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16. Abstract

This report documents the results of field studies to assess driver response to freeway lane control signals (LCS) installed on a section of I-35W in Ft. Worth, TX. TTI researchers evaluated several alternative LCS configurations upstream of single- and double-lane closures. Researchers conducted all studies during daylight, off-peak traffic conditions.

Study results indicate that the LCS had no significant effect on travel speeds approaching and passing by the lane closures. The LCS were found to elicit a small but consistent shift in lane distributions from the closed lanes to open lanes upstream of the actual lane closure. Because of study limitations, direct comparisons between the yellow and red X upon lane distributions could not be made.

Based on the work performed throughout this study, several recommendations regarding lane control signal design, installation, and operation for freeway traffic management are presented in the last chapter of the report.

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By

Gerald L. Ullman

and

Poonam B. Wiles

Research Report 1298-2F
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Freeway Lane Control Signals

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IMPLEMENTATION STATEMENT

As a product of this research, several practical recommendations regarding LCS design, installation, and operations for freeway traffic management are presented at the end of this report. These include:

- Establishing operational policies and procedures for LCS prior to system design and installation,
- Incorporating flexibility in LCS system components,
- Considering horizontal and vertical alignment of LCS arrays when selecting mounting locations,
- Placing LCS display units directly over through travel lanes, and
- Establishing a regular LCS display unit cleaning schedule.

Recommendations for future research include:

- Field testing of a downward diagonal arrow to determine its influence upon traffic operations and safety,
- Testing appropriate methods for indicating the closure of multiple lanes via LCS,
- Testing the effect of flashing LCS displays upon target value, and
- Further testing of the use of combined LCS/CMS displays.

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 does not constitute a standard, specification, or regulation, nor is it intended for construction, bidding, or permit purposes. The engineer in charge of the project was Mr. Gerald L. Ullman (Texas P.E. registration #66876).

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SUMMARY

This report presents the results of three field studies of LCS conducted on I-35W in Ft. Worth, Texas. Two studies involved the closure of the right two out of four travel lanes. TTI researchers conducted a third study during the temporary closure of the inside travel lane, also on a four-lane section of freeway. Two of the studies explored the effects of alternative LCS configurations in isolation and in conjunction with CMS messages upon driver behavior. The major findings from these studies are as follows:

- None of the LCS configurations tested significantly reduced speeds upstream of the lane closures or past the work site.

- When double yellow Xs and double red Xs were displayed on sequential LCS arrays upstream of a two-lane closure, a 3.5 percent shift in traffic from the closed lanes to the open lanes was observed just downstream from the yellow X array, and a larger 6.2 percent shift in traffic from closed lanes to the open lanes just upstream of the beginning of the cone taper. These were equivalent to 10.0 and 24.3 percent reductions, respectively, in traffic volumes in the closed lanes at those data collection locations.

- It appeared that the red X could not be seen from as far away as a yellow X at one site. This may have affected the change in lane distributions observed at one data collection location during one of the studies.

- The effect of a single yellow X displayed over an inside travel lane appears to be consistent from location to location along the same freeway section.

- TTI researchers and TxDOT personnel alike noticed that LCS visibility was poor during the initial field study. TxDOT maintenance crews subsequently cleaned away substantial dirt and grime from the LCS lens, which had accumulated over the five-year period they had been in place over the freeway. This improved visibility considerably.

1. INTRODUCTION

Background

The Manual of Uniform Traffic Control Devices (MUTCD) allows overhead lane control signals (LCS) on freeways to notify traffic that it is necessary to stay out of certain lanes at certain hours; that a lane is ending (at the terminus of a freeway); or that a lane is temporarily blocked by an accident, stalled vehicle, etc. (1). The LCS allow a traffic management system operator to provide motorists with real-time information about the driving condition of the travel lanes. Although LCS are permitted for freeway use, they have not been used very often for this purpose in the United States. For example, operational tests of LCS for freeway traffic management occurred in the 1960s as part of the Detroit freeway surveillance and control project (2). Minneapolis now employs LCS on portions of its freeway system, and the Virginia Department of Transportation installed LCS over the shoulders of portions of the freeway system to notify drivers when the shoulder can be utilized as a temporary travel lane (typically during peak periods) (3). Overall, though, there is very little data available as to how LCS affect driving behavior and resulting safety and operational measures-of-effectiveness.

The Texas Department of Transportation (TxDOT) is planning to use LCS as an integral part of the computerized freeway traffic management systems now being implemented in the six largest urban areas in Texas (Austin, Dallas, El Paso, Ft. Worth, Houston, San Antonio). The Austin District of TxDOT has begun planning for its freeway traffic management system. The Dallas District is in the design stage of their system, whereas the San Antonio and El Paso Districts are installing their systems. The Ft. Worth and Houston Districts already have certain system components already installed and are quickly approaching operational status.

Interestingly, significant differences in design and operational philosophies exist between the latter three Districts. The Houston District is installing two sets of LCS in conjunction with changeable message signs (CMS) in advance of major freeway interchanges. Ultimately, they will install approximately 100 LCS heads throughout Houston. This is a design similar to that installed in Austin in 1982 on the approaches to the split between lower-level regular travel lanes and upper-level express lanes on the double-decked section of I-35 near downtown (4) (the Austin system has since fallen into a state of disrepair and is no longer operational).

Whereas the Houston District has adopted an interchange-based LCS design strategy to supplement CMS displays, both the San Antonio and Ft. Worth Districts have pursued a more systemwide implementation of freeway LCS. Plans for the San Antonio system include approximately 500 LCS installation locations. This represents an approximate 1 mi (1.6 km) spacing of the LCS on 190 mi (305.9 km) of freeway, with closer 0.5 mi (0.8 km) spacing near major freeway interchanges. In Ft. Worth, the TxDOT District is installing approximately 860 LCS heads on 80 mi (128.8 km) of freeway, also at average spacings of between 0.5 and 1.0 mi (0.8 and 1.6 km).

TxDOT's planning and design experiences with their freeway traffic management systems have generated a number of questions as to how to best design, install, and operate freeway LCS. These questions range from basic design issues for freeway applications (i.e., the symbols that should be used as well as their color, size, and brightness), to proper installation principles (including spacing, mounting location, and orientation), to strategies for safe and efficient operations (i.e., which symbols to display, how they should be sequenced, how far upstream they should be displayed, etc.). To begin to address those questions, TxDOT and the Federal Highway Administration (FHWA) jointly sponsored a two-year research study by the Texas Transportation Institute on freeway LCS. This document is the final report from that study.

Scope of Research

Because it was not feasible to study all of the issues identified pertaining to freeway LCS, TTI and TxDOT personnel overseeing the research decided to focus on two main topic areas during the two-year research effort. During the first year of research, several laboratory studies were conducted to assess motorist comprehension of standard MUTCD and various candidate symbols for freeway LCS. Through these studies, researchers explored the system effects of LCS upon symbol interpretation; that is, how the other symbols displayed over other lanes in an LCS array at a location affect motorists interpretations of an individual symbol. A separate interim report documents the results of that research (5).

Study researchers devoted the second year of research to evaluating how LCS affect actual freeway traffic operations. At the time of the study, only Ft. Worth had LCS installed and available for testing. However, the interconnection and central control components of the system did not come online until near the end of the second year. Consequently, the field studies were much more labor-intensive, requiring personnel to change the LCS displays directly from controller cabinets adjacent to each LCS array location. In addition, automated data collection along the freeway via the loop detection system was not yet available; so, research personnel used portable count equipment and manual counts from videotape.

TTI researchers conducted three separate field studies in Ft. Worth to compare the effect of alternative LCS displays (using the standard MUTCD symbols for freeway LCS) upon motorist behavior. The results of these studies are the main focus of this final report. Supplementing the field study discussion, however, is a chapter presenting several practical recommendations regarding freeway LCS. These recommendations are based in part on the results of the laboratory and field studies. Perhaps more importantly, though, the recommendations also include several suggestions resulting from actual TxDOT experiences (particularly the Ft. Worth District) as they progressed through system planning, design, and construction of their traffic management system.

A second TxDOT and FHWA-sponsored research effort is now underway to address more freeway LCS issues (6). Specifically, researchers will explore LCS spacing and location requirements as well as visibility issues during the first year of that study. Researchers then plan to conduct additional operational studies of freeway LCS, focusing on non-standard LCS symbols that have been recommended for application. The results of this second research effort will be forthcoming in future reports.

2. OPERATIONAL FIELD STUDIES OF FREEWAY LCS IN FT. WORTH, TEXAS

Real-Time LCS Field Study Driver Response Issues

The laboratory studies conducted during the first year of this research provided valuable insight into how drivers perceive LCS symbols presented in an urban freeway driving environment, and how they should react to them (5). Because drivers' actions often differ from their interpretations of proper driving response, actual field data must be collected in order to determine how drivers actually do react to freeway LCS, and how these reactions translate into changes in traffic operations and safety. Consequently, TTI researchers conducted a series of operational studies to measure driver response to select LCS displays under actual field conditions. Researchers performed the studies on a section of I-35W in Fort Worth, Texas, where LCS were installed, operational (albeit on a limited basis), and available for study (Figure 2-1). This section of freeway also has other features, described below, which facilitated the research. Questions considered in the studies about driver field response to LCS included:

- How do LCS displays affect lane distributions, speeds, and other measurable driving characteristics?
- Where does driver response occur after viewing an LCS display?
- How do the red X and yellow X LCS symbols compare in terms of their effect upon driver response?

