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16. Abstract Project

This report has documented the research performed to assess the effectiveness of a flashing warning light system as a work zone traffic control device. Researchers investigated motorist understanding of and perceived usefulness of various designs of the warning light system in a simulated work zone at night at TTI's proving ground facility at the Texas A&M University Riverside Campus. Field studies of the warning light system were also performed at night to determine if the system would yield significant operational or safety benefits in actual work zone applications. Furthermore, researchers discussed the physical design of the warning light system in respect to the problems encountered while using the system in the proving ground and field studies.

Proving ground and field studies show that the warning light system is perceived positively and is not confusing to the motoring public, and may encourage motorists to vacate a closed travel lane sooner (which is believed to offer a potential safety benefit). However, researchers believe that the current design (cable interconnected directional LED lights) of the system will be difficult to implement and maintain in a field setting. Therefore, researchers recommend that TxDOT consider the following: 1) TxDOT should specify a desire for a wireless system that has a wider cone of vision than currently provided by the flashing LED lights; 2) if a revised system design can be reasonably obtained, TxDOT should consider limited demonstration evaluation at a few more lane closure sites to evaluate TxDOT and contractor ability to set up and maintain the system. Implementation Plan and Recommendation (IPR) funds should be pursued for purchase of such a system for field demonstration purposes; and 3) any field demonstrations of a revised system should comply with TxDOT's Request to Experiment with this type of device as approved by the FHWA.

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WORK ZONE LANE CLOSURE WARNING LIGHT SYSTEM

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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). 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 project was Dr. Gerald L. Ullman, P.E. #66876.

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1. INTRODUCTION

BACKGROUND

When a lane is closed for the maintenance and construction of a roadway, temporary traffic control devices must provide for the continuity of traffic flow and the safety of workers and motorists. Since lane closures require motorists to physically move out of a closed lane or lanes, it is important to positively indicate the direction the motorist should travel (*1*). Motorists should be given ample time to detect and perceive the closure, determine the appropriate action, find an acceptable gap in the adjacent traffic lane, and then merge into the adjacent open lane. Research and experience have shown that it is desirable to encourage the lane-changing maneuver as far upstream as practical (*2*).

Warning Lights

Temporary traffic control activities often create conditions that are unexpected, particularly at night when the visibility of motorists is reduced; therefore, it is often desirable and necessary to supplement channelizing devices with lighting devices to increase their visibility. One type of lighting device commonly used is the warning light. Warning lights are portable, lens-directed, enclosed lights that are effective in attracting motorists' attention to potential hazards. Steady-burn and flashing are the two types of warning lights (*1*).

The Texas Manual of Uniform Traffic Control Devices (TxMUTCD) states that when warning lights are needed in a temporary traffic control zone to delineate the traveled way through and around obstructions, such as detour curves, lane changes, and lane closures, the delineation shall be accomplished by using steady-burn warning lights (*1*). Table 1 contains TxMUTCD specifications for steady-burn warning lights (type "C"). Pain, McGee, and Knapp found that steady-burn warning lights provided additional delineation of reflectorized channelization devices at night compared to reflectorized channelization devices without steady-burn warning lights. They recommended that steady-burn warning lights be used at night on tapers in the transition area (*3*).

Table 1 contains the TxMUTCD specifications for flashing warning lights (type "A" and type "B"). Flashing warning lights are usually mounted on barricades, drums, or advanced warning signs and are intended to warn motorists that they are approaching a potentially hazardous situation; however, the TxMUTCD does not currently allow flashing warning lights to be used in a series to delineate the traveled way through and around obstructions in a temporary traffic control zone because it is believed that the independent flashing lights would tend to obscure the desired vehicle path (*1*). However, no mention is made in the TxMUTCD about lights flashed in a synchronous manner to convey the direction of a lane closure. It is hypothesized that such a system may help convey critical information that a lane is closed and draw more attention to the location of the actual lane closure. Consequently, the Texas Department of Transportation (TXDOT) contracted with the Texas Transportation Institute (TTI) to examine the feasibility and potential of such a system.

Table 1. TxMUTCD Warning Light Specifications (*1*).

Specification	Type of Warning Light		
	A (Low Intensity)	B (High Intensity)	C (Steady-burn)
Lens Directional Faces	1 or 2	1	1 or 2
Flash Rate per min.	55 to 75	55 to 75	Constant
Flash Duration [a]	10%	8%	Constant
Min. Effective Intensity [b]	4 Candelas	35 Candelas	--
Min. Beam Candle Power [b]	--	--	2 Candelas
Hours of Operation	Dusk to Dawn	24 hrs/day	Dusk to Dawn

[a] Length of time that instantaneous intensity is equal to or greater than effective intensity.
[b] These values must be maintained within a solid angle 9° on each side of the vertical axis, and 5° above and 5° below the horizontal axis.

Apparent Motion

When discrete stationary flashing lights are arranged sequentially, the illusion of motion can be created. This illusion of motion is called apparent motion and occurs at some range of flash rate values where the appearance of flashes changes from a succession of lamps lit up to a spot of light moving along the path (*4*).

In 1875, Sigmund Exner showed that when objects are arranged properly, two brief but stationary flashes are seen as a single object in motion (called the phi-phenomenon) (*4*). Exner's experiments led him to conclude that motion was a primary sensation, not just a deduction derived from comparing temporal order or spatial position (*5*). In 1910, Max Wertheimer began an intensive and detailed study on apparent motion. Wertheimer recognized many of the psychological and philosophical implications of apparent motion (*4*). One conclusion made by Wertheimer was that neural events contributing to the perception of motion are central (*5*). Wertheimer's experiments established the model for most of the later researchers who examined the duration and the spatial and temporal separation of the flashes. The relationship between spatial and temporal separation was expressed by Korte in 1915 in Korte's Third Law of Apparent Movement. This law states that apparent motion will occur if an increase in the distance between two successive objects is accompanied by an increase in the time between the successive presentations. Thus, the distance between the two successive objects is proportional to the speed of the apparent motion desired (*6*).

Lighted Guidance Devices Study by Vercruyssen, Williams, and Wade (*6*)

A study conducted in 1995 by the Human Factors Research Laboratory at the University of Minnesota for the Minnesota Department of Transportation examined the effectiveness of manipulations of environmental lighting on driving behavior through a simulated work zone.

Specifically, the researchers tested the hypothesis that flashing lights positioned on the side of the roadway parallel to the motorist which produce the illusion of apparent motion would cause the motorist to spontaneously and unconsciously adjust their speed to synchronize with the speed of the light flashes (*6*).

The Minnesota experiment was conducted using a fixed-based front display driving simulator. The simulated sequential flashing light system was comprised of lights that were spaced 8 ft apart on top of a 3 ft high wall located 4 ft outward from the edge of the pavement (i.e., on the shoulder) on each side of the roadway. The roadway simulated was a flat and straight 24 ft right lane with approximately one-third of the left lane visible. The experimenters investigated the influence of direction of appearance of lights and the color of lights on the velocity of the motorist. Three directions of lights (towards the motorist, stationary, and with the motorist) and two colors of lights (red and green) were examined at two zone entry speeds (40 mph and 70 mph) (*6*).

The researchers determined that lights moving towards the motorist caused motorists to reduce their vehicle speed, while lights moving with the motorist caused motorists to increase their vehicle speed. The stationary lights had little or no effect on speed. The study also concluded that green lights produced stronger effects than red lights (*6*).

The research reported herein looked at a system of moving lights in a lane closure (i.e., moving lights in front of the motorist instead of on each side of the road parallel to the motorist). Thus, the researchers did not believe that the simulator study discussed above was directly applicable to this research. However, the researchers were cognizant of the potential for the system to affect speeds (and so included speed as an operational measure in the field study data collection plan).

WARNING LIGHT SYSTEM

The subject of the research reported herein is a warning light system that is composed of a series of interconnected, synchronized individual flashing warning lights that are attached to drums that form the lane closure taper. The interconnected, synchronized individual flashing warning lights produce the perception of a light that "moves" repeatedly in a sequential manner from the beginning of the taper to the end of the taper (Figure 1). Each individual flashing warning light connects to a junction box located on the ground next to the drum via a cable. The junction boxes are connected with cables. Figure 2 shows how the light system is connected (i.e., junction box and cables). The individual flashing warning lights are illuminated by an array of light-emitting diodes (LEDs) behind the lens. Each individual flashing warning light used by the warning light system meets type "B" specifications of the TxMUTCD (*1*). The recommended power source for the warning light system is an arrow panel battery.

The flash rate of each individual flashing warning light, which in turn controls the number of times the "moving" light sequences down the taper in a given period of time, is controlled by a starter box located at the beginning of the taper (Figure 3). A knob on the starter box allows for

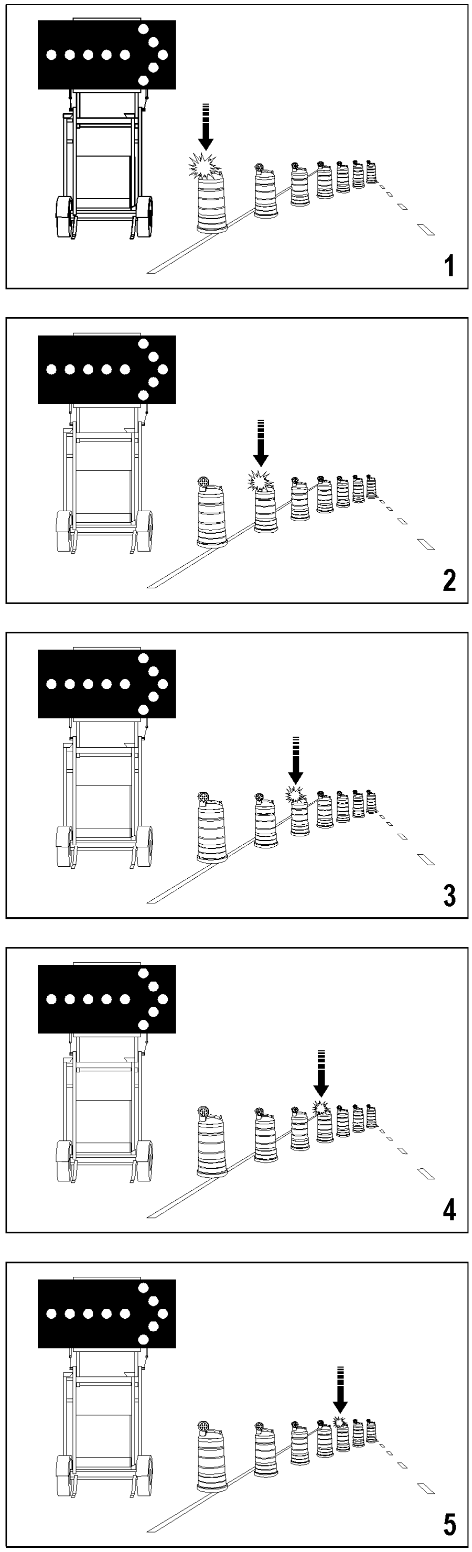

Figure 1. Warning Light System.

Figure 2. Individual Flashing Warning Light Connection.

the flash rate to be adjusted from 17 flashes per minute (fpm) to 265 fpm. It should be noted that the speed of the "moving" light down the taper is not affected when the flash rate is changed.

COMPONENTS OF THE EVALUATION PLAN

Proving Ground Studies

Prior to full-scale field testing on highways, proving ground studies were conducted at night to determine if the warning light system performed as intended. The specific objectives of this research were to:

1. select flash rates to be used on the warning light system that produce the perception of a "moving" light in the direction motorists are traveling,

2. conduct human factors studies at TTI's facility to determine motorists' reaction to and preference of the "moving" light, and

3. identify and recommend combinations of flash rates that produce the perception of a "moving" light and approach speeds to be used in subsequent field studies.

Figure 3. Starter Box.

Field Studies

Based on the positive results of the proving ground studies, TxDOT requested and received permission from the Federal Highway Administration (FWHA) to experiment with the warning light system in field applications. To determine if the warning light system would yield significant operational or safety benefits in actual work zone applications, the system was compared to the normal TxMUTCD lane closure traffic control plan (consisting of advance warning signs, a flashing arrow panel, and channelizing drums). The main objective of this research was to identify whether the system resulted in significant differences (relative to the normal TxMUTCD setup) in the following operational measures of performance:

- speed statistics at the beginning of the taper;
- lane choice statistics at the beginning of the taper and upstream of the taper (i.e., 500 ft, 1000 ft, etc.); and
- erratic maneuvers/vehicle conflicts at the beginning of the taper and upstream of the taper.

