LIGHTS AND LIGHTING FOR HAZARD WARNING AND DELINEATION

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LIGHTS AND LIGHTING FOR HAZARD WARNING AND DELINEATION

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The work described in this report reflects 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 Federal Highway Administration. This report does not constitute a standard, specification or regulation.

ABSTRACT

Hazard Warning Lighting

In a laboratory study of hazard warning lights, 24 observers representing a cross-section of driver ages, pushed a button on a steering wheel rim in response to a flashing yellow light which appeared among several other lights both flashing and steady-burning. The lights were scaled to a 1:25 simulated roadway setting. Each observer was positioned 40 ft from the roadway setting in order to obtain a simulated 1,000-ft viewing condition. The observers' response times were measured. In addition to the task of searching for warning lights, observers were also required to maintain a given speedometer reading by means of an actual accelerator pedal linkage. The test warning lights were operated at six different intensities, 17 'on' times of 5 to 90 percent of the flash cycle, and two flash rates of 50 and 100 flashes per minute.

The fastest response times occurred at an approximately 20 percent 'on' time for all six levels of intensity. At a flash rate of 100 flashes per minute when the 'on' time was maintained at 20 percent the results showed a greater than 200 millisecond (1/5 second) faster response time than for a rate of 50 flashes per minute. The chance probabilities were less than 0.001.

In a field study, hazard warning lights containing lamps (No. 957) operating at 12 volts, and others containing 6-volt lamps (No. 1850), were compared by 20 observers. Sixty-nine percent of the observers, when comparing warning lights of equal 'on' time, chose the light with the 100 per minute flash rate over the light with the 60 per minute flash rate. Approximately 88 percent of the observers chose the warning light with the 25 percent 'on' time over the light with the 10 percent 'on' time at 100 flashes per minute.

Delineation Lighting

In a laboratory study involving 108 observers, and again in a field study with 20 observers, the steady-burning delineation light proved distinctly superior to various types of flashing light delineation systems.

General Recommendations

Hazard Warning Lights: 1) Flash rate should be between 95 and 105 flashes per minute; 2) current 'on' time should be approximately 20 percent; 3) effective intensity should be a minimum of 20 to 40 candela for a 1,000-ft warning distance (or a combination of intensity and distance which yields 20×10^{-6} to 40×10^{-6} ft-c at the eye).

Delineation Lighting: 1) Steady-burning lights should be used for delineation; 2) the color of the light for delineation shall be equivalent to traffic signal yellow, but for better delineation, the left and right rows of delineation lights should be different colors.

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INTRODUCTION

PROJECT BACKGROUND

The proposal for this research project was submitted to the Federal Highway Administration in February 1963 and was approved in April 1963. Work began in July of that year.

The intent of this study was to determine the optimum characteristics of hazard warning and delineation lighting. Results of this study were to provide a basis for recommending and specifying characteristics of hazard warning lights or delineation lighting and recommending methods of utilizing lights for delineation.

The project's specific objectives as originally stated were as follows:

1) Determine the basic requirements of a hazard warning light or hazard warning lighting.

2) Determine the basic requirements of lights or lighting for delineation.

3) Develop a method for evaluating the psychological factors of lights and lighting in 1 and 2 above.

A fourth objective, designed to ascertain the effectiveness of existing commercial lights as delineating or hazard warning devices, was not completed. Due to pressure of other research activities, the time required for such a project was not available.

In pursuit of the foregoing goals, the following avenues of investigation were proposed:

1) Evaluate the effectiveness of existing hazard warning and delineation lighting as set forth in 1 and 2 above. Ascertain the current status of warning and delineation lighting effectiveness through interviews of truck drivers, project engineers, and hazard warning light rental agencies, studies of state police accident records, and a survey of warning and delineation lighting used in other states.

2) With a cross-section of drivers as observers, evaluate the psychological factors of warning and delineation lights in the laboratory and verify the findings on the roadway.

STATUS OF HAZARD WARNING AND DELINEATION LIGHTING IN MICHIGAN

In an attempt to more accurately characterize the nature of the problems associated with battery-operated hazard warning lights used on Michigan highways, and the function served by these lights, the exploratory phase of this study concerned itself with the examination of State Police accident records, and interviews with truck drivers, construction engineers, and with warning light vendors. J. A. Head of the Federal Highway Administration had indicated that such information was sorely needed before recommendations concerning the effective field use of warning devices could be formulated. The information received enabled this investigation to focus on certain specific questions and working hypotheses.

State Police Accident Reports

An attempt to determine the nature of accidents associated with battery-operated hazard warning lights by means of Michigan State Police accident reports was not too fruitful because of the lack of positive identification of such accidents. The Highway Department's Traffic Research Division (Accident Analysis Section) had approximately 40,000 State Police accident reports filed in various ways. A check of over 1,000 such reports in 1965 revealed that only 0.3 percent of the accidents were associated with warning lights.

Interviews with Truck Drivers

In 1965, a representative of the Research Laboratory conducted informal interviews with 20 interstate truck drivers, their comments and general views regarding lights and lighting for hazard warning and delineation on the main highways were recorded. The following summary of these comments concerns: 1) Their views as to the factors that account for accidents and near-accidents in situations involving warning lights; 2) their suggestions regarding the improvement of warning light usage; and, 3) the relative effectiveness of various warning lights. In accident and near-accident situations the two factors most consistently noted during these interviews were: 1) inadequate advance warning for high speed traffic; and, 2) vagueness as to the purpose of the warning flashing lights. In this connection, it was frequently mentioned that the signs, if any, and the warning lights were not far enough ahead of the potential hazard to allow the driver to adjust his driving behavior, especially when the hazard was just beyond a hill or in a passing zone. Without advance signing indicating the type of hazard ahead, resulting in driver inability to choose the appropriate driving behavior, there was a wide range of perceived individual differences in reaction to warning lights. Such variations in driver reaction, the truckers felt, might have led to irregular traffic behavior, rear-end collisions, and various types of near-accidents.

The most common suggestion for proper and safe hazard warning and delineation given by the truck drivers was: use a uniform system of advance warning lights and signs on all high speed roadways which would be essentially a series of signs beginning approximately two miles in advance to indicate: 1) the nature of the hazard; 2) the lane or lanes being closed; and, 3) the desired driver behavior. In addition, flashing warning lights should be used to attract attention to the signs; and the lights should be used in conjunction with barricades to guide traffic around the hazard area.

Other ideas proffered by the drivers concerning the placement and function of warning lights were as follows:

1) There should be more uniformity in meaning, placement, and function of hazard warning lights from state to state.

2) Advance warning lights should be placed higher (probably at least 7 ft above the roadway to conform with the bottom height of signs as required by the Manual of Uniform Traffic Control Devices). People have begun to 'school' themselves to look up for signs and signals.

3) Particularly on two-lane highways, warning lights and signs were needed on both sides of the road facing on-coming traffic. Trucks often blocked the view of the driver who was passing; or on the four-lane highway, blocked the view of the driver in the passing lane.

4) There were too many 'false alarms' which may have been caused by warning devices on work too far removed from the roadway or by signs and lights not promptly removed after work was completed.

5) A number of drivers indicated that at various construction sites in Ohio, a number of short 'on' time sequentially flashing warning lights were placed in a line so that the desired path was indicated by the apparent movement produced by the lights flashing one after another along the desired path.

6) Visual input could be augmented by auditory and kinesthetic signals by designing a portable device to simulate the feedback produced by 'speed-bumps' sometimes used at long term construction projects.

Estimation of the relative effectiveness of various kinds of warning lights by the interstate truck drivers seemed to focus on the comparison of kerosene bombshell torches with battery-operated flashing warning lights. In general, the comments concerning such a comparison were given by the following statements:

1) As long as there were a 'sufficient' number of battery-operated warning lights operating, not covered with a thick coating of mud, lights were more effective than torches for getting the driver's attention.

2) The torch seemed to have the advantage of lighting up the hazard area. The battery-operated lights did not remain lighted long enough to light up the hazard, but they had good attention value.

3) In relation to Statement 2, a few truck drivers expressed the opinion that the 'old flare pots' seem to offer a stationary light that could be used to relate how far a driver was from the hazard (i. e., facilitates orientation in addition to lighting up the hazard area). These combinations of information gave the driver a better indication of his desired action or reaction in a shorter period of time. In other words, the truckers felt that some type of steady-burning light to delineate the location of hazards should be used in addition to the flashing warning lights.

4) It was found generally that both battery-operated flashing warning lights and kerosene bombshell torches are relatively useless as attention getters during the day. It was suggested that flagmen and the necessary brightly colored cones and barrels be used in all cases during the daylight hours.

The preceding information may have important practical implications for the deployment of lights for hazard warning and delineation. Perhaps, the most effective portable warning light display would incorporate both types of warning devices, thus taking advantage of the 'attention getting' qualities of the battery-operated flashing warning lights and the delineation qualities of the torches. In the early 60's, battery-operated flashing warning lights were viewed as a substitute for the kerosene bombshell torch instead of being used in conjunction with the torch.

Interviews with Project Engineers

According to the Michigan Standard Specifications, the Department's Project Engineers have the responsibility of deciding questions regarding the acceptability and performance of safety items. Their knowledge of the relative effectiveness of the various warning lights was considered very important.

The information collected from telephone interviews with 18 MDSHT Construction Project Engineers in 1965 is summarized as follows:

1) There was general agreement that battery-operated flashing warning lights, if properly maintained and correctly installed, are just as effective—or more so—than torches for purposes of warning and guiding traffic.

2) One interesting exception to the above statement given by a Project Engineer in Royal Oak, seemed to corroborate the statements given by the truck drivers concerning flash rate and orientation or depth perception. He stated that battery-operated flashing warning lights are inadequate because the short flash duration does not provide adequate lighting needed for the judgment of distance or of the location of the hazard.

Statements made by both Project Engineers and interstate truck drivers indicated a concern for the apparent lack of routine maintenance of warning lights on the highways. In general, the truck drivers complained about the large percentage of lights with broken lamps and lenses, thick coatings of mud, not aimed toward on-coming drivers, and lights with batteries that were weak or dead. The battery-operated flashing warning lights were still preferred over torches by the drivers since the torches were characterized as being ineffective during rain storms when hazard warning is most needed. In this connection, the Project Engineers indicated that the almost daily maintenance problems associated with torches (requiring attention at night, especially during rain storms) had led to an increasing use of battery-operated flashing warning lights. However, one Project Engineer related an instance where vehicles were constantly crashing through barricades located at a sharp bend in a road. The barricade was protected by 6-v battery-operated flashing warning lights. When the warning lights were replaced one-for-one by kerosene bombshell torches, the breaching of the barricades ceased.

Interviews with Warning Light Vendors

The advantage of extra convenience gained by using battery-operated flashing warning lights appears to be offset somewhat by the large number of these lights that are destroyed or rendered ineffective for a number of reasons. Information gathered from the truck drivers and Project Engineers indicated that a large number of the lights were destroyed as a result of motor vehicle accidents. Although it is very difficult to obtain data concerning the various causes of warning light replacement, information obtained from a number of rental agencies indicates that there were a large number of causes, one of the least important being the striking of the light by motor vehicles. They indicated that the factors related to the relatively high replacement rate of battery-operated flashing warning lights were as follows:

1) Lights were often hit by gravel thrown from the tires of cars and trucks.

2) Lights were struck by oversize vehicles because no allowance was made for such vehicles in the warning light placement.

3) A large number of lights were broken by construction workers throwing them onto trucks, or carelessly driving construction equipment over them.

4) Many lights must be replaced because of vandalism. They were smashed in a variety of ways, e.g., baseball bats, wielded by moving vehicle passengers. They were stolen; at the end of each school term, many were found in college dorms.

5) Some lights were struck by automobiles because of accidents and near-accidents associated with construction and maintenance operations.

6) Weathering also led to the replacement of a number of lights each year. There were two factors which made it difficult to obtain accurate data concerning the replacement rate of warning lights. The highly competitive nature of the warning light rental business leads to a reluctance to reveal information on the part of such agencies. In addition, unofficial transfer of lights from one construction project to another has been observed, thus making it difficult to accurately estimate replacement rates from field observation. Most rental agencies estimated that one-third of all lights placed in the field would be replaced within a year. The various sources interviewed invariably used the term 'flasher' in referring to the 6-v battery-operated flashing warning lights of the type typically found at highway construction sites. No particular manufacturer's light was mentioned nor were any data gathered concerning lights of other types, e.g., neon, or propane lights.

Review of Michigan Department of State Highways and Transportation Standard Specifications

Written policy concerning the necessity of flashing warning lights, the function served by lights, and how they are to be employed in Michigan is found in the following two manuals: 'Michigan Manual of Uniform Traffic Control Devices," and 'Standard Specifications for Road and Bridge Construction."

The information concerning flashers (supposedly the 6-v battery-operated barricade warning lights) found in the 'Michigan Manual of Uniform Traffic Control Devices," 1963, can be summarized as follows:

Flashers are one type of portable lighting device, the others being torches and lanterns.

Specifications for these devices are set up by the Michigan Department of State Highways and Transportation.

Function of the flasher is to protect the work and adequately warn the motorist of potential hazards in areas where construction and maintenance operations are being conducted.

Employment of these lighting devices on State trunkline highways is covered in the 'Specifications for Road and Bridge Construction," issued by the Department.

Since it is apparent that the use of battery-operated flashing warning lights extends beyond the use specified in the Standard Specifications, exhaustive characterization of their function is a very difficult task. But, based upon the preceding description, together with telephone interviews with Construction Project Engineers, it can be said that, in general, those warning lights are presently used to:

1) Directly warn the motorist during the hours of darkness of potentially hazardous road conditions which require a reduction of speed and preparation to read explanatory signs, which in turn indicate the desired driving behavior.

2) Delineate—in conjunction with barricades—or serve a channelization function to guide the motorist safely through construction areas or around other hazardous road conditions (e.g., sewer trenches, large holes or bumps, muddy shoulders, etc.).

TABLE 1
SUMMARY OF HAZARD WARNING LIGHT SURVEY RESPONSES FOR 1964

I Percentage of Various Types of Warning Lights in Use (unweighted averages)

Battery-Operated Incandescent Flashing Warning Light	70%
Battery-Operated Neon Flashing Warning Light	6%
Kerosene Bombshell Torch	18%
Propane Flashing Warning Light	1%
a-c Incandescent Flashing Warning Light	5%

II General Specifications

Twenty-one states reported specifications on performance of warning lights.

Seventeen states reported specifications on use of warning lights.

III Flash Rate and 'on' Time Specifications

Range of flash rates specified	10 flashes/minute to 120 flashes/minute
Most frequent min/max rates specified	50-70 flashes/minute and 70-120 flashes/minute
Range of 'on' time specified	2 percent to 50 percent
Most frequently specified 'on' time	25 percent

IV Voltage Specifications

Number of states reporting 6-v spec. only	8
Number of states reporting 12-v spec. only	4
Number of states reporting 6 or 12-v spec.	16

It appears that construction engineers were requesting the use of battery-operated flashing warning lights in an increasing number of situations in lieu of the kerosene bombshell torch. In general, battery-operated lights are being used in an innumerable array of configurations (i.e., with barrels, steel beam guardrail, show fences, red lights on 'road closed' barricades, etc.) in situations where traffic must be restricted in any form during darkness (mostly at highway construction or maintenance operations and installation and maintenance operations by utility companies).

Hazard Warning Lighting - Survey of Use in Other States

The foregoing has presented the use and associated problems of hazard warning and delineation lighting in Michigan. The following will briefly outline the type and use of hazard warning lighting in all the states as of 1964.

In 1964, 51 governmental agencies (49 states, District of Columbia, and Puerto Rico) were polled regarding their specifications and usage for various types of hazard warning lights. Forty-four agencies (with 95.5 percent of the total population as of a 1965 estimate) responded to the questionnaire. Table 1 summarizes the responses.

Thirty-two states (with 72 percent of the population) reported that 50 percent or more of their warning lights are battery-operated incandescent flashing lights, 22 of the states having 80 percent or greater usage. All of the states responding were using this type of light to some extent.

Seven states (with 22 percent of the population) were using neon light; 32 states (with 70 percent of the population) were using kerosene bombshell torches. Only in Colorado were torches a majority. Six states (with 18 percent of the population) were using propane lanterns in small quantities (an average of 2 percent of their total number of hazard warning lights).

States were also using warning lights of other types such as higher wattage a-c or d-c incandescent lights and torches and lanterns. Of the 28 states with voltage requirements for battery-operated incandescent lights, eight agencies allow 6-v lights only, four states allow 12-v only, and 16 states issue specifications for both 6-v and 12-v lights.

The survey uncovered the following additional facts:

In 37 states with 68 percent of the U. S. population, contractors furnished the warning lights, but in six of these states the state also furnished warning lights to the contractors.

Twenty-one states issued specifications for the performance of warning lights, four states issued specifications for the use only of warning lights at construction sites, and 13 states issued specifications for both performance and use.

Specifications for the minimum flash rate ranged from 10 per minute in Ohio to 80 per minute in Delaware. All but one of the 36 states which do specify a minimum flash rate required at least 50 cycles per minute. Upper limit restrictions ranged from 55 to 120 per minute. Flash rates were most commonly specified in ranges of 70 to 120 flashes per minute (12 states) and 50 to 70 flashes per minute (7 states).

