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TRR
JOURNAL OF THE TRANSPORTATION RESEARCH BOARD

Transportation Research Record
2019, Vol. 2673(5) 703–708
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DOI: 10.1177/0361198119840616
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Driver Behavior in Response to Flashing Lights

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Abstract

Flashing yellow warning lights notify drivers about the presence of work along the road. Current standards for these lights address performance of the individual light but not how lights should function when multiple lights are used. In the present study, warning lights were used to delineate a lane change taper in a simulated work zone. Lights flashed with varying intensities and either randomly or in sequence, with lights flashing in turn along the length of the lane change taper, either to the right or to the left. In half of the trials, a flashing police light bar was used on a vehicle located within the simulated work zone. Participants were asked to drive a vehicle approaching the work zone and to identify, as quickly as possible, in which direction the taper's lane change was (either to the right or left). Drivers were able to correctly identify the taper from farther away when the lights flashed in a sequential pattern than when the flash pattern was random; and the presence of a police light bar resulted in shorter identification distances. The results, along with previous research, can inform standards for the use of flashing lights and police lights in work zones for the safety of drivers and workers.

Flashing yellow (amber) lights are often used in work zones to capture drivers' attention and support the performance of driving maneuvers that are needed to safely navigate the work zone without crashing into fixed objects, traffic control devices, or workers. Present requirements for flashing barricade warning lights (*1*) specify a required flash frequency near 1 Hz and a minimum nighttime effective intensity (*2*) of 17.5 cd, corresponding to a peak intensity of 25 cd when the flash duty cycle is 50%.

Recently, Kersavage et al. evaluated the impacts of nighttime flashing yellow vehicle-mounted warning beacons on a driver's ability to detect simulated workers placed near the warning beacons (*3*). When the peak intensity of the flashing warning beacons exceeded 150 cd the visibility of the simulated workers *not* wearing a reflective vest began to deteriorate; as intensity increased above 150 cd approaching drivers had to be closer to detect the simulated worker. (When the simulated workers wore reflective vests, detection distances were long and constant for all flashing beacon intensities.)

In addition to vehicle-mounted warning beacons, multiple flashing yellow lights are often used to help drivers anticipate lane closures in work zones. This is potentially important for safety because a sizeable proportion of crashes at work zones (over one-quarter) involve sideswipes in which vehicles collide at lane merges and closures (*4*). If driver awareness of the presence and nature of lane closures and merges occurs sooner, they will have more time to formulate appropriate responses when navigating through work zones that contain them, potentially reducing the likelihood of a crash.

In a recent study, Rea et al. evaluated driver responses to flashing yellow barricade warning lights arranged in lane change tapers (*5*). They found that drivers preferred the warning lights to flash in sequence along the direction of the intended lane changes, rather than flashing randomly or in a synchronized manner as is sometimes employed. Observers also judged the sequential lights as less glaring even when matched for intensity of random or synchronized flashing lights. Finley et al. found similar benefits for sequential flashing light systems (*6*). Since the standard (*1*) is silent regarding the use of multiple lights to delineate a taper indicating a lane closure, it was considered important to investigate how the intensity of

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Figure 1. Penn State's Thomas D. Larson Pennsylvania Transportation Institute test track.

course-way flashing yellow warning lights, both random and sequential, affected drivers' ability to rapidly (and correctly) identify the direction of a work-zone lane change taper at night.

Police vehicles with flashing red or blue emergency lights are often located in or near a work zone. These flashing emergency lights, particularly at night, can affect the ability of approaching drivers to ascertain the proper course-way information needed to safely traverse a work zone. Because police officers want approaching drivers to be aware of their presence, they report that the selection and operation of flashing emergency lights for their vehicles is often based on which configuration(s) have the greatest apparent brightness (*7*). Whereas bright lights may help with awareness, anecdotal experience (*8*) and empirical evidence (*3*, *9*, *10*) all suggest that bright flashing lights can negatively affect the visual performance of drivers trying to negotiate work zone course-ways at night, thereby compromising the safety of these police officers. Therefore, it was deemed important to systematically investigate the ability of drivers to identify the direction of a work-zone lane change taper in the presence of these flashing emergency lights at night.