REPORT ORGANIZATION AND SCOPE

Chapter 2 explains the research study design for the human factors studies that were conducted at night at the TTI facility at the Texas A&M University Riverside Campus. Researchers surveyed motorists in the Bryan/College Station (B/CS) area to determine motorists' reaction to and preference of the "moving" light. The studies simulated a work zone with a left-lane closure which included an arrow panel. Researchers examined two flash rates (17 fpm and 60 fpm) that produced the perception of a "moving" light in the direction motorists were traveling at two approach speeds, 30 mph and 65 mph. The two lane closure taper lengths based on TxMUTCD requirements were 180 ft and 780 ft, respectively. The studies also simulated a left-lane closure without warning lights and with steady-burn warning lights at the two approach speeds previously mentioned. Chapter 2 also documents the results of the proving ground studies.

Chapter 3 defines the research study design for the field studies that were conducted at night on Farm-to-Market (FM) road 60 west of College Station, Texas, and on Interstate (I) 10 west of the Sam Houston Tollway (Beltway 8) in Houston, Texas. The test site on FM 60 consisted of a left-lane closure which reduced the roadway from two lanes to one lane. The test site on I-10 consisted of two left-lane closures which reduced the roadway from three lanes to one lane. The two left-lane closures were separated by a tangent section approximately 1500 ft long. The warning light system was used on the second left-lane closure (i.e., the middle lane). Researchers examined one flash rate, 35 fpm, that produced the perception of a "moving" light in the direction motorists were traveling. All of the lane closures at the test sites included a flashing arrow panel. The posted nighttime speed limit at both sites was 65 mph for passenger vehicles and 55 mph for trucks. Chapter 3 also documents the results of the field studies.

Chapter 4 discusses the physical design of the warning light system in respect to the problems encountered by the researchers while using the system in the proving ground and field studies.

Chapter 5 summarizes the results from the proving ground and field studies. The conclusions and recommendations concerning the warning light system are discussed as well.

2. PROVING GROUND STUDIES

The main objectives of the proving ground studies were to determine whether a warning light system in the transition of a work zone lane closure could confuse motorists and its likely effectiveness in encouraging earlier lane changing upstream of a lane closure. The specific objectives of the research included the 1) selection of flash rates to be used to produce the perception of a "moving" light in the direction motorists are traveling, and 2) conduct of human factors studies at TTI's facility at night to determine motorists' reaction to and preference of the "moving" light.

STUDY DESIGN

Warning Light Flash Rates

As discussed in Chapter 1, the interconnected, synchronized individual flashing warning lights produce the perception of a light that "moves" repeatedly in a sequential manner from the beginning of the taper to the end of the taper. In the TTI proving ground study, the flash rate of each individual warning light was examined to determine the flash rates that produced acceptable slow and fast rates (i.e., number of times the "moving" light sequences down the taper in a given period of time). A panel of four transportation and human factors experts was shown the warning light system operating with flash rates ranging from 17 fpm to 265 fpm. These experts determined that the flash rates that produced the acceptable extreme rates (slow and fast) of the "moving" light were 17 fpm and 60 fpm, respectively. These two extreme values were, therefore, used in the proving ground studies.

Method of Study

Layout of Traffic Control Devices

Striping was applied to a runway at the TTI proving ground facility to simulate a one-way, two-lane road. Figure 4 depicts the striping of the simulated roadway.

The normal TxMUTCD lane closure traffic control plan on a divided highway consists of advance warning signs, a merging taper, a tangent, and a flashing arrow panel placed on the shoulder at the beginning of the lane closure. For this study, the simulated nighttime lane closure consisted of a merging taper, a tangent, a flashing arrow panel, and a warning light system. Four flood lights were positioned in the middle of the closed lane adjacent to the second drum in the tangent section to simulate the illumination normally used (and resulting visual contrasts) in a work area during night work. Figure 4 shows the general characteristics of the nighttime lane closures simulated in this study. The advance warning signs were not used in this study since the researchers wanted to determine the effect of the warning light flash rates and approach speeds upon motorists' reaction to and preference of the warning light system.

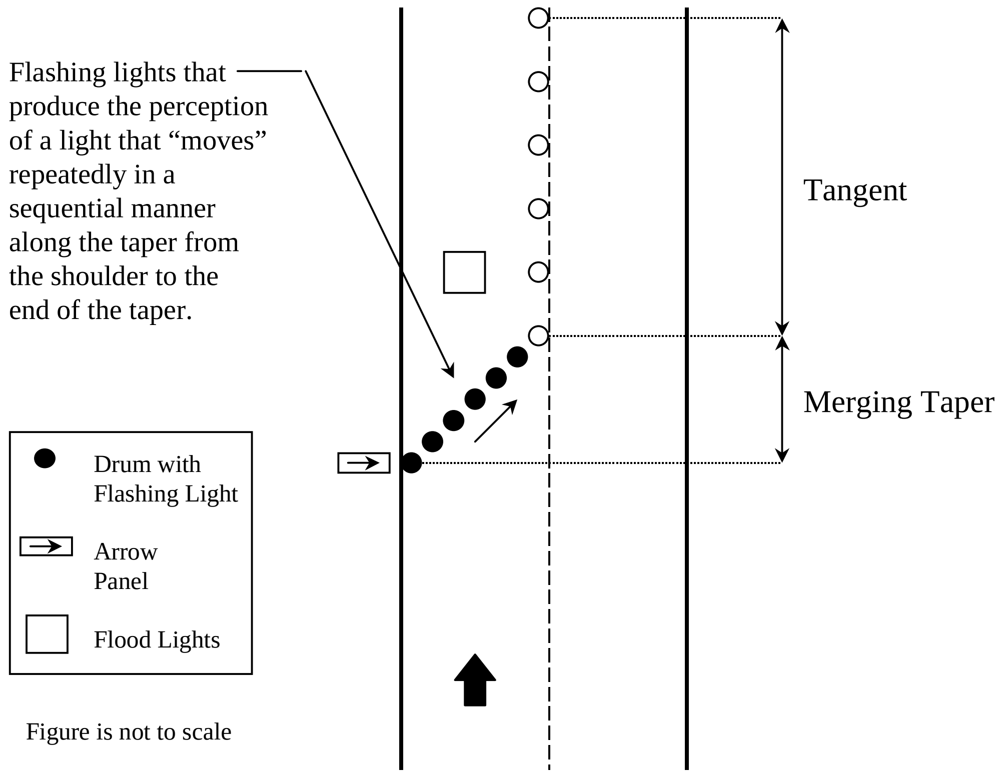

Figure 4. Characteristics of the Nighttime Simulated Lane Closures.

The two lane closure (merging) taper lengths that were examined were 180 ft and 780 ft. The following characteristics describe the two lane closure taper lengths studied:

- based on 30 mph and 65 mph speeds, respectively;
- included 7 and 13 drums, respectively;
- 30 ft and 65 ft drum spacings, respectively;
- 12 ft lane width;
- flat grades; and
- straight alignment.

The two speeds (30 mph and 65 mph) were chosen to represent a range of conditions on urban and rural major arterials and freeways. A type "C" arrow panel was placed at the beginning of the merging taper (*1*). The arrow panel displayed the flashing arrow in all of the studies.

The tangent at the end of each lane closure taper had the following characteristics for the 30 mph and 65 mph conditions:

- 540 ft and 520 ft long, respectively;
- included 10 and 5 drums, respectively; and
- 60 ft and 130 ft drum spacings, respectively.

For this study, one flashing warning light was attached to each drum in the taper except the last one, which is also the first drum of the tangent. Thus, for the 180 ft and 780 ft lane closure taper lengths there were 6 and 12 flashing warning lights, respectively.

Lane Closure Treatments Studied

As previously discussed, the TxMUTCD typical work zone traffic control plan for a lane closure does not include the use of warning lights on the drums that form the taper (*1*). Thus, one of the base treatments studied was the simulated lane closure without warning lights (no lights) in which the warning lights on the drums in the taper were not lit. The TxMUTCD does state when warning lights are needed to delineate a lane closure, steady-burn warning lights shall be used to accomplish the delineation (*1*). Thus, the second base treatment studied was the simulated lane closure with steady-burn warning lights attached to each drum in the taper (steady-burn lights).

In addition to the two base treatments, two warning light systems were studied. The first system was designed to combine the steady-burn warning lights, which have been proven to provide additional delineation of channelization devices at night, and the interconnected, synchronized flashing warning lights that are thought to improve motorist detection and recognition of a lane closure. The second system consisted of the interconnected, synchronized flashing warning lights without the steady-burn warning lights. Thus, the first system continually displays steady-burn warning lights with a higher intensity "moving" light (steady-burn light background), while the second system only displays the "moving" light (no light background).

Two flash rates, 17 fpm and 60 fpm, were studied with the no light background system, while only one flash rate, 60 fpm, was studied with the steady-burn light background system. The 17 fpm flash rate was not evaluated with the steady-burn light background system, since pilot study results revealed that 1) there was not a statistically significant difference between the two flash rates (17 fpm and 60 fpm with the steady-burn light background system) with respect to the distance upstream of the lane closure at which the lane-changing maneuver was initiated, and 2) the subjects ranked the two flash rates similarly. A full discussion of the pilot study results is given in Appendix A.

Overall, five treatments with a flashing arrow panel were studied at two approach speeds (30 mph and 65 mph): two base treatments (no lights and steady-burn lights), the steady-burn light background system with a flash rate of 60 fpm, and the no light background system with flash rates of 17 fpm and 60 fpm. Table 2 contains the five treatments and the two approach speeds (lane closure taper lengths) that were studied.

Table 2. Treatments and Approach Speeds Studied.

Approach Speed (Taper Length)	Base Treatment of Warning Lights on Drums in the Taper		Flash Rate Treatment Used with Steady-burn Light Background System (fpm)[a]		Flash Rate Treatment Used with No Light Background System (fpm)[a]	
	No Lights	Steady-burn Lights	17	60	17	60
30 mph (180 ft)	✓	✓	--	✓	✓	✓
65 mph (780 ft)	✓	✓	--	✓	✓	✓

[a] Flash rate of each individual light
✓ Comparisons made
-- Not tested

Study Approach

The study simulated a work zone at night with a left-lane closure and was subdivided into two parts:

- Part 1 – the subjects drove a test vehicle and evaluated one treatment at one approach speed (lane closure taper length), and

- Part 2 – the test administrator drove the test vehicle and the subjects evaluated all of the treatments at one approach speed (lane closure taper length).

Part 1 The objective of Part 1 of the study was to collect observations of subjects' reactions to the "moving" light produced by the flash rates of 17 fpm and 60 fpm. The subjects were asked to drive at night on a closed-course simulating a roadway typically encountered in Texas at a designated speed (30 mph or 65 mph). The subjects' reactions (measures of effectiveness) recorded with a distance measuring instrument (DMI) were the distance upstream of the lane closure at which the lane-changing maneuver was initiated, the distance upstream of the lane closure at which the motorist applied the brakes, and the change in speed caused by braking. These MOEs were reviewed to determine if the "moving" light encouraged subjects to leave the closed lane without causing any apparent confusion and the effectiveness of the warning light systems in encouraging earlier lane changing upstream of a lane closure.

Subjective impressions of the treatment each subject viewed were elicited from the subjects after each test trial by means of open-ended questions asked in a conversational manner by the test administrator (see Appendix B for the open-ended questions). It should be noted that each subject was shown only one of the treatments at one approach speed (lane closure taper length), and that all of the treatments included a standard flashing arrow panel at the beginning of the lane closure.

Part 2 The objective of Part 2 of the study was to collect observations of subjects' preferences of a "moving" light produced by the 17 fpm and 60 fpm flash rates compared to the two base treatments (no lights and steady-burn lights). A test administrator drove a test vehicle, and a maximum of three subjects were passengers. The speed (30 mph or 65 mph) corresponded to the speed driven in Part 1 of the study. The subjects examined the no lights base treatment (warning lights were not lit), steady-burn lights base treatment (steady-burn warning lights were used), the steady-burn light background system with a flash rate of 60 fpm, and the no light background system with flash rates of 17 fpm and 60 fpm.

