream CMSs and LCSs if they can, but until they receive information about the incident from police or other sources, they cannot. Again, however, this is not a problem that is due to the yellow arrow indications.

It was the consensus of the group that both the yellow diagonal and yellow downward arrows are effective means of communicating with motorists. Because the situations in which the diagonal arrow is used tend to be more severe and have a more significant impact upon traffic, operators believe that both CMS and LCS are necessary to properly convey lane status information. It may not be possible to always measure driver responses to the yellow diagonal arrow, but it may still serve a useful purpose in getting motorists to start thinking and preparing for a lane change (which they appear to initiate after they reach the first LCS array where a red X is being displayed).

OPERATIONAL STUDIES OF THE YELLOW DIAGONAL ARROW AND YELLOW X

Study 1498 included a series of field studies that assessed the effect of the yellow diagonal arrow upon freeway traffic operations in advance of lane blockages. The TransGuide system in San Antonio is currently the only location statewide that has the capability of displaying the yellow diagonal arrow in an LCS array. In fact, operators they rely on this symbol (rather than on the yellow X that is recognized by the MUTCD) as their primary transition symbol between the green arrow and red X during the day-to-day operation of the system. To avoid biasing the results toward the particular symbol being used in a given location (San Antonio relies on the yellow diagonal arrow as the transition symbol between a green arrow and a red X, whereas Fort Worth utilizes the yellow X for this purpose), researchers conducted a limited number of studies in San Antonio in which both the yellow diagonal arrow and yellow X could be evaluated at a given location for a short period of time so that a direct comparison of driver response could be made. Researchers then conducted additional studies that focused exclusively upon driver response to the yellow diagonal arrow in San Antonio. Researchers also conducted studies in Fort Worth that focused exclusively upon driver response to the yellow X.

Study Procedures

Video data of traffic approaching an LCS array where either the yellow diagonal arrow or the yellow X was displayed were recorded to determine, where possible, three basic types of data:

- The distribution of traffic volumes across the available lanes (these were measured directly underneath the LCS array),
- The lane-changing frequencies between the open and closed lanes (measured over a 76-meter distance immediately downstream of the LCS array), and
- Erratic maneuvers (severe braking, lane-changing back and forth between open and closed lanes, etc., occurring either upstream or immediately downstream of the LCS array),

Study Results

Direct Yellow Diagonal Arrow Versus Yellow X Comparisons - San Antonio

Researchers were able to conduct four studies in San Antonio in which both the yellow diagonal arrow and the yellow X were each displayed for a period of time upstream of a freeway lane blockage. These studies were of both single-lane and multiple-lane blockages located in one direction of six-, eight-, and ten-lane sections of freeway. Table 4-1 summarizes the characteristics of each direct comparison evaluation site. These evaluation sites were all upstream of roadway construction and/or maintenance work lane closures. These closures were during daylight, off-peak traffic conditions. At two of the evaluation sites, CMSs were not upstream of the first LCS array where the yellow transition symbols were evaluated. CMSs were used at the two remaining sites.

TABLE 4-1. Characteristics of Direct Comparison Evaluation Sites

Site	Location	Number of Lanes	Number of Lanes Blocked	LCS Configuration
1	I-10 EB @ Nogalitos	4	1	YGGG
2	I-10 WB @ I-35	5	1	GYGGG
3	I-10 WB @ Roland	3	2	YYG
4	I-10 WB @ Roland	3	2	GYY

Notes: EB = eastbound; WB = westbound. Y = yellow symbol (x or arrow); G = green arrow

Table 4-2 summarizes the percent of traffic in the closed lane or lanes at each site. The percentages are slightly higher when the yellow diagonal was being displayed at three of the four sites. However, none of these was found to be statistically significant (at a 95 percent level of confidence) at any of the sites.

TABLE 4-2. Closed-Lane Distributions: Yellow X Versus Yellow Diagonal Arrow

Site	Lanes Blocked	Percent of Traffic in Closed Lane(s)	
		Yellow X	Yellow ↘
1	inside lane	16.3	17.2
2	2nd inside lane	20.0	21.2
3	2 inside lanes	52.6	55.2
4	2 outside lanes[a]	82.8	80.3

[a] A CMS indicating which lanes were closed was displayed in conjunction with the LCS at this site,

Table 4-3 presents the lane-changing frequencies observed at those sites where data were available (roadway geometrics at the first site did not allow lane-changing behavior to be observed). Again, no statistical differences were observed in driver response to the yellow X or the yellow diagonal arrow.

TABLE 4-3. Lane-Changing Frequencies: Yellow X Versus Yellow Diagonal Arrow

Site	Lanes Blocked	Percent of Traffic Exiting Closed Lane(s)		Percent of Traffic Entering Closed Lane(s)	
		Yellow X	Yellow ↘	Yellow X	Yellow ↘
1	inside lane	----[a]	----	----	----
2	2nd inside lane	5.3	4.8	4.8	3.5
3	2 inside lanes	2.2	3.8	2.1	4.0
4	2 outside lanes	6.6	6.5	1.2	1.1

[a] Data were not available at this site.

