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FINAL REPORT

Barricade Lighting System

Authors:

John D. Bullough
Jeremy D. Snyder
Nicholas P. Skinner
Mark S. Rea

Lighting Research Center
Rensselaer Polytechnic Institute
Troy, NY

Lighting Research Center

Rensselaer

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16. Abstract

Presently in work zones, standard barricade warning lights are used to provide channelizing and warning functions. These yellow flashing lights are presently used without consideration of the specific work zone activities underway at any given time. Several novel concepts for a barricade lighting system (BLS) were developed and evaluated: flashing red lights for use when traffic is stopped or very slow within a work zone, flashing green lights when a work zone is inactive and traffic should proceed normally, expanding yellow lights when drivers should slow down and exercise enhanced caution, and sweeping yellow lights when lane closures require drivers to move to the right or left. Prototype BLS units were designed and fabricated. A survey of driver understanding of these BLS functions indicated that drivers would probably understand all of the functions but that the flashing red and green functions could result in conflicts with other roadway traffic control devices. A field evaluation of the expanding and sweeping BLS functions in mock-up work zones demonstrated that driver comprehension of the lights could be translated to a driving situation. Drivers changed lanes sooner (providing a 40% longer lane change margin) in response to the sweeping BLS function than to conventional flashing barricade lights, and subjective ratings of the clarity of the BLS functions were also positive.

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ABSTRACT

Presently in work zones, standard barricade warning lights are used to provide channelizing and warning functions. These yellow flashing lights are presently used without consideration of the specific work zone activities underway at any given time. Several novel concepts for a barricade lighting system (BLS) were developed and evaluated: flashing red lights for use when traffic is stopped or very slow within a work zone, flashing green lights when a work zone is inactive and traffic should proceed normally, expanding yellow lights when drivers should slow down and exercise enhanced caution, and sweeping yellow lights when lane closures require drivers to move to the right or left. Prototype BLS units were designed and fabricated. A survey of driver understanding of these BLS functions indicated that drivers would probably understand all of the functions but that the flashing red and green functions could result in conflicts with other roadway traffic control devices. A field evaluation of the expanding and sweeping BLS functions in mock-up work zones demonstrated that driver comprehension of the lights could be translated to a driving situation. Drivers changed lanes sooner (providing a 40% longer lane change margin) in response to the sweeping BLS function than to conventional flashing barricade lights, and subjective ratings of the clarity of the BLS functions were also positive.

1. INTRODUCTION

In 2007, there were 885 deaths at roadway construction and maintenance zones in the United States (National Work Zone Safety Information Clearinghouse, 2007). Work zone deaths represent 2% of all roadway deaths. Most of those killed were traveling on the roads, not working at the construction sites. Between 1995 and 2008, an average of 106 workers per year were killed at road construction sites. Of those deaths, workers had a greater chance of being killed by construction equipment and vehicles than by non-construction vehicles traveling on the road (Pegula, 2004). These statistics show that it is important to address the safety of both drivers and workers at highway work zones.

Multiple studies have shown that work zones are more dangerous on a per-mile basis than the same stretch of highway when there is no construction activity (Hall and Lorenz, 1989; Ha and Nemeth, 1995; Khattak et al., 2002). Qi et al. (2005) conducted a study of work zone crashes in New York State. Overall, these studies found that:

- Crashes in work zones occur between 7% and 119% more frequently than on the same roadway prior to construction activity.
- Rear-end collisions occur more frequently than other types of crashes.
- A higher frequency of work zone crashes is correlated with higher population density of the geographic area, and higher annual average daily traffic of the roadway under construction.

Three over-represented causes of crashes at work zones are "following too close," "misjudging stopping distance," and "driver not being in control" (Pegula, 2004). According to Chambless et al. (2002), statistics suggest that many of the accidents are rear-end collisions, suggesting that some vehicles may be traveling too fast or too slow for prevailing traffic conditions.

In addition to increasing the likelihood of crashes, work zones also increase congestion and air pollution. Kusalasai and Yai (2006) estimated that in 2001, work zones caused 350 million hours of delays and 570 million gallons of excess fuel consumption.

One way to reduce crashes and congestion in work zones is to better communicate to drivers information about conditions within the work zone, and what appropriate action they should take. For example, it might be beneficial to convey to a driver ahead of a lane closure what direction they should go to maintain traffic flow, or to convey when traffic might be stopped or substantially slowed down in a work zone ahead.

To convey these messages to drivers, it might be more effective to use intuitive visual indicators than written messages because the former can, in principle, be understood by a driver more quickly than the latter, and they are not dependent upon any specific language use. The present report documents a study of a proposed barricade lighting system (BLS) using such indicators, regarding drivers' understanding of their meaning and their responses to them in actual driving conditions.

2. BACKGROUND

The effectiveness of flashing lights of various characteristics has been studied in a number of contexts including maintenance vehicle signal lights (Gibbons et al., 2008), automotive signal lights (Bullough et al., 2001a, 2001b, 2002, 2007), aviation lighting (Rea et al., 2009; Bullough, 2011), and warning lights for illuminated displays (Department of Defense, 1999).