Method

Location

The study was conducted at Penn State's Thomas D. Larson Pennsylvania Transportation Institute test track, shown in Figure 1. The test track is a 1-mi oval, consisting of two curves and two tangent sections. The experiment was performed on only one of the tangent sections. The study location is indicated in Figure 1 by a white oval. No vehicles, other than the ones involved in the study, were on the test track during the time of the experiment. The study occurred at night (with no fixed lighting). No adverse weather conditions, such as rain, or snow, were present during the experiment.

Figure 2. SUV with police lights bar (switched off in this photograph), drums, and barricade warning lights. To the left is the passenger car used by participants.

Equipment

Figure 2 shows the equipment used in the present study. The vehicle driven by the research participants was a 2012 Chevrolet Malibu sedan. A police light bar, equipped with flashing red and blue light emitting diode (LED) lights, was mounted to the top of a stationary Chevrolet Trailblazer sport-utility vehicle (SUV) that powered the light bar. This simulated police vehicle was positioned at the far end of the work zone. Five orange traffic drums could be arranged to indicate either a left or right lane taper through the work zone. One barricade warning light was mounted to the top of each drum.

The sedan was instrumented with a Race Technology DL1-Club data collection system, including a Global Positioning System (GPS) and a data recorder that logged all data on a Secure Digital (SD) memory card. The data acquisition system collected vehicle information during the experiment at a frequency of 100 Hz. The data could then be transferred to a laptop computer for analysis.

The fully operational police light bar (Whelen, LFL Liberty) was provided to the study by a local police department. An Arduino microprocessor with a relay board was used to accept commands from the controlling computer to activate or deactivate the light bar.

The barrel-mounted warning lights were custom made. The flash intensity levels and temporal profiles were programmable through a remote computer interface. The lights were comprised of several key components: a microcontroller, radio communication link, light source and driver, GPS receiver, and the housing.

A Texas Instruments MSP430 microprocessor controlled each warning light. The microcontroller obtained a precise time reference from the GPS receiver that was used to control the temporal profile of each flash pattern. The flash period, duration of the high intensity portion of the flash, and the duration of the low intensity portion of the flash were used to define the flash profile. For scenarios in which the random flash pattern or the sequential pattern were desired an additional parameter, a unique delay from the standard "zero time" obtained from the GPS time reference, was programmed to each barrel-mounted warning light. All of these parameters were defined by the controlling computer software and transmitted to each warning light through the 900 MHz XBee radio communication link.

A single high-power phosphor-converted amber LED was used in each unit, mounted to an aluminum support and heat sink. The LED was powered by a custom designed constant-current driver circuit. Constant current was used to avoid any possibility of detectable flicker resulting from pulse width modulation dimming. Each LED-driver system was calibrated to provide the appropriate current to satisfy a defined peak/trough intensity setting, which was programmed to the light by the remote controlling computer software. All of the hardware was packaged into the housing of a commercially available barricade light.

A computer running a custom control program for the police light bar and barrel-mounted lights, written in National Instruments LabView software, was located inside the SUV. The software used predefined condition files to automatically set the brightness and temporal behavior of the barrel-mounted lights for each trial, to activate and de-activate the police light bar and to prompt the experimenters how to configure the taper barrels for the ensuing trial. The radio set was connected to the computer to control the barricade warning lights remotely and the Arduino control board for the police light bar was also connected to the computer. The configurations were programmed according to predefined files that were randomized in order for each participant.

Research Participants

Fourteen participants completed the study. All participants were required to have a valid United States (U.S.) driver's license, speak English, and be at least 18 years old. Half of the participants were female. The age range of the participants was representative of that found in the U.S. driving population, with a purposeful overrepresentation of older drivers. Two participants were between 18 and 30 years old; three participants were 31 to 40 years old; two participants were 41 and 50 years old; two participants were 51 to 60 years old; five participants were older than 60.