Although researchers monitored traffic behavior (via the videotapes) at each of the four sites, no particular instances of any type of erratic maneuvers were observed at any of the sites that would suggest driver misunderstanding or confusion about either of the yellow transition symbols examined.

Yellow Diagonal Arrow Versus a Control (No Lane Closure) Condition - San Antonio

Researchers also conducted studies that compared driver responses when a yellow diagonal arrow was displayed upstream of a lane closure to driver responses when no lane closures were present (all LCS displayed green arrows) in San Antonio at Sites 1, 3, and 4 as listed above. Also, data for the yellow diagonal arrow and a control condition were available from an additional site (labeled as Site 5). This site involved an inside lane closure on a four-lane section of I-35. The yellow diagonal arrow was displayed approximately 0.4 kilometers upstream of the lane closure. Approximately 0.4 kilometers upstream of the LCS, operators activated a CMS that informed drivers of the left lane closure downstream and to vacate that lane. Thus, the results from that site are also indicative of the combined effect of LCS and CMS.

The amount of traffic in the closed lanes where a yellow diagonal arrow (sometimes in conjunction with a CMS) was displayed is presented in Table 4-4. Also shown in that table is the percent of traffic normally using those lanes in the absence of a lane closure. Only the reduction in the last row of Table 4-4 was statistically significant, although in all cases the percentages were lower than for the control condition. Nevertheless, they do suggest that the arrows do have some effect upon motorist behavior, even a significant distance upstream of the actual point of closure.

TABLE 4-4. Closed-Lane Distributions: Yellow Diagonal Arrow Versus a Control

Site	Lanes Blocked	Percent of Traffic in Closed Lane(s)	
		Yellow ↘	Control Condition
1	inside lane	17.2	18.9
3	2 inside lanes	55.2	59.6
4	2 outside lanes[a]	80.3	81.9
5	inside lane[a]	10.3	20.4

[a] A CMS indicating which lanes were closed was displayed in conjunction with the LCS at this site.

Table 4-5 summarizes the lane changing frequencies measured just downstream of the LCS array under lane closure and normal "control" conditions at three sites. Researchers observed no statistically significant differences were at any of the sites, indicating that the yellow diagonal arrow had minimal impact upon lane-changing frequencies at the sites examined in this study. However, the values from the sample of traffic reported in Table 4-5 at two of the three locations are consistent with what would be expected to occur; namely, the percentages exiting the closed lanes were slightly higher when the diagonal arrow was present (relative to the control condition), and the percent of traffic entering the closed lanes was slightly lower.

The exception to these patterns occurs at Site 5. Given the reduction in lane distribution percentages that had already occurred at that location by the time motorists reached the LCS array (see Table 4-4), these lane-changing values may simply indicate that all motorists who were going to vacate the lane because of upstream information had done so prior to reaching the region where lane-changing was monitored. As a result, the number of motorists making the lane changing maneuver within the section of interest would be smaller than what would be measured under normal "control" conditions.

TABLE 4-5. Lane-Changing Frequencies: Yellow Diagonal Arrow Versus Control

Site	Lanes Blocked	Percent of Traffic Exiting Closed Lane(s)		Percent of Traffic Entering Closed Lane(s)	
		Yellow ↘	Control Condition	Yellow ↘	Control Condition
3	2 inside lanes	3.8	2.0	4.0	3.7
4	2 outside lanes	6.5	3.7	1.1	2.0
5	inside lane	0.5	2.6	5.3	2.6

Once again, there were no erratic maneuvers to report in the vicinity of the LCS at any of the sites.

Yellow X Versus a Control (No Lane Closure) Condition - Fort Worth

To complement the studies conducted on the yellow diagonal arrow in San Antonio, researchers conducted a series of four studies in 1995 on I-35W in Fort Worth between I-20 and I-30. TxDOT is operating an interim Traffic Management Center out of its satellite office building at the southern end of this freeway section. The freeway section includes loop detectors, CCTV, CMSs, and LCSs. This section of the chapter summarizes traffic behavior observed upstream of four lane blockages when the LCSs were activated. Table 4-6 summarizes the general roadway and lane closure characteristics of the four sites.

TABLE 4-6. Characteristics of Fort Worth Sites

Site	Location	Number of Lanes	Number of Lanes Blocked	LCS Configuration
1	I-35W NB @ Allen	4	1	YGGG
2	I-35W SB @ Seminary	4	2	YYGG
3	I-35W NB @ Hattie	4	1 (2 near incident)	YGGG, YYGG
4	I-35W NB @ Hattie	4	1 (2 near incident)	YGGG, YYGG

Note: Abbreviations same as in Table 4-1.