For example, in the U.S., Bergum and Bergum (1981) demonstrated that drivers' comprehension of the meanings of red and green lights was generally very high, with 100% recognizing red as being associated with the concept "stop" and more than 99% recognizing green as indicating "go." The Department of Defense (1999), in its human factors design standard, requires red to denote "emergency conditions which require operator action to be taken without delay, or to avert impending personnel injury, equipment damage, or both." Green is required to indicate "that it is all right to proceed."

A number of studies have been conducted to address the effectiveness of different flash rates for visibility (Bartley, 1951; Brown, 1965; Connors, 1975). Despite a variety of experimental methods used, the results of these studies are consistent with the notion that at low background light levels, there is optimum sensitivity to flash frequencies between 1 and 5 Hz (Rea et al., 2009). At higher levels up to daytime conditions (~5000 cd/m^2), the peak temporal sensitivity increases to around 10-15 Hz (De Lange, 1958). It is recommended, however, that flashing light frequencies be kept below 3 Hz to avoid seizures among individuals with photosensitive epilepsy (Harding and Jeavons, 1994).

Howard and Finch (1960) determined that a square wave flashing pattern was more conspicuous than a triangular waveform pattern (i.e., ramping up and then down) for flash durations less than 50 ms. Bullough et al. (2001a) and Bullough (2005) made similar findings, showing that shorter light source rise times led to shorter response times to the signal light onset, in the context of traffic signals and automotive stop lamps. Bullough et al. (2001a, 2002) also showed that "sweeping" an LED or neon light source with a short onset time could result in shorter response times than to an incandescent source that simply turned on at full output. In a study of rear lighting for snowplow trucks, Bullough et al. (2001b) found that closure detection times to a truck equipped with flashing lights were longer than to a truck equipped with steady-burning lights, suggesting that maintaining some steady-burning luminous component has benefits for identifying the relative speed and distance of a signal light.

Regarding the use of spatial information to convey direction or the need for changing lanes or taking detours in a roadway situation, See and Schrock (2007) evaluated drivers' comprehension of traffic control devices such as arrow or chevron panels in situations where a lane closure would be needed. Single and multiple arrows, and single and multiple chevrons were all easily understood by drivers to indicate that they should prepare to change lanes. The direction of lane closure was also readily understood. These data suggest that using directional spatial information can provide drivers with meaningful cues in work zone applications.

In a study of rear lighting on highway maintenance vehicles, an array of lights starting with small sizes in the center of the array with increasing sizes toward the periphery of the array was tested (Stout et al., 1993). The intended visual effect was to convey a sense that a driver was approaching the light faster than the actual approach speed. This array was found in field tests to result in sooner, smoother decelerations by drivers approaching the truck, in comparison with conventional flashing lights usually used on these vehicles.

3. DESCRIPTION OF BLS

Presently in work zones, standard barricade warning lights meeting specifications published by the Institute of Transportation Engineers (ITE, 2001) are used to provide channelization and warning functions. These are typically circular, yellow flashing lights having a diameter of at least 18 cm. Flash rates are around 1 Hz and the effective intensity is required to be 35 cd.

Four new barricade light configurations were evaluated as part of the proposed barricade lighting system (BLS). Table 1 contains a description of these functional configurations, including situations when they might be used and the anticipated (or desired) driver response behavior compared to driver responses when faced with ITE-compliant barricade warning lights.

Signal function	**Situation when used**	**Desired driver response**
Flashing green light	Unoccupied work zone	Proceed normally
Flashing red light	Stopped or very slow traffic ahead	Stop immediately
"Sweeping" yellow light (left to right or right to left)	Lane closure	Change lanes as soon as possible
"Expanding" yellow light (center to periphery)	Occupied/active work zone	Slow down

Table 1. Summary of potential BLS functions.

For each of these configurations, the baseline condition was assumed to be a conventional flashing yellow barricade warning light.

The use of green and red colors were included based on the literature suggesting that these colors are well understood by drivers as indicating "go" and "stop" maneuvers (Bergum and Bergum, 1981; Department of Defense, 1999). The sweeping light configuration was included based on the findings that drivers appeared to be able to interpret directional information clearly (See and Schrock, 2007). The expanding light configuration was included based on evidence that drivers might slow down sooner in response to the visual looming effect this light would produce (Stout et al., 1993). An additional possible benefit of the sweeping and expanding configurations is that when set to continually cycle through the sweeping or expanding pattern of light, there would always be some portion of the light "on," providing a steady-burning component that could help drivers judge the relative distance and position of a work zone equipped with such light configurations (Bullough et al., 2001b).