Minimum 'on' time, or percentage of the flash cycle specified, varied from 2 percent in Ohio to 50 percent in Maine, Missouri, and Utah. Ten states did not specify 'on' time, five states required a minimum of 10 percent, and 28 states specified minimum 'on' times between 20 and 50 percent, the most common being 25 percent (18 states). Five states specified maximum 'on' times from 27 to 50 percent.

Fourteen of the states followed the outlines for hazard warning lighting in the "Manual on Uniform Traffic Control Devices for Streets and Highways," U. S. Department of Transportation, Federal Highway Administration (1961) which recommended a flash rate of 70 to 120 cycles per minute with a minimum 25 percent 'on' time; however, many of these states also reported widespread use of lights with characteristics quite different from those recommended in the Manual.

A survey of 42 states by the Pennsylvania Department of Transportation (1) in 1973 disclosed that 79 percent of the states responding to their questionnaire were using warning lights as specified in Paragraph 6D-5 of the U. S. Department of Transportation, Manual on Uniform Traffic Control Devices (1971), while 51 percent were using lights conforming to the Institute of Traffic Engineers "Standard for Flashing and Steady Burn Barricade Warning Lights," (1971). Seven states had no specifications.

Eight states tested the lights at their own facility, seven used independent testing laboratories, and 18 states used other methods for evaluating performance of lights, such as manufacturer's or vendor certification, or visual inspections in the field.

History of Warning and Delineation Lighting Research and Specification in Michigan

Prior to 1958, warning lights as safety devices on roadway maintenance and construction projects consisted almost solely of kerosene bombshell torches or kerosene lanterns. Both of these lights were effective as warning devices, but in some cases it was highly questionable that they were safe. For example, bulk fuel haulers were concerned about their safety in passing through construction and maintenance areas lined with torches, especially in urban roadway maintenance areas. Careless placement in some cases started fires and when such fires destroyed a road closure barricade, part of a driver's warning message had been destroyed. It was claimed that bad weather conditions required continual checking to replace outages and that daily maintenance of torches and lanterns was relatively costly. Battery-operated flashing lights were introduced with claims of being safer than, and equivalent to, bombshell torches. Some of these lights used gaseous discharge sources and others used very fragile filament lamp sources. The sources were enclosed in lens designs which varied from a 360-degree dome, to a 4-in. bi-directional lens, to a 7-in. mono-directional lens with an integral metal reflector. Flash durations were usually short, especially for the discharge lamp sources; flash rates were relatively high (over 90), and intensities relatively low except for a small spot in the center of the lens.

Initial use of battery-operated flashers in Michigan generated opinions that the flashers were weak and ineffective. Comments usually indicated that the flashers could not be seen soon enough and that it was difficult to locate the flashers with respect to the roadway. The high flash rate and short flash duration were often noted in the comments. Improvements in the lights were predictable and the advantages offered over torches were recognized by the Department. This resulted in initiating an investigation for the purpose of preparing specifications.

A nighttime field comparison between kerosene bombshell torches and battery-operated flashers became the basis for Michigan's initial specifications. Personal preference choices between torches and flashers from six vendors satisfied the observers that battery-operated flashers were competitive with torches. The observers agreed that high flash rates destroyed their interpretation of normal depth perception and produced an irritating effect which was considered undesirable. The flasher with the lowest rate (46) was preferred and the flasher with the highest rate (73) was considered least desirable. Some of the observers indicated that the best flasher was as effective as the bombshell torch. On the basis of the field evaluation, flashers were considered suitable for immediate use and in May of 1959 an interim specification was issued pending laboratory testing of the flashers. The specification required a flash rate of 50 to 70 per minute, a flash duration of 25 percent (25 percent of flash cycle), and a lens diameter of not less than 4 in. Laboratory testing of the flashers evaluated in the field showed that the best ranked flasher not only had the lowest flash rate but also the shortest flash duration (11 percent). The flasher operated at 12 v, was mono-directional, and had the highest beam intensity.

Testing also showed that flasher lens designs had a symmetrical beam about the lens axis with a very narrow high-intensity peak on the axis. This was considered highly undesirable but a desired intensity and distribution could not be defined. By July of 1959 it had been decided that battery-operated flashers would be operated by a 6-v power source, and that the lens color and candlepower distribution based on an 1850 lamp would be similar to the color and distribution requirements established for vehicular traffic control signal yellow lens. A continuing testing program showed that the flasher industry was not capable of furnishing lights conforming with these requirements. A Stimsonite lens, which was designed to spread the flasher beam horizontally, was tested in 1960, but non-conformance with specifications persisted and field maintenance of the flashers was considered excessive. In January of 1961 the Department took action to delete flashing lights from its specifications and to prohibit their use. By mid-1961, specifications were revised in cooperation with Michigan's flasher lessors. Lessors had proposed maintenance procedures and the use of flashers which would assure a highly improved field performance. Field evaluation of flashers continued and alternate types of flashing lights were investigated. A flasher operating from a propane gas source (Fig. 1) was used in a February 1962 field comparison with kerosene bombshell torches and battery-operated flashers. In that comparison the kerosene torch was considered the best delineation device and also a better hazard warning device than the propane flasher. Additionally, the observers noted that reflective materials on associated barricades were as bright as the flashers.

Complaints noting that flashers could not be seen soon enough were still prevalent and therefore a proposal to conduct a detailed study was developed. During the study period, plastic cases were introduced by the flasher industry and Michigan initially rejected them in favor of steel. This led to discussions of revising the 1961 specifications, but a consensus of necessary revisions was not available. In April of 1965, known fabricators of flashing lights and Michigan's lessors of flashing lights participated in a review of specifications. Opinions varied considerably on the performance of flashers, on materials used in flashers, and also on requirements that would assure use of high quality materials. It was obvious that an equitable specification based on materials characteristics was not attainable and, therefore, requirements were considered which would specify the minimum performance expected at all times in the field. The requirements needed the results of the study and thus it became very important to obtain results which could be directly applicable to incandescent sources.

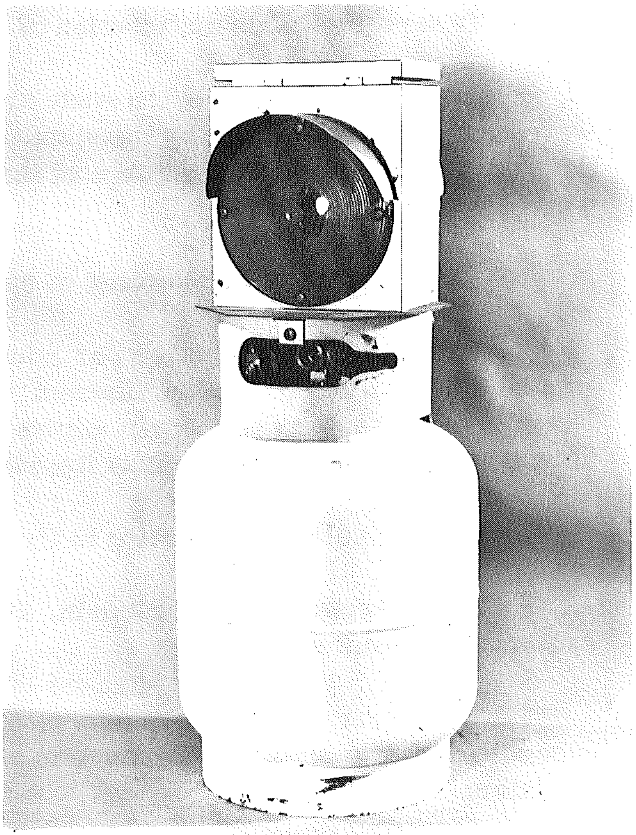

Figure 1. Propane-fueled light used in the hazard warning and delineation tests.

In a June 1965 meeting, Richard N. Schwab of the FHWA suggested that the physical characteristics and economics of flashing warning lights be investigated. His recommendations were to use the following parameters in a laboratory study of warning lights to be later validated in part by a limited field study:

1) 'On' time - 10 to 100 percent of flash cycle, i.e., flash duration of 10 up to 100 percent (steady-burning) of the duration of the flash cycle.

2) Rate - 10 to 600 flashes per minute.

3) Color - yellow, since this color is recommended for signal devices by the Manual of Uniform Traffic Control Devices.

4) Size - point source, since most warning lights are seen first as a point source.

5) Waveform of flash - vary from square, triangle, ramp, to sine wave.

6) Observers - wide distribution of ages.

It was decided to conduct the study around incandescent flashers which were most frequently used by the states in 1964. Since the use of incandescent lamps restricted the range of the flash characteristics, variables were elected as follows:

1) 'On' time - 5 to 100 percent of cycle.

2) Rate - 50 to 100 flashes per minute. Rates greater than 110 per minute did not allow the lamp filament to incandesce for the shorter 'on' times. Rates slower than 50 per minute were considered too slow for any demand on attention (see Previous Research section).

3) Color - yellow conforming to the ITE 'traffic signal' yellow.[1]

4) Size - apparent size of a 6-in. diameter warning light at 1,000-ft; essentially a point source.

5) Waveform - natural waveform of incandescent lamp. Studies of gaseous discharge sources such as neon and xenon lamps would be reservfor later.

As a means for determining economy of flashing lights, Mr. Schwab, in January 1967, suggested that Ciccolella's technique be applied to warning light lamps (2). Voltages other than the rated lamp voltage should be included in the study to show the effect of the battery on lamp efficiency. It was decided later that the results of the studies of flashing warning light economics should be included in a separate report.

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[1] Required by Institute of Traffic Engineers, "A Standard for Adjustable Face Vehicle Traffic Control Signal Heads," May 1966.

PREVIOUS RESEARCH

Detectability of Flashing Lights

The problem of the effectiveness of flashing lights has been studied for as long as there have been lighthouses, and pharaologists to study them. With the advent of high-speed vehicles, the problems have only become more critical. The use of flashing warning lights on highways has caused this to become a concern of manufacturers of portable lighting devices and to highway departments. These devices are required to attract the driver's attention, communicate the fact that he is approaching a hazard, and give him information as to the location and size of the hazard. The warning lights must do all this when the motorist is far enough away so that he has time to slow down or change lanes. This is in some respects similar to the task of a lighthouse or airway beacon, and so the data on visibility of these devices can be relevant to the highway case.

Several different approaches for assessing the relevant variables affecting detectability of flashing lights have been used, and investigators using these approaches have all used different methods. These will be reviewed in turn.

Effective Intensity

The work of Blondel and Rey (3) has been extensively reviewed in many sources, but since it is the generator of almost all subsequent work, and since the basic form of the equations they derived have remained unchanged for over 60 years, it is worthwhile to review their study, with special attention to their assumptions and experimental method.

Reviewing Broca and Sulzer's work of 1902 (4), Blondel and Rey in 1911 noted that the apparent intensity of a short flash of light varied according to the length of the flash. Using two different types of apparatus, one checking the results of the other, they presented 25 series of flashes to 17 heterogenous observers who were dark-adapted. The observers adjusted the test flash to apparent equality with a long control flash of known intensity. Three seconds were left between presentations of test flashes, as Blondel and Rey assumed that this would avoid any interference effects of one flash with the next flash presented. The authors noted that the results, in terms of intensity for subjective equality, were so heterogenous that taking arithmetic means was suspect, so they used geometric means. They hypothesized that some of the variance was probably due to the fact that they did not use an artificial pupil, which meant that variations in the state of dark adaption of the observers were not controlled. Despite these problems, they arrived at a set of points which were fit by an equation of the form

$$Et = A + Bt$$

where:
E = illuminance on the pupil
t = time of flash (duration)
A and B = constants

(assuming E remained constant during the flash, i.e., a square wave). They then showed that $A = E_0 a$, and $a = 0.21$. If one assumes an infinitely long flash, $B = E_0$, where E_0 = illuminance at the eye of a steady light at threshold[2], then at threshold

$$Et = E_0 (0.21 + t) \tag{1}$$

This equation is also found today in the equivalent forms

$$t(E - E_0) = 0.21\, E_0 \qquad \text{and} \qquad \frac{E}{E_0} = \frac{0.21 + t}{t}$$

The assumptions under which these equations were derived limit their usefulness to square pulses, although they seem to be a fairly good approximation even if this condition is ignored, as is commonly done.

Blondel and Rey realized that all light pulses were not of this shape, and conjectured that for a non-rectangular pulse, since "... we have shown that the useful excitation is at each moment proportional to the difference $E-E_0$ between the real illumination E and the limiting illumination E_0 of the threshold" the equation would take the form

$$I_e = \int_{t_1}^{t_2} \frac{I\, dt}{a + t_2 - t_1} \tag{2}$$

where
I_e = the "effective intensity" of a flash
I = the actual intensity
a = 0.21

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[2] Threshold illuminance is the minimum illuminance producing a sensation in the eye, ordinarily with a probability of detection (5) of 50 percent, although for roadway application it should be between 99 and 99.9 percent.

Note that since the equation is applied at threshold, intensity (I) and illuminance (E) are used interchangeably because the two terms are related through a constant; viz, the square of the distance from light source to observer.

They asserted that "... the integral of excitation can be obtained by the simple quadrature of the curve representing E by measuring with the planimeter the area of the curve which is placed above the straight line E_0, " (Fig. 2). Note that this is the part of the curve above the threshold representing total flux above threshold.

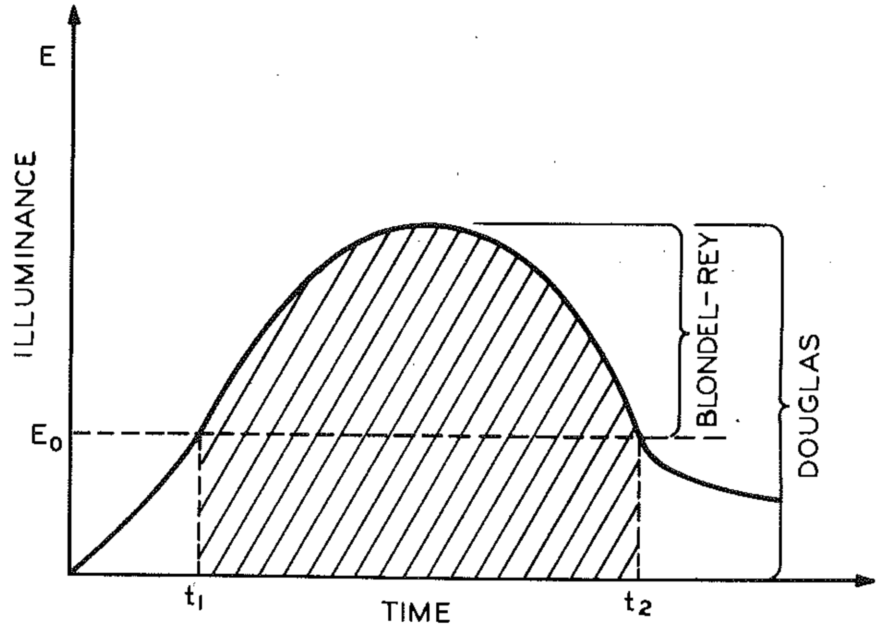

Figure 2. Idealized illuminance - time curve.

Summing up their paper, Blondel and Rey state the practical implications of their work as follows: "It is always advantageous to reduce the duration of the flashes without the necessity of fixing a limit of minimum duration. The limit is in reality fixed by the conditions for producing the source of light at the apparatus, " when only a given amount of energy is to be used in the flash. For other cases, the formulas could be used to state the optimal conditions. No variances were given for the values which were "too heterogenous" to use means.