Experimental Design

There were four independent variables in the study: warning light peak/trough intensity (25/2.5, 150/15, and 700/70), flash pattern (random or sequential), operation of the police light bar (on or off), and direction of the taper (one lane shift to the left or to the right). This resulted in 24 possible configurations (see Table 1).

The peak/trough intensities of 25/2.5, 150/15 and 700/70 cd correspond to effective intensities (*2*) of 18, 107, and 500 cd, respectively, all conforming to the minimum requirements for Type B flashing lights used at night (*1*). For the sequential flash pattern, only one warning light was energized to the peak intensity at a time and the order of the flashing cycle began with the beacon nearest the approaching driver and ended with the beacon furthest from the approaching driver, thus indicating, one after the other, the direction that the vehicle should move.

The sole dependent variable was the distance at which the participant could correctly identify the direction of travel through the taper.

Procedures

An experimental session began with a study team member driving the sedan onto the test track and parking it at the starting location (Figure 1), just beyond the position of the flashing lights and SUV. The police light bar was mounted on top of the SUV, and connected to the power outlet and to the computer in the vehicle. The orange drums were placed according to the first configuration from the randomly selected order for that session. An operational warning light was placed on and connected to each orange drum. The computer that controlled the police light bar and warning lights was then started.

Each participant was met by a study team member in the test track parking lot and escorted to a conference room. All participants were given a consent form approved by the Institutional Review Board of Penn State and of Rensselaer Polytechnic Institute to read and to sign after the opportunity to ask clarification questions. Participants were informed verbally that they would be driving around the test track (in counterclockwise direction) with a study team member in the passenger seat and to assume the speed limit was 30 mph. Further, they would be driving past a parked vehicle behind orange plastic drums like those in a work zone that would delineate a lane shift, or taper. They were told to begin driving straight toward the taper in the lane indicated by two traffic cones. They should keep driving straight until they could accurately identify the taper direction, at which time they should immediately tell the study team member in the vehicle "left" or "right" and

Table 1. Lighting Conditions, Mean Identification Distances and 95% Confidence Intervals (CIs)

Configuration #	Intensity (peak/trough, cd)	Flash pattern–taper direction	Police light bar	Mean identification distance (ft) (95% CI)
1	25/2.5	Random—L	Off	290 (164–416)
2	25/2.5	Random—L	On	234 (139–329)
3	25/2.5	Random—R	Off	361 (214–508)
4	25/2.5	Random—R	On	287 (149–425)
5	25/2.5	Sequential—L	Off	368 (293–443)
6	25/2.5	Sequential—L	On	312 (242–382)
7	25/2.5	Sequential—R	Off	393 (330–456)
8	25/2.5	Sequential—R	On	364 (300–428)
9	150/15	Random—L	Off	329 (214–444)
10	150/15	Random—L	On	365 (222–508)
11	150/15	Random—R	Off	345 (214–476)
12	150/15	Random—R	On	340 (234–446)
13	150/15	Sequential—L	Off	415 (359–471)
14	150/15	Sequential—L	On	412 (359–465)
15	150/15	Sequential—R	Off	395 (324–466)
16	150/15	Sequential—R	On	304 (233–375)
17	700/70	Random—L	Off	306 (170–422)
18	700/70	Random—L	On	310 (185–435)
19	700/70	Random—R	Off	391 (332–450)
20	700/70	Random—R	On	355 (255–455)
21	700/70	Sequential—L	Off	369 (293–225)
22	700/70	Sequential—L	On	329 (235–423)
23	700/70	Sequential—R	Off	428 (379–477)
24	700/70	Sequential—R	On	362 (278–446)