Red and green BLS functions were developed by using light emitting diode (LED) luminaires designed originally for use in theatrical applications (Optima Lighting, PAR64). These units contain red, green and blue LEDs that can be modulated individually by color. The blue LEDs were not used in the study. Flashing was achieved by using a timing relay circuit that could flash them at approximately 1 Hz. Because the LEDs were highly directional, the luminaires were fitted with a diffusing material to decrease on-axis intensity and to increase the viewing angle. Figure 1 shows the red and green BLS components (when in the "on" portion of the flashing cycle), attached to a traffic cone.

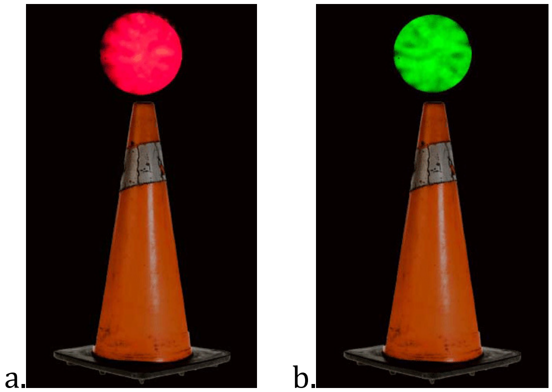

Figure 1. a) Red and b) green BLS flashing functions.

The sweeping and expanding BLS functions were created through custom-built arrays of yellow LEDs on 18-cm diameter circular circuit boards. Each board was populated with 125 (for the sweeping BLS) or 126 (for the expanding BLS) LEDs. Figure 2 shows the sweeping and expanding BLS units (when fully illuminated) mounted onto a traffic cone. The LEDs in each of the arrays were divided into six segments so that for the sweeping BLS, each of the segments could be illuminated in turn from left to right or from right to left to create an animated sequence of the signal light face sweeping in either direction. For the expanding BLS, the central ring of LEDs was illuminated first, followed by each subsequent concentric ring to provide an animated appearance that the signal was expanding in size. The speed of the animation was set to provide all six components of the cycle each second.

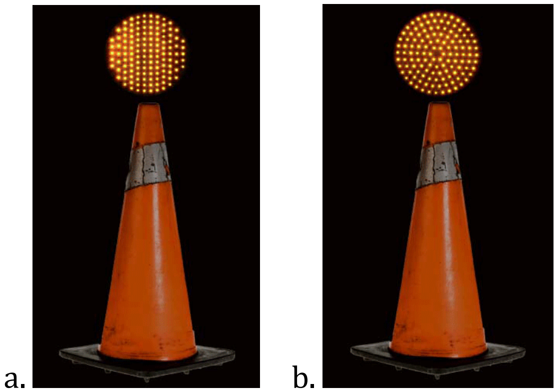

Figure 2. a) Fully-illuminated sweeping BLS, and b) fully-illuminated expanding BLS functions.

Figure 3 shows the expanding and sweeping BLS units in the middle of each of their animation sequences. This figure also illustrates the daytime appearance of the units. The printed circuit board was yellow in color to be more consistent with the expected daytime appearance of a barricade warning light. The animation sequences were provided through microprocessor controllers mounted on the back of each circuit board. Mounting holes for the lights were drilled to allow them to be attached to brackets containing 12 V batteries to power the units. Four BLS prototype units of each type were constructed (additionally, there were four units that included the red and green flashing LEDs).

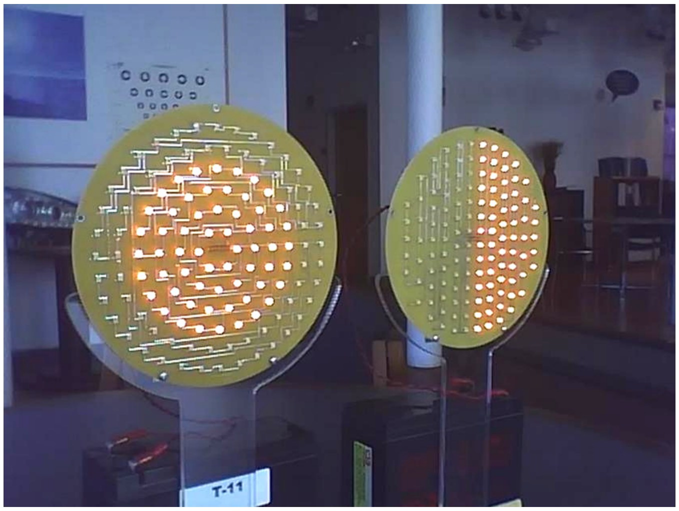

Figure 3. Photograph of expanding (left) and sweeping (right) BLS units in mid-sequence. Also shown is the mounting bracket and 12 V battery for power.

The units were also equipped with a jumper on the circuit board that allowed them to operate in simple flashing mode at 1 Hz (as a conventional flashing barricade warning light would). For the sweeping BLS units, a separate jumper allowed the units to sweep either from left to right or from right to left.