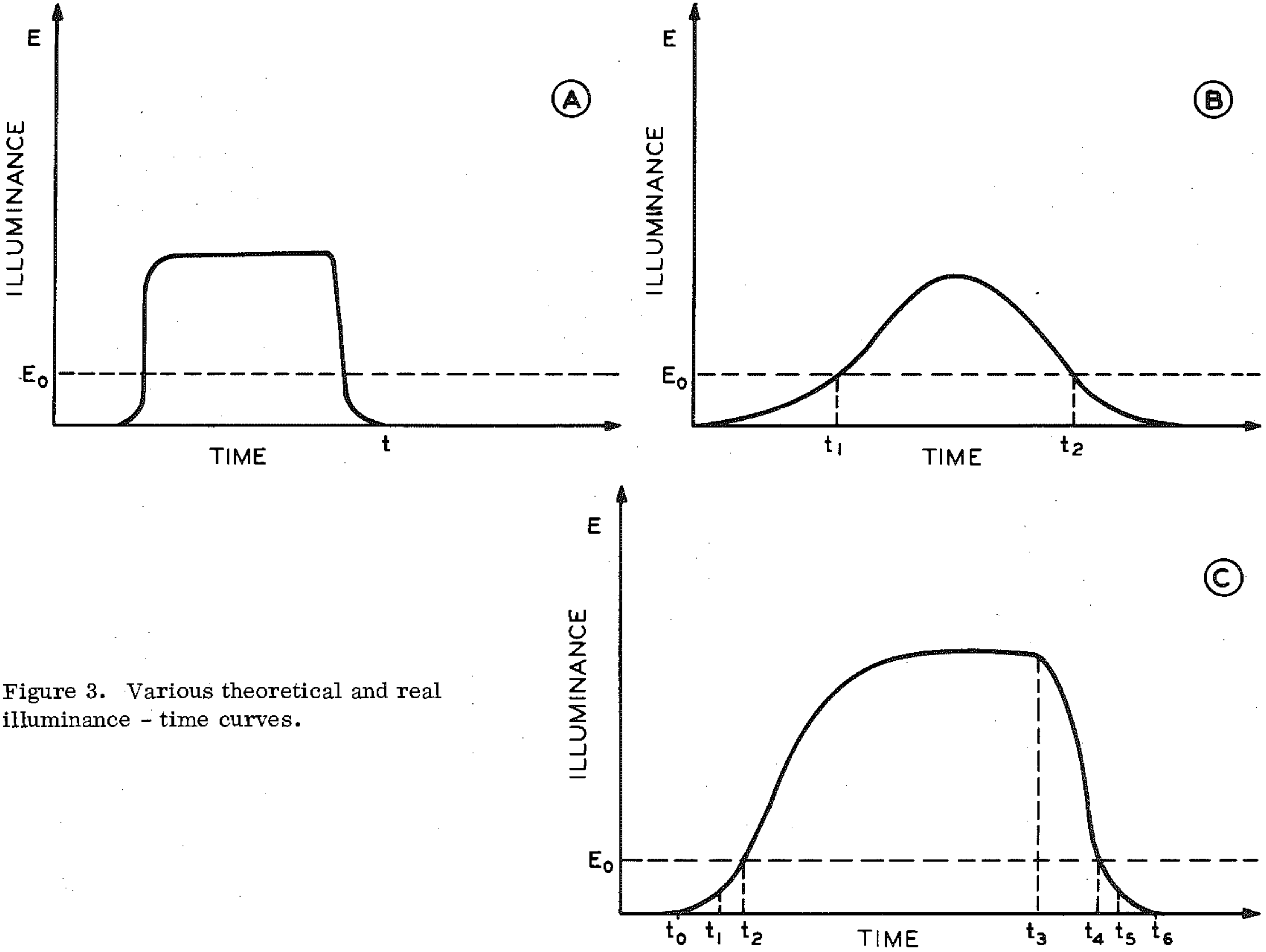

Figure 3. Various theoretical and real illuminance - time curves.

This pioneering study has stood the test of time well, having been investigated by several researchers, and found to work well for flash durations between 0.1 and 1 second.

Studies have been done more recently to check the Blondel-Rey equations, and one of the most often quoted as a verification is the work of Neeland, Laufer, and Schaub (6). Briefly, their method was to set up several airway beacons on buildings 8.3 and 2.9 miles from the subject. Next to the beacons was a projector which could be varied in intensity to match the apparent brightness of the beacon flash. They obtained fair agreement with the Blondel-Rey equation

$$\frac{E}{E_o} = \frac{0.21 + t}{t}$$

Instructions to their subjects were apparently ambiguous, as "... some observers ... stated that they used the apparent size of the source as a measure of its visibility; ... other observers undertook to match the fixed light with the most visible portion of the flash." The effect of the atmosphere, of course, could not be held constant, and the authors at times noted a variation in the measured threshold of the subject as large as a factor of nine in the intensity of the steady source necessary for subjective equality. The color temperature of the comparison projector was also noted to vary with intensity, and this had unknown effects on the observers judgments. The investigators inserted a red filter in one of the beacons for some measurements and not for others, doubled the flash rate on some beacons for some measurements, and then averaged all these data in presenting their findings. More important, they indicated that the flash probably does not have a square shape, as it properly should, to satisfy the Blondel-Rey equation they used; but they did not indicate what the shapes might be, and used the square-pulse equation anyway.

Calculations of 'a' in the equation were also done by the investigators to check the 0.21 obtained by Blondel and Rey. It was found to vary between 0.10 and 0.46 over the whole study, and between 0.20 and 0.46 for the data for one flash duration, depending on the type of beacon.

Some investigators have attempted to fit their data with the integral form of the Blondel-Rey equations (7, 8) but here a dispute has arisen as to what limits should be used for the integral. Figure 3 may clarify this dispute. Equation (1) applies to the square-pulse case (Fig. 3a). Here, the time (t) is simply the total time the pulse is on, and the equation considers the total flux emitted. In practice, only flashed acetylene flames, lights with rotating shutters or choppers, gas discharge lamps such as xenon or neon, or laboratory sources give this shape of wave.

For some idealized wave, such as Figure 3b, where Eq. (2) applies, it is clear that choice of the limits of integration will cause differences, often large, in calculated values for equivalent intensity. Blondel and Rey's choice of t_1 and t_2 (where the effective intensity, I_e, equals the threshold value) is not the obvious one, and in fact others have at various times used quite different limits. For instance, in the case of an incandescent lamp flashed by a relay (Fig. 3c) one could use the whole emitted flux ($t_6 - t_0$), or the time when the lamp's intensity passes some arbitrary value such as 10 percent of its total intensity ($t_5 - t_1$), the Blondel-Rey values ($t_4 - t_2$) or the relay contact closure time ($t_3 - t_0$). Each of these will yield a different result, and there are arguments in favor of, and against, each.

In 1957, Douglas (9), using Blondel and Rey's work as a base, derived a method of choosing t values so that I_e was a maximum. Starting with a theorem that I_e is a maximum when the limits t_1 and t_2 are the times when the instantaneous intensity is equal to I_e and deriving two corollaries,

> "If the instantaneous intensity is integrated over a period of time t_1' to t_2' shorter than t_1 to t_2, and I' is the instantaneous intensity at these times, a value I_e' is obtained for the effective intensity that is always less than I'."

and

> "If the instantaneous intensity is integrated over a period of time t_1'' to t_2'' longer than t_1 to t_2 and I'' is the instantaneous intensity at the times t_1'' and t_2'', a value I_e'' is obtained for the effective intensity that is always greater than I''."

he then had the tools to compute effective intensity values which are maximal. This coincided with the limits of integration suggested by Blondel and Rey, i.e., limits at which the instantaneous intensity is equal to the threshold intensity. However, Blondel and Rey suggested taking the area above threshold (as shown in Fig. 2) while Douglas' formula yields the additional area shown in Figure 2. He gives no explanation for this difference.

There has been no universal agreement on the value for the constant 'a' in the Blondel-Rey equation. Projector (10), in a review, found values for this constant as different as 0.055 to 0.35 seconds. He suggested a standardization on a value of about 0.1 to 0.2 seconds, since most of the data were near these values. C.I.E. Committee E-3.3.7 recommended (1963) that, because of the imprecise nature of the studies, a value of 0.2 seconds should be used. For flashes other than square wave, the British Standard (BS 5942:1949) (11) recommended 'a' = 0.15 seconds.

Douglas and other investigators cautioned that the foregoing equations apply only at threshold for achromatic lights and are only approximations at greater intensities. This does impose a limit on their usefulness, and one must check any results obtained in suprathreshold ranges, or conditions different from the dark background, dark adapted observer, etc., as used in the original work.

Effective Intensity - Suprathreshold Flashing Lights

Flashing lights producing illuminance on the retina above the minimum necessary to stimulate a sensation are called suprathreshold, or supraliminal lights.

Some researchers have suspected that the constant 'a' in the Blondel-Rey equation would be different for suprathreshold viewing. Hampton (12) adjusted Blondel and Rey's equation using Toulmin-Smith and Green's (13) data such that 'a' was a function of the illuminance (E) at the eye:

$$\frac{I_e}{I} = t \Bigg/ \left[\left(\frac{0.0255}{E} \right)^{0.81} + t \right]$$

where E is illuminance at the eye in lumens per square mile. Toulmin-Smith had obtained their data at illuminance levels from 0.2 to 4.0 lumens/sq mile. However, Schuil (14) apparently did not confirm the value of 'a' at an E of 2.0 lumens/sq mile.

C.I.E. Committee E-3.3.2.1 (1963) recommended a value of 0.2 for 'a' for suprathreshold viewing, the same value as Committee E-3.3.7 had recommended for threshold viewing. C.I.E. Committee E-3.3.2.1 also claimed that the Blondel-Rey formula worked well at levels above threshold.

In summary, we can calculate the visual range for any flashing light, or, conversely, can determine if a given light will be visible at a given range, for any type of flash waveform. But considering the lack of agreement on constants, and on the methods for determining these constants these calculations should be considered an approximation.

Relevance to Present Study

Effective intensity, calculated by whatever means, can specify only the intensity of a steady light which will appear as bright as a flashing one. While this measure is useful in many cases, and lends itself to calculations in other formulas, it is of little use as a psychological variable in attention-value studies. One may be able to show that a flashing source of a certain waveshape and peak intensity has the same apparent brightness as a certain non-flashing source, when viewed by a dark-adapted observer staring at the source or comparing the two sources directly, but this does not necessarily relate the comparative value of each to attract an observer's attention when the lights are not expected or viewed peripherally when the observer's attention is elsewhere. In short, calculations of "effective intensity" will certainly enter into an experiment using flashing light stimuli, but only as a means of determining how bright a steady-burning reference light would be.

Conspicuity

A rather different measure has been used on flashing lights by Gerathewohl (15) who used a reaction time measure to find what he terms conspicuity. His method consisted of placing a subject in front of a screen on which were displayed complex signals at random intervals. These signals could differ in color, flash rate, brightness, etc. The subject also had to respond to an auditory task. He utilized foot pedals and levers to signal his reactions to the various tasks. In this way, Gerathewohl measured reaction time to flashing as compared to steady signals at different contrast levels. For small contrasts the conspicuity of flashing signals was considerably greater than steady-burning lights (16). In another study it was found that at low contrast levels of flashing light of short duration the signal was more conspicuous than a slow flashing one of a longer duration (17). Later, a recommendation was made that the most conspicuous signal was three flashes per second when the signal was at least twice as bright as the background (18). However, in a similar study, and a replication of it, Dean (19), was unable to duplicate these results, failing to reach the 0.05 statistical significance level with similar reaction time data. He hypothesized that flicker rate might not be a determinant of signal conspicuity when apparent brightness has been controlled.

Gerathewohl stated that the timing circuits were such that if a subject missed or did not respond to a signal, the time until detection of the next signal was automatically added to his reaction time score. If one were extrapolating to a situation where a flashing light, if not detected, simply reappeared elsewhere (as in a radar scope) the recorded reaction time for the reappearing light would be too long. It would seem that a record of "misses" might have been useful.

Inspection of Gerathewohl's data shows that a significant difference occurs with reaction time differences as small as 200 milliseconds. This difference may or may not have a practical significance, but in any case, in a situation only slightly different from the one in which it was derived, the response time values might have changed. For instance, in a panel with more lights, or more compelling distracting stimuli, the reaction times might have differed. Whether the rank order of the data would be preserved is not known.

Erdmann (20) also measured observer response to flashing lights but without measuring response time. He used a device which presented a one-second train of flashes of known waveshape (square) and frequency, against a background of known controlled luminance. His dependent variable was percent of positive responses to the flashes. The subjects were warned that a series of flashes was about to be presented by a buzzer sounding before each flash train. There were only two subjects. He found that increasing flash luminance increased the probability of detection. For low background illuminances, probability of detection increased as flash frequency increased; for higher background illuminances, 10 flashes per second was found to be the most detectable. Erdmann interpreted this in terms simply of the number of opportunities to make the detection, since the flash characteristics were the same, and explained a puzzling drop-off in detection at the higher frequencies as an effect of a period of diminishing sensitivity of the receptors due to the effect of the preceding flashes.

The sounding of a buzzer before presenting the flashes might have affected attention-getting characteristics of the flashes. Since Erdmann had used only two subjects, some of the irregularities in the curves could be artifacts.

The finding of a 10 per second rate being most detectable agrees with Bartley's (21, 22, 23) "brightness enhancement" which occurred at this flash rate. Bartley's maximal brightness enhancement occurred at about 10 flashes per second. Erdmann's findings for this frequency could have been due to the greater apparent brightness of the stimuli.

In any case, the enhancement effect would seem to be of little use in designing warning flashers, because mechanisms to produce the 10 per second rate would probably be too expensive, and would be uneconomical in terms of battery life, maintenance, etc.

Flashing Light Efficiency

In a different, but related vein, efficiency formulas have been derived, again based on the Blondel-Rey equations (2, 7), which make calculations possible of the effective lumens/watt-second, for any given type of light, if a few easily measurable physical parameters of the lights are known. These are useful in comparing one light with another in terms of cost, power supply utilization, etc. However, a light can be shown to use energy most efficiently and may be far less noticeable, or (in Gerathewohl's terms) have less conspicuity than a less efficient light. This laboratory has completed measurements of the efficiency of several miniature incandescent lamps. The results will be reported at a later time.

Proposed Experiment

Reviewing the work on flashing lights has shown that the intensity of a light flash can be equated to the intensity of a steady-burning light, but it still remains that variations in attention value of flashing lights as influenced by variations in flash rate, pulse shape, etc., or conditions above threshold, are not readily defined.

In view of this, a study was proposed which included investigating the attention value of suprathreshold lights. The lights were expected to have different flash waveforms and different flash durations. However, literature data indicated that flashes longer than 0.5 seconds added little to flash detectability (24). This was considered an approximate upper limit with the lower limit of flash duration being as short as the flash obtained from gas-discharge tubes.

A survey by the Pennsylvania State Department of Transportation in 1971 (see Introduction) showed that a majority of states use warning lights conforming to the 1971 U. S. Department of Transportation "Manual of Uniform Traffic Control Devices." The 1971 MUTCD requires a flash rate of 55 to 75 flashes per minute and an 'on' time of 8 percent for Type B high-intensity lights. Research has indicated that higher rates should be used. Gerathewohl (18) and Erdmann (20) found that at low contrast levels (where warning lights are likely to be used) increasing flash frequency resulted in increasing conspicuity and detectability. Gerathewohl also found that a 20 percent 'on' time had much more conspicuity than a 10 percent 'on' time. Strughold (25) investigated subjective feelings about flash rate. His results showed that 60 cpm was "tolerable" while 120 cpm was "unpleasant." We note that perhaps a greater attention value is linked to the flash rate inducing the "unpleasant" feeling. Furthermore, a frequency of 180 per minute produced a "very disagreeable" feeling.

Katchmar and Azrin (26) likewise discovered increasing "effectiveness" of a flashing light (strobes) with increasing frequencies up to 60 Hz, with a sharp increase in performance for 180 cpm compared to 60 cpm. Howard and Finch (27) noticed that as the flash rate of an incandescent light decreased below 50 cpm the light source began to lose its demand on attention and its "localization."

We note also that SAE Standard J590b, 1973, Automotive Turn Signals, requires a flash rate of 90 ± 30 cpm at 30 to 75 percent 'on' time. The current airline practice for anti-collision lights in the U. S. is 75 ± 10 cpm. The normal setting for railway crossing flashers is 96 cpm (two lights alternate flashing at 48 cpm).

It was considered advisable to have observers respond in some manner to the various flashing lights while the observers were performing an auxiliary task which would fix their point of regard and also maintain their attention during the interval between test stimuli (25, 26).

It was further decided that the observer's response or the dependent variable in the experiment would be the finger reaction time of the observer in response to the visual stimuli.

Jones, et al (29), noted that truck driver's finger reaction time to a visual stimulus averaged 154 milliseconds with a standard deviation of 18 milliseconds. Mean accelerator response time was 233 milliseconds ($\sigma =$ 27 milliseconds); mean braking time was 484 milliseconds ($\sigma = 27$ milliseconds). Other researchers have also noted excessive variability in measured reaction times to various stimuli, but as Gerathewohl has found, have nevertheless been able to measure significant changes in response time to different levels of stimuli. It was hoped that relative attention values of lights of different flash characteristics would significantly affect the observers' response time.

HAZARD WARNING LIGHTING

LABORATORY STUDY PROCEDURE

In the indoor laboratory study of hazard warning lighting, observers viewed six simulated warning lights on a 1:25 scale model four-lane divided and two-lane roadway intersection at grade. The intersection was a 1,000-ft scale (40-ft actual) distance from the observer and appeared to the observer as shown in Figure 4. A set of three warning lights were placed laterally across two lanes of the divided roadway, 250 (scale) ft on the near and far sides of the intersection.

During the tests, six cars (1/25 scale) were in the right hand lanes with red turn-signal indicators flashing and tail-lights and headlamps lighted.[3] Two automobiles were on the intersecting two-lane road with their headlamps illuminating the intersection at random times. Other distracting lights were a flashing yellow intersection control beacon 17 (scale) ft above the center of the two right-hand lanes, a billboard to the right (not visible in Fig. 4) which lit up for five seconds at random intervals, and a white light to the left which flashed from time to time. Random number tables resolved the flash and interflash time spans of these lights except for the intersection signal and turn signal indicators which flashed at 60 cycles per minute with a 50 percent 'on' time. Blue lamps overhead provided an equivalent moonlight illumination.