Description of the Field Studies

Researchers utilized a section of I-35W in TxDOT's Fort Worth District for the three field studies conducted during 1993. This freeway was the first in Texas that had a series of freeway LCS arrays installed that could be used for testing. The freeway section is heavily instrumented with closed-circuit television (CCTV), surveillance loop detection, and a satellite operations center (a control building). Researchers conducted all three studies during pre-planned maintenance activities at three locations along the freeway. For each of the three studies, maintenance personnel implemented an actual physical lane closure as per standard TxDOT traffic control plans utilizing advance warning signs, cone tapers, and flashing arrow panels.

For the purpose of these studies, an LCS display is defined as a signal indication on one LCS head mounted over one lane. Displays available for testing included a downward-pointing green arrow, yellow X, and a red X (standard symbols specified in the MUTCD for LCS). LCS displays located over each freeway lane at a single station and visible to drivers approaching from a given direction are referred to as an "array." All of the LCS displays in an array may be viewed concurrently by approaching drivers. As the driver proceeds along the freeway, sequential LCS arrays have been identified in this study as a "configuration." A study configuration denotes a series of arrays which, when used in conjunction with each other, attempt to convey a related idea (such as an impending lane closure). Study researchers presented various LCS configurations for intervals of approximately 30 minutes in duration. In these studies, drivers were able to view configurations with up to three LCS arrays as they approached the physical lane closure.

Figure 2-2 shows the layout of the I-35W study section, identifying entrance and exit ramps, LCS locations, CCTV camera poles, surveillance detector loop stations, and the building site for the satellite operations center. Data collected during the studies included CCTV videotape of traffic flow in all freeway lanes at selected locations, loop detector volumes by lane in five minute intervals, floating car speed information, and drive-through videotape documentation of the study site. The studies were conducted during off-peak daylight hours between 9:00 AM and 4:00 PM when traffic volumes were lower and sight distance to the lane closures was adequate. Also, because the LCS had to be operated manually from the roadside controller cabinets, researchers conducted the studies during normal working hours when TxDOT personnel were available to help with the studies and to do the actual maintenance work.

Scope of the Studies

The field studies were limited to the geometric and work zone constraints of the study sites (i.e., one or two-lane closures on a four-lane freeway section). It is not known whether the results of these studies can be transferred to other freeway sections with different traffic characteristics, geometrics, or work zone conditions. Also, two of the studies involved outside lane closures near exit and entrance ramps. The ramps were left open during the studies, but did not appear to affect the study results for driver response to the LCS.

Study A Objectives, Procedures, and Results

Objectives and Procedures

TTI researchers conducted Study A on January 21, 1993, a clear and bright sunny day. The study site was located on a northbound section of the I-35W freeway, as shown in Figure 2-3. The detector loop in the outside lane (lane 4, with lane 1 denoted as the median lane and numbered consecutively) just prior to Berry St. required repair, which necessitated the closure of the outside travel lane. The Fort Worth District maintenance personnel set up the traffic control and conducted the loop replacement operation on the freeway.

Once the basic lane closure strategy had been determined by TxDOT maintenance personnel, study researchers designed an evaluation of alternative LCS configurations upstream of the work zone. Initially, the study had two main objectives:

1. Determine driver response to standard LCS configuration of a yellow X followed by a red X symbol in advance of a lane closure.

2. Determine how a CMS display notifying drivers of the lane closure affects motorist responses to the LCS configurations.

LCS displays and changeable message sign (CMS) messages were changed by Fort Worth District staff as the study progressed. Drivers were shown LCS displays on the approach to the lane closure at three separate locations; Felix St., Seminary Dr., and Ripy St. (see Figure 2-3). The Ripy St. LCS array was located just upstream (500-1000 ft [(152-305 m]) of the beginning of the cone taper for the lane closures. The Seminary Dr. LCS were situated another 4700 ft (1433 m) upstream, and the initial LCS at Felix St. were another 3100 ft (950 m) upstream of that. Using these three LCS arrays, study researchers evaluated five different LCS configurations during the study. Table 2-1 summarizes these configurations.

TABLE 2-1. LANE CONTROL SIGNAL ARRAYS FOR STUDY A

Configuration[a]	LCS Array at Felix	LCS Array at Seminary	LCS Array at Ripy	CMS Message
1	off	off	off	off
2	↓ ↓ ↓ ↓[b]	↓ ↓ ↓ YX	↓ ↓ ↓ RX	off
3(mod.)[c]	↓ ↓ ↓ ↓	↓ ↓ YX YX	↓ ↓ RX RX	off
4(mod.)	↓ ↓ ↓ YX	↓ ↓ YX RX	↓ ↓ RX RX	off
5(mod.)	↓ ↓ ↓ YX	↓ ↓ YX RX	↓ ↓ RX RX	Flashing[d] Message

[a] Each configuration was in place for at least 30 minutes, with a 5-minute clearance interval between configurations. Reading from left to right, the array symbols correlate to lanes 1 through 4.

[b] ↓ - green arrow   YX - yellow X   RX - red X

[c] (mod.) - field modification of configurations was required due to additional closure of lane 3.

[d] Flashing CMS message consisted of: ROAD WORK AHEAD
FORM TWO LINES LEFT

Turning off all LCS and CMS displays constituted configuration 1, which served as the control condition. In configuration 2, drivers approaching the work zone saw a yellow X in lane 4 at Seminary Dr., and a red X at Ripy St. Study researchers modified the original study design after collecting data for configuration 2, when maintenance repair difficulties necessitated the additional closure of lane 3. In configuration 3 (when lane 3 was closed as well), drivers encountered two yellow Xs over lanes 3 and 4 at Seminary, followed by two red Xs at Ripy St. A different closure philosophy was tested in configuration 4, where only one yellow X was displayed at a time to motorists. In this configuration, drivers saw a yellow X in lane 4 at Felix St., followed by yellow X and red X in lanes 3 and 4 at Seminary, and finally two red Xs in lanes 3 and 4 at Ripy St. In effect, this configuration mimicked the standard traffic control method for a multiple freeway lane closure. Finally, configuration 5 displayed the same LCS sequence as configuration 4, but added a CMS message upstream of Seminary warning drivers of the downstream lane closure. Because of a change in the work zone traffic control plan, it was not appropriate to compare conditions during configuration 2 with the latter configurations.

Effect of LCS Configuration on Traffic Speeds

In general, the display of alternative LCS configurations upstream of the lane closure at this site had no appreciable effect on speeds through the study section. Average floating vehicle travel times collected during each test configuration, shown in Table 2-2, were essentially identical (differing by less than 4 seconds [1.5 percent]). In terms of average travel speeds over the 4.5-mi [7.2 km] study section, differences between any two LCS configurations were less than 1 mph (from 59.9 to 60.8 mph [96.4 to 97.9 km/h]).

TABLE 2-2. EFFECT OF LCS UPON TRAVEL TIMES: STUDY A

LCS Configuration	Average Travel Time, Min:Sec (sample size)	Average Travel Speed, Mph (Km/h)
1	4:26 (n=7)	60.5 (97.4)
2	4:25 (n=6)	60.8 (97.9)
3	4:29 (n=6)	59.9 (96.4)
4	4:27 (n=5)	60.2 (96.9)
5	4:29 (n=5)	59.9 (96.4)

Mph = miles per hour
Km/h = kilometers per hour

The freeway loop detectors at Berry street (where the work activity occurred in lanes 3 and 4) provided spot speed data for lanes 1 and 2 past the work zone. These data indicate that there was no effect of LCS configuration upon speeds in the open travel lanes past the work site. As shown in Table 2-3, average spot speeds differed by no more than 1.4 mph (2.3 km/h), ranging from 55.0 mph (88.6 km/h) to 56.4 mph (90.8 km/h) between configurations. None of these average speeds were significantly different than the 55.9 mph (90.0 km/h) average speed recorded during configuration 1, when all LCS and the CMS were turned off. The LCS configuration also had no appreciable effect on the variability of the spot speeds, as evidenced by the nearly identical standard deviations shown in Table 2-3. This result was not unexpected, since the data comes from a location downstream of the actual bottleneck (i.e., the lane closure). Spot speed data just upstream of the bottleneck would have provided a better indication of any effect of LCS on the traffic within the merge area. However, these data were not available for this study.

TABLE 2-3. EFFECT OF LCS UPON SPOT SPEEDS: STUDY A

LCS Configuration	Average Spot Speed, Mph (Km/h)	Standard Deviation of Speeds, Mph (Km/h)
1	55.9 (90.0)	5.4 (8.7)
2	56.4 (90.8)	5.0 (8.1)
3	55.7 (89.7)	5.3 (8.5)
4	55.8 (89.8)	5.5 (8.9)
5	55.0 (88.6)	5.3 (8.5)

Mph = miles per hour
Km/h = kilometers per hour
sample sizes ranged from 250 to 500 vehicles per configuration

Effect of LCS Configuration on Lane Volume Distributions

The I-35W CCTV system collected volume data from the freeway mainlanes at three locations upstream of the lane closure. Research then analyzed these volumes to determine whether any of the various LCS configurations affected the relative distribution of traffic in each lane at those locations. For all of the studies, researchers selected the first location upstream of the first LCS array used in the configuration to serve as a control. Since traffic at that first location had not yet been exposed to alternative LCS arrays, researchers hypothesized that there would be no change in lane distributions at that location. If this occurred, then changes in lane distributions measured at the other two locations farther downstream could be assumed to reflect the influence of the LCS configuration.