Table 4-7 summarizes the changes in closed lane traffic distributions observed at four site locations in Fort Worth at the location of LCS arrays where a yellow X was being displayed. At Sites 3 and 4, TxDOT utilized yellow X's on two LCS arrays in series to facilitate the lane closure. Consequently, this report includes data from both LCS array locations.

As Table 4-7 illustrates, the percent of the traffic at each site that was in the closed lane at the LCS array decreased significantly at three of the four sites. At Sites 1 and 3a, where a single yellow X was displayed over the inside lane, the shift in traffic from the closed lane ranged between 3.4 percent and 6.6 percent of the total freeway traffic volumes. For the two-lane closure display at Sites 2 and 3b, the shift in traffic from the closed lanes ranged from 9.9 percent to 11.5 percent of the total traffic volumes at each location. If one considers only the traffic in the closed lanes (that for which the yellow X indications are primarily intended), these shifts in traffic represent between a 19 percent and a 36 percent reduction in expected traffic volumes in the closed lane(s) (dividing the percentage shift by the percentage of traffic in the closed lane during the control condition).

Also evident in Table 4-7 is the fact that the yellow X at Site 4 did not reduce traffic percentages in the closed lane(s). However, traffic queued in the open lanes at these LCS array locations, whereas it did not in the closed lanes. Researchers observed many motorists deliberately staying in the closed lane (and in some cases, moving from the open lane to the closed lanes) to bypass part of the queue at this site. As a result, the numbers in Table 4-7 for Site 4 more directly reflect the influence of traffic congestion upstream of a lane blockage rather than an effect of the yellow X.

TABLE 4-7. Closed-Lane Distributions: Yellow X Versus a Control

Site	Lanes Blocked	Percent of Traffic in Closed Lane(s)	
		Yellow X	Control Condition
1	inside lane	13.6	17.0
2	2 inside lanes	40.9	50.8
3a[a]	inside lane	11.9	18.5
3b[a]	2 inside lanes	33.5	45.0
4a[a]	inside lane	24.6	18.5
4b[a]	2 inside lanes	52.4	45.0

[a] A single yellow X was displayed at the most upstream LCS at these sites, followed by an array that had two yellow Xs displayed.

Table 4-8 documents the effect of the yellow X upon lane-changing behavior at the four Fort Worth sites. All but one of the sites for which data were available experienced a significant increase in the percent of traffic exiting the lane(s) under a yellow X, relative to the lane-changing behavior that normally occurs at that location (the control condition). Meanwhile, the percent of traffic entering into the closed lane or lanes at these sites remained unchanged or was slightly lower when the yellow X was displayed.

The lone exception to this trend again occurred at Site 4a. Here, the amount of traffic exiting the closed lane was unchanged from normal lane-changing rates, but the percent of traffic entering the closed lane was significantly higher than occurred in normal traffic conditions. As already stated, a traffic queue in the open lanes and a lack of queuing in the closed lane at that location apparently was enough of an incentive for some motorists to move into that closed (but uncongested) lane to bypass some of the queue.

As was the case for the San Antonio studies, researchers observed no instances of any type of erratic maneuvers at any of the sites.

TABLE 4-8. **Lane-Changing Frequencies: Yellow X Versus Control**

Site	Lanes Blocked	Percent of Traffic Exiting Closed Lane(s)		Percent of Traffic Entering Closed Lane(s)	
		Yellow X	Control Condition	Yellow X	Control Condition
1	inside lane	9.2	3.0	2.0	1.5
2	2 inside lanes	19.8	2.1	2.9	2.7
3	2 inside lanes	-----[a]	-----[a]	-----[a]	-----[a]
4a	inside lane	5.1	4.2	14.7	1.5
4b	2 inside lanes	6.8	1.6	0.8	2.9

[a] Data were not available at this site.

SUMMARY

This chapter documents the research performed to assess the effectiveness and applicability of yellow diagonal and downward arrows for freeway traffic management purposes. The results of the motorist surveys indicate that both the yellow diagonal and downward arrows are perceived positively in freeway driving situations. A large majority of survey respondents rated both types of yellow arrows as helpful to them, and only a small portion of the survey sample felt either arrow symbol was confusing. The ratings are very similar to those given for the yellow X by Fort Worth motorists. Some evidence collected again suggests that the yellow X does not possess a strong inherent meaning. However, once motorists can see the symbol used in an actual freeway driving context, they can deduce its intended message.

The TransGuide system operators could not think of specific driver behavioral problems they had observed that would suggest that drivers were confused by either the diagonal or downward yellow arrows in San Antonio. They indicated that no accidents had occurred that were attributable to the yellow arrows, either. Operators' impressions of the effectiveness of the yellow diagonal arrow are generally favorable. They agree that most drivers do appear to respond to the arrows, although there are always those that wait until the last minute to exit a given lane. Favorable operator responses were obtained about the effectiveness of the yellow downward arrow as well. As they noted, however, it is difficult to identify specific driving actions (speed reductions, reduced lane changing, etc.) from the CCTV or other data to determine objectively how the indications are influencing drivers. An unexpected benefit obtained from the downward arrows is that emergency personnel can find incident and vehicle stall locations on the shoulders as they patrol the freeways more quickly because the arrow gives them advance warning about its location.