4. SURVEY OF BLS COMPREHENSION

In order to assess how drivers might interpret the BLS configurations, and to assess potential concerns about the use of each BLS function, a survey questionnaire was developed. The survey used animated video clips of the BLS functions described in Table 1 (and illustrated in Figures 1 and 2; for the sweeping BLS, the animation swept from right to left). The video clips were made in the photometric laboratory of the Lighting Research Center.

Participants in the survey were subscribers to the Work Zone Safety Information Clearinghouse email discussion list. The survey was developed using an online survey construction service (SurveyMonkey.com). Participants were asked to view each of the video clips and to answer a single question for each: What action should a driver take if this light is seen while driving along a highway work zone?

Following each question, the following seven possible responses were listed:

- Slow down
- Stop
- Proceed
- Increase speed
- Turn/bear left
- Turn/bear right
- Other

The order of responses was randomized for each respondent and for each question. Participants could only select a single response. If the selection "Other" was made, participants were requested to enter their response in a text box. There were a total of five questions, corresponding to the four BLS functions illustrated in Figures 1 and 2, and to a conventional flashing yellow barricade light. A total of 86 people participated in the survey.

Flashing Yellow

Approximately 67% of the participants selected "Slow Down," and 8% selected "Proceed." Just over 24% selected "Other;" the majority of these responses indicated that the driver should use "caution."

Flashing Red

A majority of participants, about 62%, selected "Stop" as the response to the flashing red light, with 9% selecting "Slow Down." "Other" was selected by 29%. Of these responses, there was substantial variation in the reported meaning. Some suggested that a driver should stop and then proceed, some indicated that they simply were not certain what the light was supposed to convey. A number of respondents pointed out that a flashing red light is not a currently-allowed use in a work zone.

Flashing Green

Most participants, about 71% indicated that the flashing green light meant "Proceed." A smaller proportion, about 7%, selected "Speed Up" as the intended response, and 1% selected "Slow Down." About 20% selected "Other" as a choice; of these, most of the responses either were of confusion on the participants' part regarding the intended meaning, or pointed out that a flashing green should not be used in a work zone.

Sweeping Yellow

For the sweeping yellow light, 59% correctly indicated that the light meant "Turn/Bear Left." (No respondents selected "Turn/Bear Right.") About 20% indicated that it meant drivers should "Slow Down," and 2% that drivers should "Proceed." "Other" was selected by 20% of the respondents. Most of these "Other" responses suggested that the light meant to use caution. A few of these responses also stated that the sweeping light would probably look different from a conventional flashing light.

Expanding Yellow

About 52% of the respondents selected "Slow Down" in response to the expanding yellow light. The "Proceed" option was selected by 9%, while "Increase Speed" and "Stop" were selected by 4% and 1% of the respondents, respectively. Of the 35% of respondents who selected "Other," most of the responses indicated that a driver should use caution. Two respondents suggested that the expanding animation of the signal would be difficult to see.

Summary

For each question in the survey, a single answer (different for each BLS function) received a majority of responses. There were a number of concerns about the flashing red and flashing green BLS functions, based on the "Other" responses, however. The use of these colors in active or inactive work zones was strongly discouraged by a number of survey respondents. There was particular anxiety about the use of flashing green lights. Although more than two-thirds of the survey respondents indicated that this signal meant "Proceed," was concern that it could result in confusion by a number of drivers who might not have a clear understanding of what a flashing green signal means. This is consistent with recent research that suggested there is significant variability in drivers' interpretation of a flashing green signal (Factor et al., 2010).

In addition, feedback from engineers in the New York State Department of Transportation (NYSDOT) also indicated that there would be a great deal of apprehension about using flashing lights with red or green color in work zones. Primarily this is because of conflicts with the Manual on Uniform Traffic Control Devices (MUTCD, 2009) and concerns about driver comprehension of these signals in a work zone context. In comparison, the same engineers felt that the sweeping and expanding yellow BLS signals had substantial merit and would be less prone to a driver misinterpretation that would lead to an inappropriate driving maneuver in a work zone.

For these reasons, the field investigations of the BLS functions focused on the sweeping and expanding yellow lights, in comparison to a conventional flashing yellow warning light.

5. FIELD DEMONSTRATION OF BLS FUNCTIONS

In order to assess how drivers would respond to the sweeping and expanding BLS functions, relative to their responses to a conventional yellow flashing barricade warning light, and to demonstrate their performance in a mock-up work zone setting, they were employed in a field study along a controlled test-road location. It was expected that drivers would slow down more in response to the expanding BLS light than to the flashing yellow light, and that they would change lanes (if needed) sooner in response to the sweeping BLS light and find this light clearer in meaning than the flashing yellow light.

Test Location

The test location used for the field studies was Temple Lane, in the Town of East Greenbush, NY (Figure 4). This is a dead-end road with a business and a single residence at one end of the road, and it largely flat with several straight sections separated by large-radius curves. In cooperation with the Town Supervisor and the Chief of Police, the road was closed to traffic using traffic cones, and the work zone locations were set up on two of the straight sections.