For Study A, researchers measured volumes just north of the entrance ramp from I-20, followed by measurements south of the entrance ramp from Seminary Drive and again just north of the exit ramp to Ripy St. (see Figure 2-3). Consequently, changes in the lane distribution at the second location illustrated the influence of changes in the Felix Street and Seminary Drive LCS arrays plus the changeable message sign (CMS) just to the south of Seminary Drive (when activated for configuration 5). In comparison, data from the third location reflected the influence of changes in those upstream LCS and CMS displays plus any additional effect of the different LCS arrays at Ripy St. Student technicians reduced the lane volume data into five-minute intervals to coincide with initiation and termination times of each configuration. A five-minute transition period separated each change in LCS configuration to allow traffic caught within the transition to clear the section before data collection resumed.

Researchers employed identical data analysis procedures for each location, designed to detect significant changes in the amount of traffic using the lanes closed downstream at the work zone versus the amount of traffic using the open lanes. Specifically, researchers relied upon categorical data analysis techniques to test for any changes in the relative proportions using the open and closed lanes at each location (the intent of the LCS and CMS configuration was to increase the proportion using the open lanes at the second and third data collection locations). The appendix at the end of this report presents the details of the statistical analyses.

A change in the traffic control plan at the work site during the study required researchers to compare configuration 2 separately against configuration 1 (the control condition), and not against the other configurations. Researchers used the same analysis approach, comparing the distribution of traffic in open and closed lanes, but considered only the shoulder lane (lane 4) closed.

Tables 2-4 and 2-5 present the lane distributions recorded at each location during the study. As expected, the distribution of traffic in open and closed lanes at location I for any of the alternative LCS configurations were not significantly different than for configuration 1 (the control condition). Table 2-4 shows that configuration 2 had no appreciable effect upon traffic distributions at locations II and III as well; whereas, Table 2-5 indicates that only configuration 5 significantly affected traffic measured at location III, resulting in a 4.1 percent shift in the distribution of traffic in the closed and open lanes at that location. In terms of the amount of traffic in the closed lane, this 4.1 percent shift represents a 7.3 percent reduction in closed lane traffic volumes at that location.

TABLE 2-4. EFFECT OF LCS UPON LANE DISTRIBUTIONS: STUDY A (SINGLE-LANE CLOSURE)

LCS Configuration	Percent[a] of Traffic in:		Statistical Significance
	Open Lanes	Closed Lanes	
Location I:			$X^2 = 2.6$
1 (control)	58.8	41.2	configurations are not
2	55.6	44.4	significantly different[b]
Location II:			$X^2 = 1.4$
1 (control)	48.5	51.5	configurations are not
2	47.8	52.2	significantly different[b]
Location III:			$X^2 = 3.2$
1 (control)	44.0	56.0	configurations are not
2	44.9	55.1	significantly different[b]

a total volumes ranged between 2200 and 2500 vph at each location

b $X^2_{(0.05,1)} = 3.8$

The effect of configuration 5 was most likely a result of the CMS display provided rather than the LCS, since the analysis did not detect a similar change in traffic distribution at location III for configuration 4 (which was identical to configuration 5 but without the CMS present). The lack of LCS effect was, in all likelihood, due to a lack of LCS visibility during the study because of the bright sunlight. As the study progressed, data collection personnel noted that the LCS displays themselves were very hard to see and thus provided little stimulus to drivers to exit the closed lanes.

TABLE 2-5. EFFECT OF LCS UPON LANE DISTRIBUTIONS: STUDY A (TWO-LANE CLOSURE)

Configuration	Percent[a] of Traffic in:		Statistical Significance
	Open Lanes	Closed Lanes	
Location I:			$X^2 = 4.4$
1 (control)	41.2	58.8	
3	39.7	60.3	configurations are not
4	38.3	61.7	significantly different[b]
5	39.7	60.3	
Location II:			$X^2 = 7.4$
1 (control)	48.5	51.5	
3	50.0	50.0	configurations are not
4	49.7	50.3	significantly different[b]
5	53.3	46.7	
Location III:			$X^2 = 7.8$
1 (control)	44.0	56.0	
3	46.2	53.8	configuration 5 differs from
4	44.1	55.9	configurations 1 and 4[b]
5	48.1	51.9[c]	

a total volumes ranged from 2200 to 2500 vph at each location

b $X^2_{(0.05,3)} = 7.8$

c The 4.1 percent shift (relative to configuration 1) is equal to a 7.3 percent reduction in closed lane traffic volumes at that location

Study B Objectives, Procedures, and Results

Objectives and Procedures

TTI researchers conducted a second field study in the southbound direction of I-35W on January 26, 1993. Weather conditions during this study were again clear and sunny with dry pavement. However, the orientation of the sun did not cause as much of a glare problem as it did for Study A (since vehicles travelled in the opposite direction). The concrete adjacent to the surveillance loop in lane 3 just beyond Allen Ave. needed repair (see Figure 2-4). However, the loop detectors at that location were operational. Again, TxDOT District maintenance forces performed the maintenance work and set up the necessary traffic control. The traffic control plan required the closure of lanes 3 and 4 during the off-peak hours between 9:00 AM and 3:30 PM. TxDOT District personnel were also responsible for changing the LCS displays at the roadside controllers and the CMS messages at the operations center as the study progressed.

TxDOT officials did not expect the work zone operation to last for more than a few hours. Consequently, researchers evaluated a control configuration (no LCS) and two alternative configurations. Since the work zone layout for this study was identical to what ultimately evolved for Study A, researchers studied an LCS configuration identical to one of those tested in that study. Specifically, the objectives of Study B were to:

1. Determine how drivers respond to an LCS configuration warning of a two-lane work zone lane closure; and

2. Determine how a CMS message, also warning of the downstream lane closure, affects driver response to an LCS configuration.

Table 2-6 presents the LCS arrays displayed for Study B. Referring back to Table 2-1, these are similar to the modified LCS configuration 3 tested in Study A. Drivers approaching the work activity were first shown two yellow Xs at Hattie St.(approximately 4300 ft [1300 m] upstream of the lane closure), followed by two red Xs displayed at Allen St. (located just at the beginning of the work zone cone taper). LCS configurations 2 and 3 were identical except for the CMS message displayed between Hattie St. and Allen Ave. during configuration 3, which told motorists to move to the two left lanes. Because of the proximity of a railroad overpass just upstream, sight distance to the Hattie St. LCS was limited to only a few hundred feet.

TABLE 2-6. LANE CONTROL SIGNAL ARRAYS FOR STUDY B

Configuration[a]	LCS Array at Hattie	LCS Array at Allen	CMS Message
1	off	off	off
2	↓ ↓ YX YX[b]	↓ ↓ RX RX	off
3	↓ ↓ YX YX	↓ ↓ RX RX	Flashing Message[c]

a Each configuration was in place for at least 30 minutes with a 5-minute interval between configurations. Reading left to right, array symbols correlate to lanes 1 through 4.

b ↓ - green arrow YX - yellow X RX - red X

c Flashing CMS message consisted of: ROAD WORK AHEAD
FORM TWO LINES LEFT

Effect of LCS Configuration on Travel Times

Table 2-7 summarizes the average travel times and corresponding average speeds over the section of freeway evaluated in study B. As with Study A, the LCS configurations in Study B had very minimal effects upon travel times and speeds. Travel times during configurations 2 and 3 were only 6 and 2 seconds faster, respectively, than they were for configuration 1.

Spot speed data were not available at the point of work activity for Study B. Rather, the researchers utilized speed data from a loop detector station approximately 1 mile (1.6 km) upstream of the two-lane closure adjacent to the exit ramp to Rosedale St. (see Figure 2-4). Data from that station, presented in Table 2-8, indicate no significant difference in average spot speeds in the open lanes (the two inside lanes) as a function of the LCS configuration.

However, analysis results indicated slight increases in spot speeds (1.5 to 1.7 mph [2.4 to 2.7 km/h]) for the two outside lanes (those closed downstream) as shown in Table 2-8. At this data collection station, motorists have just passed one set of LCS at Hattie St. (displaying two yellow Xs over the outside lanes during configurations 2 and 3). Although the increases in spot speeds are statistically significant, it is not immediately apparent whether these increases are of a practical significance. However, it is apparent that the alternative LCS configurations did not significantly reduce average speeds upstream of the closure.

TABLE 2-7. EFFECT OF LCS UPON TRAVEL TIMES: STUDY B

LCS Configuration	Average Travel Time, Min:Sec (sample size)	Average Travel Speed, Mph (Km/h)
1	2:24 (n=6)	51.7 (83.2)
2	2:18 (n=6)	54.0 (86.9)
3	2:22 (n=6)	52.5 (84.5)

Mph = miles per hour
Km/h = kilometers per hour

TABLE 2-8. EFFECT OF LCS UPON SPOT SPEEDS: STUDY B

LCS Configuration	Average Spot Speed, Mph (Km/h)		Standard Deviation of Speeds, Mph (Km/h)	
	Open Lanes	Closed Lanes	Open Lanes	Closed Lanes
1	56.8 (91.4)	57.0 (91.8)	6.5 (10.5)	6.8 (10.9)
2	56.9 (91.6)	58.5 (94.2)	6.3 (10.1)	6.4 (10.3)
3	57.7 (92.9)	58.7 (94.5)	6.3 (10.1)	6.4 (10.3)

sample sizes averaged 300 to 500 vehicles per configuration
Mph = miles per hour
Km/h = kilometers per hour

Effect of LCS Configuration Upon Lane Volumes

The I-35W CCTV system recorded freeway lane volumes at three locations upstream of the lane closure:

- Immediately south of the exit to Hattie St.,
- Immediately south of the exit to Rosedale St., and
- Immediately north of the entrance from Rosedale St. (approximately 1000 ft [305 m] prior to the LCS array at Allen Ave).