The operators felt that incidents in the vicinity of lane drops and additions were the most difficult to treat and manage with LCS (including the yellow arrow symbols). However, these difficulties are not due to the yellow indications themselves, but rather to the dilemma of trying to convey information upstream, where one type of roadway cross-section exists, about conditions downstream, where a different cross-section exists. Another type of difficulty encountered by operators occurs at the boundaries of TransGuide system, when an incident is outbound beyond the limits of TransGuide surveillance. Operators want to provide information on the upstream CMSs and LCSs if they can, but until they receive information about the incident from police or other sources, they cannot. Again, however, this is not a problem that is due to the yellow arrow indications. There was some discussion among operators about the potential of having the arrows flash to increase their conspicuity. They felt that flashing CMS messages attracted more attention, and a flashing arrow might do the same. A few of the operators recommended more extensive public information and driver training regarding the intended meaning of the downward yellow arrow.

The data from San Antonio showed very little difference in how drivers respond to a yellow diagonal arrow and a yellow X in a freeway driving environment under the conditions studied. Statistically, neither closed-lane volume distributions nor lane-changing frequencies were significantly different at any of the sites where both yellow indications were tested. However, researchers studied the yellow indications at both San Antonio and Fort Worth locations in arrays consisting of only yellow symbols (arrows or Xs) and green arrows. In these type of LCS array configurations, drivers commonly interpret the yellow X (and the yellow diagonal arrow) as indicating the need to vacate the lane. Consequently, one would expect driver response to both symbols to be similar in these type of LCS arrays (as the evidence in this report indicates). The major question that still remains is whether the yellow X could be displayed in conjunction with a red X and green arrow(s) at an array location and achieve the same results.

5. LCS GUIDELINES AND RECOMMENDATIONS

The various research activities performed over the duration of this study have resulted in several practical recommendations regarding the design, installation, operation, and maintenance of lane control signals for freeway traffic management. These are summarized in the following sections. In particular, freeways serving a significant amount of tourist traffic requires LCS symbols that are immediately understood, whereas freeways serving primarily commuter traffic.

LCS DESIGN

- Operators or traffic agencies should test double-stroked LCS head designs prior to purchase to ensure that they can be adequately seen by older drivers. Large pixels (15 mm or more) coupled with a wide stroke width (38 mm) on 450-mm LCS symbols create irradiation problems for older drivers.

- The use of back panels on freeway LCSs is recommended to increase the conspicuity of the signals. Experiences in Fort Worth and San Antonio suggests a border of 150 mm around the signal is fairly effective.

- If cross-street bridge structures are available at appropriate locations for LCS mounting, they will generally provide superior target value for the LCS as compared to an overhead sign structure mounting location.

- The use of LCS with narrow (i.e., 20° cone of vision or less) may limit visibility of LCS from other lanes approaching the LCS array. Given that motorists consider the entire array at a location when interpreting the meaning and proper driving response to the signal in their lane, LCS with a wider cone of vision might be desirable in certain situations to allow maximum opportunities for motorists to see the array as they are approaching.

LCS INSTALLATION

- As a general rule, LCS should be installed at approximately 0.8 to 1.6 kilometer spacings. This results in drivers receiving lane status information approximately every 30 to 60 seconds when traffic conditions are uncongested. This is within the limited short-term memory span of drivers (30 seconds to 2 minutes) and so serves to help drivers retain lane status information.

- The choice of exact locations for LCS arrays should be based on principles of positive guidance, providing enough decision-reaction time at critical decision points, providing adequate sight distance, and avoiding areas of driver information overload.

- If LCS are to be mounted on overhead sign structures, traffic engineers should limit the number of guide signs displayed in conjunction with the LCS on a given structure to three panels or fewer, if possible.

- Efforts should be made to avoid installing LCS on horizontal curves to avoid parallax problems.

LCS OPERATIONS

- Operators should not turn on LCS heads until traffic surveillance is expected to be available along the freeway so that the LCS can be operated in real-time. It may be possible to install LCS upstream of sections where major freeway reconstruction is occurring and set the LCS displays in a static mode to indicate downstream lane closures. Other than for this special situation, however, LCS displays should not be activated if they cannot be operated in real-time.

- Yellow diagonal arrows and yellow X's appear to result in similar driver responses upstream of lane blockages, as long as the LCS array includes only the yellow symbol and green arrow. TxDOT should assess whether it desires the additional flexibility of displaying red X's, yellow symbols, and green arrows together on a single array. If so, the use of the yellow diagonal arrow will likely result in better motorist comprehension and understanding of appropriate driving actions.

LCS MAINTENANCE

- Maintenance crews should clean the pixels on LCS heads and replace bulbs on a regular (i.e., 6-months to 1-year) basis to maintain acceptable levels of visibility. Legibility distances will decrease by as much as 50 percent due to the accumulation of dirt on the pixel lenses over time.