The observer sat in a simulated vehicle with a steering wheel, accelerator pedal, and illuminated speedometer (Fig. 5). Before being seated the observer was shown the six locations where a hazard warning light might appear. The observer was instructed to respond as quickly as possible to what he would consider as warning lights by pressing either one of two pushbuttons (one for the left hand, one for the right) on the steering wheel rim. The speedometer was programmed to vary speed, indicating randomly within a range of 0 to 120 mph. Instructions emphasized that the observer must maintain a speedometer reading as close to 55 mph as possible by means of the accelerator pedal provided, concurrently with his responding to the hazard warning lights.

In another room an experimenter controlled the experiment by means of the system console, dubbed a 'Data Assembler"[4] (Fig. 6), which controlled presentation of the light stimuli to the observers and recorded their

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[3] Courtesy of F. L. Marangon, Chrysler Corp.

[4] See Data Assembler User's Guide, Research Laboratory Section, Michigan Department of State Highways and Transportation, 1968, unpublished.

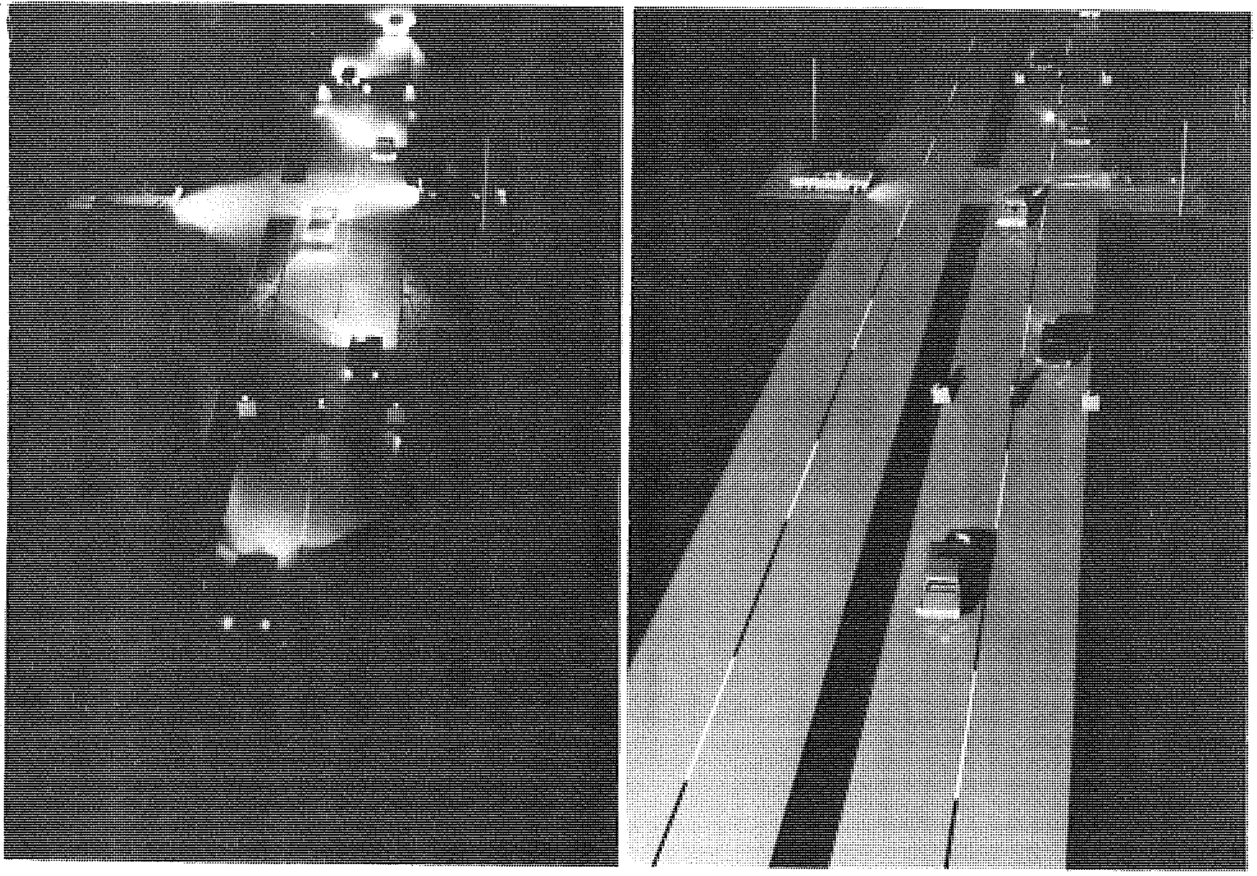


Figure 4. Roadway model as it appears to the viewer.

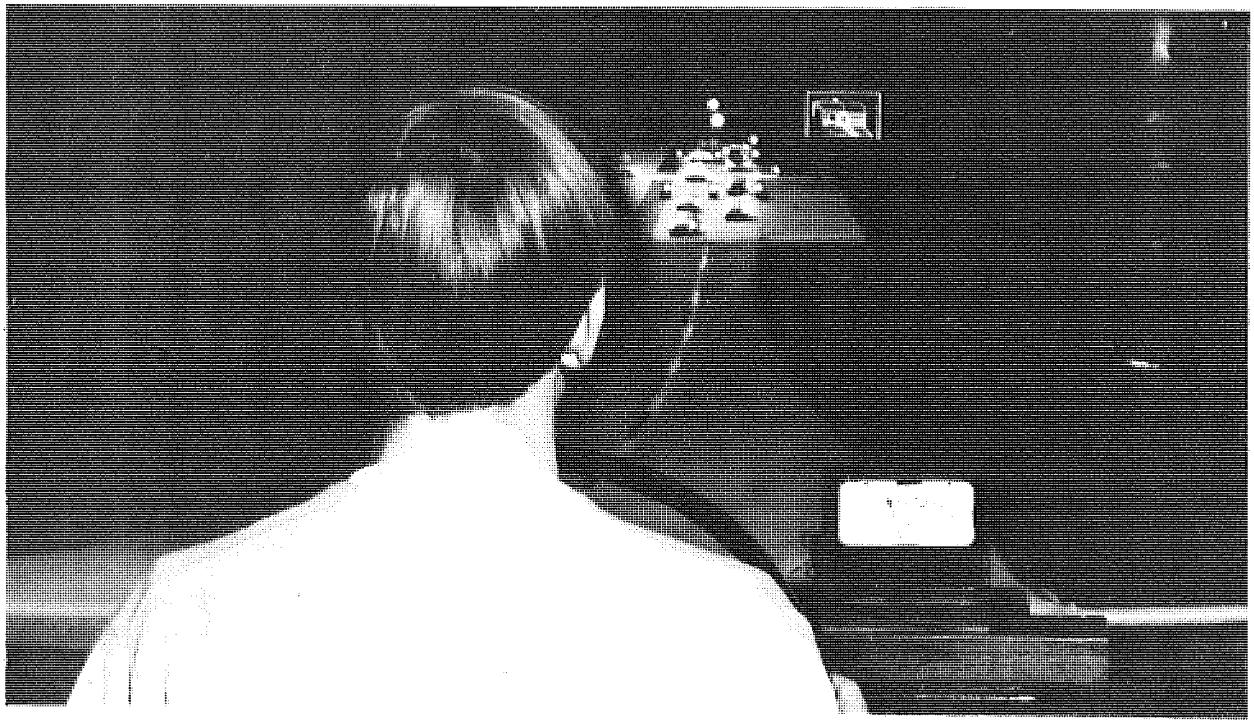


Figure 5. Simulated vehicle driver position.

responses or reaction times in tenths of milliseconds on a timer (Eput Meter Model 6146, Beckman Instruments Corp.) shown in Figure 7.

The experimenter also monitored the speedometer via a remote readout. If an observer allowed the speedometer reading to stray outside a range of 55 ± 5 mph, the experimenter cautioned the observer through an intercom. No data were recorded while these limits were exceeded.

The Data Assembler was constructed to facilitate the presentation to many observers of large numbers of variables such as those controlling the flash characteristics of the warning lights, and could be applied to almost any type of stimulus-response study involving large numbers of variables and responses.

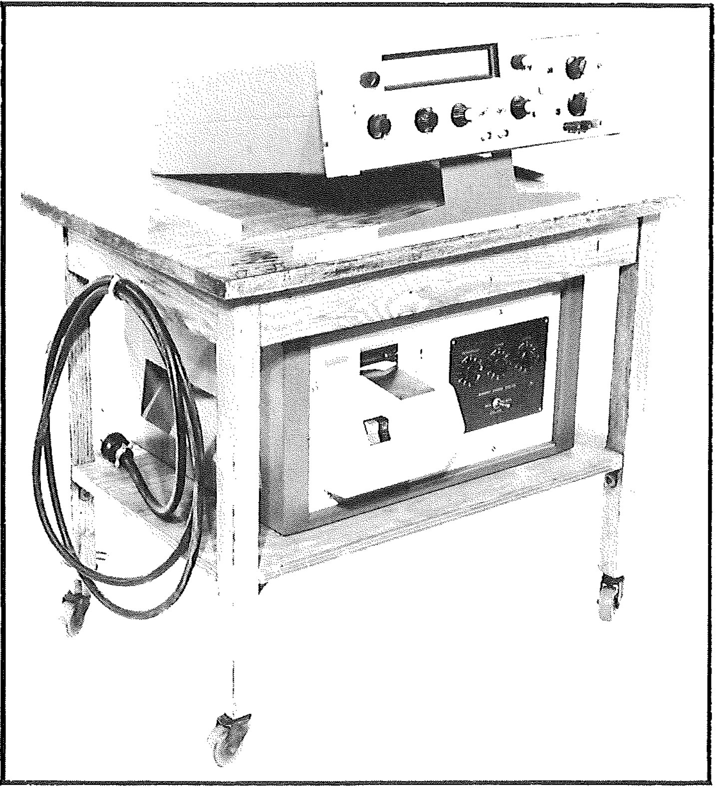
All combinations of the variables in Table 2 were presented to the observers in computer-randomized order. The flash rates and 'on' times were selected as a result of pilot studies described later in this report. In addition, steady-burning lights at the six levels of intensity were included for a total of 210 presentations to each observer over a period of approximately 50 minutes. A timer automatically limited each presentation to six seconds while the operator varied the time interval between presentations from 3 to 180 seconds, randomly. The lamps used in the warning lights were the ANSI Type 1850, selected for uniformity of intensity in a flashing mode. The lamp rated voltage was 5.0 volts. Neutral density filters, made from photographic negatives, smoothed out any remaining differences in intensity. Filters with a color conforming to the ITE yellow for vehicular traffic signal lenses corrected the color of the lights to that recommended for hazard warning lights in the "Uniform Manual of Traffic Control Devices."

Intensity, or Illuminance at the Eye of Warning Lights

The levels of illuminance at the observer's eyes listed in Table 2 were obtained by two means: distance of the warning lights from the observer, and applied lamp voltage. The three warning lights on the far side of the intersection at 1,250 (scale) ft (actual 50 ft) provided approximately 36 percent as much (as a result of the inverse square law) illuminance at the eye as the other three warning lights at 750 (scale) ft (actual 30 ft) from the observer, thus providing two levels of illuminance (abbreviated I_D) at the eye. Each of the two levels were converted into three other levels of illuminance (signified by I_V) by the application of three different potentials to the lamp; 4.5, 6.0, and 9.0 volts, or 90, 120, and 180 percent of lamp rated voltage (5.0-v), respectively. The two illuminance levels at the eye

Figure 6. Experiment controller at the system console, programming situations presented to the observer and recording observer reaction times and responses.

Figure 7. Response timer with printer.



(I_D) obtained by variation of the distance of the warning lights from the observer were treated as a different variable than the three illuminance levels (I_V) obtained through varying the lamp voltage. The two methods for obtaining different illuminance levels at the eye were treated independently in order to evaluate the significance of each with respect to the other study variables in the event that there were second or third-order interactions.

TABLE 2
RANDOMIZED VARIABLES
(Flashing Light Characteristics)

Characteristic	No. of Levels	Values
Effective Illuminance as affected by simulated distance from observer, ft	2	750.0 1,250.0
Effective Illuminance as affected by voltage, percent of lamp rated volts	3	90.0 120.0 180.0
Rate, cpm (Hz)	2	50.0(0.83) 100.0(1.67)
'On' Time, percent of cycle	17	5.0 7.5 10.0 12.5 15.0 17.5 20.0 25.0 30.0 40.0 50.0 60.0 70.0 75.0 80.0 85.0 90.0

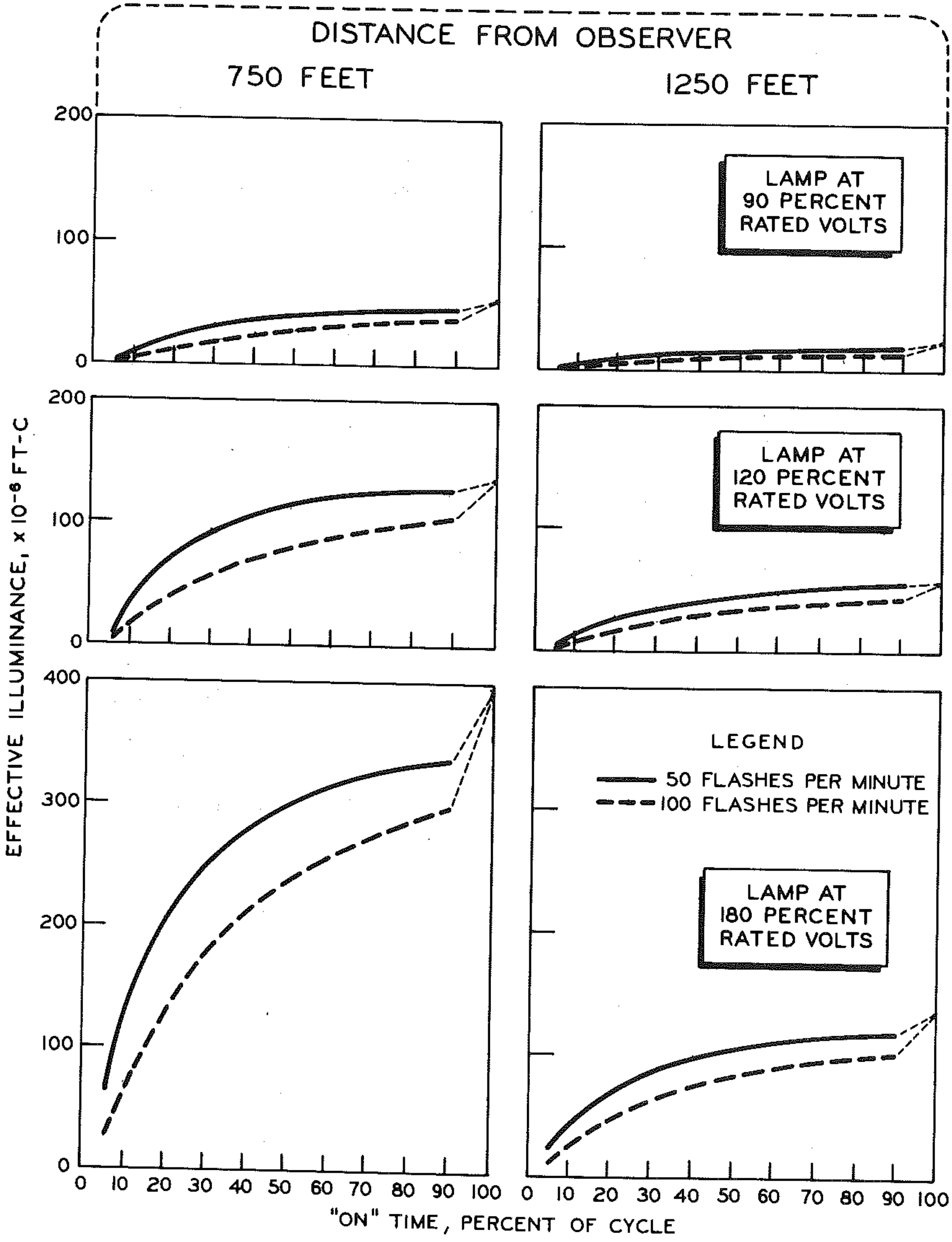


Figure 8. Effective illuminance of warning lights.

Observers

Average visual acuity of the observers as measured with a Bausch and Lomb Orthorator, was 10 -- equivalent to 20/20 Snellen acuity. No observer had less than 20/23 Snellen acuity. Any refractive errors were adequately corrected with glasses or contact lenses.

The observers were Michigan Department of State Highways and Transportation employees and retirees. There were 24 observers with ages ranging from 20 to 76 years. In order to evaluate the effect of age, the observers were divided into six age groups: Group I - 20 to 25 years; Group II - 26 to 35 years; Group III - 36 to 45 years; Group IV - 46 to 55 years; Group V - 56 to 65 years; and Group VI - 66 to 76 years. The average acuity of each age group was approximately 20/20 (with eyeglasses, if normally used for driving).

None of the observers were color blind, had uncorrected astigmatism, or poor depth perception, as tested by the Orthorator. With the exception of the youngest age group, the observers had been driving vehicles for over 10 years; in the youngest group, all had been driving over five years. All of the observers drove an average of at least 10,000 miles per year, except one observer who drove 5,000 miles.