Again, the first location served as a control station prior to the potential influence of the LCS configurations. In actuality, the LCS at Hattie St. could just be seen from the first data collection location, but the researchers felt that drivers did not have sufficient time to react to the array before being counted at that point. Consequently, the second location then reflected the influence of the Hattie St. LCS; whereas, the third station reflected the combined influence of the Hattie St. LCS plus the influence of the CMS displayed during configuration 3. Although visibility of the LCS was better during Study B than for Study A, the displays were still not bright enough for motorists to see the LCS at Allen Ave. from the third data collection location. Whereas TxDOT standards specify that the LCS should be visible 800 feet (243.9 m), it was estimated that they were visible for a distance of only 300 to 500 ft, depending the array.

Table 2-9 presents the average distributions of traffic in the open and closed lanes at each location during each LCS configuration. Statistical analyses, performed to verify the consistency of lane utilization at location I for the three configurations, showed that the distribution of traffic across the open and closed lanes at that location were different for configuration 3 than for configurations 1 and 2. Upon closer scrutiny, researchers noted that volumes during the testing of configuration 3 were substantially higher (by approximately 25 percent) than they were during the testing of configurations 1 and 2. Apparently, this increase was enough to alter the lane distributions at the first data collection location, and so any differences between configuration 3 and configurations 1 and 2 at the downstream data collection locations could not be attributed solely to the differences between configurations. Therefore, subsequent analyses focused solely on the differences between configurations 1 and 2.

TABLE 2-9. EFFECT OF LCS UPON LANE DISTRIBUTIONS: STUDY B

Configuration	Percent[a] of Traffic in:		Statistical Significance
	Open Lanes	Closed Lanes	
Location I:			$X^2 = 0.7$
1 (control)	64.5	35.5	
2	65.8	34.2	configuration 2 does not
3	58.3	41.7	differ from configuration 1[b]
Location II:			$X^2 = 3.2$
1 (control)	65.1	34.9	
2	68.6	31.4	configuration 2 does not
3	70.0	30.0	differ from configuration 1[b]
Location III:			$X^2 = 12.6$
1 (control)	74.5	25.5	
2	80.7	19.3[c]	configuration 2 differs from
3	80.3	19.7	configuration 1[b]

[a] total volumes ranged between 2200 and 2400 vph at each location

[b] $X^2_{(0.05,1)} = 3.8$

[c] The 6.2 percent shift (relative to configuration 1) represents a 24.3 percent reduction in closed lane traffic volumes at that location

Analyses at location II showed that the lane distributions were not significantly different between configurations 1 and 2. At location III, however, the LCS significantly increased the proportion of traffic traveling in the open lanes. Here, there was a 6.2 percent shift in traffic from the closed lanes to open lanes during configuration 2 relative to configuration 1 (25.5 percent minus 19.3 percent). This 6.2 percent change in closed versus open lane traffic distribution from configuration 1 to configuration 2 represents a 24.3 percent reduction in the traffic volumes expected in the closed lanes at that location.

At this time, it is not known whether the display of two yellow X indications together in a single LCS array is as conducive to the safe and efficient closure of travel lanes as a sequencing of single-lane closures. In Study B, no erratic maneuvers or vehicular conflicts occurred at locations II and III during testing of configurations 2 and 3. Rather, the data show some drivers shifting to the open lanes as a result of displaying two yellow Xs on the same array at Hattie St. Unfortunately, there was not enough time available to compare how drivers respond when red Xs were displayed instead of yellow Xs at Hattie St.

It is also difficult to draw solid conclusions as to the effect of the CMS upon lane distributions at data collection locations II and III for Study B. Although the distributions at these locations are similar for configurations 2 and 3 (the LCS configuration with and without a CMS), a higher closed-lane distribution existed for configuration 3 at the start of the study section (i.e., at location I). Whether or not this indicates that the CMS had a substantial incremental effect upon the lane distribution, or is the natural lane distribution pattern that results when lane volumes increase, could not be determined from the data. Additional study of the CMS under lower volume conditions (when the lane distributions at location I would be comparable) and under a no-LCS condition is needed to more fully understand the interactions between the CMS and LCS effects upon drivers.

Study C, Objectives, Procedures, and Results

Objectives and Procedures

Following the two studies performed in January 1993, TxDOT personnel determined that a significant part of the LCS visibility problems experienced during those studies were due to dirt accumulation on the LCS lens faces. Maintenance personnel thus embarked on a cleaning program of the I-35W LCS to improve visibility.

After TxDOT maintenance crews cleaned the LCS, TTI researchers conducted a third study of a single-lane closure of the median lane (lane 1) implemented prior to the southbound LCS array at Felix St. Figure 2-5 presents a schematic of the third study site. TxDOT personnel closed the lane to perform maintenance work on the median-mounted CMS at that location. TTI researchers conducted the study on July 14, 1993, between the off-peak hours of 9:30 AM and 4:00 PM under fair skies and dry pavement conditions.

The objectives of the third study were to:

1. Determine if the LCS lens cleaning had significantly improved visibility,

2. Determine driver response to LCS configurations that indicate an inside lane closure,

3. Compare the effect of a red X display with and without a prior yellow X.

4. Determine if driver response to a red X indication differs significantly when it is flashed as opposed to when it is displayed in a steady mode.

During Study C, TxDOT staff could modify the LCS displays from the Satellite Operations Center rather than manually change the displays at the roadside cabinets adjacent to each LCS location. CCTV cameras again collected volume data upstream of the lane closure. TTI data collection personnel conducted concurrent floating car travel time and drive-through video studies. Researchers did not use the CMSs in the study corridor for Study C.

Table 2-10 shows the configurations tested in Study C. As with the other two studies, configuration 1 in study C served as the control with no LCS displayed. In configuration 2, drivers approaching the lane closure saw a yellow X displayed over lane 1 at Ripy St. (situated approximately 2100 ft [640 m] upstream of the actual lane closure), and a red X over the lane at Seminary Dr (which was actually 2200 ft [670 m] downstream from the beginning of the lane closure). Configuration 3 included a yellow X displayed over lane 1 at Berry St. (3600 ft [1100 m] upstream of Ripy St.), and a red X displayed at Ripy St. and at Seminary Dr. Comparison of these two configurations provided an opportunity to determine the consistency of driver responses to a yellow X between locations. In configuration 4, drivers saw a red X displayed over lane 1 at Ripy St. and at again at Seminary Dr. Comparison of the responses from configuration 4 to those of configuration 3 allowed the researchers to explore the effect of the presence or absence of an upstream yellow X. Likewise, comparison of the responses to configuration 4 and configuration 2 provided an indication of whether the yellow X affects drivers differently than a red X. Finally, configuration 5 was identical to that of configuration 3, except that drivers saw a flashing red X at Ripy St. Consequently, a comparison of those two configurations represents the relative effect of the flashing display upon driver response.

TxDOT anticipated that the work activity would last several hours. Therefore, data for configurations 1 through 4 were collected in the morning and again in the afternoon to counterbalance any effects differences in volume throughout the day would have on LCS responses. Because of time constraints, only afternoon data were collected for configuration 5.

TABLE 2-10. LANE CONTROL SIGNAL ARRAYS FOR STUDY C

Configuration[a]	LCS Array at Berry	LCS Array at Ripy	LCS Array at Seminary
1	off	off	off
2	↓ ↓ ↓ ↓[b]	YX ↓ ↓ ↓	RX ↓ ↓ ↓
3	YX ↓ ↓ ↓	RX ↓ ↓ ↓	RX ↓ ↓ ↓
4	↓ ↓ ↓ ↓	RX ↓ ↓ ↓	RX ↓ ↓ ↓
5	YX ↓ ↓ ↓	FRX ↓ ↓ ↓	RX ↓ ↓ ↓

[a] Each configuration was in place for at least 30 minutes with a 5-minute interval between configurations. Reading from left to right, the array symbols correlate to lanes 1 through 4.

[b] ↓ - green arrow YX - yellow X RX - red X
FRX - flashing red X

Effect of LCS Configuration Upon Travel Times

Table 2-11 presents the average freeway travel times collected during each of the LCS configurations evaluated in Study C. Once more, the results showed no significant effect upon travel times as a result of the LCS configuration displayed. Travel times varied by no more than 9 seconds between any two configurations. In terms of the average speeds these travel times represent, differences amounted to no more than 2.4 mph (3.9 km/h). Due to the locations of the loop detectors in the southbound direction of I-35W, researchers did not collect spot speed data as part of Study C.