Each subject viewed the five treatments three times. This was accomplished by showing the treatments in sets. Each set contained all five of the treatments with the no lights base treatment always being shown first. The other four treatments (steady-burn lights base treatment, steady-burn light background system with a flash rate of 60 fpm, and no light background system with flash rates of 17 fpm and 60 fpm) were then presented in random order to counter any learning effects that may have been present. Within each set, the subjects were asked how the four randomized treatments effected the lane closure and to compare the four randomized treatments with the treatments previously viewed in that set. After the subjects had viewed all of the treatments three times, the subjects were asked to rank all of the treatments. A written survey composed of multiple choice questions and one ranking question was used by the subjects to indicate their answers (see Appendix C for the written survey). The subjects' preferences were reviewed to determine if the "moving" light caused confusion and to assess whether or not the warning light systems were preferred by subjects over the two base treatments (no lights and steady-burn lights). Again, it should be noted that all of the treatments included a standard flashing arrow panel at the beginning of the lane closure.

PROVING GROUND STUDY RESULTS

Subjects

Fifty-nine subjects from the Bryan/College Station community were recruited and financially compensated to participate in the study. The subjects were stratified by gender and age. Three age groups (18-35, 60-74, and 75+ years old) were categorized to simplify subject recruitment and to represent two extreme age groups (young and old). Two of the age groups represented the older motorist since it has been documented in previous research that there is a decline in the cognitive and sensory functions of the older motorist (*7*, *8*, *9*). Thus, a worse-case scenario was studied. Approximately half of the subjects were between 18 and 35 years old and half were 60 years old or older. Both males and females were recruited. The age and gender distribution of the subjects is shown in Table 3.

Table 3. Subject Demographics.

Gender	18-35	60-74	75+	Total
Male	15	7	7	29
Female	15	8	7	30

Part 1 Results

The objective of Part 1 was to collect observations of subjects' reactions to the "moving" light produced by the selected flash rates with a steady-burn light background and a no light background. The subjects' reactions were used to determine if the warning light systems encouraged subjects to leave the closed lane without causing confusion and to determine the effectiveness of the systems in encouraging earlier lane changing upstream of a lane closure. The subjects' reactions (measures of effectiveness) evaluated were the distance upstream of the lane closure at which the lane-changing maneuver was initiated, the distance upstream of the lane closure at which the subjects applied the brakes, and the change in speed caused by braking. The three motorist reactions were collected for each subject, except for one because the laptop computer failed during the study.

Lane-Changing Distance

Table 4 contains the average distance upstream of the lane closure at which the lane-changing maneuver was initiated for each approach speed, treatment, and age group. The two approach speed sample averages are essentially the same, while two of the treatment sample averages (the steady-burn lights base treatment and the no light background system with a flash rate of 17 fpm) are greater (approximately 300 ft) than the other three treatments. Also, the average distance upstream of the lane closure at which the lane-changing maneuver was initiated for the 18-35 age group was greater (approximately 200 ft) than the sample average for the 60+ age group. However, no significant difference between the five treatment sample averages or the two age group sample averages (at a 95 percent level of confidence) was found. It was also determined (at a 95 percent level of confidence) that there was no significant difference between the approach speed sample averages, and that the variables (approach speed, treatment, and age group) were not dependent on each other. Since there was not a significant difference among treatment sample averages, it may be concluded that the warning light systems did not encourage earlier lane changing upstream of a lane closure compared to the two base treatments (no lights and steady-burn lights).

Table 4. Average Lane-Change Distance Upstream of the Lane Closure.

Variable	Categories	Average Distance Upstream of the Lane Closure at Which the Lane-Changing Maneuver Was Initiated (ft)
Speed	30 mph	323 (N=30)
	65 mph	288 (N=28)
Treatment	No Lights Base	208 (N=11)
	Steady-burn Lights Base	481 (N=11)
	Steady-burn Light Background System with 60 fpm[a]	215 (N=9)
	No Light Background System with 17 fpm[a]	495 (N=12)
	No Light Background System with 60 fpm[a]	154 (N=15)
Age	18-35	400 (N=29)
	60+	213 (N=29)

[a] Flash rate of each individual warning light

Braking Distance and Change in Speed

Twenty-eight (16 for the 30 mph approach speed and 12 for the 65 mph approach speed) out of the 58 subjects (approximately 50 percent) applied their brakes during Part 1 of the study. However, the reason why the subjects applied their brakes is unknown. (The researchers did not ask the subjects why they applied their brakes.) Therefore, the distance upstream of the lane closure that the subjects applied the brakes and the change in speed associated with the braking could not be used to determine if the warning light systems caused confusion.

Subjective Impressions

Subjective impressions were also recorded during Part 1 of the study. The positive and negative statements about the warning light systems are summarized in Table 5. Overall, only two out of the 27 (7 percent) subjects who viewed the no light background system with flash rates of 17 fpm and 60 fpm expressed that they did not understand what to do; however, five out of the 27 (19 percent) subjects commented that they did not like the "moving" light on the drums. On the other hand, one (4 percent) subject indicated that he liked the "moving" light on the drums. Out of the nine subjects who viewed the steady-burn light background system with a flash rate of 60 fpm, only one (11 percent) stated that he did not know until the last moment to exit the closed lane. Out of the same nine subjects, two (22 percent) commented that they liked the "moving" light on the drums. None of the subjects expressed that they did not like the steady-burn light background system with a flash rate of 60 fpm.

Table 5. Part 1 Subjective Impressions of the Warning Light System.

Treatment	Number of Subjects That Commented	Total Number of Subjects That Viewed the Treatment	Percentage of Subjects That Commented	Comment
No Light Background System with Flash Rates of 17 fpm[a] and 60 fpm[a]	2	27	7%	Did not understand
	5	27	19%	Did not like the "moving" lights
	1	27	4%	Liked the "moving" lights
Steady-burn Light Background System with a Flash Rate of 60 fpm[a]	1	9	11%	Did not know until last moment to exit the closed lane
	2	9	22%	Liked the "moving" lights

[a] Flash rate of each individual warning light

Summary of Part 1 Results

Overall, the subjects' performance data indicated that all five of the treatments with a flashing arrow panel encouraged subjects to leave the closed lane without causing confusion. It was also determined that the warning light systems with a flashing arrow panel did not encourage earlier lane changing upstream of the lane closure compared to the two base treatments (no lights and steady-burn lights) with a flashing arrow panel.

Part 2 Results

The purpose of Part 2 of the study was to collect observations of subjects' preferences of the "moving" light produced by the selected flash rates with a steady-burn light background and a no light background. The observations of subjects' preferences were used to determine if the warning light systems caused confusion and to assess whether or not the systems were preferred by subjects over the two base treatments (no lights and steady-burn lights). It should be noted that the first treatment was always the no lights base treatment (normal TxMUTCD lane closure traffic control plan).

The written survey used in Part 2 of the study was composed of the following:

- effect questions (e.g., How did the second treatment you just viewed affect the lane closure compared to the first treatment?);
- comparison questions (e.g., Is treatment two better or worse than the first treatment?); and
- a ranking of the five treatments.

Therefore, the subject responses were organized into three categories: effect, comparison, and ranking.

Treatment Effect on the Subjects' Perception of the Helpfulness of the Traffic Control Devices

The effect the steady-burn lights base treatment, the steady-burn light background system with a flash rate of 60 fpm, and the no light background system with flash rates of 17 fpm and 60 fpm had on the subjects' perception of the helpfulness of the traffic control devices in the lane closure compared to the no lights base treatment (first treatment) was evaluated in the form of a multiple choice question (e.g., How did the second treatment you just viewed affect the lane closure compared to the first treatment?). The three effects the subjects could choose from were "caused confusion," "did not make any difference," and "was helpful." It should be noted that the steady-burn light background system with a flash rate of 60 fpm and the no light background system with a flash rate of 17 fpm were not evaluated by four subjects because of a system malfunction during the study.

The percentage of subjects that chose each effect (caused confusion, did not make any difference, and was helpful) based on the approach speed, age group, and treatment variables are given in Tables 6, 7, and 8, respectively. It was determined (at a 95 percent level of confidence) that the subjects' perception of the relative helpfulness of the traffic control devices in the lane closure was not dependent on the approach speed ($\chi^2_{computed} = 2.03 < \chi^2_{table} = 9.21$) or age group variables ($\chi^2_{computed} = 4.82 < \chi^2_{table} = 9.21$). However, it was dependent (at a 95 percent level of confidence) on the treatment variable ($\chi^2_{computed} = 29.19 > \chi^2_{table} = 16.81$). Based on the percentages given in Table 8, the following findings can be summarized:

- For the steady-burn lights base treatment and the steady-burn light background system with a flash rate of 60 fpm, the majority of the subjects (68 percent and 79 percent, respectively) stated that the treatments were helpful, while only 4 percent and 10 percent of the subjects, respectively, stated the treatments caused confusion.
- For the no light background system with flash rates of 17 fpm and 60 fpm, 56 percent and 45 percent of the subjects, respectively, stated that the treatments were helpful, while 29 percent and 34 percent of the subjects, respectively, stated the treatments caused confusion.

Table 6. Percentage of Subjects That Chose Each Effect Based on Approach Speed.

Answer	Speed (mph)	
	30	65
Caused Confusion	16%	22%
Did Not Make Any Difference	22%	16%
Was Helpful	62%	62%
Sum	100%	100%
Computed χ^2 Value = 2.03		
Table χ^2 Value = $\chi^2_{\alpha,df}$ = 9.21[a]		

[a] Type I error (α) = 0.01 and degrees of freedom (df) = 2

Table 7. Percentage of Subjects That Chose Each Effect Based on Age Group.

Answer	Age Group	
	18-35	60+
Caused Confusion	15%	23%
Did Not Make Any Difference	16%	23%
Was Helpful	69%	54%
Sum	100%	100%
Computed χ^2 Value = 4.82		
Table χ^2 Value = $\chi^2_{\alpha,df}$ = 9.21[a]		

[a] Type I error (α) = 0.01 and degrees of freedom (df) = 2

Table 8. Percentage of Subjects That Chose Each Effect Based on Treatment.

Answer	Treatment			
	Steady-burn Lights Base	Steady-burn Light Background System with a Flash Rate of 60 fpm[a]	No Light Background System with a Flash Rate of 17 fpm[a]	No Light Background System with a Flash Rate of 60 fpm[a]
Caused Confusion	4%	10%	29%	34%
Did Not Make Any Difference	28%	11%	15%	21%
Was Helpful	68%	79%	56%	45%
Sum	100%	100%	100%	100%
Computed χ^2 Value = 29.19*				
Table χ^2 Value = $\chi^2_{\alpha,df}$ = 16.81[b]				

[a] Flash rate of each individual warning light
* Significant since the computed χ^2 value is greater than the table χ^2 value
[b] Type I error (α) = 0.01 and degrees of freedom (df) = 6

Thus, the steady-burn lights base treatment and the steady-burn light background system with a flash rate of 60 fpm were considered to be more helpful and cause less confusion than the no light background system with flash rates of 17 fpm and 60 fpm when the four treatments where compared to the no lights base treatment (normal TxMUTCD lane closure traffic control plan).

Ranking of Treatments

The ranking of the treatments was determined by examining the subjects' answers to the comparison questions (e.g., Is treatment two better or worse than the first treatment?) and the subject ranking of the five treatments. Based on the subjects' answers to the comparison questions, the rankings of the treatments shown in Table 9 were identified. Overall, the steady-burn light background system with a flash rate of 60 fpm and the steady-burn lights base treatment were ranked better than the no light background system with flash rates of 17 fpm and 60 fpm and the no lights base treatment at both speeds.

Based on the subject ranking of the five treatments, a total score for each treatment was computed by assigning one point each time a treatment was ranked first and five points each time a treatment was ranked fifth. Thus, the treatment perceived to be best would have the lowest score. Table 10 shows the number of subjects that chose each rank for each treatment and the

Table 9. Ranking of the Treatments Based on the Subjects' Answers to the Comparison Questions.