The visual angle subtended at the observer's eye by each simulated flashing warning light was about a 1.7 minute solid angle, or approximately the same as a 6-in. diameter warning light at 1,000 ft. The visual angles subtended by other flashing lights in the field of view were all proportional to the angle that their true size would subtend at 1,000 ft. The depression angle of the warning lights from a horizontal plane at the observer's eyes was 1° 35' and 2° 15' for the far and near sets of three lights, respectively.

The angular separations between the barricade lights horizontally and vertically were each 40' of arc. The total angular width of the three warning lights in each row was 1° 20' so that all six lamps could be viewed from the observer's position within the foveal region of the eye.

The greatest vertical angular separation of the vehicle turn signal indicators was 47' of arc from the center of each set of three warning lights; the flashing billboard was 1 to the right of the center of each set of three warning lights. The angle between the observer's line of sight to the warning light and the observer's line of sight to the speedometer was 15°.

The graphs in Figure 8 give the average effective illuminance at the eye of the flashing warning lights. The effective illuminances at the eye of the distraction lights in the field of view are given in Table 3.

TABLE 3
EFFECTIVE ILLUMINANCE AT THE EYE
OF DISTRACTION LIGHTS AT 1,000 ft

Light	Effective Illuminance, ft-c
Intersection beacon (yellow)	256.0×10^{-6}
Vehicle turn signal indicators (red)	3.0×10^{-6}
Vehicle tail-light (red)	4.6×10^{-6}

Glare, or disability veiling brightness at the observer's eye when looking at a warning light averaged 0.002 ft-L including all distraction lights and the light from the speedometer face. A Pritchard telephotometer with the disability glare lens attachment was used to measure glare (30).

The "moonlight" lamps provided about 0.001 ft-L of roadway surface brightness. The automobile headlamps and other distraction lights raised the average background brightness of the warning lights to approximately 0.01 ft-L.

Eventhough the constant level of background illumination was considerably higher than threshold, it was decided to adapt the observers to the field luminance for 10 minutes.

All tests were run with a background of white noise (simulating engine and road noise) well above the level required to mask clicks from microswitches controlling the distraction lights, and to cover sounds emanating from other rooms.

Pilot Studies

Several pilot studies on observer reaction time to the flashing warning lights were conducted prior to the main study. One study with five observers investigated six dwells, between 5 and 95 percent of cycle. It was learned that the greatest change in response time occurred at 'on' times between 5 and 25 percent of cycle. The final study, therefore, included several additional 'on' times between 5 and 25 percent. Another study showed little difference in response time between rates of 50 cpm and 70 cpm, so 70 cpm was dropped from the final study. In this study it was also found that many ANSI 1950 lamps would not flash because of filament thermal inertia at 120 cpm or greater except when 180 percent over-voltage was applied to the lamp. Still another five-observer study showed that if all combinations of variables were repeated for each of the six warning light positions, the results were statistically the same regardless of position. Thus in the main experiment each unique combination of flash characteristics appears at only one position for each observer. That study also included two identical experiments of 25 minutes each. Since the results of the second replicate were the same as the first, it was judged that extension of the experiment to 50 minutes would not unduly fatigue the observers.

In another repetition of the experiment, eight observers were used. For this experiment, the background flashing lights were maintained at a rate of 100 flashes per minute rather than 60 flashes per minute as in the main experiment. The results of this experiment indicated that the flash frequency of the background distraction lights had little effect on the study results.

Measurement of Effective Intensity

The apparatus pictured in Figure 9 measured the instantaneous light output of, and current to, a flashing lamp. The photometer was a Pritchard Telephotometer (Photo Research Corporation). A photocell with a Viscor filter was later substituted. A Honeywell oscillograph (Model 906c) with 3,000 Hz galvanometers simultaneously recorded waveforms of the light output and of the current to the lamp. Amplification of the phototube signal and of the lamp current to the levels suitable for the oscillograph was accomplished by a Honeywell Accudate Model 104 amplifier and an Astrodata Model 885 amplifier. For calibration of the oscillograph traces, a Leeds and Northrup Model 7553-6 Type K-3 potentiometer was used to measure the voltage output of the photometer and, with a Leeds and Northrup precision shunt, to measure the current used by the lamp burning steadily. From results as obtained above, the effective intensity was computed according to Douglas (9).

ANALYSIS OF VARIANCE

Reaction times in 0.1 milliseconds were recorded for each combination of experimental conditions and an analysis of variance was carried out.

Table 4 gives the analysis of variance in abbreviated form. Besides the degree of freedom and mean square for each main effect of interaction, the appropriate degrees of freedom, the mean square for error, and the

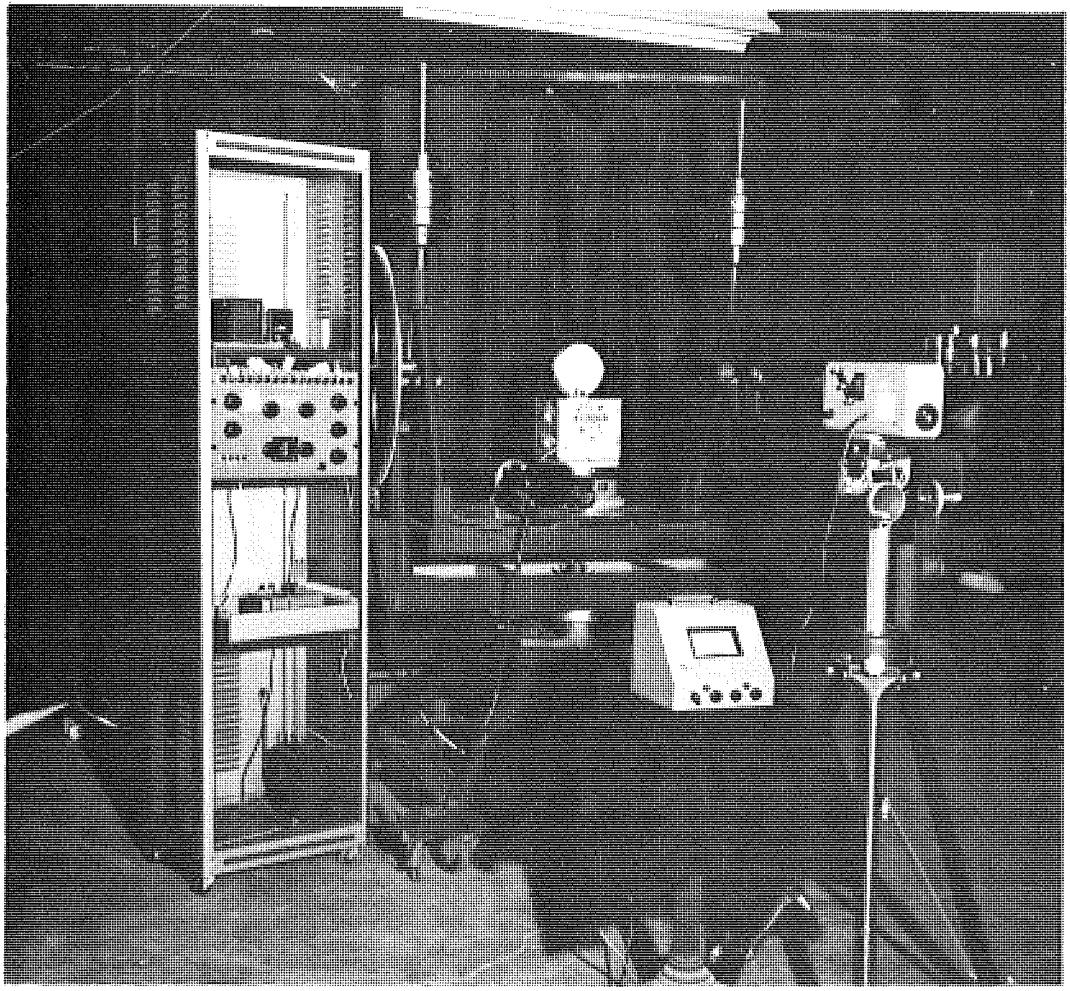


Figure 9. Apparatus for measuring the instantaneous light output of, and current to, a flashing lamp.

contribution to total variance by each variable are also listed. Those results which are significant at the 0.001 level carry the expectation that approximately 99.9 percent of the means would fall within the same limits if the experiment were repeated.

Note that, as anticipated, the reaction time results were "noisy." The variance due to error within and between observers was 56 percent of the total variance. Nevertheless, as Table 5 shows, there were several very significant effects.

TABLE 4
ANALYSIS OF VARIANCE

Experimental Factor	Degrees of Freedom	Mean Square	Variance due to Experimental Factor, percent	F-Ratio
A (Age)	5	4,687	10.4	76.0[1]
I_D (Illuminance, distance)	1	472	0.2	7.7[2]
I_D x A	5	39	0.0	0.6
I_V (Illuminance, voltage)	2	8,307	4.7	36.1[1]
I_V x A	10	185	0.5	3.3[2]
I_V x I_D	2	25	0.0	0.4
I_V x I_D x A	10	33	0.0	0.5
R (Rate)	1	1,158	0.4	19.0[1]
R x A	5	61	0.0	1.0
R x I_D	1	103	0.1	3.3
R x I_D x A	5	30	0.0	0.5
R x I_V	2	811	0.8	13.3[1]
R x I_V x A	10	106	0.3	1.7
R x I_V x I_D	2	14	0.0	0.2
R x I_V x I_D x A	10	35	0.0	0.6
O ('On' Time)	16	1,826	5.6	29.9[1]
O x A	80	123	1.2	2.0[2]
O x I_D	16	44	0.0	0.7
O x I_D x A	80	46	0.0	0.8
O x I_V	32	1,278	11.7	20.9[1]
O x I_V x A	160	60	0.0	1.0
O x I_V x I_D	32	55	0.0	0.9
O x I_V x I_D x A	160	55	0.0	0.9
O x R	16	702	4.1	11.5[1]
O x R x A	80	43	0.0	0.7
O x R x I_D	16	59	0.0	1.0
O x R x I_D x A	80	41	0.0	0.6
O x R x I_V	32	294	4.2	4.8[2]
O x R x I_V x A	160	45	0.0	0.7
O x R x I_V x I_D	32	36	0.0	0.6
O x R x I_V x I_D x A	160	40	0.0	0.7
σ^2	1,223	61	56.0	0.0

[1] Indicates statistical significance at the 0.001 level.

[2] Indicates statistical significance at the 0.01 level.

TABLE 5

MOST SIGNIFICANT EXPERIMENTAL FACTORS

Experimental Factor	Variance due to Experimental Factor, percent	Significance
A (Age)	10.4	0.001
O ('On' Time)	5.6	0.001
I_V (Illuminance, voltage)	4.7	0.001
R (Rate)	0.4	0.001
I_D (Illuminance, distance)	0.2	0.010
O x I_V	11.7	0.001
O x R	4.1	0.001
O x A	1.2	0.001
I_V x R	0.8	0.001
I_V x A	0.5	0.010
O x I_V x R	4.2	0.001

HAZARD WARNING LIGHTS
RESULTS AND CONCLUSIONS

'On' Time-Rate-Illuminance (I_V)

Figures 10, 11, and 12 show the effect on reaction time of 17 levels of 'on' times, two rates, and the three levels of illuminance, I_V (as affected by lamp voltage) at the observer's eyes from the warning lights. Since there were no interactions of illuminance levels, I_D, (as affected by distance of the warning lights from the observers) with any of the other variables, the two levels of I_D were averaged for all data.

Note first that a flashing light resulted in generally faster responses than did a steady-burning light (Figs. 10, 11, and 12); this in spite of the fact that a steady-burning light had much greater illuminance (Fig. 8). The reaction time at very short or long 'on' times, though, was slower than for a steady-burning light.

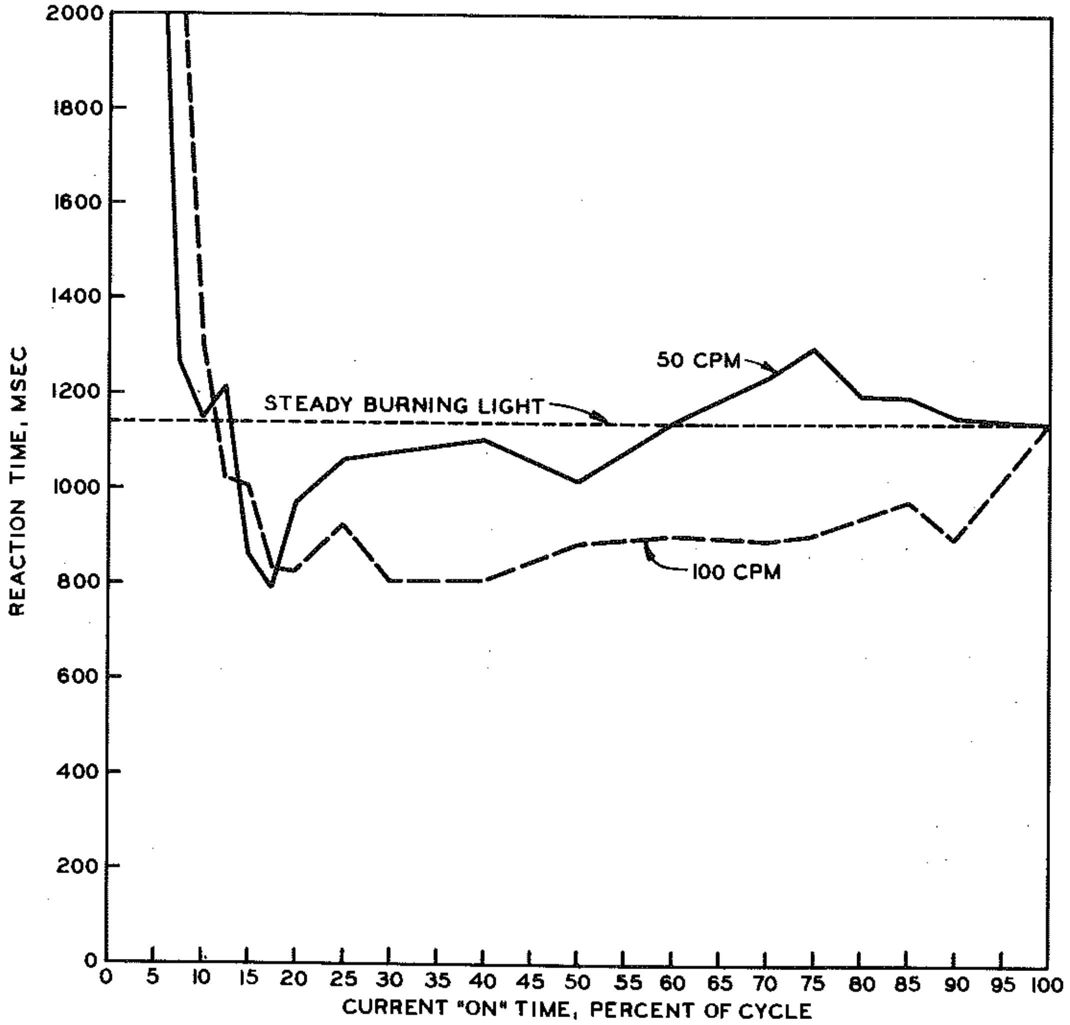


Figure 10. Effect of 'on' time and rate with lamp at 90 percent of rated lamp voltage.

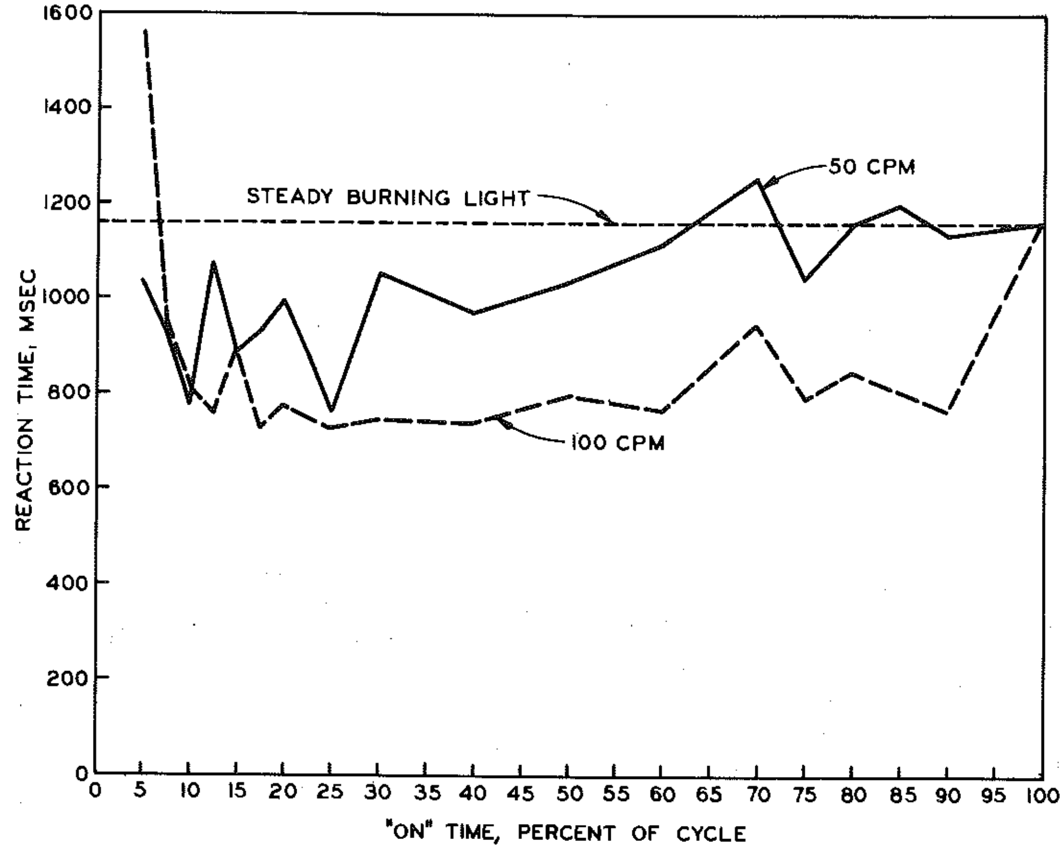


Figure 11. Effect of 'on' time and rate with lamp at 120 percent of rated lamp voltage.