Effect of LCS Configuration Upon Lane Volumes

Volume data were recorded by lane at three locations approaching the left-lane single-lane closure. The first data collection location was just beyond the exit ramp to Morningside Dr. (see Figures 2-2 and 2-5). Lane distributions at Morningside served as the control to verify the comparability of lane distributions across configurations at the second and third locations. Researchers positioned the second data collection location just before the entrance ramp from Berry St. to determine the influence of the Berry St. LCS array during configurations 3 and 5. Finally, researchers set the third data collection location south of the Ripy St. exit ramp, within sight of the actual LCS array at Ripy St. This location represented the effect of the Berry St. LCS array and the start of the effect of the Ripy St. LCS array. A fourth data collection location, planned for just prior to the entrance ramp from Ripy St., would have provided better information regarding the influence of the Ripy St. LCS. Unfortunately, a malfunction with the videotape recorder during the study resulted in no data being obtained at this location.

TABLE 2-11. EFFECT OF LCS UPON TRAVEL TIMES: STUDY C

LCS Configuration	Average Travel Time, Min:Sec (sample size)	Average Travel Speed, Mph (Km/h)
1	3:49 (n=12)	57.4 (92.4)
2	3:43 (n=10)	58.8 (94.7)
3	3:44 (n=10)	58.6 (94.3)
4	3:44 (n=10)	58.7 (94.5)
5	3:40 (n=5)	59.8 (96.3)

Mph = miles per hour
Km/h = kilometers per hour

Table 2-12 shows the lane distributions recorded during Study C. Initial statistical analyses performed on the data from location I indicated a significant difference in the distribution of traffic in the open and closed lanes prior to introducing the effects of LCS at downstream locations. This precluded proper comparison between LCS configurations at the downstream data collection locations. Upon closer scrutiny, however, researchers found that the distribution of traffic during configuration 5 at location I was substantially different than for the other four configurations. This could have occurred because of a driver who stopped on the right shoulder prior to the Morningside overpass during the testing of this configuration, or because of the significantly higher traffic volumes present during that configuration than during the other configuration test periods.

TABLE 2-12. EFFECT OF LCS UPON LANE DISTRIBUTIONS: STUDY C

Configuration	Percent[a] of Traffic in:		Statistical Significance
	Open Lanes	Closed Lanes	
Location I:			$X^2 = 0.9^*$
1 (control)	83.7	16.3	
2	84.0	16.0	no significant differences
3	83.2	16.8	between configurations 1
4	83.4	16.6	through 4[b]
5	78.7	21.3	
Location II:			$X^2 = 7.5^*$
1 (control)	83.5	16.5	
2	83.8	16.2	no significant differences
3	85.5	14.5	between configurations 1
4	82.3	17.3	through 4[b]
5	81.8	18.3	
Location III:			$X^2 = 13.7^*$
1 (control)	87.2	12.8	
2	90.1	9.9[c]	configurations 2 and 3 differ
3	89.4	10.6[d]	from configuration 1[b]
4	87.9	12.1	
5	86.3	13.7	

* Statistic was computed without configuration 5 included

a Total volumes ranged between 2600 and 2900 vph for configurations 1 through 4, and were about 3300 vph for configuration 5

b $X^2_{(0.05,3)} = 7.8$

c The 2.9 percent shift (relative to configuration 1) represents a 22.7 percent reduction in closed lane traffic volumes at that location

d The 2.1 percent shift (relative to configuration 1) represents a 16.4 percent reduction in closed lane traffic volumes at that location

Upon eliminating configuration 5 from consideration, researchers determined that comparisons between the remaining configurations at locations II and III were appropriate.

Without configuration 5, the test statistic for location I was non-significant, indicating that there was no difference in lane distributions among the four other configurations at that location.

Statistical analyses of configurations 1 through 4 at location II also failed to detect any significant difference in lane distributions (although it was close to being significant at an $\alpha=0.05$). Researchers observed a slightly lower percentage of traffic in the open lane for configuration 3 (relative to configuration 1). Meanwhile, researchers documented nearly identical percentages for configurations 1, 2, and 4. This was expected, as only configuration 3 involved a change in the Berry St. LCS array (once configuration 5 had been dropped from consideration). Referring back to Table 2-10, the Berry St. LCS was the only display that motorists had been exposed to by the time they reached data collection location II.

TTI researchers also detected significant differences in lane distributions among the four configurations at location III (see Table 2-12). Both configurations 2 and 3 resulted in significant changes in the amount of traffic recorded in the closed lane to that in the open lanes, relative to configuration 1. However, they were not significantly different from each other. Overall, the two LCS configurations appeared to shift 2.2 to 2.9 percent of the closed lane traffic to the open lanes. The 2.2 to 2.9 percent shift in traffic using the closed and open lanes represents a 16.4 to 22.7 percent reduction in traffic volumes which would normally use the closed lane.

Strangely, configuration 4 did not result in a lane distribution significantly different than that of configuration 1. The overall LCS sequence for configuration 4 was identical to that of configuration 2, except that a red X was used at Ripy St. instead of the yellow X. Nonetheless, data collected at location III showed that traffic moved out of the closed lane in response to configuration 2 and not for configuration 4. One possible reason for this discrepancy is that the red X had a lower legibility distance under daylight conditions than the yellow X. Whereas, motorists driving through the study section during configuration 2 may have been able to see the yellow X at Ripy St. prior to reaching location III, motorists driving through during configuration 4 may not have been able to see the red X at Ripy St. (or at least far enough in advance to have changed lanes). Data collection personnel also noticed this difference in visibility distance during the field study. The lack of a significant difference between configurations 2 and 3 at location III also suggests that observations made during configuration 3 at location III represent only the effect of the Berry St. yellow X and not the red X displayed at Ripy St. Both morning and afternoon data were collected for each study configuration, so it is unlikely that the differences between configuration 2 and 4 are due to different traffic volumes.

Looking at the numbers in Table 2-12, the effects of the yellow X are very similar (a 2.0 percent change at location II for configuration 3, and a 2.9 percent change at location III for configuration 2). This would indicate that response to the yellow X on a given freeway section is fairly consistent from location to location. Of course, this would not necessarily hold true in regions where significant lane-changing occurs (i.e., prior to major freeway-to-freeway interchanges). Additional research will be necessary to explore these preliminary findings.

Summary

This chapter presented the results of three field studies of LCS conducted on I-35W in Ft. Worth, Texas. Two studies involved the closure of the right two out of four travel lanes; whereas, the third study was conducted around the temporary closure of the inside travel lane, also on a four-lane section of freeway. Two of the studies explored the effect of alternative LCS configurations in isolation and in conjunction with CMS messages upon driver behavior. A list of the major findings from these studies include:

- None of the LCS configurations tested significantly reduced speeds upstream of the lane closures or past the work site. TTI researchers conducted all studies during off-peak periods when volumes were lower and speeds were high. The effect of LCS upon speeds during high-volume peak-period conditions is not known at this time.

- A two-lane closure where double yellow Xs and double red Xs were displayed on sequential LCS arrays resulted in a 6.2 percent shift in traffic from closed lanes to the open lanes just upstream of the beginning of the cone taper. This represented a 24.3 percent reduction in traffic volumes in the closed lanes at that location.

- Evidence suggests that the red X was not seen from as far away as the yellow X at one site, which affected the change in lane distributions observed during one of the studies. Lane distributions at a single-lane closure measured upstream of a second LCS array resulted in a 2.2 to 2.9 percent shift in traffic from the closed lane to the open lanes when drivers saw a yellow X at the first or second LCS array. When drivers approached the lane closure with only a red X displayed at the second LCS array, researchers did not detect any statistically significant shift in lane distributions. Data were not available closer to or beyond the second array to measure the influence of the red X, unfortunately.

- Subjective evaluations by TTI and TxDOT study personnel suggested that flashing the red X did appear to increase its target value to motorists. However, data to fully test the effect of that symbol upon driver response could not be collected.

- The effect of a single yellow X displayed over an inside travel lane appears to be consistent from location to location along the same freeway section.

- Displaying CMS messages in conjunction with LCS may result in an additional shift of traffic from closed lanes to open lanes. However, because of non-comparability of data collected at upstream locations, researchers could not determine the relative magnitude of this effect in these studies. Likewise, it was not possible to determine the effects of CMS independent of the LCS displays (to determine the incremental benefit of LCS to a given CMS message).

- TTI researchers and TxDOT District personnel noticed poor LCS visibility during the initial field study. TxDOT maintenance crews found significant dirt and grime accumulation on the LCS heads, which had been in place over five-years. Cleaning efforts by TxDOT did appear to improve their brightness considerably.

3. RECOMMENDATIONS REGARDING FREEWAY LCS APPLICATIONS

This chapter presents several practical recommendations regarding the design, installation, and operation of freeway LCS. These recommendations are based on the findings from the laboratory and field studies, as well as observations and experiences of TxDOT and research personnel. Future research topics are also recommended to address certain issues which could not be addressed in this study.

LCS Design, Installation, and Operations Recommendations

Establish Operational Policies and Procedures for LCS Prior to Design and Installation

The proper time to consider exactly how system operators will use the LCS for freeway traffic management is before the actual design of the system takes place. In this way, designers can specify proper spacing, mounting locations, and display unit capabilities to meet the goals and objectives of the system. The San Antonio District, for example, has developed LCS operations plans for each segment of freeway based on the number of lanes blocked and time-of-day as part of the design of the computerized traffic management system. They envision these plans being implemented automatically when their traffic management operations center detects and verifies an incident.