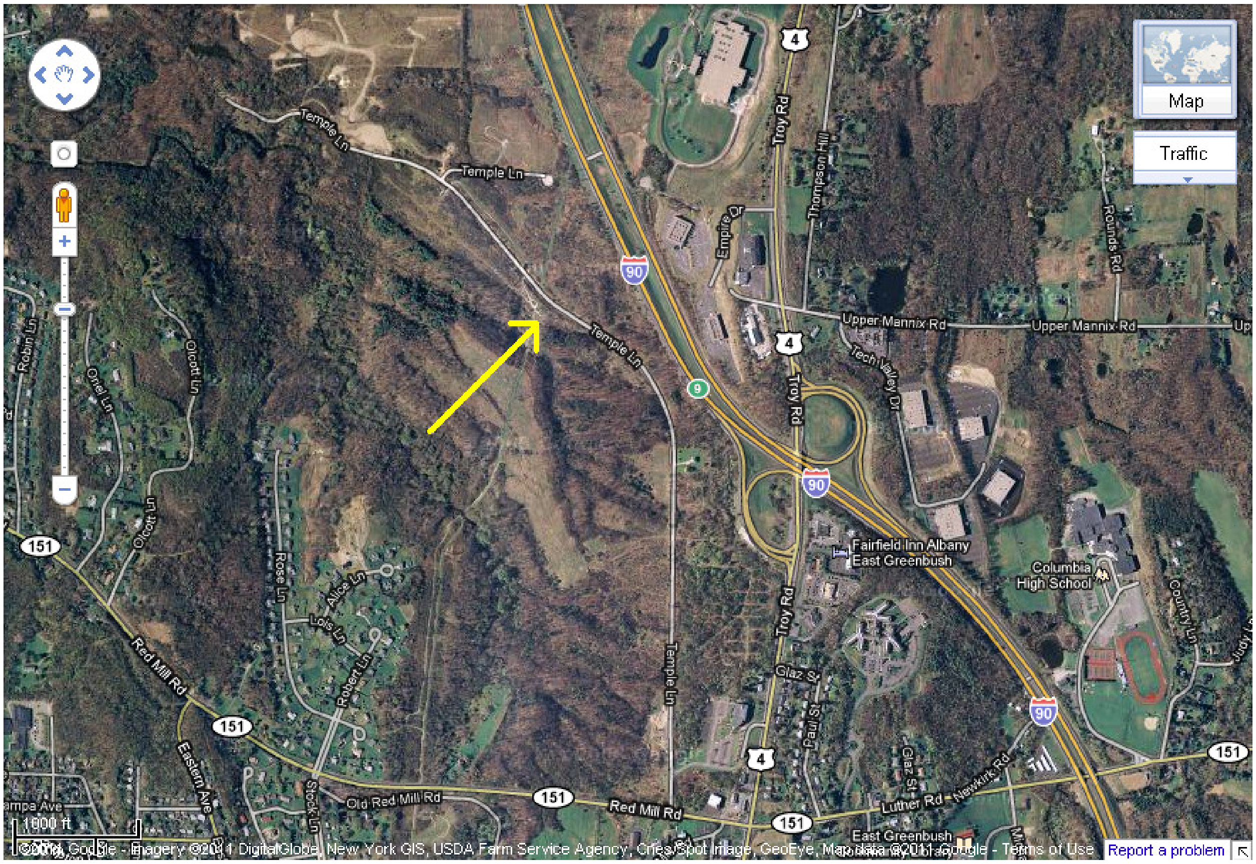

Figure 4. Satellite view of the test road location, indicated by a yellow arrow.

Experimental Setup

As described above, four sweeping and four expanding BLS prototypes were constructed. These were mounted to traffic cones as illustrated in Figures 1 and 2. Engineering personnel from NYSDOT assisted in the design of simple mock-up work zone locations along the test road. Layouts for work zones requiring a lane change and with no lane changes were developed. The local NYSDOT residency (Rensselaer County, Region 1) provided traffic cones that were used to demarcate the simulated work zones. The layouts are shown in Figure 5, and Figure 6 illustrates the appearance of each type of simulated work zone.