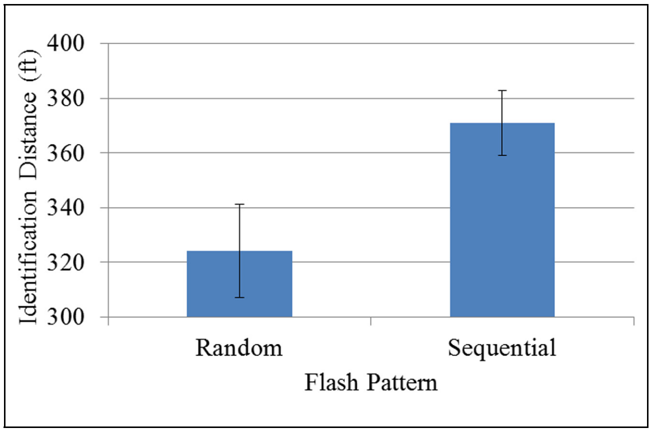

Figure 3. Mean (+/−standard error) identification distances for each flash pattern.

then safely pass the parked vehicle. Finally, the participants were told that this procedure would be repeated for 18 laps around the test track after first driving an initial practice lap. The practice lap enabled the participants to become familiar with driving the vehicle and with the appearance of the taper and stationary SUV.

The participant was then escorted to the sedan and instructed to make any necessary seat or mirror adjustments. The data collection system in the sedan was started, and the participant proceeded to drive around the test track for a total of 19 laps. When the participant said the direction of the taper ("left" or "right") the study team member in the passenger seat would press and hold a button attached to the data recorder until the sedan was adjacent with the first orange drum in the taper. This procedure measured the distance from the taper to the point of taper identification. After the vehicle passed the SUV, the study team members in the SUV would set up the next test conditions.

The participants in each session saw 18 of the configurations presented in one of four different randomized orders: all 12 configurations that included the sequential flash pattern but only six (half) of the configurations that included the random pattern. The number of random flash pattern conditions was reduced to keep the duration of each experimental session under an hour. The entire session, including instructions, took approximately 1 h to complete. The participants were paid $50.

Results and Analysis

The data for each session were recorded on an SD memory card and subsequently transferred to a laptop. All data, compatible with the software Race Technology v8.5, were manually extracted into a Microsoft Excel spreadsheet in which Minitab 17.3 could be used to perform the statistical analyses.

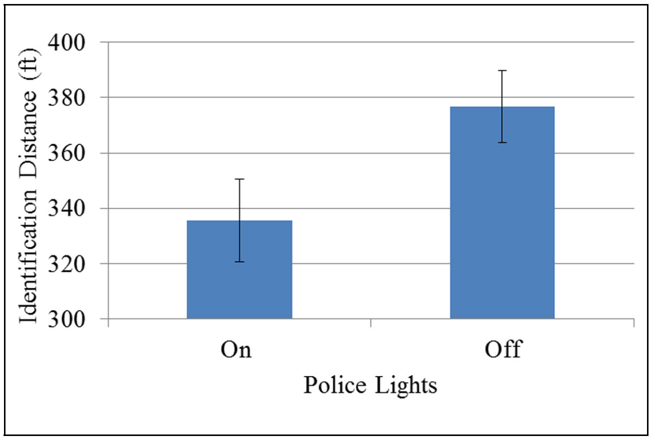

Figure 4. Mean (+/− standard error) identification distances with police lights on and off.

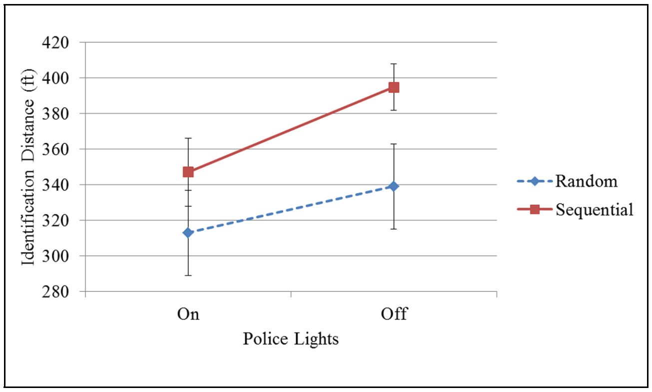

Figure 5. Mean (+/− standard error) identification distances for each combination of flash pattern and the presence of police lights.