6. REFERENCES

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APPENDIX: EFFECT OF LCS HEAD AGE ON LEGIBILITY

INTRODUCTION

This appendix presents the results of legibility studies of a used lane control signal (LCS) head manufactured by ElectroFiberoptics, Inc. The LCS head used for testing purposes was originally installed in the southbound direction of the Seminary Street overpass on I-35W in Fort Worth, Texas. As stated previously, signal installation occurred around 1989, making the device approximately 6 years old at the time of testing. In the spring of 1995, TTI purchased a replacement set of signal heads, which the Fort Worth District substituted for the original set of signals for the array. The Fort Worth District then sent one of the used signals to TTI in an "as is" condition, meaning that the signal lenses were neither cleaned nor were the bulbs replaced prior to shipping. The Fort Worth District reported that it had last maintained these signals in January 1994. Therefore, an approximate 18-month accumulation of dirt and road grime existed on the face of the signal. In addition, the light bulbs for the green downward arrow had experienced more than 4,000 hours of use (the bulbs for the other symbols likely experienced very few hours of use because the other symbols are displayed rather infrequently at that location).

TTI installed the used LCS head on an overhead sign truss at the proving grounds on the Texas A&M University Riverside Campus in June 1995. Researchers then performed a series of legibility studies on the signal in its "as is" state, and then after the face of the signal was cleaned and new light bulbs were installed for each of the symbols. These studies were completed in August 1995.

STUDY METHODOLOGY

Subjects, positioned as drivers in a standard passenger vehicle a given distance upstream of the signal head, were shown one of the three symbols (green arrow, yellow X, or red X) for a 1.5-second interval. The subject was then asked to identify the color and the symbol displayed. If the subject could not do this, he or she was moved closer to the signal, and the symbol was redisplayed for a 1.5-second interval. This process was repeated until the subject correctly identified the symbol.

The study design included 10 subjects less than 45 years old and 10 subjects age 65 or over. Subjects were split evenly between gender. One group of 20 subjects was used to evaluate the LCS head in its "as is" condition, and another group of 20 subjects evaluated the signal after it had been cleaned and the bulbs replaced. For each subject, the sequence of symbols presented was randomized to counterbalance any learning effects that might occur. All studies were conducted in bright sunlight between the hours of 10:00 am and 4:00 pm in July and August 1995.

RESULTS

Legibility Distances

Figures A-1 through A-3 present the "before" and the "after" maintenance median legibility distances recorded for the green arrow, yellow X, and red X, respectively. These data are separated according to the two age categories. The horizontal lines shown over each set of bar graphs are the median legibility distance for that symbol and age category for new signal heads (documented in the earlier study). As shown, the legibility distances before maintenance ranged between 183 and 335 meters for the under-45 age category, depending on the symbol. For the over-65 age category, legibility distances for these same symbols ranged between 107 and 274 meters. Generally speaking, the legibility distances for the green arrow and red X were fairly similar and lower than those obtained for the yellow X. In other words, the degradation of signal visibility over time due to dirt and light bulb intensity loss were more significant for the green arrow and red X than for the yellow X.