Consider Flexibility in LCS System Components

Guidelines and procedures for freeway LCS have not yet been fully defined. For example, symbols not yet specified in the MUTCD (i.e., downward and diagonal yellow arrows, flashing symbol indications) may prove to be useful tools in a freeway traffic management setting. Also, existing LCS daylight illumination levels on freeway facilities may or may not need to be increased because of the higher operating speeds present. Consequently, it would be wise to utilize system components that have the flexibility to implement new practices and findings as they occur.

Consider Horizontal and Vertical Alignment of LCS Arrays When Selecting Mounting Locations

Current design practice in Texas is to incorporate LCS onto overhead bridge structures or sign structures. This appears to be a reasonable and cost-effective approach. However, system designers should consider the implications of horizontal and vertical curvature approaching LCS during the location selection process. The fiber-optic LCS being used throughout Texas has a relatively narrow cone of vision. This narrow cone can reduce the effective viewing distance of the LCS when installed on horizontal and vertical curves. Also, a problem with parallax occurs with LCS installed on structures within a horizontal curve. To drivers approaching such an LCS installation, the individual LCS displays can appear shifted a lane or more to the right or the left (depending on the direction of the curve). Consequently, designers should attempt to select LCS locations that have level, tangent approaches.

Place LCS Display Units Directly Over through Travel Lanes

There is debate over whether LCS placed at locations with auxiliary and/or acceleration/deceleration lanes should have LCS displays installed over those lanes as well. Current practices appear to be to not signalize those lanes to avoid confusing drivers by leading them to think that the lane is available for through travel during incident conditions. However, by not displaying LCS over auxillary lanes, the number of LCS shown at a location can be less than the number of lanes visible to drivers, a condition which may also confuse motorists in certain situations. At this time, the Ft. Worth District strongly recommends against placing LCS over auxillary lanes. Meanwhile, to reduce the confusion, LCS should be installed directly over the middle of the travel lanes for which they are intended.

Establish a Regular LCS Display Unit Maintenance Schedule

The LCS on I-35W were noticeably brighter after maintenance personnel cleaned each one during the summer of 1993. These units had been in place for approximately 5 years without requiring repairs or other maintenance work. The accumulation of dirt and road grime on the lenses was not noticed prior to the first field study. Given the durability of fiber-optic LCS displays (the predominant LCS technology in Texas), maintenance supervisors should adopt a regular maintenance schedule (such as once a year) to clean the LCS lens faces. Of course, the maintenance crews could also perform hardware inspection and other types of maintenance on the units at that time.

Recommendations for Future Testing

Above and beyond the collection of much more operational data to determine driver response to freeway LCS displays, a number of specific research topic areas warranting additional consideration have been identified. These are summarized below.

Effect of LCS Upon Driver Response Under Peak-Period Traffic Conditions

TTI researchers conducted each of the three studies discussed in this report during off-peak periods as part of regular maintenance activities. During these studies, traffic volumes did not exceed the reduced capacity past the work zone. Driver response to LCS may be quite different when traffic volumes are high and lane blockages cause significant queuing to develop. Research is still needed to evaluate LCS effectiveness during these peak conditions.

Effect of Downward Diagonal Arrow Upon Traffic Operations and Safety

The results of the laboratory studies suggest that a yellow downward diagonal arrow provides a very clear and consistent meaning to drivers that they need to exit the lane in the direction of the arrow. Field testing of this symbol is needed and should be compared to responses to a yellow X to determine if a change in the MUTCD is warranted.

Appropriate Methods for Safely Indicating the Closure of Multiple Lanes

There is some debate as to the proper method of indicating a multiple lane closure to drivers via the LCS. Standard traffic control techniques at work zones are to close one lane at a time and systematically move drivers out of each closed lane. This approach could be implemented via LCS, starting with a single yellow X over one lane at an upstream array, then showing a red X over that lane and illuminating another yellow X over the adjacent lane at the next array, and so on until red X's are shown over all closed lanes at an array just prior to the actual closures. This approach is appealing from the standpoint of providing positive guidance to the motorist.

However, this approach requires several LCS arrays upstream of the point of closure for most multiple lane closures. Also, this method results in red Xs displayed to motorists miles upstream of where the lane is actually closed, possibly reducing the credibility of that symbol and of the LCS system in general. Limited operational studies conducted when the LCS configuration consisted of dual yellow X's displayed at one array followed by dual red X's at the next array appeared to work reasonably well and did not seem to cause any problems (i.e., erratic maneuvers, vehicle conflicts) for the duration of testing.

Effect of Flashing Displays Upon the Target Value of LCS

The laboratory studies indicated that flashing certain LCS symbols did not significantly alter motorist's interpretations of what they meant about the condition of the lane or of the appropriate driving response to the symbol. Limited data collected elsewhere (7) suggested that flashing reduces LCS legibility distances slightly. However, it has not been possible to determine whether a flashing display provides greater target value to motorists.

Use of Combined LCS/CMS Displays at Spot Locations

Additional testing of LCS and CMS together is needed to determine the relative effect of each upon traffic operations. In particular, researchers should further explore the interaction between LCS and CMS near major freeway interchanges (as they are being used in Houston) and appropriate CMS message designs to facilitate driver understanding and proper response.

4. REFERENCES

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APPENDIX - STATISTICAL PROCEDURES TO COMPARE LCS EFFECT UPON LANE VOLUMES

The analysis methodology of the field study lane volume data was designed to answer one fundamental question: namely, were there differences in the proportions of traffic driving in the open lanes (those open at the work site) at each data collection location that were due to the LCS configurations tested? Given that there was more than one LCS configuration tested at each site, TTI statisticians employed a logit analysis to test the differences in open lane proportions among the configurations.

Conceptually, the logit analysis performs the same type of evaluation as an analysis-of-variance for regular numerical data, with the type of configuration being modelled as the factor affecting the open lane proportion. Initially, the intent was to "lump" all the data collected during a LCS configuration test to evaluate a single proportion. However, upon further discussions with TTI statisticians, it was decided that any variations in proportions within a given configuration test period would be useful to consider in the logit analysis. Consequently, the structure of the model used in the evaluation was as follows:

$$\log(m_{ijo}/m_{ijc}) = \alpha + \beta_i + \gamma_{j(i)}$$

where,

m_{ijo}	=	expected number of vehicles driving in open lanes during 5-minute time interval j for configuration i
m_{ijc}	=	expected number of vehicles driving in closed lanes during 5-minute interval j for configuration i
α	=	mean logit value
β_i	=	deviation of logit value from mean due to configuration i
$\gamma_{j(i)}$	=	deviation of logit value for configuration i for 5-minute time interval j

In this way, the nested effect of the 5-minute time interval within each configuration test period could be considered in the analysis. Computations were performed using the CATMOD procedure of SAS.

Researchers compared a maximum-likelihood estimate of the degree to which the overall model represented the data collected to a chi-square statistic. For example, researchers compared the effect of the nested time variable to a chi-square value with the degrees of freedom equal to the sum of the number of time intervals in each configuration test period (since different configurations could be tested for different durations) minus the number of configurations tested. Meanwhile, the variable representing the effect of the configuration was compared to a chi-square statistic with the degrees of freedom equal to one less than the number of configurations tested.

If the researchers found the model to be significant, contrast statements were used to determine which configurations differed significantly from each other. The computed statistic for each contrast was again compared to a chi-square statistic value with a single degree of freedom.

Study A Results

Effect of LCS Configuration on Traffic Speeds

In general, the display of alternative LCS configuarations upstream of the lane closure at the study A site had no appreciable effect on speeds through the study section. Average floating vehicle travel time measurements collected during each test configuration, shown in Table xx, were essentially identical (differing by less than 4 seconds (1.5 percent)). In terms of average travel speeds over the 4.5-mi (7.2 km) section that these travel times were measured, differences between any two LCS configurations were less than 1 mph (from a low of 59.9 mph (96.4 kmph) to a high of 60.8 mph (97.9 kmph)).

TABLE XX. EFFECT OF LCS CONFIGURATION UPON TRAVEL TIMES

LCS Configuration	Average Travel Time (Min:Sec)	Average Travel Speed, Mph (Kmph)
1	4:26	60.5 (97.4)
2	4:25	60.8 (97.9)
3	4:29	59.9 (96.4)
4	4:27	60.2 (96.9)
5	4:29	59.9 (96.4)

Mph = miles per hour
Kmph = kilometers per hour

Spot speed data at this site were also available from the freeway loop detectors in lanes 1 and 2 at Berry street (where the work activity occurred in lanes 3 and 4). These data indicate that there was no effect of LCS configuration upon speeds in the open travel lanes past the work site. As shown in Table xx, average spot speeds differed by no more than 1.4 mph (2.3 kmph), ranging from 55.0 mph (88.6 kmph) to 56.4 mph (90.8 kmph) between configurations. None of these average speeds were significantly different than the 55.9 mph (90.0 kmph) average speed recorded during configuration 1 when all LCS and the CMS were turned off. The LCS configuration also had no appreciable effect on the variability of the spot speeds, as evidenced by the nearly identical standard deviations reported in Table xx.