Ranking	Speed (mph)	
	30	65
1 (Most Preferred)	Steady-burn Light Background System with a Flash Rate of 60 fpm[a]	Steady-burn Light Background System with a Flash Rate of 60 fpm[a]
2	Steady-burn Lights Base Treatment	Steady-burn Lights Base Treatment
3	No Light Background System with a Flash Rate of 60 fpm[a]	No Light Background System with a Flash Rate of 17 fpm[a]
4	No Light Background System with a Flash Rate of 17 fpm[a]	No Lights Base Treatment
5 (Least Preferred)	No Lights Base Treatment	No Light Background System with a Flash Rate of 60 fpm[a]

[a] Flash rate of each individual warning light

total scores for each treatment. The following is the subject ranking (total score) of the treatments from the best treatment to the worst treatment:

1. steady-burn light background system with a flash rate of 60 fpm (107),

2. steady-burn lights base treatment (132),

3. no light background system with a flash rate of 17 fpm (163),

4. no light background system with a flash rate of 60 fpm (165), and

5. no lights base treatment (183).

Summary of Part 2 Results

Overall, the majority of the subjects stated that the steady-burn lights base treatment (68 percent) and the steady-burn light background system with a flash rate of 60 fpm (79 percent) were helpful compared to the no lights base treatment (normal TxMUTCD lane closure traffic control plan). For the no light background system with flash rates of 17 fpm and 60 fpm, 29 percent and 34 percent of the subjects, respectively, stated that the treatments caused confusion compared to the no lights base treatment, while only 10 percent of the subjects stated that the steady-burn light background system with a flash rate of 60 fpm caused confusion. Based on the ranking of the five treatments, the steady-burn light background system with a flash rate of 60 fpm was ranked first (best) over the other treatments studied.

Table 10. Rank Scores of the Treatments.

Number of Subjects That Chose Each Rank						
Treatment	Rank 1	Rank 2	Rank 3	Rank 4	Rank 5	Total # of Subjects
NL	11	2	5	7	25	50
S	8	17	10	15	0	50
S/60	21	11	12	2	4	50
NL/17	5	9	10	20	6	50
NL/60	5	11	13	6	15	50
Rank Score						
Treatment	Rank 1 Score	Rank 2 Score	Rank 3 Score	Rank 4 Score	Rank 5 Score	Total Score
NL	11	4	15	28	125	183
S	8	34	30	60	0	132
S/60	21	22	36	8	20	107
NL/17	5	18	30	80	30	163
NL/60	5	22	39	24	75	165

NL - No lights base treatment
S - Steady-burn lights base treatment
S/60 - Steady-burn light background system with a flash rate of 60 fpm
NL/17 - No light background system with a flash rate of 17 fpm
NL/60 - No light background system with a flash rate of 60 fpm

FINDINGS

No differences were found among the three warning light systems studied and the two base treatments (no lights and steady-burn lights) in terms of subject performance. Specifically:

- All five of the treatments encouraged subjects to leave the closed lane without causing confusion.

- The warning light systems did not encourage earlier lane changing upstream of the lane closure compared to the two base treatments (no lights and steady-burn lights).

Based on the subjects' <u>preferences</u>, the following findings are summarized:

- The majority of the subjects stated that the steady-burn lights base treatment (68 percent) and the "moving" light produced by the steady-burn light background system with a flash rate of 60 fpm (79 percent) were helpful compared to the no lights base treatment.

- For the no light background system with flash rates of 17 fpm and 60 fpm, 29 percent and 34 percent of the subjects, respectively, stated that the treatments caused confusion compared to the no lights base treatment, while only 10 percent of the subjects stated that the steady-burn light background system with a flash rate of 60 fpm caused confusion.

- The following is the subjects' ranking of the five treatments studied from the best treatment to the worst treatment:

    1. steady-burn light background system with a flash rate of 60 fpm,

    2. steady-burn lights base treatment,

    3. no light background system with a flash rate of 17 fpm,

    4. no light background system with a flash rate of 60 fpm, and

    5. no lights base treatment.

3. FIELD STUDIES

As mentioned in Chapter 1, TxDOT received permission from the FHWA to experiment with the warning light system in field applications. The main objective of this research was to determine if the warning light system would yield significant operational or safety benefits in actual work zone applications. As part of the approval process, a plan to evaluate the use of the system was required. The plan approved by the FHWA is discussed in the Method of Study section.

METHOD OF STUDY

Lane Closure Treatments Studied

The results of the proving ground studies indicate that none of the warning light systems (steady-burn background system with a flash rate of 60 fpm and no light background system with flash rates of 17 fpm and 60 fpm) caused any apparent adverse effects (i.e., confusion) to the subjects in terms of subject performance. Thus, it was not deemed necessary to evaluate all of the warning light systems in the field. The steady-burn light background system with a flash rate of 60 fpm was ranked best by the subjects; therefore, it was examined in subsequent field studies.

To evaluate the warning light system in field applications, a before-after (i.e., without lights versus with lights) study methodology was used. Several traffic operational measures were collected when the normal TxMUTCD lane closure traffic control plan (no lights base treatment) was in place (consisting of advance warning signs, a flashing arrow panel, and channelizing drums). The same measures were also taken when the lights (steady-burn light background system with a flash rate of 35 fpm) were attached to the top of the channelizing drums in the lane closure taper and activated. Any differences in the performance measures between the two conditions would be indicative of the effect of the warning light system upon motorist response.

It should be noted that the flash rate used with the warning light system was modified prior to the field studies to account for photosensitive epilepsy. Photosensitive epilepsy is a type of epilepsy in which seizures are caused by visual stimuli, such as flashing or flickering lights (*10*, *11*). The frequency of the flashing light that provokes seizures varies from person to person; however, it is generally between five to 30 flashes per second (300 fpm to 1800 fpm, respectively). Some people are photosensitive at higher flash frequencies, but it is uncommon to have photosensitivity below five flashes per second (*11*).

The recommended flash rate of each individual warning light (60 fpm) does not fall into the frequency range discussed above; however, the flash rate of the whole system (720 fpm for 65 mph and 360 fpm for 30 mph) does. Although it was not known for sure if the warning light system could cause such seizures, the system was altered such that the flash rate of the whole system was below 300 fpm. To accomplish this task the "flash" time (time that the higher intensity flash is on) of each individual warning light has to be at least 0.2 seconds. The resulting flash rate of each individual warning light that produces the perception of a "moving" light similar to the 60 fpm used in the proving ground study is 35 fpm.

Performance Measures

The primary focus of the field studies was to identify whether the warning light system resulted in significant differences in the following operational measures of performance:

- speed statistics at the beginning of the taper (average, percent exceeding the posted speed limit, and standard deviation);
- lane choice statistics upstream of the taper (percent of traffic in each lane and percent of last-minute lane changes); and
- erratic maneuvers/vehicle conflicts.

As a minimum, lane choice statistics were computed at 1000 ft upstream, 500 ft upstream, and at the beginning of the lane closure (i.e., last-minute lane-changers). Erratic maneuvers were also assessed over the 1000 ft distance upstream of the taper. As a minimum, speeds of at least 125 free-flowing vehicles were collected for the normal TxMUTCD lane closure traffic control plan with and without the warning light system. To evaluate motorist lane choice, between 300 and 1000 vehicle samples per condition were obtained.

FIELD STUDY RESULTS

Test Site 1 – College Station, Texas

Test site 1 was located on FM 60 west of College Station, Texas. A bridge construction project at the Brazos River required that the westbound (outbound) direction of FM 60 be reduced from two lanes to one lane. A left-lane closure upstream of the bridge was installed by the contractor according to TxMUTCD requirements. Figure 5 illustrates the test site.

The posted nighttime speed limit at the site is 65 mph. The roadway has a gentle rolling alignment and no overhead lighting. A motorist can see the arrow panel for the left-lane closure from a significant distance (2500 ft+) upstream of the closure. Motorists then proceed into a sag vertical curve where the arrow panel disappears from view and reappears once they are approximately 1500 ft from the closure. The actual lane closure occurs on a gentle horizontal curve to the right (note that the figure actually overrepresents the severity of that curve). The warning light system was installed on 12 drums in the 770 ft section beyond the arrow panel where the travel lane is actually being closed.

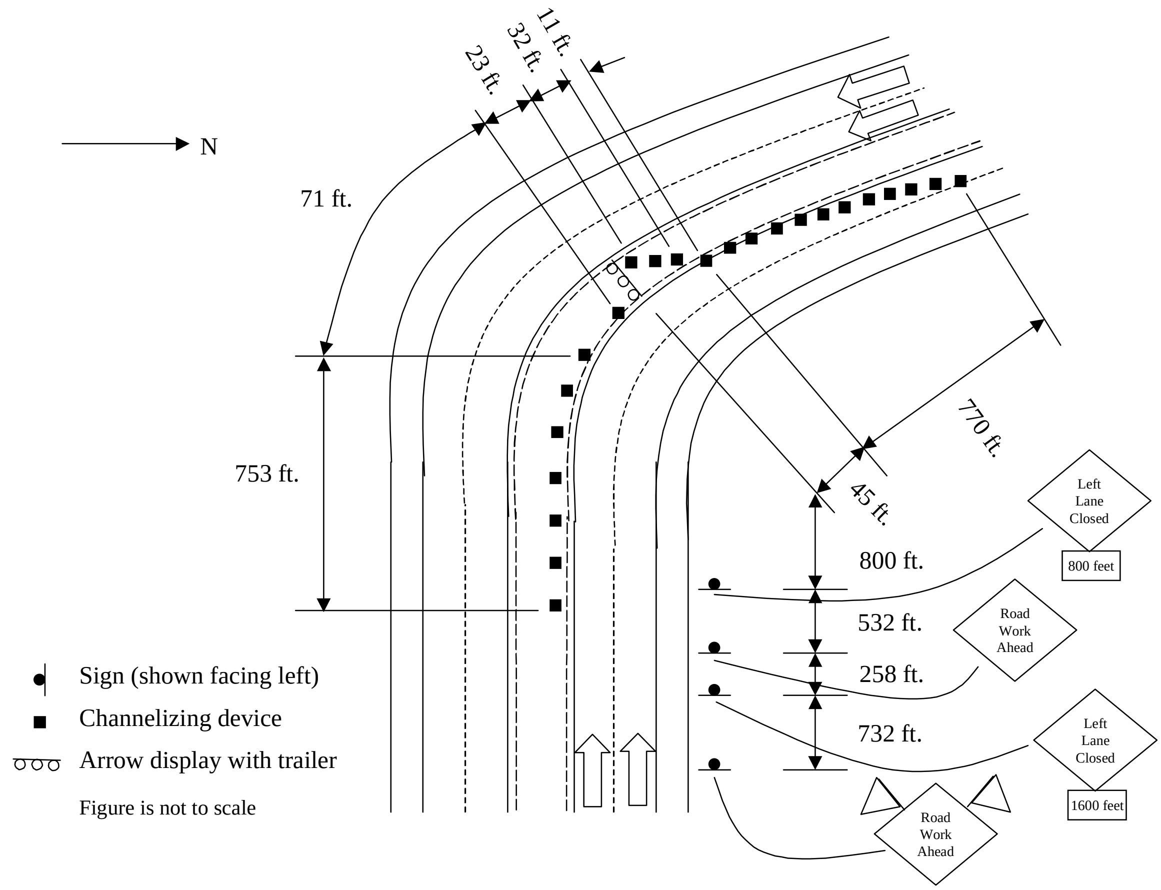

Figure 5. Test Site 1 on FM 60 Westbound, College Station, Texas.

This test site was chosen by the researchers to conduct a pilot test of the warning light system to verify that the system was operating correctly and that there was no obvious confusion about the system or the lane closure setup. However, it should be noted that the lane closure itself was installed in January 1999 (six months prior to this study). Consequently, most motorists using the roadway were already highly accustomed to the presence of the lane closure and the need to be in the right lane prior to reaching the closure.