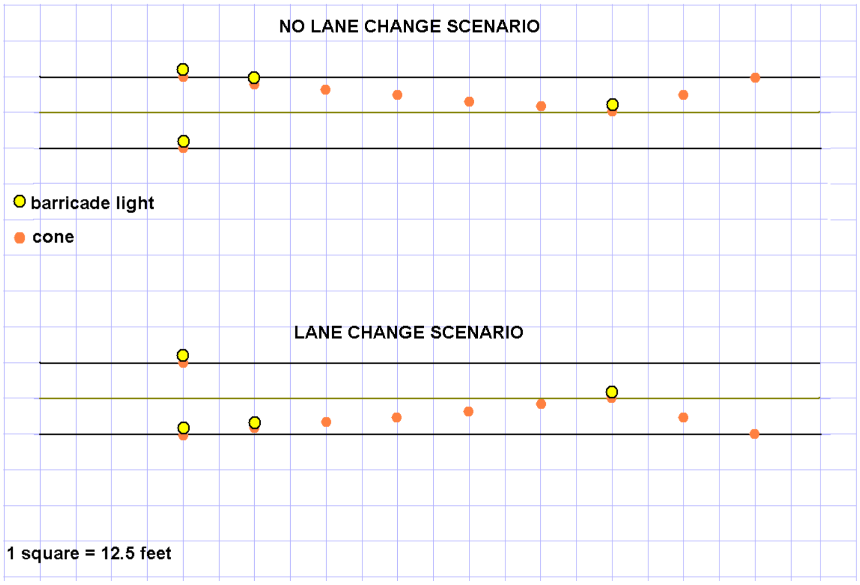

Figure 5. Plan view layouts for the work zone scenarios mocked up in the field study.

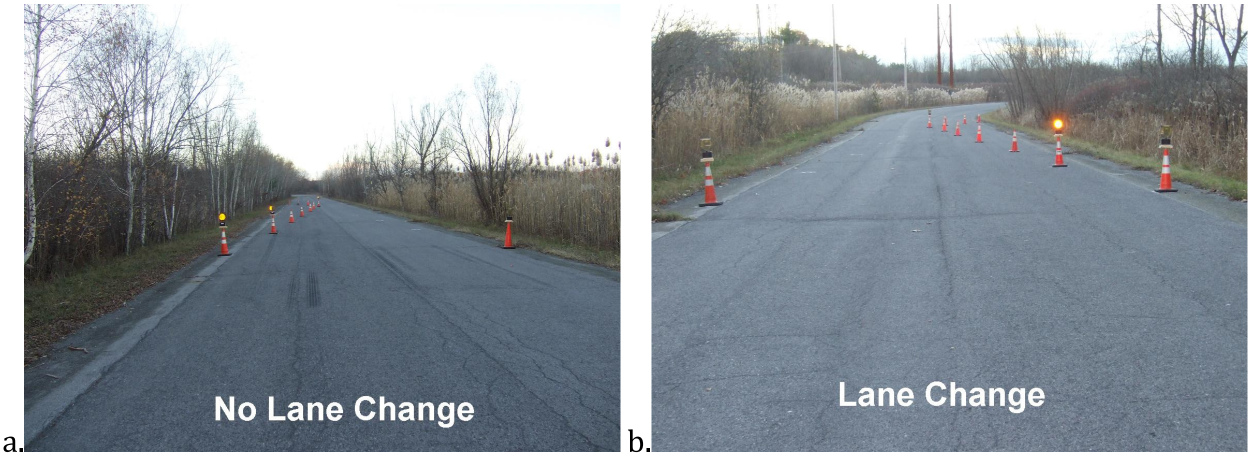

Figure 6. Photographs of the mock-up work zone locations set up along the test road.

Experimental Procedure

The experiment occurred during two nighttime sessions, starting after the end of civil twilight, during November 2010. A total of ten experimental subjects (five female, age 23 to 62 years, mean age 49 years, standard deviation 16 years) participated in groups of five. Both nighttime sessions occurred during clear weather. Upon arrival at the field study location, subjects signed an informed consent form. The consent form and experimental procedure were approved in advance by Rensselaer's Institutional Review Board.

During each experimental trial, two simulated work zones were set up. One involved a lane change and one did not. At each work zone, one of four barricade light conditions was utilized based on the layouts in Figure 5:

- Conventional flashing light
- Expanding BLS
- Sweeping BLS (right to left)
- Sweeping BLS (left to right)

Regarding the sweeping BLS functions, it was assumed that for the lane change scenario (where the normal right-side driving lane would be closed), the right-to-left sweeping BLS would be most appropriate. For the situation where the lane was not closed, but the work zone would be toward the left, the left-to-right sweeping would be most appropriate. The test included the "inappropriate" sweeping BLS conditions as well (left-to-right for the lane change, and right-to-left for no lane change) because it was expected that drivers might find this condition confusing.

Each of the work zone situations (lane change or no lane change) were employed with all four of the lighting conditions listed above. The order of conditions that were experienced by the study participants between the two sessions was randomized and counterbalanced so that no condition was more likely to appear near the beginning of a session than any other. With a total of eight conditions, and two work zone locations per trial, each subject completed four experimental trials. After they had driven through both simulated work zones in a single trial, they were instructed to turn the vehicle and return to a rendezvous location where other subjects were waiting to compete their trials.

All subjects were legally licensed drivers and drove the same vehicle (a 1999 Ford Contour with automatic transmission) for all trials. This vehicle was equipped with a GPS antenna and a data logger connected to the vehicle's on-board computer so that it could measure vehicle speed, distance, location, and acceleration at a frequency of 100 Hz and store the resulting data onto a flash memory card for subsequent analysis.