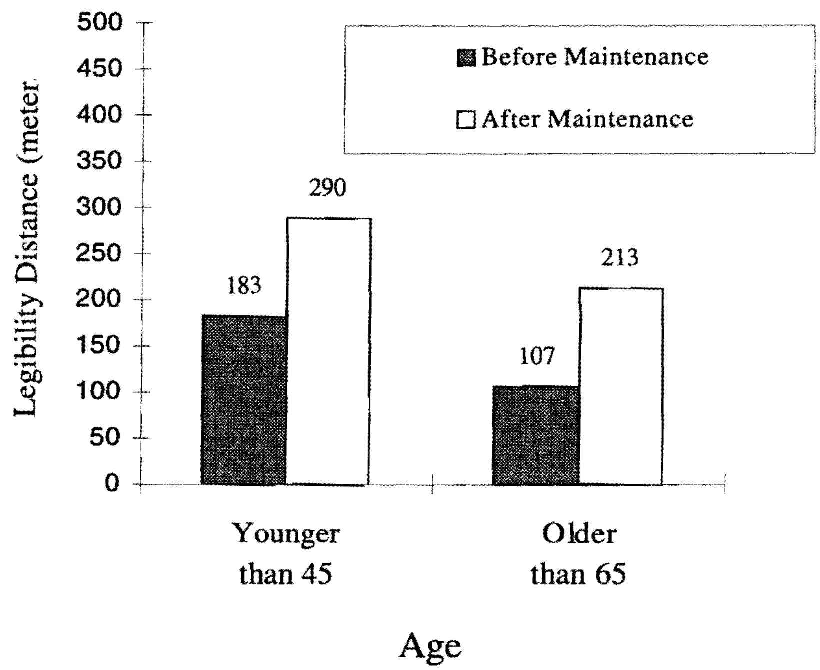

FIGURE A-1. Median Legibility Distances for the Green Arrow

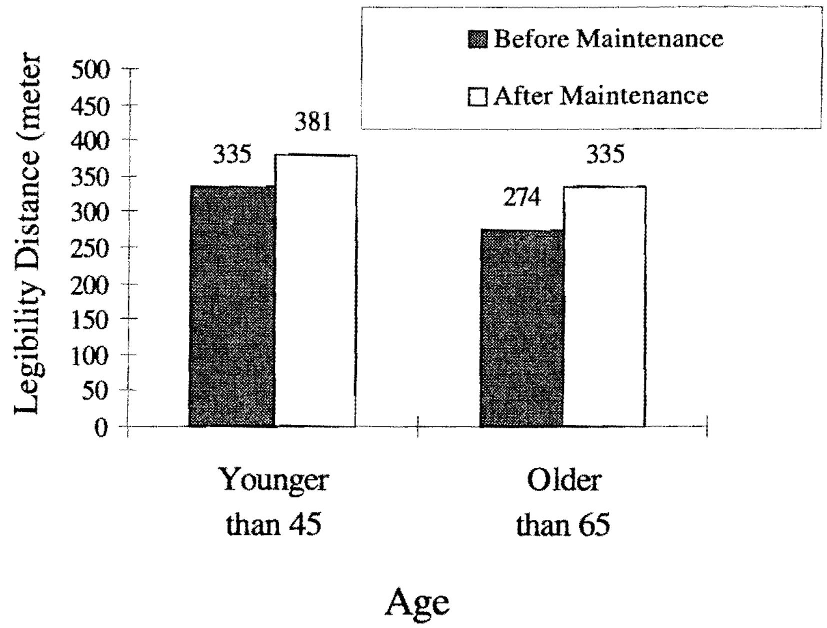

FIGURE A-2. Median Legibility Distances for the Yellow X

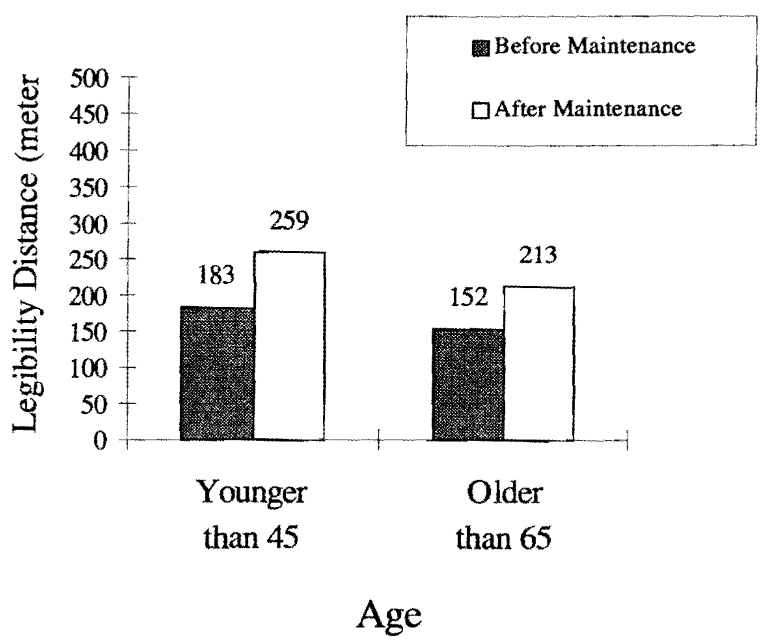

FIGURE A-3. Median Legibility Distances for the Red X

Figures A-1 through A-3 also show the median legibility distances for the three symbols after cleaning the signal lenses with solvent and a cloth and replacing each of the 50-watt halogen light bulbs in the signal face. Following these signal maintenance activities, visibility distances for the LCS ranged between 259 and 381 meters for the under-45 age category and between 213 and 335 meters for the over 65 age group. Again, the visibility of the yellow X was superior to either the green arrow or the red X. Interestingly, the maintenance of the signal returned the visibility of the yellow X by the over-65 age group to nearly that of a new signal. This did not occur for the other two symbols tested by that age group or for any of the symbols tested by younger age group.

Comparison to New Signal Legibility

For comparison purposes, Figures A-4 through A-6 present the visibility of each symbol before and after signal maintenance measured relative to the legibility distance of each symbol for a new signal head. These relative measures are again subdivided according to subject age. On a percentage basis, the visibility of the green arrow suffered the greatest over time. The visibility distance of the green arrow before signal maintenance was 35 to 43 percent of that of a new signal head (for the older and younger driver categories, respectively). In contrast, the visibility distance of the red X before signal maintenance was 49 to 53 percent of new signal capabilities (for the under-45 and over-65 age categories, respectively), and the legibility distance before maintenance for the yellow X was 73 to 88 percent of a new signal (again for the under-45 and over-65 age categories, respectively). The more substantial degradation of the legibility of the green arrow symbol is most likely attributable to a combination of halogen light bulb deterioration (these bulbs are on all the time unless an incident requires that a different symbol be displayed) and the accumulation of dirt and grime on the lenses of the fiberoptic pixels. Although the lenses of the red and yellow X would be expected to accumulate the same amount of road grime as the green arrow, the halogen light bulbs are not used nearly as much and so would not be expected to have deteriorated as significantly.