Data Collection

The operational measures of performance were collected for both treatments (normal TxMUTCD traffic control plan with and without the warning light system) at night. A portable video camera trailer was used to collect lane choice and erratic maneuver traffic data upstream of the test site. The trailer was positioned upstream of the test site such that a camera view of the 1000 ft zone upstream of the lane closure was obtained as shown in Figure 6. Lane choice traffic data was also collected 2000 ft upstream of the lane closure in an unmarked research vehicle located off of

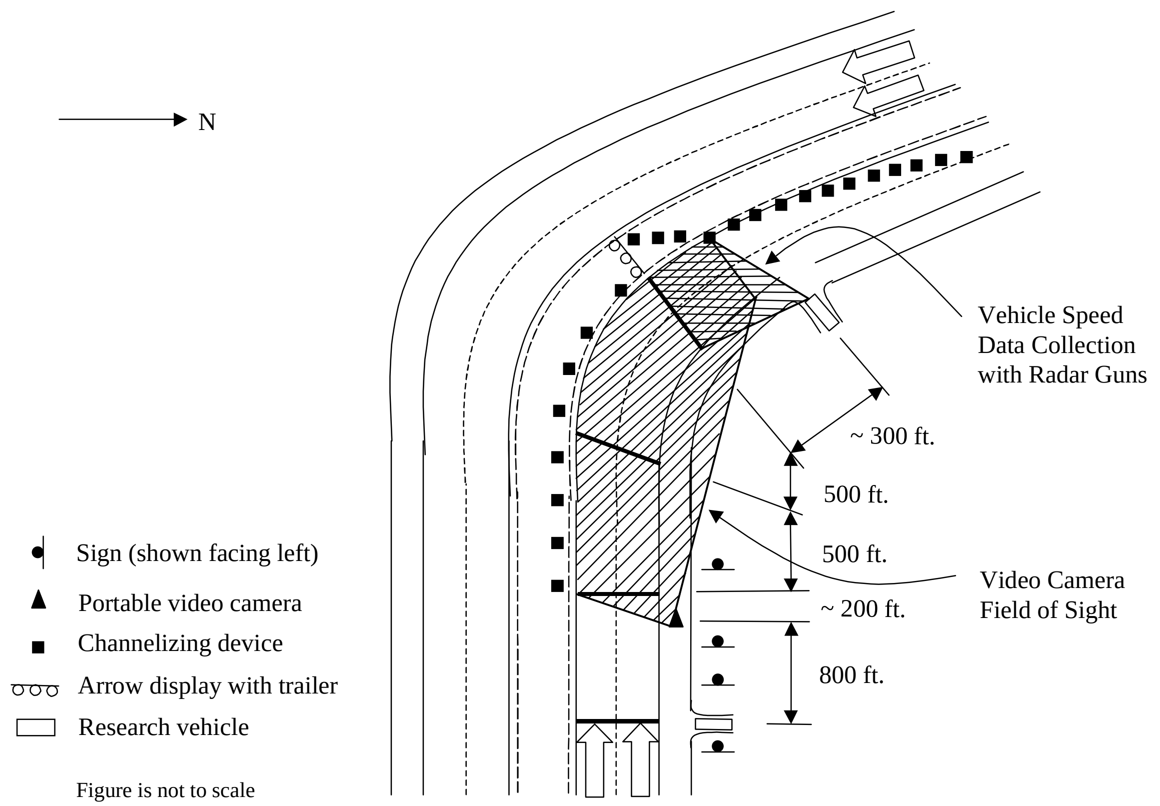

Figure 6. Test Site 1 Data Collection Layout.

the travel lanes. At 2000 ft upstream of the lane closure the motorists were in the sag vertical curve and could not see the arrow panel and/or the warning light system. Speed data at the beginning of the lane closure taper was collected using a laser speed gun from an unmarked research vehicle located off of the travel lanes. Figure 6 also shows the location of the two unmarked vehicles.

It should be noted that there are numerous driveways along FM 60 at the test site. Vehicles that exited FM 60 via these driveways were identified. These vehicles were not included in the analysis.

Speed Results

Table 11 contains the average speed at the beginning of the taper and associated standard deviation for the normal TxMUTCD lane closure traffic control plan with and without the the warning light system. Table 11 also contains the percent of vehicles exceeding the posted speed limit (65 mph) at the beginning of the taper for both treatments. It was determined that there were no significant differences (at a 95 percent level of confidence) between the two treatments with respect to the average speed and the percent of vehicles exceeding the posted speed limit at the beginning of the taper. Thus, the warning light system did not effect the speed of the vehicles at the beginning of the taper.

Table 11. Test Site 1 Speed Statistics.

Normal TxMUTCD Lane Closure Traffic Control Plan	Sample Size	Average Speed[a] (mph)	Standard Deviation (mph)	Percent of Vehicles Exceeding the Posted Speed Limit (65 mph)[a]
With Warning Light System	277	61.4	6.01	23
Without Warning Light System	161	61.0	5.89	23

[a] Vehicle speeds were measured at the beginning of the taper

Lane Choice Statistics

Table 12 contains the percent of traffic in each lane upstream of the lane closure (i.e., 2000 ft, 1000 ft, 500 ft) and at the beginning of the taper (i.e., last-minute lane changing) for both treatments. In general, the percentages of traffic in the closed lane are lower when the warning light system was activated. However, it was determined that the differences between the two treatments with respect to lane choice upstream of the closure and at the beginning of the taper were not significant (at a 95 percent level of confidence). This was expected by the researchers since the lane closure had been installed for six months and the motorists in the area are predominately commuters. Thus, the motorists were familiar with the bridge construction project and the left-lane closure upstream of the bridge.

Researchers monitored the traffic behavior at the site via video tapes. They did not observe any erratic maneuvers that would suggest that the warning light system caused any driver misunderstanding or confusion.

Table 12. Test Site 1 Lane Choice Statistics.

Normal TxMUTCD Lane Closure Traffic Control Plan	Distance Upstream of the Lane Closure (ft)			
	2000	1000	500	0[a]
	Percent of Traffic in Closed Lane			
With Warning Light System	32%	30%	21%	14%
Without Warning Light System	35%	31%	24%	13%

[a] At the beginning of the lane closure taper (i.e., last-minute lane changing)

Test Site 2 – Houston, Texas

Test site 2 was located on I-10 west of the Sam Houston Tollway (Beltway 8) in Houston, Texas. A re-striping project required that the westbound (outbound) direction of I-10 be reduced from three lanes to one lane. A double left-lane closure upstream of the re-striping work was installed by the contractor according to TxMUTCD requirements. Figure 7 illustrates the test site.

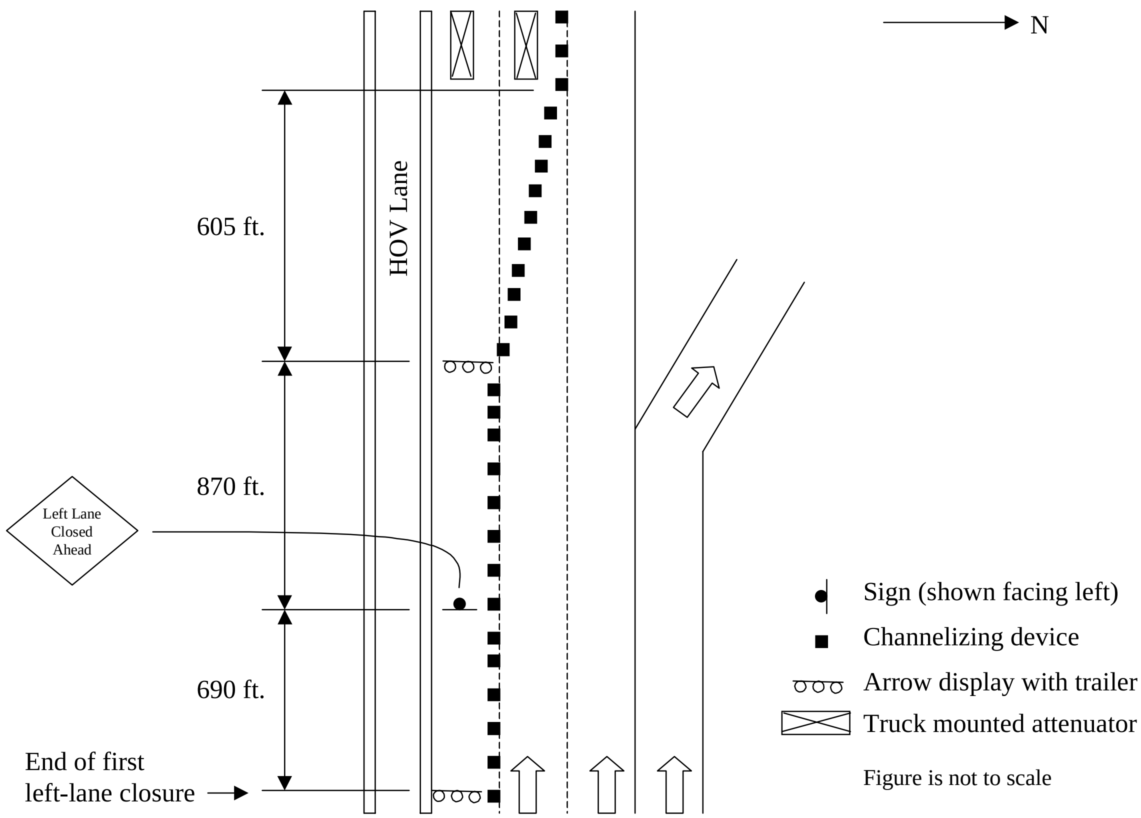

Figure 7. Test Site 2 on I-10 Westbound, Houston, Texas.

The posted nighttime speed limit at the site is 65 mph for passenger vehicles and 55 mph for trucks. The roadway has a gentle rolling alignment, and overhead lighting in the median between the eastbound main lanes and the eastbound frontage road. A motorist can see the arrow panels for both left-lane closures from a significant distance (2500 ft+) upstream of the first lane closure. The first lane closure occurs on a tangent section after a crest vertical curve. The second lane closure occurs on the ascent of a crest vertical curve, with the arrow panel and first drum of the taper located at the bottom of the crest vertical curve and the last drum in the taper located at the top of the crest vertical curve. A tangent section approximately 1500 ft long separates the two left-lane closures. The warning light system was installed on 11 drums in the 605 ft section beyond the second arrow panel, where the middle travel lane is actually being closed. It should be noted that the re-striping project began in July 1999; thus, alternate lanes in the area had been closed at night for only about three weeks prior to this study. Furthermore, these closures did not occur each night. Consequently, motorists had little or no opportunity to develop expectations about the presence of a lane closure on the facility.

Data Collection

The operational measures of performance were collected for both treatments (normal TxMUTCD traffic control plan with and without the warning light system) at night. Lane choice traffic data was collected 1000 ft upstream, 500 ft upstream, and at the beginning of the taper in unmarked research vehicles located in the high occupancy vehicle (HOV) lane. Speed data at the beginning of the lane closure taper was collected using a laser speed gun from an unmarked research vehicle in the HOV lane. Figure 8 shows the location of the unmarked vehicles.

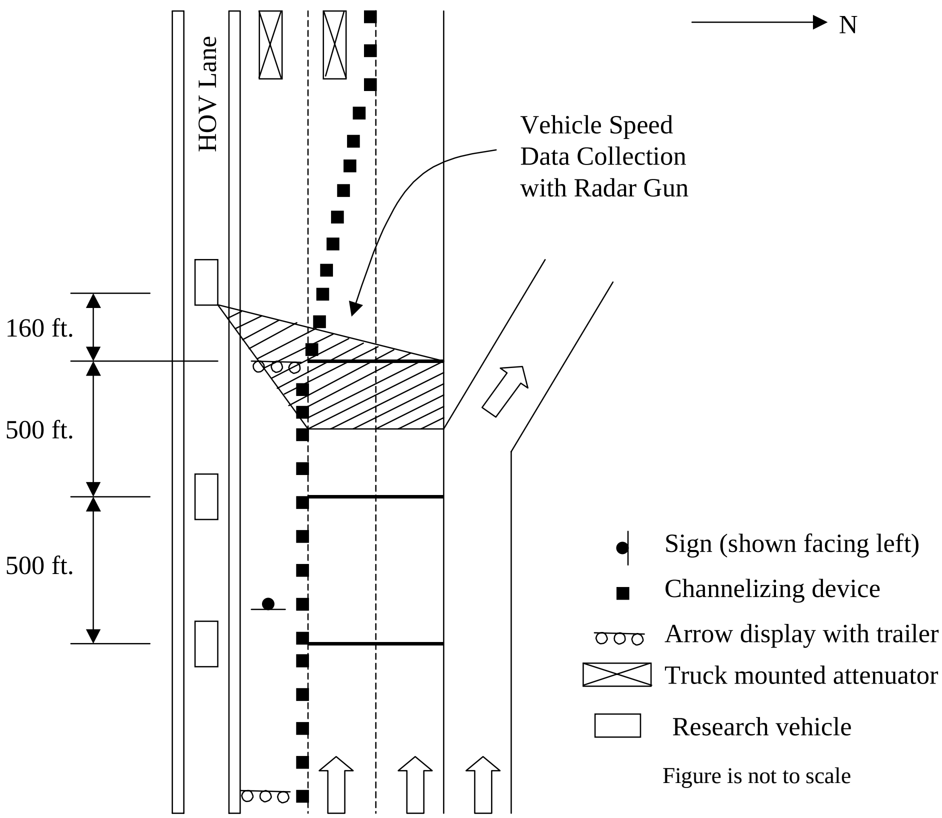

Figure 8. Test Site 2 Data Collection Layout.