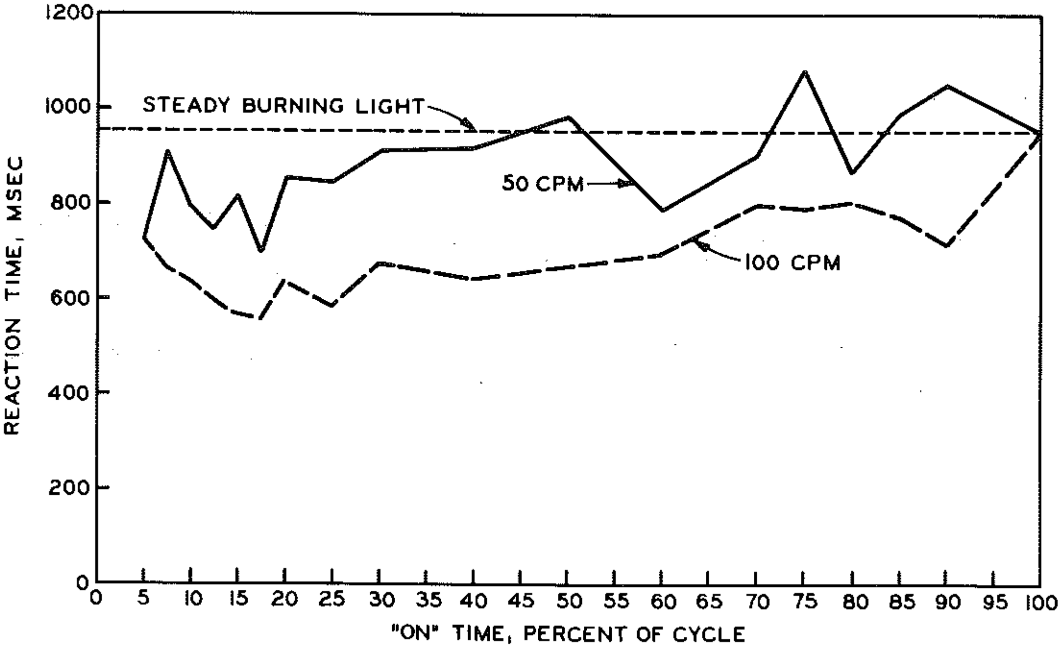


Figure 12. Effect of 'on' time and rate with lamp at 180 percent of rated lamp voltage.

It appears that the shortest reaction times were associated with 'on' times from approximately 15 percent to no more than 25 or 30 percent for the illuminances resulting from the three lamp voltages. For the purpose of conserving battery energy an 'on' time between 17.5 and 20 percent is near optimum. And, since there is some degradation of 'on' time with aging of lamp and battery, the 'on' time should be a minimum of 20 percent. Figure 13 shows the response time for all 'on' times for each rate averaged across the illuminances.

A possible explanation for the fact that the optimum 'on' time was 20 percent, whereas longer 'on' times associated with much greater effective illuminances (Fig. 8) resulted in longer reaction times, might be a retinal backward inhibitory effect hypothesized by some researchers (31, 32, 33) where the latter segments of longer flash durations reactively inhibits the magnitude of the sensory effect in the eye of the onset and earlier portions of the flash.

The shortest response times for all 'on' times and rates occurred at the illuminances produced by the warning light at 180 percent lamp rated voltage (9.0 v) (Fig. 12). Figure 12 seems to indicate that if the voltage is high enough, i.e., 180 percent of rated, there is a steadily decreasing reaction time with decreasing 'on' times to as low as perhaps 10 percent. There was no appreciable difference in results between illuminances at 90 and 120 percent rated lamp volts except at 'on' times below 20 percent. Although it appears that for illuminances at 180 percent lamp voltage, the shorter the 'on' time the shorter the response time, a 15 to 25 percent 'on' time at 100 cpm would give the shortest all-around reaction time for all three lamp voltages. Note that the 'on' times discussed in this report are electrical 'on' times, i.e., the percent of flash cycle that current flowed through the lamp filament. The actual 'on' times of the flash were slightly less than the electrical 'on' times for the 4.5 and 6.0 lamp voltages. The light 'on' times were equivalent or slightly greater than the electrical 'on' times at 9.0 v because of a more protracted nigrescence.

Rate

It is apparent from Figures 10, 11, and 12 that a rate of 100 flashes per minute was superior to a rate of 50 flashes per minute. Figure 14 shows that there was a reduction of approximately 100 flashes per minute compared to 50 flashes per minute averaged across all 'on' times. For a recommended 'on' time of 20 percent the improvement in reaction time for a 100 cpm rate over a 50 cpm rate was approximately 200 milliseconds (Figs. 10, 11, and 12).

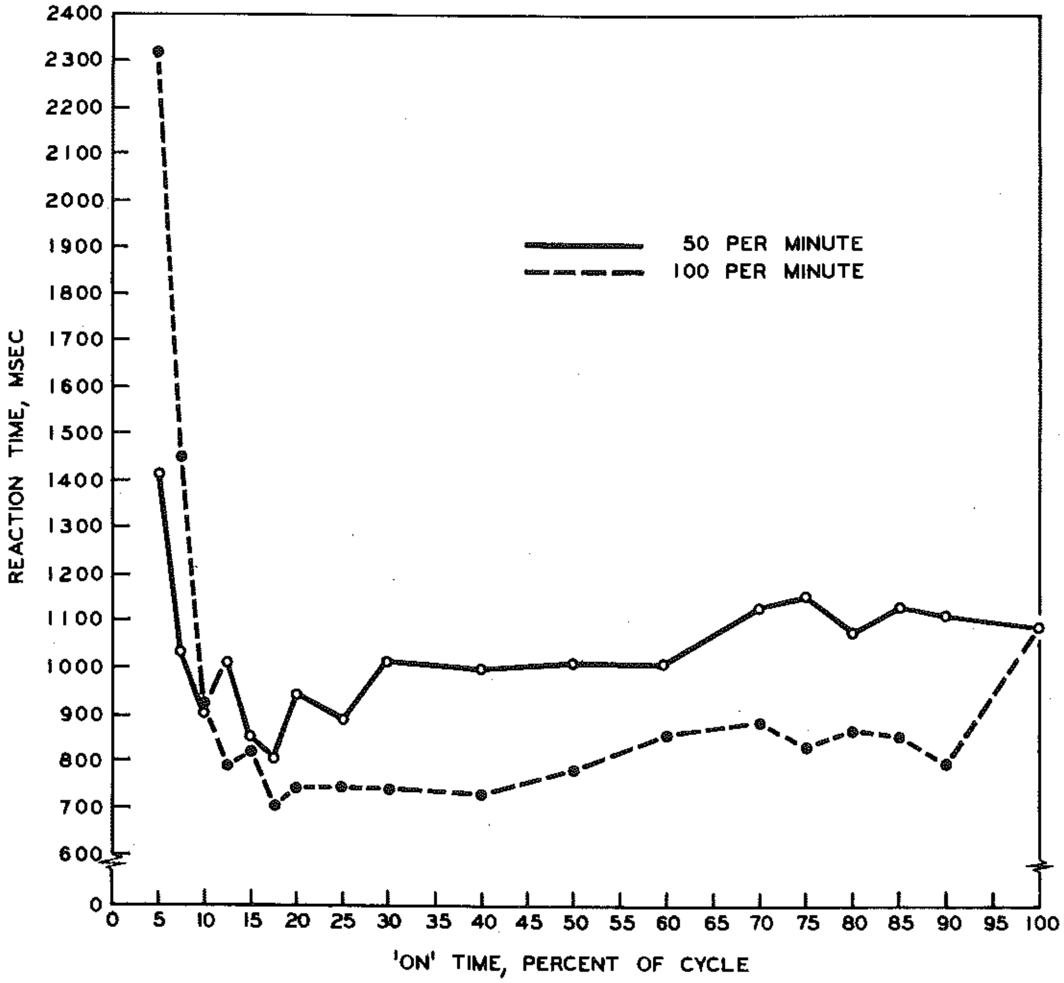


Figure 13. Reaction time vs. 'on' time (24 observers).

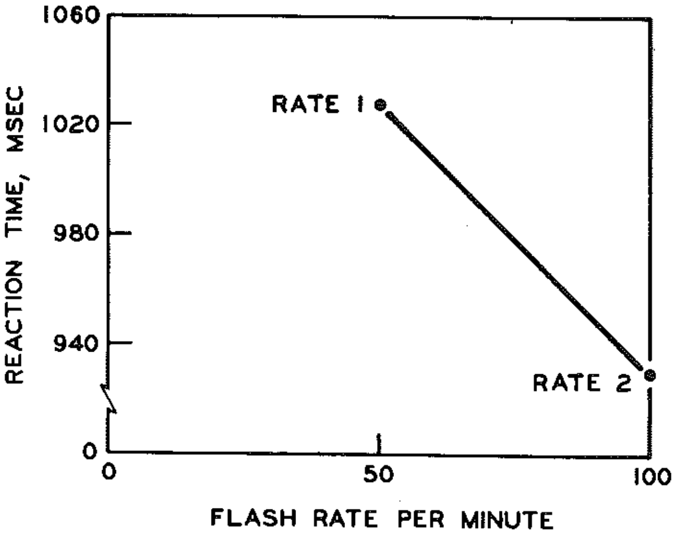


Figure 14. Flash rate: 100 flashes per minute compared to 50 flashes per minute, averaged across all 'on' times.

The reaction of the 20 percent 'on' time, 100 flashes per minute light was over 300 milliseconds faster than the reaction to a steady-burning light (Figs. 10, 11, and 12). Therefore, a warning light should flash at an approximate rate of 100 cpm and an 'on' time of 20 percent.

Analysis of variance determined that the light with recommended flashing characteristics (100 cpm, 20 percent 'on' time) was significantly different at the 0.001 level in reaction time from a steady-burning light, regardless of the illuminance.

A rate of 50 cycles per minute at a lamp potential of 90 percent rated lamp volts resulted in a faster response time than for 100 flashes per minute below 20 percent 'on' time. This effect might be due to the much greater effective intensity of the flashes at 50 cpm for shorter 'on' times.

Illuminance (I_V) at the Eye, by Lamp Voltage Change

Table 5 showed that I_V interacted with 'on' time, rate, and age, and with 'on' time and rate simultaneously. These interactions were probably caused by the effect on illuminance by 'on' time and flash rate (Fig. 8) and on age by illuminance.

From Figures 10, 11, and 12, for the warning light with the recommended 'on' time and flash rate of 20 percent and 100 per minute, the decrease in reaction time from a change in the potential applied to the lamp from 90 to 180 percent of lamp rated voltage was approximately 200 milliseconds. This effect was probably produced by the approximately thirteenfold increase in effective illuminance with an increase in lamp potential from 4.5 to 9.0 v. This large change in effective luminance (I_V) caused by alteration of the lamp voltage did not affect response time as much as did the fact that the light was flashing rather than burning steadily (see above). It was noted that the lamp life was very short at 180 percent applied voltage.

Illuminance (I_D) at the Eye, by Distance of Warning Light from Observer

The effect on response time of an approximate threefold increase in effective luminance at the eye equivalent to moving a warning light from 1,250 to 750 ft (the simulated distances in this study) from the observers eye while significant at the 0.01 level, was relatively small, about a 60 millisecond drop (Fig. 15).

An important result here was that the lack of any second-order interactions of illuminance (I_D) (Table 5) meant that illuminance (I_D) did not in-

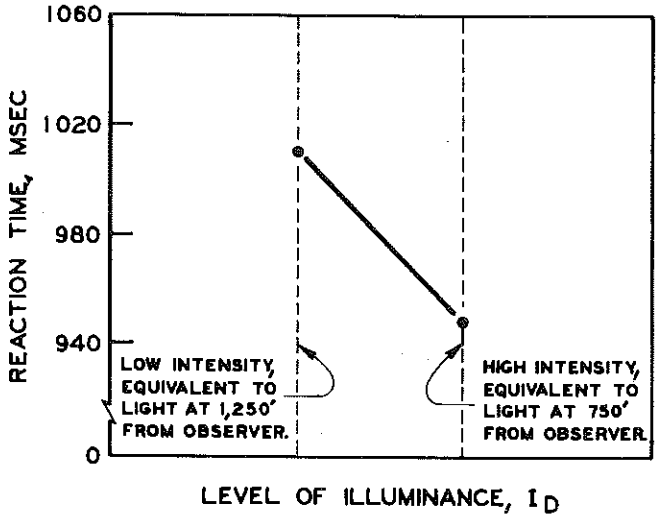


Figure 15. Illuminance, I_D.

teract significantly with 'on' time, rate, or illuminance (voltage), I_V. This indicated that for the range of illuminances at the eye used in the experiment, recommendations concerning 'on' time and rate would not be affected by the distance of the light from the driver's eyes under these conditions.

In general, effective illuminance, either I_V or I_D, had a moderate effect on observer's response time. A greater than one log level change in I_V changed response time by less than 200 milliseconds. Therefore, any recommendations for a minimum effective intensity for adequate warning at, say 1,000 ft, would be very general. Figure 16 shows the illuminance of all the 100 flash per minute warning lights observed under the laboratory test conditions versus response time. The illuminances for each lamp voltage show as distinct curves which separate at points roughly between 20 x 10^{-6} and 40 x 10^{-6} ft-c. Response time rises abruptly below this range. This range lies at approximately 670 to 770 milliseconds response time. As the illuminance from the light at 180 percent over voltage (9.0 v) increased above 40 x 10^{-6} ft-c there was a corresponding small decrease in response time down to a minimum of about 600 milliseconds near 120 x 10^{-6} ft-c.

Therefore, it is recommended that a minimum illuminance at the eye within the range of 20 to 40 x 10^{-6} ft-c be produced for a near minimum response time.

Since most of the observers in this study were responding to the onset of the second flash, or perhaps the cessation of the first flash, it appears

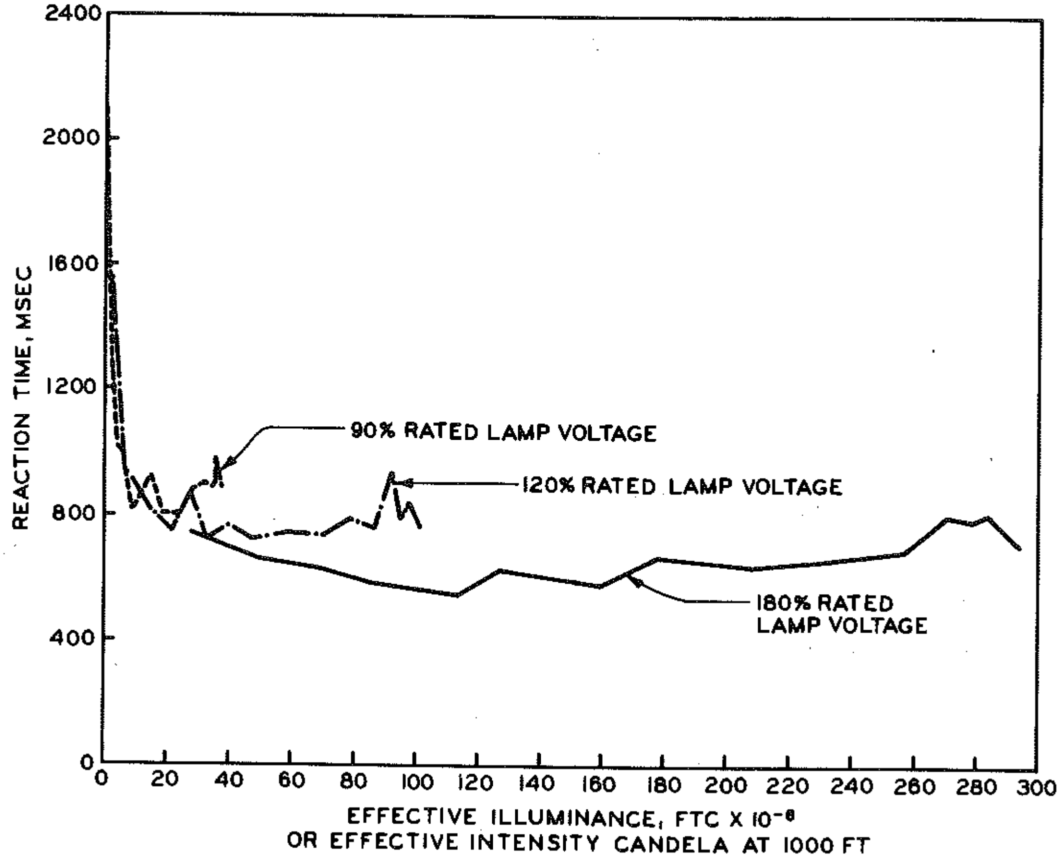


Figure 16. Illuminance of all 100 flash per minute warning lights vs. response times.

likely that response times could be reduced further with a higher intensity light. However, an intensity necessary to obtain predominant response to the first flash may not be suitable for roadway application. A reasonable minimum range for effective intensity might be 20 to 40 candela at 1,000 ft with the light operating at a minimum 20 percent 'on' time and at 100 flashes per minute.