TABLE XX. EFFECT OF LCS CONFIGURATION UPON SPOT SPEEDS: STUDY A

LCS Configuration	Average Spot Speed, Mph (Kmph)	Standard Deviation of Speeds, Mph (Kmph)
1	55.9 (90.0)	5.4 (8.7)
2	56.4 (90.8)	5.0 (8.1)
3	55.7 (89.7)	5.3 (8.5)
4	55.8 (89.8)	5.5 (8.9)
5	55.0 (88.6)	5.3 (8.5)

Mph = miles per hour
Kmph = kilometers per hour

Effect of LCS Configuration on Lane Volume Distributions

Using the I-35W CCTV system, data were collected from the freeway mainlanes at three locations upstream of the lane closure. These volumes were analyzed to determine whether any of the various LCS configurations affected the relative distribution of traffic in each lane at those locations. The first location was selected upstream of the first LCS array used in the configuration to serve as a control. Since traffic at that first location had not yet been exposed to the LCS, it was hypothesized that there would be no change in lane distributions at that location. If this was determined to be the case, then any changes in lane distributions measured at the other two locations farther downstream would reflect the influence of the LCS configuration.

Volumes were first measured just north of the entrance ramp from I-20, followed by measurements south of the entrance ramp from Seminary Drive and again just north of the exit ramp to Ripy St. (see Figure xx). Consequently, data from the second location represented the influence of the Felix Street and Seminary Drive LCS arrays plus the changeable message sign (CMS) just to the south of Seminary Drive (when activated for configuration 5). In comparison, data from the third location reflected the influence of those upstream LCS and CMS displays plus any additional effect of the LCS array at Ripy St. Lane volumes were recorded in five-minute intervals to coincide with times each configuration was initiated and terminated (A five-minute transition period separated each change in LCS configuration to allow traffic caught within the transition to clear the section before data collection resumed).

The data analysis procedures for each location were identical, designed to detect signficant changes in the amount of traffic using those lanes which were closed downstream at the work zone versus those using the open lanes. Categorical data analysis techniques were employed to test for any changes in the relative proportions using the open and closed lanes at each location (the intent of the LCS and CMS configuration was to increase the proportion using the open lanes at the second and third data collection location). Details of the statistical analyses are presented in Appendix A.

The lane distributions recorded at each location during the study are presented in Tables xx and xx. Because of the change in the traffic control plan at the work site, configuration 2 could not be compared directly to the other configurations. The same analysis approach was used to evaluate configuration 2, comparing the distribution of traffic in open and closed lanes, but with only the shoulder lane closed (whereas both outside lanes were closed for configurations 3 through 5). All data were compared against configuration 1, the control configuration during which no LCS or CMS was displayed. The actual lane closure configuration at Berry St. could not be seen at any of the data collection locations. Consequently, the change in traffic control that was required during the study (from a single-lane to a two-lane closure) was not believed to have influenced data collected during configuration 1, allowing it to be used as a comparison against which the other LCS configurations could be tested.

TABLE XX. EFFECT OF LCS CONFIGURATION UPON LANE DISTRIBUTIONS: STUDY A (SINGLE-LANE CLOSURE)

LCS Configuration	Percent of Traffic in:		Statistical Significance
	Open Lanes	Closed Lanes	
Location 1:			$X^2 = 2.6$ ($X^2_{(0.05,1)} = 3.8$)
1 (control)	58.8	41.2	configurations are not
2	55.6	44.4	significantly different
Location 2:			$X^2 = 1.4$ ($X^2_{(0.05,1)} = 3.8$)
1 (control)	48.5	51.5	configurations are not
2	47.8	52.2	significantly different
Location 3:			$X^2 = 3.2$ ($X^2_{(0.05,1)} = 3.8$)
1 (control)	44.0	56.0	configurations are not
2	44.9	55.1	significantly different

TABLE XX. EFFECT OF LCS CONFIGURATION UPON LANE DISTRIBUTIONS: STUDY A (TWO-LANE CLOSURE)

Configuration	Percent of Traffic in:		Statistical Significance
	Open Lanes	Closed Lanes	
Location 1:			$X^2 = 4.4$
1 (control)	41.2	58.8	($X^2_{(0.05,3)} = 7.8$)
3	39.7	60.3	
4	38.3	61.7	configurations are not
5	39.7	60.3	significantly different
Location 2:			$X^2 = 7.4$
1 (control)	48.5	51.5	($X^2_{(0.05,3)} = 7.8$)
3	50.0	50.0	
4	49.7	50.3	configurations are not
5	53.3	46.7	significantly different
Location 3:			$X^2 = 7.8$
1 (control)	44.0	56.0	($X^2_{(0.05,3)} = 7.8$)
3	46.2	55.8	configuration 5 differs from
4	44.1	55.9	configurations 1 and 4
5	48.1	51.9	

As expected, the distribution of traffic in open and closed lanes at location 1 for any of the alternative LCS configurations were not signficantly different than for configuration 1 (the control condition). Also, the poor visibility of the LCS (as noted subjectively by data collection personnel) appeared to affect motorist response to the LCS during this study. Table xx shows that configuration 2 had no appreciable effect upon traffic distributions at locations 2 and 3 as well, whereas Table xx indicates that only configuration 5 significantly affected traffic measured at location 3, resulting in a 4.1 percent reduction in the amount of traffic in the closed lanes at that location. The effect of configuration 5 was most likely a result of the CMS display provided rather than the LCS, since a similar change in traffic distribution at location 3 was not detected for configuration 4 (identical to configuration 5 but without the CMS present).

Study B Results

(since the orientation of the sun did not cause as much of a glare problem in the southbound direction of I-35W)

Effect of LCS Configuration on Travel Times

Table xx summarizes the average travel times and corresponding average speeds over the section of freeway evaluated in study B. As with Study A, the LCS configurations in Study B had very minimal effect upon travel times and speeds. Travel times during configurations 2 and 3 were only 6 seconds and 2 seconds faster than they were for configuration 1.

TABLE XX. EFFECT OF LCS CONFIGURATION UPON TRAVEL TIMES: STUDY B

LCS Configuration	Average Travel Time (Min:Sec)	Average Travel Speed, Mph (Kmph)
1	2:24	51.7 (83.2)
2	2:18	54.0 (86.9)
3	2:22	52.5 (84.5)

Mph = miles per hour
Kmph = kilometers per hour

Spot speed data were not available at the point of work activity for Study B. Data were obtained from a loop detector station approximately 1 mile upstream of the two-lane closure adjacent to the exit ramp to Rosedale St. (see Figure xx). Data from that station, presented in Table xx, indicate no significant difference in average spot speeds in the open lanes (the two inside lanes) as a function of the LCS configuration. However, spot speeds in the two outside lanes (those closed downstream) indicate a slight increase (1.5 to 1.7 mph). At this data collection station, motorists have just passed one set of LCS at Hattie St. (displaying two yellow Xs over the outside lanes during configurations 2 and 3). Although the 1.5 and 1.7 mph increases in spot speeds are statistically significant, it is not immediately apparent whether these increases are of a practical significance. Nonetheless, it can be said that the LCS configurations did not significantly lower average speeds upstream of the closure.

TABLE XX. EFFECT OF LCS CONFIGURATION UPON SPOT SPEEDS: STUDY B

LCS Configuration	Average Spot Speed, Mph (Kmph)		Standard Deviation of Speeds, Mph (Kmph)	
	Open Lanes	Closed Lanes	Open Lanes	Closed Lanes
1	56.8 (91.4)	57.0 (91.8)	6.5 (10.5)	6.8 (10.9)
2	56.9 (91.6)	58.5 (94.2)	6.3 (10.1)	6.4 (10.3)
3	57.7 (92.9)	58.7 (94.5)	6.3 (10.1)	6.4 (10.3)

Mph = miles per hour
Kmph = kilometers per hour

Effect of LCS Configuration Upon Lane Volumes

Freeway lane volumes were recorded via CCTV at three locations upstream of the lane closure:

- Immediately south of the exit to Hattie St.,
- Immediately south of the exit to Rosedale St., and
- Immediately north of the entrance from Rosedale St (approximately 1000 ft prior to the LCS array at Allen Ave).

The relative position of these locations can be seen in Figure xx. Again, the first location was chosen as a control station prior to the potential influence of the LCS configurations. In actuality, the LCS at Hattie St. could just be seen from the first data collection location, but it was felt that drivers would not have had enough time to react to the array before being counted at that point. It was then assumed that the second location reflected the influence of the Hattie St. LCS, whereas the third station reflected the combined influence of the Hattie St. plus the influence of the CMS displayed during configuration 3 (although visibility of the LCS was better during study B than for study A, they were still not bright enough for motorists to see the LCS at Allen Ave. from that location).

Table XX presents the average distributions of traffic in the open and closed lanes at each location during each LCS configuration. Statistical analyses were first performed to verify the consistency of lane utilization at location 1 for the three configurations tested. However, the analyses showed that the distribution of traffic across the open and closed lanes at that location were different for configuration 3 than for configurations 1 and 2. Upon closer scrutiny, it was found that volumes during the testing of configuration 3 were substantially higher (by approximately 25 percent) than they were during the testing of configurations 1 and 2. Apparently, this increase was enough to alter the lane distributions at the upstream location, and so the differences between configuration 3 and the other configurations at the downstream data collection locations must be viewed cautiously.