The lane choice and speed data were recorded for passenger vehicles and trucks, separately. The data for trucks was recorded separately because the eye level of a truck driver is higher than that of a passenger vehicle driver. Researchers recognized that truck drivers may see and react to the lane closure (i.e., arrow panels, warning light system, etc.) before the drivers of passenger vehicles. It should also be noted that the lane choice data collected at 1000 ft and 500 ft upstream of the lane closure did not include the vehicles in the "exit only" lane. However, vehicles moving out of the "exit only" lane into the outside through lane at the last minute were observed by the researchers.

A Houston TRANSTAR closed-circuit television camera (CCTV) located upstream of the test site was used to collect erratic maneuver traffic data. The camera's view captured the 1000 ft zone upstream of the lane closure.

Speed Results

Tables 13 and 14 contain the following speed statistics for the normal TxMUTCD lane closure traffic control plan with and without the warning light system for passenger vehicles and trucks, respectively: the average vehicle speed, the standard deviation of the average vehicle speed, and the percent of vehicles exceeding the posted speed limit (65 mph for passenger vehicles and 55 mph for trucks) at the beginning of the taper. No significant differences (at a 95 percent level of confidence) were detected between the two treatments with respect to the average vehicle speed (passenger and truck) and the percent of vehicles (passenger and truck) exceeding the posted speed limit at the beginning of the taper. Thus, the warning light system did not effect the speed of traffic at the beginning of the taper.

Table 13. Test Site 2 Passenger Vehicle Speed Statistics.

Normal TxMUTCD Lane Closure Traffic Control Plan	Sample Size	Average Speed[a] (mph)	Standard Deviation (mph)	Percent of Vehicles Exceeding the Posted Speed Limit[a] (65 mph)
With Warning Light System	109	62.5	7.28	28
Without Warning Light System	131	62.4	6.49	34

[a] Passenger vehicle speeds were measured at the beginning of the taper

Table 14. Test Site 2 Truck Speed Statistics.

Normal TxMUTCD Lane Closure Traffic Control Plan	Sample Size	Average Speed[a] (mph)	Standard Deviation (mph)	Percent of Vehicles Exceeding the Posted Speed Limit[a] (55 mph)
With Warning Light System	28	57.4	4.11	64
Without Warning Light System	21	57.4	6.01	62

[a] Truck speeds were measured at the beginning of the taper

Lane Choice Statistics

Table 15 contains the percent of passenger vehicles in each lane upstream of the lane closure (i.e., 1000 ft and 500 ft) and at the beginning of the taper (i.e., last-minute lane changing) for both treatments. In general, the percentages of passenger vehicles in the closed lane were lower when the warning light system was activated. In particular, researchers identified a significant difference (at a 95 percent level of confidence) between the two treatments with respect to lane choice 1000 ft upstream of the closure. When the warning light system was used with the normal TxMUTCD lane closure traffic control plan, 23 percent of the passenger vehicles were in the closed lane compared to 30 percent of the passenger vehicles when the normal TxMUTCD lane closure traffic control plan was used without the warning light system. Thus, there was a 7 percent reduction in the number of passenger vehicles in the closed lane at 1000 ft upstream of the lane closure when the warning light system was activated.

Table 15. Test Site 2 Passenger Vehicle Lane Choice Statistics.

Normal TxMUTCD Lane Closure Traffic Control Plan	Distance Upstream of the Lane Closure (ft)		
	1000	500	0[a]
	Percent of Traffic in Closed Lane		
With Warning Light System	23%*	15%	9%
Without Warning Light System	30%	19%	12%

[a] At the beginning of the lane closure taper (i.e., last-minute lane changing)

* Significantly different from the normal TxMUTCD set up without system at a 95 percent level of confidence

Table 16 contains the percent of trucks in each lane upstream of the lane closure (i.e., 1000 ft and 500 ft) and at the beginning of the taper (i.e., last-minute lane changing) for both treatments. The percentages of trucks in the closed lane were lower at 1000 ft and 500 ft upstream of the lane closure when the warning light system was activated. However, it was determined (at a 95 percent level of confidence) that there was only a significant difference between the two treatments with respect to lane choice 1000 ft upstream of the closure. When the warning light system was used with the normal TxMUTCD lane closure traffic control plan, 7 percent of the trucks were in the closed lane compared to 19 percent of the trucks when the normal TxMUTCD lane closure traffic control plan was used without the warning light system. Thus, there was a 12 percent reduction in the number of trucks in the closed lane at 1000 ft upstream of the lane closure when the warning light system was activated. It should be noted that there was not a significant difference (at a 95 percent level of confidence) between the two treatments with respect to lane choice at the beginning of the taper.

The data discussed previously was not collected until free-flowing traffic conditions were observed by the researchers. However, at the request of the TxDOT project manager, the warning light system was activated during a congested period to improve motorist detection and recognition of the lane closure. The TxDOT project manager stated that he thought traffic was changing lanes further upstream when the warning light system was used than when the normal TxMUTCD lane closure traffic control plan was used by itself.

Table 16. Test Site 2 Truck Lane Choice Statistics.

Normal TxMUTCD Lane Closure Traffic Control Plan	Distance Upstream of the Lane Closure (ft)		
	1000	500	0[a]
	Percent of Traffic in Closed Lane		
With Warning Light System	7%*	5%	5%
Without Warning Light System	19%	10%	3%

[a] At the beginning of the lane closure taper (i.e., last-minute lane changing)
* Significantly different from the normal TxMUTCD set up without system at a 95 percent level of confidence

Researchers monitored the traffic behavior at the site via a video tape. They did not observe any erratic maneuvers that would suggest that the warning light system caused any driver misunderstanding or confusion.

Summary of Field Studies

The warning light system did not significantly effect the lane choice or speed of vehicles at the FM 60 test site. This was expected by the researchers since the lane closure had been installed for six months, and the motorists in the area were predominately familiar with the bridge construction project and the left-lane closure upstream of the bridge. In contrast, the warning light system did significantly effect the lane choice of both passenger vehicles and trucks at the I-10 test site 1000 ft upstream of the lane closure. When the warning light system was activated, there was a 7 percent and 12 percent reduction in the number of passenger vehicles and trucks, respectively, in the closed lane. However, the warning light system did not significantly effect the passenger vehicle or truck speeds at the beginning of the taper.

4. WARNING LIGHT SYSTEM DESIGN ISSUES

DESIGN CONSTRAINTS

As discussed in Chapter 1, the warning light system is composed of a series of interconnected, synchronized individual flashing warning lights that are attached to drums that form the lane closure taper. Each individual flashing warning light connects to a junction box located on the ground next to the drum via a cable that is built into the light. Each junction box is then connected to two larger cables. These larger cables are each 70 ft long and are located on the ground inside the closed lane. The starter box, which controls the flash rate of each individual flashing warning light, is connected directly to the first junction box and to a DC power supply via a cable. If the power supply is not located within a few feet of the first junction box, then a large cable can be used to connect the first junction box to the starter box. The recommended power source for the system is an arrow panel battery. If the lane closure taper requires that more than 500 ft of the large cable be used, then a cable booster box must be placed between the first junction box and the starter box to amplify the signal sent down the taper. However, the total length of the large cable used to connect the system cannot exceed 900 ft.

FIELD EXPERIENCES

Finding actual work zone applications that the warning light system could be used in conjunction with was difficult, since the total length of the large cable used to connect the system could not exceed 900 ft. This especially causes problems in lane closures where chevrons are used on every other drum in the taper. In general, when chevrons are used in this manner, the distance between every other drum without a chevron is longer than 70 ft (the length of one large cable used to connect two junction boxes). Thus, two large cables (140 ft) instead of one have to be used to connect two junction boxes. This additional length of large cable causes the total length of large cable used to connect the system to exceed 900 ft. Thus, the cable interconnect limits the ability of a project engineer to modify drum spacing to incorporate chevrons and other devices.

During the proving ground study, and especially the field studies, the researchers found it very cumbersome and time consuming to unload and connect all of the components. For example, for the field study on I-10 west in Houston, Texas, the lane closure taper consisted of 11 drums; thus, 11 warning lights, 11 junction boxes, 10 large cables, one starter box, and one cable booster box had to be connected. This took four people approximately 30 minutes to connect.

The main problem encountered by the researchers was the inability to keep the warning light system working properly. On several occasions during the proving ground study, the connections between the junction boxes and the large cables would lose contact such that the signal sent down the taper was interrupted. This also occurred during the field study on FM 60 west of College Station, Texas, when vehicles crossed over the cables (i.e., vehicles turning from and into driveways across the lane closure).

Also, the warning lights that are attached to the drums that form the lane closure taper are comprised of unidirectional light-emitting diodes (LEDs). Thus, if a drum is even slightly misaligned, the warning light may not be visible to oncoming motorists, and so the perception of a “moving” light produced by the warning light system would be disrupted.

During discussions with TxDOT personnel about the system, several of them also indicated concerns with the cable interconnect as a major limitation in the system’s usefulness in the field. Concerns were also expressed about the narrow (15 degree) cone of vision provided by the LED warning lights.

5. SUMMARY AND RECOMMENDATIONS

SUMMARY

This report has documented the research performed to assess the effectiveness of a warning light system as a work zone traffic control device. Researchers investigated motorist understanding of and perceived usefulness of various designs of the warning light system in a simulated work zone at night at TTI's proving ground facility at the Texas A&M University Riverside Campus. These results were used to develop recommendations for the use of the system in field applications. Field studies of the warning light system were performed at night to determine if the system would yield significant operational or safety benefits in actual work zone applications. Operational measures of performance were collected for the normal TxMUTCD lane closure traffic control plan with and without the warning light system to assess the effect of the system upon motorist response. Researchers also discussed the physical design of the warning light system in respect to the problems encountered while using the system in the proving ground and field studies.

The results of the nighttime proving ground study indicate that the warning light systems studied (steady-burn light background system with a flash rate of 60 fpm and no light background system with flash rates of 17 fpm and 60 fpm) encouraged subjects to leave the closed lane without causing any apparent confusion. However, the systems did not encourage earlier lane changing upstream of the lane closure compared to the two base treatments (no lights and steady-burn lights). A majority of the subjects (79 percent) stated that the "moving" light produced by the steady-burn light background warning light system was helpful compared to the normal TxMUTCD lane closure traffic control plan without the "moving" light (no lights base treatment). The steady-burn light background warning light system was also ranked first (best) over the other treatments studied.

Field studies were conducted at night at the following two test sites: 1) FM 60 west of College Station, Texas, at the Brazos River where a bridge construction project required that the westbound (outbound) direction of FM 60 be reduced from two lanes to one lane, and 2) I-10 west of the Sam Houston Tollway (Beltway 8) in Houston, Texas, where a re-striping project required that the westbound (outbound) direction of I-10 be reduced from three lanes to one lane. The warning light system did not significantly effect the speed of vehicles at either test site. The system also did not significantly effect the lane choice of vehicles at the FM 60 test site. However, this was expected by the researchers since the lane closure had been installed for six months and the motorists in the area were familiar with the bridge construction project and the left-lane closure upstream of the bridge. In contrast, the warning light system did significantly effect the lane choice of both passenger vehicles and trucks at the I-10 test site. When the warning light system was activated there was a 7 percent and 12 percent reduction in the number of passenger vehicles and trucks, respectively, in the closed lane 1000 ft upstream of the lane closure.

During the proving ground and field studies, researchers identified several problems with the physical design of the warning light system. In general, the setup of the system is cumbersome and time consuming because it is comprised of numerous components. Also, the warning light system cannot be used on lane closures that require the use of more than 900 ft of cable to connect the system. The major problem encountered was the inability to keep the system working properly. This was attributed to the connections between the junction boxes and the large cables losing contact such that the signal sent down the taper was interrupted. Another problem noted by the researchers was that the warning lights used were unidirectional. Thus, if the drums they were attached to became slightly misaligned, the lights would not be directly facing the oncoming traffic, which in turn would disrupt the perception of a "moving" light produced by the warning light system.