Age

The effect of age on reaction time is well known, and was borne out in this experiment by the fact that it contributed to more than 10 percent of the variance, and by the steadily rising reaction times with age, except for the youngest age group (22 to 25 years) which contained one individual with extremely low overall reaction time. Figure 17 shows the vast difference in response time between age Group II (26 to 35 years) and age Group VI (66 to 76 years) amounting to about 700 milliseconds at 20 percent 'on' time.

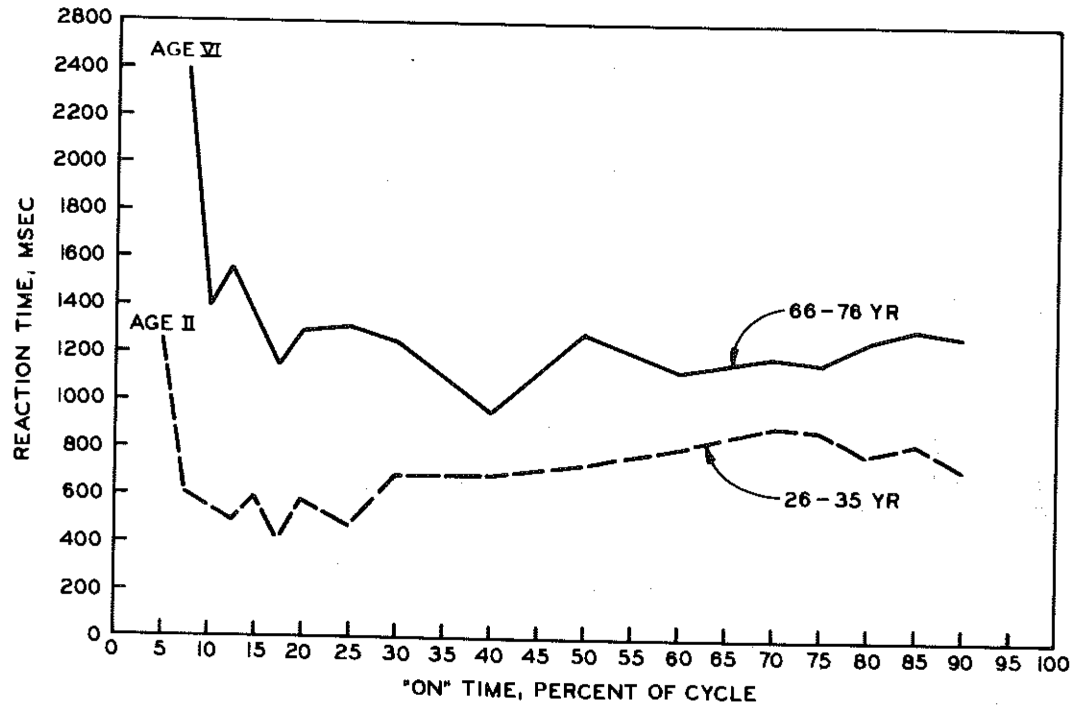


Figure 17. Response time: age group VI vs. age group II.

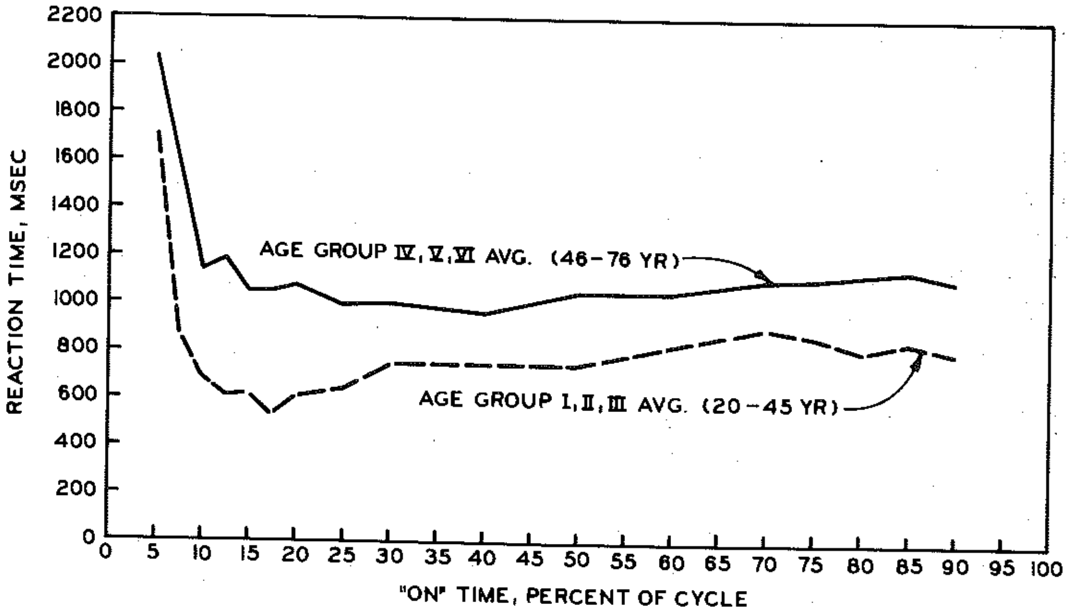


Figure 18. Response time: 20 to 45 year old group vs. 46 to 75 year old group.

The interactions of age with other variables was interesting. There was an insignificant difference in reaction times to the two flash rates; however, the effect of age on reaction time results due to 'on' time was highly significant. While the reaction time of 22 to 45 year olds decreased very little from the longest warning light 'on' times down to perhaps 10 percent (Fig. 18), 46 to 76 year olds required a longer 'on' time -- at least 20 percent -- for a near minimum response time.

The effect of age on effective illuminance changes due to voltage changes (I_V) was small. Lower applied lamp voltage tended to lengthen response time more drastically for older persons than for the young (Fig. 19). Therefore, it would be advisable to not let the lamp voltage fall below 120 percent rated. To do so might seriously slow response time for older persons. For most of the age groups applied lamp voltage of 180 percent rated was little more benefit than 120 percent rated.

Again, note that the illuminance levels, I_D, did not interact with the variable of age. In other words, the above results concerning age would apply regardless of distance of the warning light from the observer, at least within the range of illuminance, I_D, evaluated.

Figure 20 shows the number of misses, or observer failures to respond to a flashing light, versus age. The majority of flashing lights missed had 'on' times between 5 and 10 percent with the lamp at 4.5 v, a further indication that the lamp should be operated above rated voltage and at 'on' times greater than 10 percent.

Even high-intensity flashing lights may be little help in reducing accidents. A study by Janson and Smith, showed that of the 24 most frequent accident intersections in Michigan which were flasher protected, 60 percent had traffic signal flashing lights with above standard intensity. Upon closer examination, many of the intersections were found to contain potential accident-causing factors such as blind corners and obstacles.

HAZARD WARNING LIGHTING FIELD PHASE

In the outdoor hazard warning field phase, 6-v and 12-v hazard warning lights with various flash-rate and 'on' time characteristics were compared by observers in moving vehicles. A comparison of 6-v vs. 12-v hazard warning lights was also included in this phase to study the effect on drivers of the flash characteristics of the higher intensity lights.

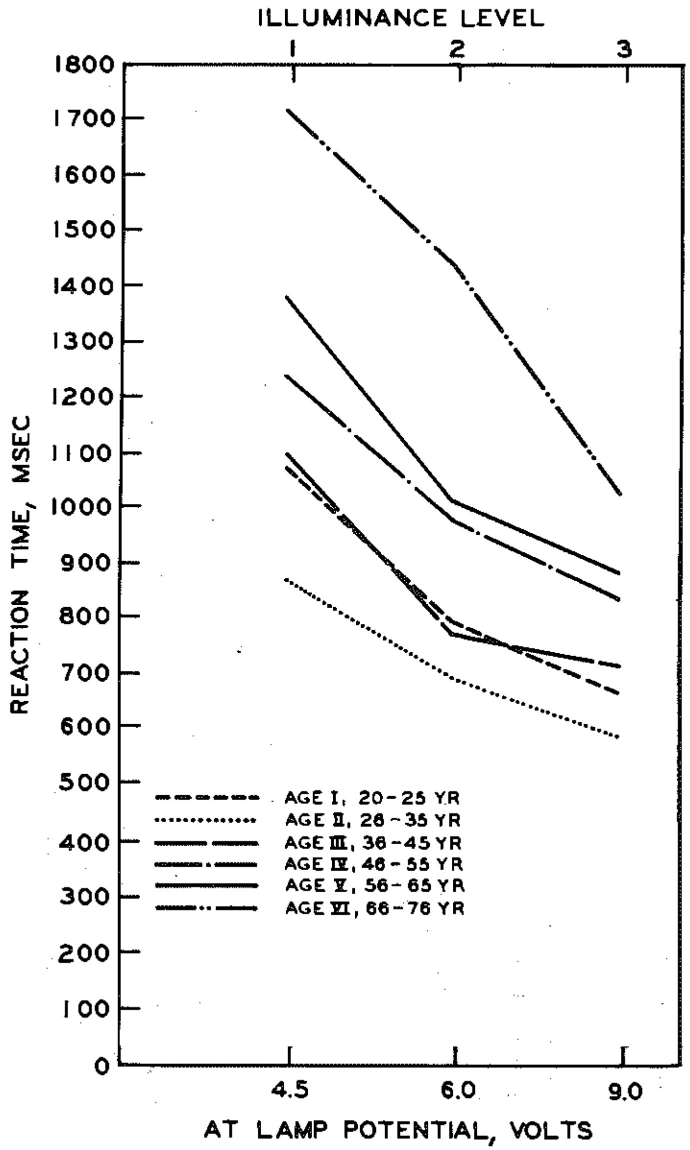
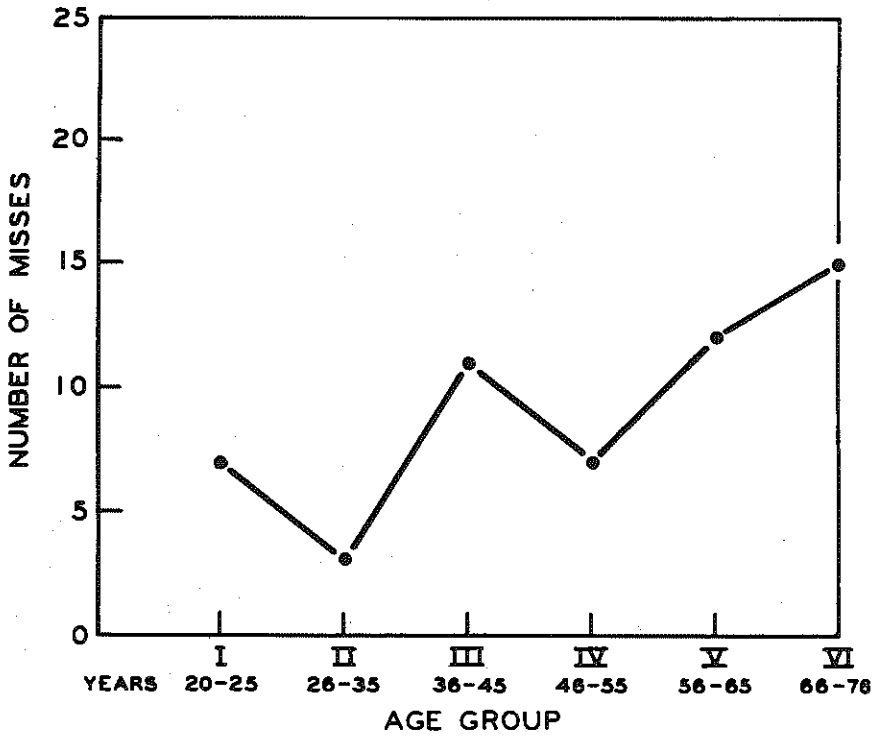


Figure 19. Effective illuminance (I_V) vs. age.

Figure 20. Observers' failure to respond to a flashing light, by age.



The test was designed to force an observer choice in a very short time interval in order to obtain "first impression" preferences. The personal preference method of evaluation was known to have undesirable limitations but other simple and rapid methods of obtaining meaningful observer responses were not practical at this time.

Twenty observers were used in the study. Ten of the observers served as drivers and the remaining ten were passenger-observers. Passenger-observers were necessary to complete the test in one night. Drivers were selected from the Research Laboratory to permit convenient briefing prior to the test concerning driving speed, test route, and coordination between observer cars. All the observers were licensed drivers, and represented various offices and divisions of the Department; i.e., Maintenance, Construction, Traffic and Safety, and the Research Laboratory. Eleven of the observers were in a 30 to 50 year age group and five of the observers ranged in age from 50 to 70 years. The other four observers were less than 30 years of age.

The hazard warning lights were mounted on commercial barricades with the barricades placed parallel to the direction of traffic to eliminate effects of barricade reflective markings. Observer vehicles passed between two paired sets of barricades at each site.

Each pair were separated approximately 3 ft laterally with respect to traffic flow, and an approximate 12-ft spacing was allowed for vehicle passage between each paired set. One light was mounted on each barricade and the lights on a given pair were of the same type. Similar paired sets of barricades were located at three test sites in the area as shown in Figure 21. Figure 21 also shows the delineation lighting test site described later.

Ten types of battery-operated hazard warning lights were used in the test as shown in Table 6.

Each 12-v light was compared directly but in random sequence with each 6-v light for a total of 24 combinations, and each type of 12-v light was compared in random sequence with the other 12-v lights for another six combinations.

Drivers were instructed to proceed through the three test sites at 35 to 40 mph at each site. Sufficient interval was maintained between vehicles to avoid observer distraction from preceding tail-lights. The observers were instructed to indicate their preference for the warning light pair at

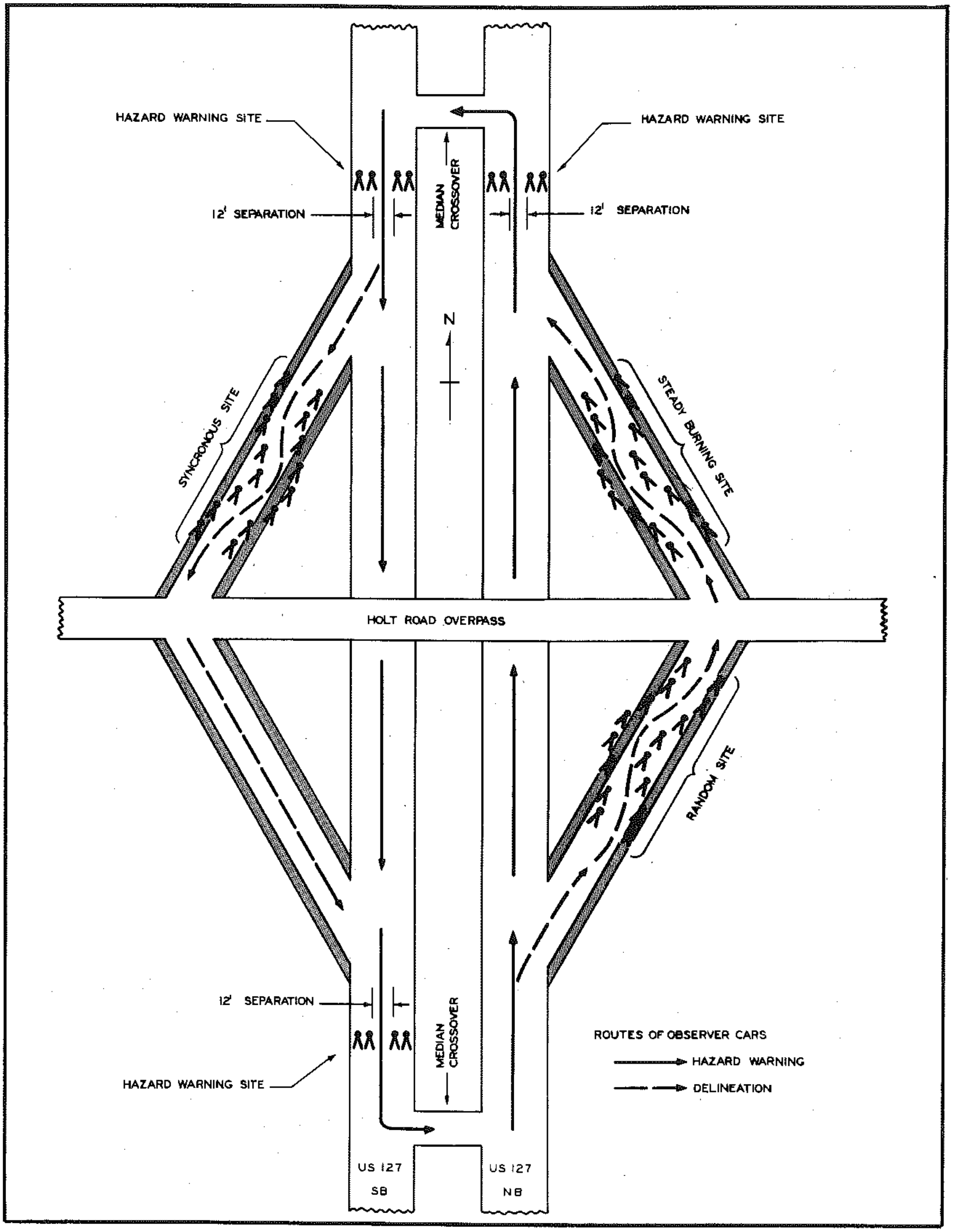


Figure 21. Hazard warning and delineation field test sites.