TABLE XX. EFFECT OF LCS CONFIGURATION UPON LANE DISTRIBUTIONS: STUDY B (TWO-LANE CLOSURE)

Configuration	Percent of Traffic in:		Statistical Significance
	Open Lanes	Closed Lanes	
Location 1:			$X^2 = 17.3$
1 (control)	64.5	35.5	($X^2_{(0.05,2)} = 6.0$)
2	65.8	34.2	configuration 3 differs from
3	58.3	41.7	configuration 1
Location 2:			$X^2 = 7.3$
1 (control)	65.1	34.9	($X^2_{(0.05,2)} = 6.0$)
2	68.6	31.4	configurations 2 and 3
3	70.0	30.0	differ from configuration 1
Location 3:			$X^2 = 17.6$
1 (control)	74.5	25.5	($X^2_{(0.05,2)} = 6.0$)
2	80.7	19.3	configurations 2 and 3
3	80.3	19.7	differ from configuration 1

Analyses at locations 2 and 3 indicate that the LCS significantly increased the proportion of traffic travelling in the open lanes at those locations. Relative to the control condition, the percentage of traffic in the closed lanes at location 2 was 3.5 percent lower (34.9 percent - 31.4 percent) for configuration 2 than for configuration 1. The change in configuration 3 relative to configuration 1 was even more dramatic (4.9 percent); however, it could not be said for certain that this change was due to the LCS and CMS displays, given that a difference in lane distributions had already existed for that configuration upstream. At location 3, there was 6.2 percent less traffic in the closed lanes during configuration 2 than for configuration 1. Again, a similar reduction was evident for configuration 3, even though that could not be positively attributed to the LCS and CMS displays.

These percentage changes indicate how the volumes redistributed among the available lanes as a function of the type of LCS configuration displayed. Although statistically correct, these estimates count both closed lane traffic (that for which the LCS is primarily intended) and open lane traffic (that which does not have to respond to the LCS). If only the closed lane traffic is considered in the comparison, the effect of the LCS configurations is more substantial. At location 2, for example, the 3.5 percent change from closed lane traffic to open lane traffic is equivalent to a 10.0 percent reduction in the amount of traffic that would have been expected to be in the closed lanes if configuration 2 had not been displayed. At location 3, the 6.2 percent change in closed versus open lane volumes between configurations 1 and 2 represents a 24.3 percent reduction in traffic volumes travelling in the closed lanes at that location.

Study C Results

Effect of LCS Configuration Upon Travel Times and Speeds

Average freeway travel times collected during each of the LCS configurations evalauted in study C are presented in Table xx. Once more, the results show no signficant effect upon travel times as a result of the LCS configuration displayed. Travel times vary by no more than 9 seconds between any two configurations. In terms of the average speeds these travel times represent, differences amount to no more than 2.4 mph (3.9 kmph). Meanwhile, spot speed data were not collected as part of Study C.

TABLE XX. EFFECT OF LCS CONFIGURATION UPON TRAVEL TIMES: STUDY C

LCS Configuration	Average Travel Time (Min:Sec)	Average Travel Speed, Mph (Kmph)
1	3:49	57.4 (92.4)
2	3:43	58.8 (94.7)
3	3:44	58.6 (94.3)
4	3:44	58.7 (94.5)
5	3:40	59.8 (96.3)

Mph = miles per hour
Kmph = kilometers per hour

Effect of LCS Configuration Upon Lane Volumes

Data were recorded at three locations approaching the left-lane single-lane closure. The first location was just beyond the exit ramp to Morningside Dr. (see Figure X). The LCS at Morningside always displayed green arrows for all configurations (except when all LCS were turned off during configuration 1). Consequently, the lane distributions at this location were used as a control to verify the comparability of lane distributions across configurations at the second and third locations. The second location was positioned just before the entrance ramp from Berry St. This location reflected the influence of the Berry St. LCS array (which from Table xx was expected to have an influence during configurations 3 and 5). Finally, the third location was positioned south of the Ripy St. exit ramp, within sight of the actual LCS array at Ripy St. This location was used to indicate the of the Berry St. LCS array and the start of the effect of the Ripy St. LCS array. Unfortunately, a problem with the videotape recorder during the study eliminated another data collection location just prior to the entrance ramp from Ripy St., which would have provided better information regarding the influence of the Ripy St. LCS.

Unfortunately, initial statistical analyses performed on the data from location 1 as shown in Table xx indicated a significant difference in the distribution of traffic in the open and closed lanes prior to introducing the effects of LCS at downstream locations. Upon closer scrutiny, it was noted that the distribution of traffic during configuration 5 at that location was substantially different than for the other four configurations. A stalled vehicle parked on the right shoulder prior to the Morningside overpass during this configuration, as well as significantly higher traffic volumes than during the other configuration test periods, probably combined to influence the lane distributions. Regardless of the reason(s), it was determined that the comparisons between configurations at locations 2 and 3 would have to be done without considering configuration 5. Upon eliminating configuration 5 from the computations, the test statistic for location 1 become non-significant (see Table xx), indicating that there was no difference in lane distributions among the four other configurations.

TABLE XX. EFFECT OF LCS CONFIGURATION UPON LANE DISTRIBUTIONS: STUDY C (SINGLE-LANE CLOSURE)

Configuration	Percent of Traffic in: Open Lanes	Percent of Traffic in: Closed Lanes	Statistical Significance
Location 1:			$X^2 = 0.9^*$
1 (control)	83.7	16.3	($X^2_{(0.05,3)} = 7.8$)
2	84.0	16.0	no significant differences
3	83.2	16.8	between configurations 1
4	83.4	16.6	through 4
5	78.7	21.3	
Location 2:			$X^2 = 7.5^*$
1 (control)	83.5	16.5	($X^2_{(0.05,3)} = 7.8$)
2	83.8	16.2	no significant differences
3	85.5	14.5	between configurations 1
4	82.3	17.3	through 4
5	81.8	18.3	
Location 3:			$X^2 = 13.7^*$
1 (control)	87.2	12.8	($X^2_{(0.05,3)} = 7.8$)
2	90.1	9.9	configurations 2 and 3
3	89.4	10.6	differ from configuration 1
4	87.9	12.1	
5	86.3	13.7	

* Statistic was computed without configuration 5 included

Statistical analyses at location 2 also failed to detect any significant difference in lane distribution among the first four configurations. However, a slightly lower percentage of traffic was counted in the open lane for configuration 3 (relative to configuration 1) which was extremely close to being significant at an $\alpha=0.05$. Meanwhile, the percentages for configurations 2 and 4 were essentially identical to those of configuration 1. This was to be expected, as only configuration 3 involved a change in the Berry St. LCS array (once configuration 5 had been dropped from consideration).

Significant differences in lane distributions were detected among the four configurations at location 3 (see Table xx). Both configurations 2 and 3 resulted in signficant changes in the amount of traffic recorded in the closed lane to that in the open lanes, relative to configuration 1. However, they were not significantly different from each other. Overall, the two LCS configurations appearred to shift 2.2 to 2.9 percent of the closed lane traffic to the open lanes. The 2.2 to 2.9 percent shift in lane utilization reflects a 17.2 to 22.6 percent reduction in traffic volumes normally using the closed lane.

Strangely, configuration 4 did not result in a lane distribution significantly different than that of configuration 1. The overall LCS sequence for configuration 4 was identical to that of configuration 2, except that a red X was used at Ripy St. instead of the yellow X. Nonetheless, data collected at location 3 showed traffic to move out of the closed lane in response to configuration 2 and not to have for configuration 4. It is hypothesized that the main reason for this discrepency is that the red X has a much lower legibility distance under daylight conditions than the yellow X. Whereas motorists may have been able to see the yellow X prior to reaching location 3, it may not have been possible to see the red X at that location (or at least seen it far enough in advance to have changed lanes). This appears to support subjective observations and comments by study personnel of the red X and yellow X during the field study.

Finally, the lack of a signficant difference between configurations 2 and 3 at location 3 suggests that the effect of the yellow X in an LCS array may not depend on the number of times motorists encounter that symbol as they pass through a section of freeway. It may be that once a LCS symbol is seen by drivers, those who would decide to respond to the symbol do so as soon as they encounter it, whereas those who choose not at that first point to will not be encouraged to do so by seeing another yellow X further downstream, resulting in the same number of vehicles in open and closed lanes at a given point regardless of the LCS arrays displayed upstream. Of course, this would not necessarily hold true in regions where significant lane-changing occurs (i.e., prior to major freeway-to-freeway interchanges). Additional research will be necessary to explore these preliminary findings.

Design Issues and Guidelines

- Need to have an established set of goals and objectives for the LCS system being designed and implemented
- recognize that yellow X does not always convey same meaning to all motorists
- recognize that yellow downward arrow does not convey same meaning always either.
- Recognize that visibility needs for LCS on freeways are different than on arterials
- suggest use double line widths for LCS symbols

Installation Guidelines

- Horizontal and vertical alignment (locating on overhead structures at locations which present a skewed visual alignment
- replacement and maintenance concerns

Operations Guidelines

- How to handle multiple closures
    - typical lane closure approach as for work zones
    - application relying on keeping information consistent (i.e., red X just before closure, yellow X or arrows to show need to exit lane upstream)
- Operations are tied to objectives
    - total roadway coverage (i.e., Ft. Worth or SA versus spot (interchange) location in Houston). Implementing a spot system reduces intitial operational flexibility, but allows configuration to be implemented with most current approach possible.
- No need for flashing yellow X
- Limited evidence suggests that those who will divert may do so as soon as they encounter a symbol that tells them to. Additional warning may not result in any additional response. Suggests that operational plans should display closed lane signals only as far upstream as necessary to allow those who will move to do so in a safe manner. As use with LCS increases, driver confidence and response to them may increase.
- coordinated use of CMS and LCS
- consider shoulder use (to show as a temporary travel lane)

Public Information

- Evidence suggests PI may be useful in teaching drivers correct use of LCS
- Non-traditional methods may be needed