Each trial was conducted in the same way. From the rendezvous location where each trial started, the first work zone setting was not visible until subjects drove around a slight curve. Similarly, the second work zone setting was not visible until subjects had completed driving through the first work zone setting and navigated another slight curve. Subjects were instructed to drive along the road at a comfortable speed and to make any appropriate maneuvers needed to navigate through any work zone situations they might encounter. An experimenter rode with all subjects during all experimental trials, and after each simulated work zone had been driven through, asked each subject to rate how clear the *meaning* of the work zone signal lights was (not how clearly *seen* the lights were), using a scale of 1 to 4:

- 1: very unclear
- 2: somewhat unclear
- 3: somewhat clear
- 4: very clear

Between trials, experimenters rearranged traffic cones and lights at each work zone location. Each experimental session took approximately 90 minutes, to complete all twenty trials (five subjects and four trials per subject) for each session.

Outcome Measures

Three dependent measures were utilized: the reduction in speed when approaching the work zone location, the distance ahead of the work zone that the driver changed lanes (only for the lane change scenarios), and the subjective rating of the clearness of the signal light meaning.

Through the data logger software, it was possible to identify the driving speeds throughout each experimental session. Observations of the speed data for each subject revealed similar driving speed patterns for each trial. Along the straight portion of road leading up to the work zone location, drivers accelerated to some maximum speed, typically around 30 mph, and then slowed down upon entering the actual work zone location, typically to about 25 mph. Each subject was different in the speed they selected; some subjects were substantially faster drivers than others. In order to account for these variations, the difference between the maximum and minimum speeds for each trial was calculated as a measure of how much subjects slowed down upon approaching the simulated work zones.

The distance ahead of the lane-change work zone that drivers executed their lane change was measured by using the lateral (side-to-side) acceleration data recorded by the data logger. When subjects were driving along the road, there was little lateral acceleration, but as soon as drivers began to steer the vehicle toward the left to change lanes in response to the lane-change traffic cone layout (see Figure 6b), a sharp onset in lateral acceleration toward the left was observed. After drivers cleared the work zone location, they returned to their normal driving lane on the right side of the road, and a sharp onset in lateral acceleration toward the right was observed. There were no systematic differences in the location of the latter acceleration relative to the end of the work zone location (they were always shortly after the lane closure ended), but there were differences in the former acceleration (toward the left). The distance between these locations, minus the length of the lane change taper (45 m, or 125 ft) was defined as the lane change margin. There were no sharp changes observed in lateral acceleration for the no-lane-change scenarios.

The subjective ratings were calculated by taking the mean of all subjects' responses to each lighting condition. All statistical comparisons were made using repeated-measures analyses of variance (ANOVAs).

Results

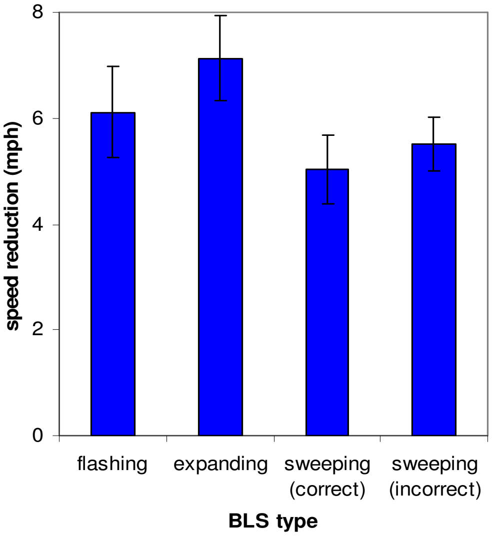

Figure 7. Mean speed reductions (+/- s.e.m.) for each BLS condition.

Figure 7 shows the mean speed reduction values for each BLS function. An ANOVA revealed a statistically significant ($p<0.05$) effect of BLS function type, but no reliable difference in speed reductions between lane-change and no-lane-change scenarios. Comparing the conventional flashing lights to the expanding lights, the expanding lights produced greater speed reductions, but a paired t-test showed that this difference was not statistically significant ($p>0.05$).

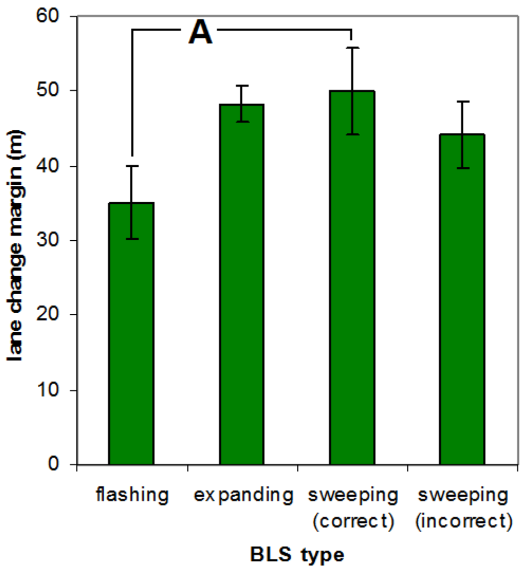

Figure 8. Mean lane change margins (+/- s.e.m.) for each BLS condition.