RECOMMENDATIONS

Proving ground and field studies show that the work zone lane closure flashing warning light system is perceived positively and is not confusing to the motoring public, and may encourage motorists to vacate a closed travel lane sooner (which is believed to offer a potential safety benefit). However, researchers believe that the current design (cable interconnected directional LED lights) of the system will be difficult to implement and maintain in a field setting. Therefore, researchers recommend that TxDOT consider the following:

- TxDOT should specify a desire for a wireless system that has a wider cone of vision than currently provided by the flashing LED lights.

- If a revised system design can be reasonably obtained, TXDOT should consider limited demonstration evaluation at a few more lane closure sites to evaluate TxDOT and contractor ability to set up and maintain the system. Implementation Plan and Recommendation (IPR) funds should be pursued for purchase of such a system for field demonstration purposes.

- Any field demonstrations of a revised system should comply with TxDOT's Request to Experiment with this type of device as approved by the FHWA.

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APPENDIX A: PILOT STUDY

INTRODUCTION

A pilot study was conducted at night at TTI's proving ground facility to assess initial observations of the subjects' reactions to and preferences of the "moving" light produced by the selected flash rates and to test the methodology of the research. The data collected were used to determine if the warning light system encouraged the subjects to leave the closed lane without causing confusion and to assess whether or not the system was preferred by the subjects. The flash rates that did not cause confusion were then recommended to be studied further.

METHOD OF STUDY

The layout of the traffic control devices and the study approach described in Chapter 2 were followed in the pilot study. However, it should be noted that a different written survey was used. A copy of the survey is located at the end of this appendix.

Lane Closure Treatments Studied

The two base treatments (no lights and steady-burn lights) described in Chapter 2 were used in the pilot study. In addition to the two base treatments, two flash rates (17 fpm and 60 fpm) were studied in conjunction with the warning light system. This system (steady-burn light background) was designed to combine the steady-burn warning lights, which have been proven to provide additional delineation of channelization devices at night, and the interconnected, synchronized flashing warning lights that are thought to improve motorist detection and recognition of a lane closure. Overall, four treatments with a flashing arrow panel were studied at 30 mph and 65 mph, which correspond to 180 ft and 780 ft lane closure taper lengths, respectively.

Subjects

Twenty-two subjects from TTI participated in the pilot study. The subjects' ages ranged from 21 to 55 years old. Both males and females were recruited.

PART 1 RESULTS

The objective of Part 1 of the pilot study was to collect initial observations of the subjects' reactions to the "moving" light produced by the selected flash rates. These observations were used to determine if the warning light system encouraged the subjects to leave the closed lane without causing confusion. The subjects' reactions (measures of effectiveness) evaluated were the distance upstream of the lane closure at which the lane-changing maneuver was initiated, the distance upstream of the lane closure at which the subjects applied the brakes, and the change in speed caused by braking. The three reactions were collected for each subject.

Lane-Changing Distance

Table 17 contains the average distance upstream of the lane closure at which the lane-changing maneuver was initiated for each approach speed and treatment. It was determined (at a 95 percent level of confidence) that there were no significant differences among the two approach speed sample averages or the four treatment sample averages. Thus, it can be concluded that the warning light system with flash rates of 17 fpm and 60 fpm facilitated the same motorist reactions as the two base treatments (no lights and steady-burn lights).

Table 17. Pilot Study Average Lane-Changing Distance Upstream of the Lane Closure.

Variable	Categories	Average Distance Upstream of the Lane Closure at Which the Lane-Changing Maneuver Was Initiated (ft)
Speed	30 mph	310 (N=11)
	65 mph	359 (N==11)
Treatment	No Lights Base	365 (N=6)
	Steady-burn Lights Base	294 (N=6)
	Steady-burn Light Background System with 17 fpm[a]	326 (N=5)
	Steady-burn Light Background System with 60 fpm[a]	353 (N=5)

[a] Flash rate of each individual warning light

Braking Distance and Change in Speed

Only five out of the 22 subjects applied their brakes during Part 1 of the pilot study; thus, statistical analysis was not used to evaluate the distance upstream of the lane closure at which the subject applied the brakes and the change in speed caused by braking. The researchers examined the distance upstream of the lane closure at which the subject applied the brakes and the change in speed caused by braking and found no indication that the warning light system caused confusion to the subjects.

Subjective Impressions

Subjective impressions were also recorded during Part 1 of the pilot study. Overall, two out of the 10 subjects (20 percent) who viewed the warning light system expressed that they did not know that a lane was closed. On the other hand, one out of the 10 subjects (10 percent) commented that he liked the warning light system. The other seven subjects' (70 percent) subjective impressions did not concern the warning light system.

Summary of Part 1 Results

Overall, the subjects' performance data indicated that all four of the treatments with a flashing arrow panel encouraged subjects to leave the closed lane without causing confusion. It was also determined that the warning light system with a flashing arrow panel did not encourage earlier lane changing upstream of the lane closure compared to the two base treatments (no lights and steady-burn lights) with a flashing arrow panel.

PART 2 RESULTS

The purpose of Part 2 of the pilot study was to collect initial observations of the subjects' preferences of the "moving" light produced by the selected flash rates (17 fpm and 60 fpm). The initial observations of the subjects' preferences were used to determine if the warning light system caused confusion and to assess whether or not the system was preferred by the subjects over the two base treatments (no lights and steady-burn lights).

Treatment Effect on the Subjects' Perception of the Helpfulness of the Traffic Control Devices in the Lane Closure

The effect the steady-burn lights base treatment and the warning light system with flash rates of 17 fpm and 60 fpm had on the subjects' perception of the helpfulness of the traffic control devices in the lane closure compared to the no lights base treatment was evaluated in the form of a multiple choice question (e.g., How did the second treatment you just viewed affect the lane closure?). The three effects the subjects could choose from were "caused confusion," "did not make any difference," and "was helpful."

As discussed in the Chapter 2 Method of Study section, the no lights base treatment with flashing arrow panel (TxMUTCD standard) was always the first treatment to be shown in each set. Thus, the subjects were suppose to compare the effect the steady-burn lights base treatment and the warning light system with flash rates of 17 fpm and 60 fpm had on the subjects' perception of the helpfulness of the traffic control devices in the lane closure to the no lights base treatment. However, due to the wording of the question on the written survey (e.g., How did the second treatment you just viewed affect the lane closure?) it could not be determined if the subjects were comparing the three treatments to the no lights base treatment. Thus, the data was not used to determine if the warning light system caused confusion.

Ranking of Treatments

The ranking of the treatments was determined by examining the subjects' answers to the comparison questions (e.g., Is treatment two better or worse than the first treatment?) and the subject ranking of the four treatments. Based on the subjects' answers to the comparison questions, the following ranking of the treatments from most preferred treatment to least preferred treatment was determined for both speeds:

1. warning light system with a flash rate of 60 fpm,

2. warning light system with a flash rate of 17 fpm,

3. steady-burn lights base treatment, and

4. no lights base treatment.

Based on the subject ranking of the four treatments, a total score for each treatment was computed by assigning one point each time a treatment was ranked first and four points each time a treatment was ranked fourth. Thus, the treatment perceived to be best would have the lowest score. Table 18 shows the number of subjects that chose each rank for each treatment and the total scores for each treatment. The following is the subject ranking (total scores) of the treatments from the best treatment to the worst treatment:

1. warning light system with a flash rate of 60 fpm (41),

2. warning light system with a flash rate of 17 fpm (42),

3. steady-burn lights base treatment (55), and

4. no lights base treatment (72).

Summary of Part 2 Results

Overall, the initial observations of the subjects' preferences could not be examined to determine if the warning light system caused confusion due to the wording of the effect question on the survey. However, the initial observations of the subjects' preference were used to assess whether or not the warning light system was preferred by subjects over the two base treatments (no lights and steady-burn lights). Based on the ranking (total scores) of the four treatments, it was concluded that the warning light system was preferred over the two base treatments.

Summary of Pilot Study Results

The initial data of the subjects' performance indicated that all four of the treatments with a flashing arrow panel encouraged subjects to leave the closed lane without causing confusion. It was also determined that the warning light system with a flashing arrow panel did not encourage earlier lane changing upstream of the lane closure compared to the two base treatments (no lights

Table 18. Pilot Study Ranking of Treatments.

Number of Subjects That Chose Each Rank					
Treatment	Rank 1	Rank 2	Rank 3	Rank 4	Total # of Subjects
NL	3	1	1	16	21
S	3	3	14	1	21
S/17	3	15	3	0	21
S/60	12	2	3	4	21
Rank Score					
Treatment	Rank 1 Score	Rank 2 Score	Rank 3 Score	Rank 4 Score	Total Score
NL	3	2	3	64	72
S	3	6	42	4	55
S/17	3	30	9	0	42
S/60	12	4	9	16	41

NL - No lights base treatment
S - Steady-burn lights base treatment
S/17 - Steady-burn light background system with a flash rate of 17 fpm
S/60 - Steady-burn light background system with a flash rate of 60 fpm

and steady-burn lights) with a flashing arrow panel. The initial observations of subjects' preferences showed that the warning light system was preferred over the two base treatments.

The methodology of the research used in Part 1 and Part 2 of the pilot study achieved the desired goal of the research, except for the effect question in Part 2. Due to the wording of the effect question (e.g., How did the second treatment you just viewed affect the lane closure?) it could not be determined if the subjects were comparing the three randomized treatments to the no lights base treatment. Thus, the subjects' perception of the relative helpfulness of the traffic control devices in the lane closure compared to the no lights base treatment could not be determined.

PILOT STUDY RECOMMENDATIONS

The pilot study results revealed that 1) there was not a statistically significant difference between the warning light system with flash rates of 17 fpm and 60 fpm with respect to the distance upstream of the lane closure at which the lane-changing maneuver was initiated, and 2) subjects ranked the two flash rates similarly. Thus, the 17 fpm was not recommended for further study. Based on the initial data collected and analyzed, only the warning light system (steady-burn light background system) with the flash rate of 60 fpm was recommended to be studied further in order to reduce the test administration time for each subject.

After reviewing the pilot study results, the panel of four transportation and human factors experts decided that the “moving” light produced by the warning light system should be tested without the steady-burn light background in addition to the setup with a steady-burn light background. This additional system would only produce a light that “moved” repeatedly in a sequential manner along the taper from the shoulder to the end of the taper, instead of continually displaying steady-burn lights with a higher intensity “moving” light. The panel also decided that the two extreme flash rate values (17 fpm and 60 fpm) that were studied in the pilot study should be evaluated without the steady-burn light background at the same two approach speeds (30 mph and 65 mph) examined in the pilot study. Thus, the following five treatments were recommended to be evaluated at 30 mph and 65 mph in further studies:

- no lights base,
- steady-burn lights base,
- steady-burn light background system with the flash rate of 60 fpm,
- no light background system with the flash rate of 17 fpm, and
- no light background system with the flash rate of 60 fpm.

To ensure that the subjects were comparing the effect of the randomized treatments on the subjects’ perception of the relative helpfulness of the traffic control devices in the lane closure to the no lights base treatment it was recommended that the wording of the effect question be changed to include the phrase “compared to the first treatment” at the end of the question (e.g., How did the second treatment you just viewed affect the lane closure compared to the first treatment?). The revised written survey is shown in Appendix C.

PILOT STUDY WRITTEN SURVEY

PART II Subject #______ ID2______
Section 1:

(Please circle the answer that you feel is the most appropriate.)

Second Condition:
1. How did the second condition you just viewed effect the lane closure? The condition
a) caused confusion;
b) did not make any difference; or
c) was helpful.

2. Based on the first condition you saw, is condition two better or worse?
a) better
b) worse

Third Condition:
1. How did the third condition you just viewed effect the lane closure? The condition
a) caused confusion;
b) did not make any difference; or
c) was helpful.

2. Is condition three better or worse than the first condition?
a) better
b) worse

3. Is condition three better or worse than the second condition?
a) better
b) worse

Fourth Condition:
1. How did the fourth condition you just viewed effect the lane closure? The condition
a) caused confusion;
b) did not make any difference; or
c) was helpful.