After cleaning the LCS and replacing the bulbs, the legibility distances for the green arrow and red X (as a percentage of the new signal legibility distances) became more consistent. For the under-45 age categories, the legibility distances after signal maintenance were 68 to 69 percent of those achieved by the new signal for the green arrow and red X, respectively. For the over-65 age category, the green arrow and red X legibility distances after signal maintenance were 70 to 74 percent of a new LCS, respectively. The relative legibility distance of the yellow X after signal maintenance was considerably higher than the other two symbols, reaching 83 and 96 percent of the new signal values for the under-45 and over-65 age categories, respectively.

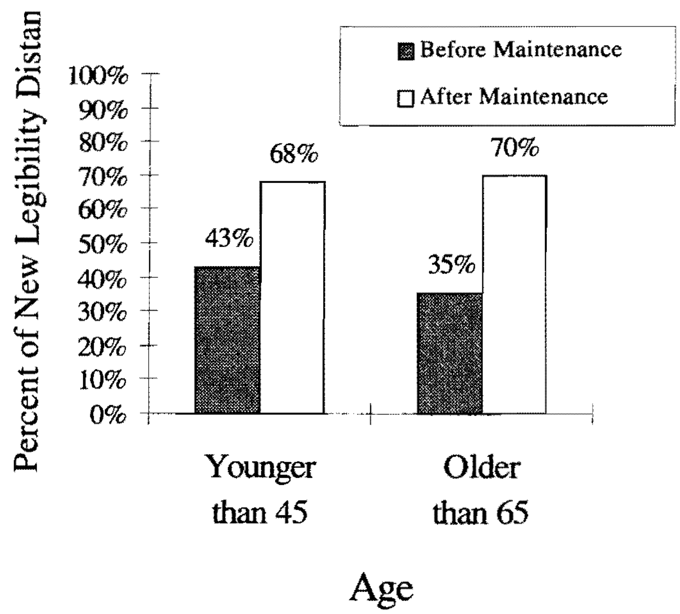

FIGURE A-4. Relative Legibility Distance: Green Arrow

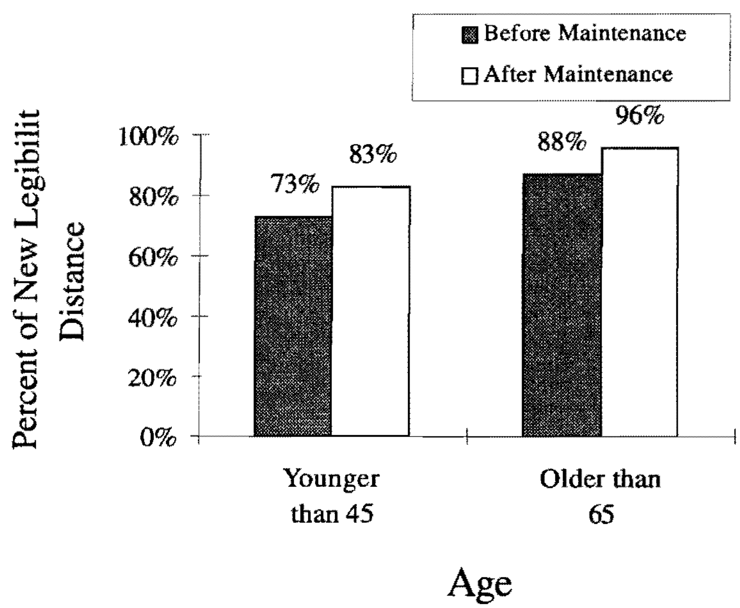

FIGURE A-5. Relative Legibility Distance: Yellow X

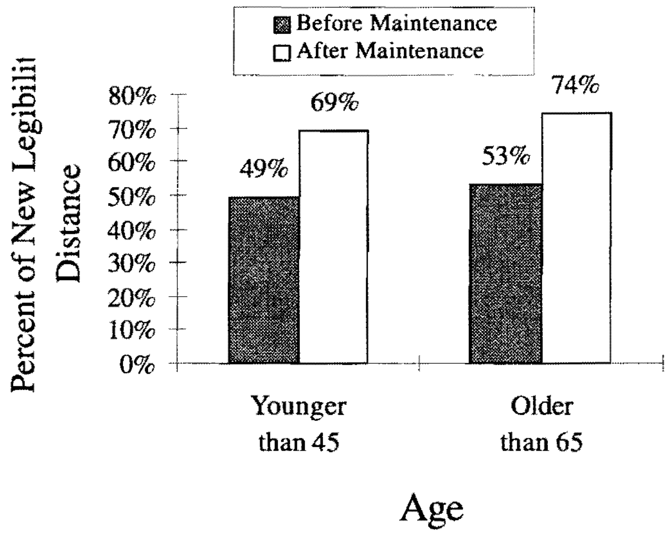

FIGURE A-6. Relative Legibility Distance: Red X

Effect of Signal Maintenance on Legibility

The final item of interest in this analysis is the measure of relative improvement achieved through the signal maintenance efforts. This measure is computed as shown below:

$$\frac{\text{(symbol leg. distance after maintenance) - (symbol leg. distance before maintenance)}}{\text{(symbol leg. distance of new signal) - (symbol leg. distance before maintenance)}} \times 100\%$$

In effect, this measure indicates how much of the loss in legibility distance due to signal aging was recouped through the maintenance efforts. Figure A-7 summarizes the relative improvement achieved by each of the three symbols for both age categories. Generally speaking, the relative improvements gained through maintenance were very consistent for each symbol for the younger driver age category, recouping 38 to 44 percent of the legibility distance lost over time by the signal.

Examined in this fashion, it is somewhat surprising that the relative improvement was not greater for the green arrow than for the other symbols. Recall that both the degradation in light bulb brightness and road grime accumulation were hypothesized as significant factors affecting the visibility of the green arrow, whereas only road grime was suspected as affecting the red and yellow X since they are not used all that extensively. However, it was noted during bulb replacement that those for both the yellow and red X were coated with a very heavy layer of dust, whereas the green arrow light bulbs looked relatively clean. It is possible that the red and yellow X bulbs had not last been changed in January 1994 as originally thought, but may have been in that signal head for several years. Whatever the reason, it could be that this layer of dirt reduced the reflected light brightness of the bulbs to the same degree as the long-term use of the bulbs for the green arrow reduced their output illuminance.

It is also interesting to note that the relative improvements in legibility distance were greater for the older driver age category for each symbol than they were for the younger driver age group. Signal maintenance resulted in older drivers regaining 44 to 52 percent of the legibility distances lost over time by the red X and green arrow, respectively. For the yellow X, signal cleaning and bulb replacement recouped almost all of the legibility distance that was lost over time for the older drivers.

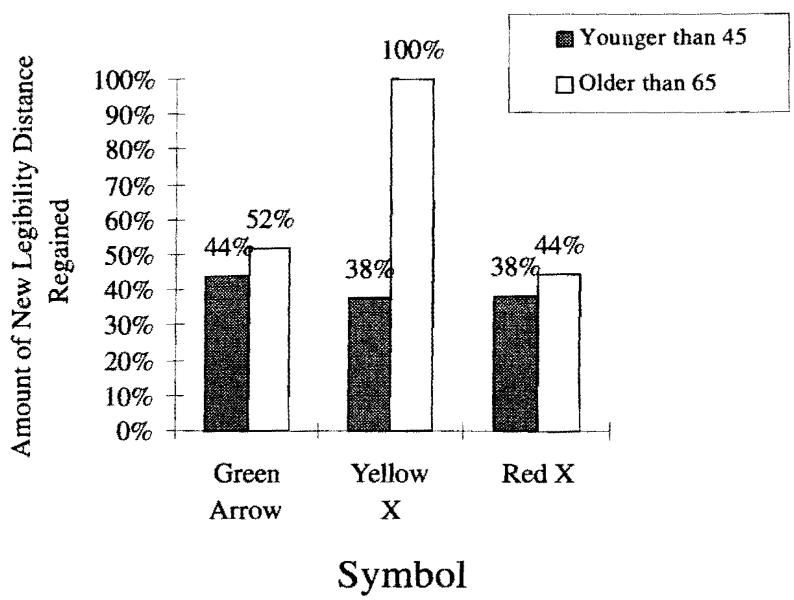

FIGURE A-7. Effect of Signal Maintenance to Regain Legibility Distance

SUMMARY

Plans exist in several Texas metropolitan areas to install fiberoptic LCSs on urban freeways. The results of the legibility distance study documented in this memorandum indicates that as these signals age, the visibility of the symbols displayed will diminish significantly. For the specific signal tested in this research, legibility distances for the green arrow and red X were less than one-half of what they were for a new LCS. Meanwhile, the legibility distance of the yellow X was about three-quarters of a new signal.

The results of this research illustrate the importance of a regular signal head cleaning and bulb replacement maintenance program to keep the LCS operating at an effective level. It appears that nearly one-half of the losses in legibility distance that occur over time (an approximate 18-month accumulation of road grime and bulb deterioration) can be recouped by cleaning the lenses of the signal pixels and replacing the light bulbs. For the six-year-old signal head examined in this research, median legibility distances of 213 to 381 meters were still achievable after the signal heads had been maintained. These values are 68 to 96 percent of the legibility distances expected for a new signal head of this type.