Figure 8 shows the mean lane change margins for each function. There was a statistically significant ($p<0.05$) effect of BLS type. It was expected that the sweeping BLS function (when operating in the correct direction) would result in a larger margin (i.e., drivers would change lanes sooner) than would be seen under the conventional flashing light configuration, and a paired t-test comparing these conditions revealed that this difference was statistically significant ($p<0.05$, comparison A in Figure 8). Of interest, the lane change margin for the incorrect-sweeping BLS function was not statistically significantly different ($p>0.05$) than for the correct sweeping BLS function, nor was the lane change margin for the expanding BLS function.

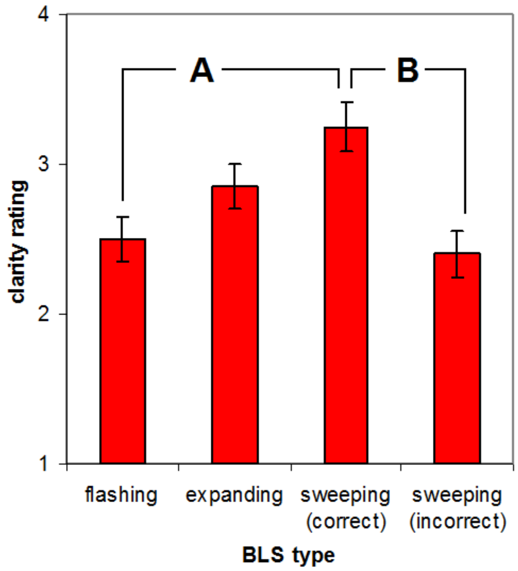

Figure 9. Mean clarity ratings (+/- s.e.m.) for each BLS function.

Figure 9 shows the mean ratings of clarity for each BLS function. According to an ANOVA, there were statistically significant ($p<0.05$) differences among the BLS types. The sweeping BLS, when indicating the correct direction, resulted in higher ratings of clarity than the conventional flashing BLS type, and this difference was statistically significant ($p<0.05$, comparison A in Figure 9) according to a paired t-test. There was also a statistically significant ($p<0.05$, comparison B in Figure 9) difference between the clarity ratings for the sweeping BLS functions in the correct and incorrect directions, suggesting that subjects could correctly ascertain the meaning of the direction of sweeping.

6. DISCUSSION AND CONCLUSIONS

The results of the survey of BLS comprehension and of the field evaluation of the sweeping and expanding BLS functions were consistent with several important caveats. The survey utilized "close-up" views of the BLS devices, whereas when drivers were approaching the mock-up work zones in the field study, they began to view the signal lights from a relatively larger distance, when the visual appearance of the expanding and sweeping BLS functions would not necessarily look dramatically different.

There is some evidence that the expanding BLS function resulted in greater (but not statistically significantly greater) speed reductions than the conventional flashing barricade light (Figure 7), but the largest differences were between the expanding and sweeping BLS functions, rather than between the flashing and expanding functions. If drivers' decisions to slow down were made while the work zone lights were too far away to readily identify as sweeping or expanding, that could serve to explain why the observed effects were not as hypothesized.

With respect to the impact of the BLS functions on lane changing, Figure 8 illustrates that the correct sweeping BLS function resulted in the earliest lane changes, while the conventional flashing light resulted in the latest changes. The correctly sweeping signal resulted in an average lane change margin about 40% longer than a standard flashing barricade light. Of interest, though, both the incorrect sweeping and the expanding BLS functions also yielded earlier lane changes than the flashing light. As described previously, the primary difference between the conventional flashing light and the BLS functions was that the BLS functions always had some portion of the signal illuminated so that it was never fully "off." If the decision to change lanes is based in part on a driver's ability to detect how quickly they are approaching a work zone with a closed lane, the BLS functions should provide better closure detection than a flashing light (Bullough et al., 2001b).

The ratings of clarity for the expanding and sweeping BLS functions were generally as hypothesized (Figure 9). In particular, the sweeping BLS function seemed to be found consistent with the need to change lanes, and when it was presented in the incorrect direction, was rated with the lowest level of clarity among all the configurations evaluated. This suggests that the BLS might possibly help to serve as a reinforcing cue to drivers within a work zone that they should remain in the appropriate lane until further instructed, although this inference was not evaluated in the present study.

Regarding the prototypes themselves, the BLS devices were developed from readily available circuit boards and LED sources commonly used for similar signal lighting applications. The microprocessor control of the BLS dynamic configurations through simple software provides substantial design flexibility regarding the implementation of any conceivable visual animation.

In summary, the BLS prototypes described and evaluate in the present report can be implemented practically through LED light source technology and readily mounted to barriers and other channelizing devices in work zones. They can generally be interpreted correctly by drivers without special training or education, and can produce beneficial driving behaviors under certain conditions. Further study should identify the range of conditions under which BLS lights as those described here would be most beneficial for improving the safety and traffic conditions in work zones.

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