2. Is condition four better or worse than the first condition?
a) better
b) worse

3. Is condition four better or worse than the second condition?
a) better
b) worse

4. Is condition four better or worse than the third condition?
a) better
b) worse

Section 2: Subject #______ ID2______

(Please circle the answer that you feel is the most appropriate.)

Second Condition:
1. How did the second condition you just viewed effect the lane closure? The condition
a) caused confusion;
b) did not make any difference; or
c) was helpful.

2. Based on the first condition you saw, is condition two better or worse?
a) better
b) worse

Third Condition:
1. How did the third condition you just viewed effect the lane closure? The condition
a) caused confusion;
b) did not make any difference; or
c) was helpful.

2. Is condition three better or worse than the first condition?
a) better
b) worse

3. Is condition three better or worse than the second condition?
a) better
b) worse

Fourth Condition:
1. How did the fourth condition you just viewed effect the lane closure? The condition
a) caused confusion;
b) did not make any difference; or
c) was helpful.

2. Is condition four better or worse than the first condition?
a) better
b) worse

3. Is condition four better or worse than the second condition?
a) better
b) worse

4. Is condition four better or worse than the third condition?
a) better
b) worse

Section 3: Subject #______ ID2______

(Please circle the answer that you feel is the most appropriate.)

Second Condition:
1. How did the second condition you just viewed effect the lane closure? The condition
a) caused confusion;
b) did not make any difference; or
c) was helpful.

2. Based on the first condition you saw, is condition two better or worse?
a) better
b) worse

Third Condition:
1. How did the third condition you just viewed effect the lane closure? The condition
a) caused confusion;
b) did not make any difference; or
c) was helpful.

2. Is condition three better or worse than the first condition?
a) better
b) worse

3. Is condition three better or worse than the second condition?
a) better
b) worse

Fourth Condition:

1. How did the fourth condition you just viewed effect the lane closure? The condition
a) caused confusion;
b) did not make any difference; or
c) was helpful.

2. Is condition four better or worse than the first condition?
a) better
b) worse

3. Is condition four better or worse than the second condition?
a) better
b) worse

4. Is condition four better or worse than the third condition?
a) better
b) worse

Subject #______ ID2______

Finally, we would like you to rank the four conditions (Arrowboard, Flash Low, Flash High, Steady) that you have viewed tonight. One being the best or preferred condition and four being the worst or least desired condition.

Test Condition	Ranking (1 to 4)
Arrowboard	
Flash Low	
Flash High	
Steady	

APPENDIX B: PART 1 SURVEY

Nighttime Data Collection Form

Subject #:___________ Date:________________ Administrator:___________

Gender:___ DOB:_______ Age:_____ Driving Restriction:_____________________ _____________________________________	Own Restriction:_______________ ______________________________ _____________________________

PART I

ID1 (L, H, S, N) _____ Speed (mph) ____

Question 1: Overall, how effective did you feel the traffic control devices were in notifying you of the lane closure? ____

Question 2: Was there anything that you particularly liked or did not like about the traffic control devices? If so, please explain. ____

Comments: ____

Verbal Instructions to Participants in Test Vehicle

Ask the participant if they are familiar with the test vehicle. If not, let them drive the vehicle around the hanger. Drive all the participants to the holding location. Take one participant at a time to the test vehicle. Allow the participant to get in the vehicle, explain to the participant how to adjust the mirrors, and seat and show the participant where the lights are located. Explain to the participant that they must wear their seat belt, since it is a state law.

(READ THE FOLLOWING FOR THE FIRST PARTICIPANT ONLY)

I would like to remind you that your most important job is to drive safely, always paying attention to the road ahead and keeping the test vehicle under control. Also, remember to pay close attention to other vehicles on the roadway and obey all traffic control devices you encounter. I must also ask that you do not use your brights during the study. *Check lights!*

Now, for a little information about your driving task. As you were told earlier, you will be driving a vehicle on a simulated highway that we have set up on the runway system here. The simulated highway consists of two lanes headed in the southbound direction. You will need to accelerate to (*30 to 65 mph depending on which study is being conducted)* as rapidly as possible and then continue to drive as you would if you were traveling on a roadway with that posted speed limit. However, remember you are to pay close attention and obey all traffic control devices you encounter. Once you have driven through the study section you will return to the waiting vehicle, and the next person will participate in Part I. Once everyone has participated in Part I, we will begin Part II.

In Part II the test administrator will drive a vehicle, and you will be passenger. Remember, **during both parts of the study you may not discuss or convey with each other on anything pertaining to the study.** Do you have any questions?

START HERE FOR EACH PARTICIPANT AFTER THE FIRST:

As you were told earlier, you will need to accelerate to (*30 to 65 mph depending on which study is being conducted)* as rapidly as possible and then continue to drive as you would if you were traveling on a roadway with that posted speed limit. However, remember you are to pay close attention and obey all traffic control devices you encounter. Once you have driven through the study section, we will turn around and return to the waiting location. Do you have any questions before we begin?

(Start audio recorder) Now we are ready to begin the first part of the study. You will need to drive the vehicle between the two vertical panels that are located in front of you and accelerate to (*30 or 65 mph depending on which study is being conducted*) as rapidly as possible. Shortly after you pass between the vertical panels a white edge line will appear on your left, please treat this as

the left edge of pavement. You will need to remain in the left lane until you feel that it is not safe to remain in the lane any longer. Do you have any questions before we begin?

As soon as the participant passes the vertical panel on the right edge of pavement, hit the space bar on the computer and the record button on the VCR to start recording data. When the participant starts to move out of the closed lane, press and hold down the red button. Release the red button when the participant has completed the lane change maneuver (is completely in the adjacent lane). Press the yellow button once at the end of the taper (first drum without a light). Stop the computer program and the VCR after the participant enters the tangent section.

At the end of the simulated highway ask the participant the following questions and record the answers on the data form: "Overall, how effective did you feel the traffic control devices were in notifying you of the lane closure." "Was there anything that you particularly liked or did not like about the traffic control devices? If so, please explain."

Now, we will return to the waiting location.

APPENDIX C: PART 2 SURVEY

PART II Subject #______ ID2_____ Vehicle_____ Seat__

Section 1:

(Please circle the answer that you feel is the most appropriate.)

Second Condition:

1. How did the second condition you just viewed effect the lane closure compared to the arrowboard condition? The condition

a) caused confusion;

b) did not make any difference; or

c) was helpful.

2. Based on the first condition you saw, is condition two better or worse?

a) better

b) worse

Third Condition:

1. How did the third condition you just viewed effect the lane closure compared to the arrowboard condition? The condition

a) caused confusion;

b) did not make any difference; or

c) was helpful.

2. Is condition three better or worse than the first condition?

a) better

b) worse

3. Is condition three better or worse than the second condition?

a) better

b) worse

Fourth Condition:

1. How did the fourth condition you just viewed effect the lane closure compared to the arrowboard condition? The condition

a) caused confusion;

b) did not make any difference; or

c) was helpful.

2. Is condition four better or worse than the first condition?

a) better

b) worse

3. Is condition four better or worse than the second condition?
**a)	better**
**b)	worse**

4. Is condition four better or worse than the third condition?
**a)	better**
**b)	worse**

Fifth Condition:
1. How did the fifth condition you just viewed effect the lane closure compared to the arrowboard condition? The condition
**a)	caused confusion;**
**b)	did not make any difference; or**
**c)	was helpful.**

2. Is condition five better or worse than the first condition?
**a)	better**
**b)	worse**

3. Is condition five better or worse than the second condition?
**a)	better**
**b)	worse**

4. Is condition five better or worse than the third condition?
**a)	better**
**b)	worse**

5. Is condition five better or worse than the fourth condition?
**a)	better**
**b)	worse**

Section 2: Subject #______ ID2_____ Vehicle_____ Seat___

(Please circle the answer that you feel is the most appropriate.)

Second Condition:

1. How did the second condition you just viewed effect the lane closure compared to the arrowboard condition? The condition

a) caused confusion;

b) did not make any difference; or

c) was helpful.

2. Based on the first condition you saw, is condition two better or worse?

a) better

b) worse

Third Condition:

1. How did the third condition you just viewed effect the lane closure compared to the arrowboard condition? The condition

a) caused confusion;

b) did not make any difference; or

c) was helpful.

2. Is condition three better or worse than the first condition?

a) better

b) worse

3. Is condition three better or worse than the second condition?

a) better

b) worse

Fourth Condition:

1. How did the fourth condition you just viewed effect the lane closure compared to the arrowboard condition? The condition

a) caused confusion;

b) did not make any difference; or

c) was helpful.

2. Is condition four better or worse than the first condition?

a) better

b) worse

3. Is condition four better or worse than the second condition?
a) better
b) worse

4. Is condition four better or worse than the third condition?
a) better
b) worse

Fifth Condition:
1. How did the fifth condition you just viewed effect the lane closure compared to the arrowboard condition? The condition
a) caused confusion;
b) did not make any difference; or
c) was helpful.

2. Is condition five better or worse than the first condition?
a) better
b) worse

3. Is condition five better or worse than the second condition?
a) better
b) worse

4. Is condition five better or worse than the third condition?
a) better
b) worse

5. Is condition five better or worse than the fourth condition?
a) better
b) worse

Section 3: Subject #______ ID2_____ Vehicle_____ Seat___

(Please circle the answer that you feel is the most appropriate.)

Second Condition:

1. How did the second condition you just viewed effect the lane closure compared to the arrowboard condition? The condition

a) caused confusion;
b) did not make any difference; or
c) was helpful.

2. Based on the first condition you saw, is condition two better or worse?

a) better
b) worse

Third Condition:

1. How did the third condition you just viewed effect the lane closure compared to the arrowboard condition? The condition

a) caused confusion;
b) did not make any difference; or
c) was helpful.

2. Is condition three better or worse than the first condition?

a) better
b) worse

3. Is condition three better or worse than the second condition?

a) better
b) worse

Fourth Condition:

1. How did the fourth condition you just viewed effect the lane closure compared to the arrowboard condition? The condition

a) caused confusion;
b) did not make any difference; or
c) was helpful.

2. Is condition four better or worse than the first condition?

a) better
b) worse

3. Is condition four better or worse than the second condition?
a) better
b) worse

4. Is condition four better or worse than the third condition?
a) better
b) worse

Fifth Condition:
1. How did the fifth condition you just viewed effect the lane closure compared to the arrowboard condition? The condition
a) caused confusion;
b) did not make any difference; or
c) was helpful.

2. Is condition five better or worse than the first condition?
a) better
b) worse

3. Is condition five better or worse than the second condition?
a) better
b) worse

4. Is condition five better or worse than the third condition?
a) better
b) worse

5. Is condition five better or worse than the fourth condition?
a) better
b) worse

Subject #______ ID2_____ Vehicle_____ Seat__

Finally, we would like you to rank the five conditions (Arrowboard, Steady, Flash Low Blank, Flash High Steady, Flash High Blank) that you have viewed tonight. One being the best or preferred condition and five being the worst or least desired condition.

Test Condition	Ranking (1 to 5)
Arrowboard	
Steady	
Flash Low Blank	
Flash High Steady	
Flash High Blank	

Verbal Instructions to Participants in Test Vehicle

After all participants have completed Part I, Part II will be started. Two participants should be in the first vehicle with a test administrator and three participants should be in the second vehicle with a test administrator. Each participant should have a clipboard and answer sheet.

Part II

In Part II of the study you will be examining different lane closure conditions. You will be asked to view three sets, each containing five conditions. After we have driven through each test condition, you will be asked your opinion of that condition. You will also be asked to compare each condition with the other conditions you previously viewed in that section. We will then repeat this process for the next two sets. Do you have any questions before we begin?

Before we start, I need to tell you that you will not need to answer any of the questions on your answer sheet for the first condition of each section. However, you will need to examine this condition so that you may use it for comparison purposes later on in the study. *(Radio for first test condition)* Is everyone ready to begin?

Drive through the first condition, and explain to the participants that the next drive through they will need to answer the two questions while returning to the starting location. Be sure and call out each condition that is viewed. That condition was the (arrowboard, flash low, flash high, steady) condition, now if you will answer the two questions on your answer sheet.

Question 1. How did the condition you just viewed effect the lane closure compared to the arrowboard condition? The condition:

a) caused confusion
b) did not make any difference
c) was helpful

Based on the first condition you saw, is condition 2 better or worst?

(Repeat the same process for the remaining test conditions.)