Table 1 provides the mean identification distance and the 95% confidence interval for each configuration. The confidence interval was computed for each configuration by multiplying the standard error of each condition by 1.96. There were no misses or false positives in the data set.

A multi-factor, within-subjects analysis of variance (ANOVA) was conducted on the identification distance data. The ANOVA revealed that the flash pattern ($F = 5.86$, $p = 0.016$; Figure 3) and the presence of the police lights bar ($F = 4.06$, $p = 0.045$; Figure 4) had statistically significant main effects on the identification distance. Neither the intensity of the barricade warning lights ($F = 1.21$, $p = 0.299$) nor the taper direction ($F = 1.21$, $p = 0.273$) had a statistically significant effect on identification distance. None of the interactions among these variables were statistically significant. Figure 5 illustrates the relatively small, non-significant interaction ($F = 0.3$, $p = 0.582$) between the flash pattern and the presence of the police light bar on identification distances. In general, the police light bar had a similar impact on identification distances for each flash pattern, resulting in a reduction in the distance.

Discussion and Conclusions

These results demonstrate, again (*5*), that sequential flashing of flashing barricade warning lights can have a beneficial impact on a driver's ability to judge the direction of a lane change taper, compared with random flash patterns. Drivers were able to make their judgments from longer distances, which would give them additional time to plan and execute appropriate driving maneuvers, potentially mitigating crashes in lane closures (*4*). For example, the mean identification distance for the sequential flash pattern was 371 ft, whereas the mean distance for the random pattern was 324 ft (Figure 3). Traveling at 30 mph (44 ft/s), sequential flashing provided 1.1 s of additional response time.

The intensity characteristics of the flashing barricade lights did not have a significant impact on the mean identification distances in the present study. However, similar flashing light intensity characteristics were shown in a previous study by Kersavage et al. to affect detection distances for simulated workers when they were not wearing reflective vests (*3*). For the present study, the self-luminous flashing lights served as the critical visual information for this task and drivers were not required to detect and identify potential hazards and workers in or near the work zone. Clearly though, the results of both studies should be integrated into the design and implementation of yellow flashing warning lights in work zones. And while the present study was carried out along an otherwise unlighted test location, illumination and glare from work-zone lighting such as light towers might affect the influence of the barricade lights and the emergency lights in other similar situations.

Finally, the results of the present study clearly show that the flashing police light bar negatively affected identification distances in work zones. This was particularly true when the yellow warning beacons were flashing randomly, a common situation on roadways today. Certainly, there is evidence that flashing police lights are useful at capturing drivers' attention and in encouraging them to slow down when approaching a work zone or other location where a police vehicle and its flashing lights are present (*11*). The present results, however, along with those from Kersavage et al. (*3*), strongly suggest that new standards and recommendations are needed not only for yellow flashing warning beacons but also for red, blue, or both red and blue flashing emergency lights, to ensure that the benefits of emergency lights are not countered by potential drawbacks. These findings suggest that current standards and practices may compromise the safety of drivers, highway construction workers, and emergency personnel.

Acknowledgments

Preparation of this paper was supported by Grant no. R01OH010165 to Mark S. Rea and funded by the National Institute for Occupational Safety and Health (NIOSH) of the Centers for Disease Control and Prevention. The authors acknowledge Martin Pietrucha of The Pennsylvania State University for assistance in experimental design; John Swab, Krishna Desai, and Paul Marcinkevage of The Pennsylvania State University for assistance in conducting the field experiment; and the City of Troy Police Department for loan of the police lights used in the study.

Author Contributions

The authors confirm contribution to the paper as follows. Study conception and design: MR, JB, NS, PG, ED; programming and data collection: NS, KK, PG; analysis and interpretation of results: KK, ED, JB; draft manuscript preparation: KK, NS, JB. All authors reviewed the results and approved the final version of the manuscript.

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The Standing Committee on Visibility (AND40) peer-reviewed this paper (19-05128).

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