TABLE 6
TYPES OF BATTERY-OPERATED HAZARD WARNING LIGHTS

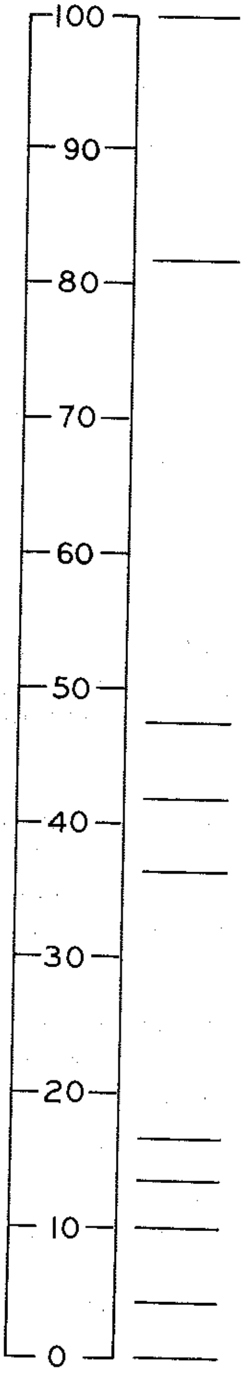
Voltage	Flash Rate, flashes per minute	'On' Time, percent
6	60	10
6	60	25
6	60	50
6	100	10
6	100	25
6	100	50
12	60	10
12	60	25
12	100	10
12	100	25

each site that would give the better warning of a serious road hazard. First impressions were desired and therefore observers simply marked their choice in the left or right column of a data sheet corresponding with the chosen left or right pair of lights.

The test area was in total darkness except for the headlights on the observer cars. Visibility was not affected by haze and there were no distractions from traffic. Data sheets were taken from the observers following the 24 comparisons between 6 and 12-v lights and new data sheets were used for the 12-v light comparisons.

Figure 22 illustrates the relative ranking of all the warning lights in the field study based on a modification of the Thurstone pair comparison method (5) and explained in more detail in the Laboratory Study Section and in the Appendix regarding the delineation study.

In general the observer data showed that flash energy was not the only factor affecting observer preferences. Flash rate was a significant factor as well as the peak intensity of the light. For purposes of this report, peak intensity can be considered as the maximum intensity or candlepower that a light will achieve during a flash cycle, and flash energy the product of the average intensity during a flash and the flash duration.



Arbitrary Thurstone Scale	Rank	Warning Light Characteristics		
		Voltage	Rate in Flashes Per Minute	'On' Time in Percent
100.00	1	12	100	25
81.73	2	12	60	25
47.21	3	6	100	50
41.83	4	12	100	10
36.35	5	6	60	50
16.54	6	6	100	25
13.46	7	6	100	10
10.00	8	12	60	10
4.60	9	6	60	25
0.00	10	6	60	10

Figure 22. Relative ranking of field warning lights.

Observer data were examined by means of a graph showing the ratio of flash energies as calculated from each warning light comparison, versus the percentage of observer choices for the pair of warning lights with the higher energy. This presentation of the data was expected to show that small differences in flash energy between flashers would result in an equal number of observer choices for each pair of flashers, and as the energy difference increased the observer choices would approach a 100-percent choice for the warning light pair with the highest flash energy. The observer choices, however, ranged from 55 to 100 percent when the flash energies were equal and from 55 to 90 percent when the ratio between flash energies was greater than 6 to 1. From this it was concluded that flash energy was not the only factor which controlled observer choices and therefore the data were examined in detail for the effects of other factors. Those factors which characterize flashing lights were defined and observer data were tabulated on the basis of each factor and combinations of these factors. The defined factors were:

1) Flash Energy, i.e., the product of the flash duration in seconds and the average intensity of the flash.

2) Peak Intensity, i.e., the maximum intensity or candlepower achieved by a light during a flash cycle. Peak intensity of warning lights in this test was much greater for 12-v flashers than for 6-v flashers.

3) Flash Rate, i.e., the number of flashes per minute. Two flash rates were used in this test: 60 and 100.

4) Dwell or Percent 'On' Time, i.e., the percentage of time that a light is 'on' during one complete 'on and off' cycle. Three dwells were used in this test: 10, 25, and 50 percent.

5) Flash Duration, i.e., the time in seconds that a light is 'on' during each cycle.

The percentage of choices based on the total possible choices was calculated and tabulated for the factors and combinations of factors listed above. For example, each comparison having a pair of warning lights with a higher flash energy and higher flash rate than the other pair was considered a possible choice and therefore was tabulated for each observer. In the test there was a total of 120 possible choices involving this energy and rate combination of factors; 99 choices or 82.5 percent of the possible choices favored the higher energy and higher flash rate combination. Table 7 shows the percentage of choices for some of the factors.

TABLE 7
OBSERVER PREFERENCES - FACTORS

Factors	Percent Favorable Choices	Possible Choices
Peak Intensity	70.2	480
Flash Energy	61.4	580
Flash Rate	60.3	320
'On' Time	55.8	400
Duration	51.1	520
Flash Energy and Flash Rate	82.5	120
Peak Intensity and Flash Rate	80.0	120
Peak Intensity and 'On' Time	77.5	80
Flash Energy and Peak Intensity	72.2	360
Flash Energy and 'On' Time	63.3	180

The table gives the percentage of choices which favored the factor or combination of factors with the greater value, i.e., longer 'on' time, higher rate, higher intensity, etc. The chi-squared statistical test was applied to this tabulation of data and the calculation showed that all of the comparisons were significant at the 95 percent level. This means that the observed deviations from 50 percent are considered real and not due to chance alone. This is true for both individual comparisons as well as the experiment as a whole. Peak intensity appears to be the most important single factor affecting observer choices but the factor was not strong enough to influence more than seven out of ten choices. The higher flash rate along with the higher peak intensity of flash energy was a stronger combination and influenced eight out of ten choices. Flash rate, then, appears to have influenced the observers choices and probably explains why flash energy or effective intensity was not the controlling factor as expected. It is significant to note that none of the factors or their combinations had a 90 percent or better influence. This shows that some of the 6-v lights at various flash rates and 'on' times were preferred over 12-v lights. In other words, the higher flash intensity of the 12-v warning light was not high enough to obtain an overwhelming control over observer preferences. The influence of the various flash characteristics was shown in the observer preferences for one of the 12-v lights. In this comparison all of the 20 observers preferred a 12-v, 100 flash per minute, 10 percent 'on' time light when compared with a 6-v, 60 flash per minute, 10 percent 'on' time light. However, when the 'on' time was increased to 25 and 50 percent on the 6-v flasher, 1/4 of the observers preferred the 6-v light. When the flash rate of the warning light pairs was equal at 100, and the 'on' time on the 6-v warning lights was increased to 25 and 50 percent, the observers were almost equally divided in their preferences. A similar comparison of a 12-v, 100 flash per minute, 25 percent 'on' time light with the various 6-v warning lights showed that while some of the observers preferred the 6-v lights even though the 12-v light had a greater flash energy, most of the observers preferred the 12-v light. When the 12-v, 100 flash per minute, 10 percent 'on' time light was compared with the 12-v, 100 flash per minute, 25 percent 'on' time light the observers preferred the light with the longer 'on' time nine out of ten times. Approximately 70 percent of the observers chose 100 flashes per minute over 60 flashes per minute when comparing 12-v lights of equal 'on' time.

In summarizing these results it was found that the higher, or 100 flash rate, strongly influenced observer preferences. Peak intensity apparently had a greater effect than flash energy but this was accepted after realizing the observers were making their preferences at light levels well above threshold. (Literature data regarding effective intensity was usually obtained under threshold conditions.) When peak intensities and flash rates were approximately equal, flashers with the longest 'on' time were definitely preferred.

In considering recommendations, we wish to stress the point that observations in this field test were based on personal preference which may not be an accurate index of the warning value of the light. In all cases the observer was comparing one type of light with another. Further, under actual conditions, the driver does not compare, but relies on the type of light he sees to effectively make him aware of a hazard or to efficiently guide him around it.

Recommendations, therefore, are limited and conservative, but results from the field test phase indicate the following:

1) The flash rate of hazard warning lights should be about 100 flashes per minute. Further work may indicate that even higher flash rates should be used, but only two rates, 60 and 100, were tested. Laboratory work has shown that increasing the flash rate beyond 100 for incandescent lights that flash 'off and on' may not be feasible, since the time of applied voltage becomes so short that the lamps fail to achieve complete incandescence.

2) The length of 'on' time of hazard warning lights should be approximately 25 percent. Observer results indicated that longer 'on' times were strongly preferred but the only direct comparison involved 10 and 25 percent 'on' times. It is doubtful that these results can be extrapolated to include the 50 percent 'on' time. Laboratory results, based on observer reaction times, support the necessity of 'on' times over 10 percent but no significant improvements in reaction time were noted for 'on' times over 20 percent.

3) Twelve-volt flashers should not be considered as a high-intensity light to be used in extremely hazardous locations. Observer data showed that 12-v lights were preferred by a large majority when compared with all 6-v lights. However, in those comparisons between 6-v lights operating at 100 flashes per minute, 25 percent 'on' time and all 12-v lights (both 10 and 25 percent 'on' time), observer preferences were more equally divided. This shows that the 12-v light was not an overwhelming choice over certain 6-v lights and that the characteristics of a 6-v battery-operated light could be revised sufficiently to gain the preference of a significant number of individuals. It was assumed that a special warning light or a light to be used in extremely hazardous locations should be unquestionably superior to other commonly used hazard warning lights because a driver must receive the special warning without reference to other warning lights. It was assumed that a light with a voltage higher than 12-v would elicit the necessary overwhelming observer preference over 6-v lights.

4) An investigation of high-intensity warning lights should be undertaken. The lights should have sufficient energy while operating at the optimum 'on' time for the lamp used, to be an overwhelming preference over the 6-v warning light operating under any given flash characteristic. A light with one to two log levels greater intensity than a 6-v light was suggested, i.e., perhaps an 18 or 24-v incandescent light.

5) Flashing lights were recommended only for hazard warning and not for delineation lights (see Delineation Lighting Recommendations) and therefore the use of mono-directional lights to improve the warning effect in the desired direction was recommended.

DELINEATION LIGHTING

LABORATORY STUDY

The laboratory phase of the delineation lighting study evaluated observer preferences for delineation lighting systems that were photographed at a field installation.

Procedure

The installation site was an exit ramp from northbound Business Route US 131 at the Douglas Rd Interchange just north of Kalamazoo. The delineation lighting system consisted of a line of 25 6-v lights on barricades lining each side of a 12-ft lane shaped to an S-curve route as might occur at a spot hazard (Figs. 21 and 23). The separation between lights was 25 ft, making the total length of the route approximately 600 ft. A camera car traveled through the route at 15 mph. The camera, a Bell and Howell Model HR 70, was mounted next to the steering wheel on an autopod. The film was Ansco Chrome Daylight D200. An 80B Kodak filter was used to correct to tungsten light. To approximate typical pavement brightness in the finished film, two high-intensity (200,000 cp) headlamps replaced the in-board high-beam headlamps and another pair of high-intensity lamps were mounted on the bumper next to the outboard low-beam lamps.

Two major types of delineation lighting systems, flashing and steady-burning, were filmed. The lights were yellow except where noted. There were nine sub-types of the two major delineation lighting systems as follows:

Flashing Lights

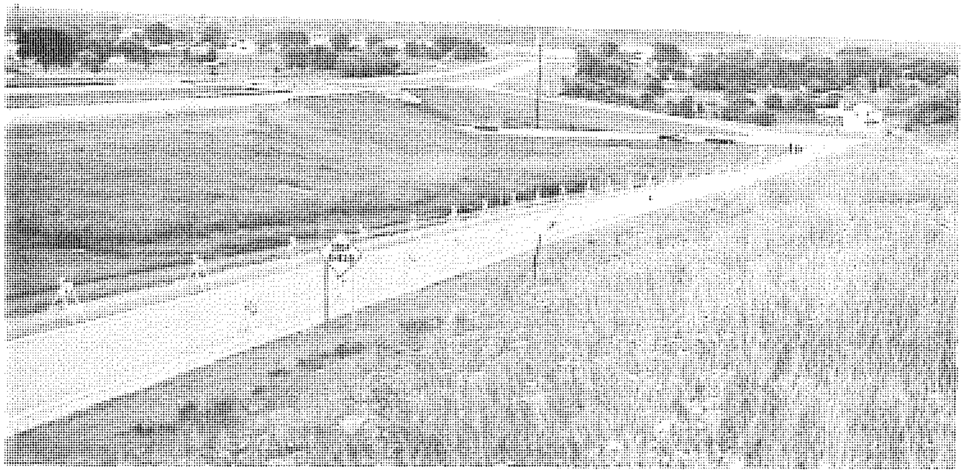
1) Random - lights flashing but not in an arranged sequence

2) Synchronous - all lights flashing together

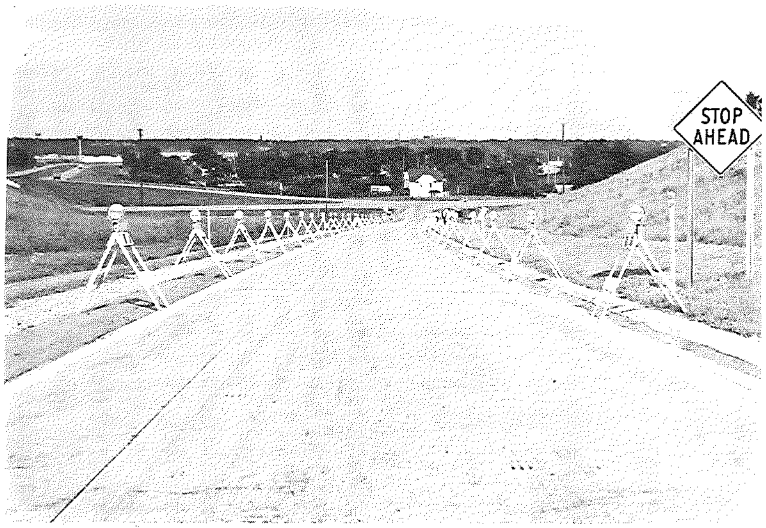
3) Synchronous (green and yellow) - yellow lights on the left, or driver's side, and green lights on the right flashing simultaneously

4) Synchronous alternating - all lights on one side of the route flashing together followed by all lights on the other side flashing together

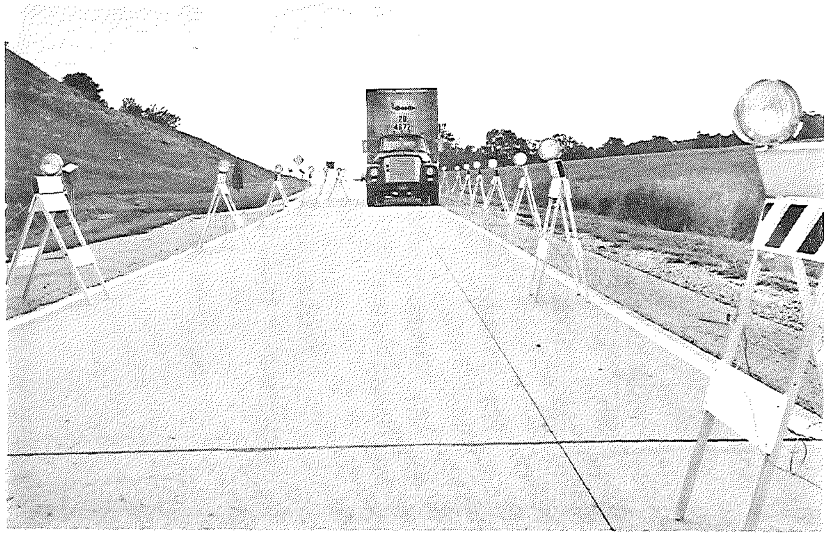
5) Sequential - lights flashing in sequence moving away from the driver.



Overall view of test site.



Delineation lights as seen from driver's view. Signs and reflector buttons were masked during filming.



Vehicle passing through the 12-ft route between the barricades.

Lighted barricade used for delineation lighting system.

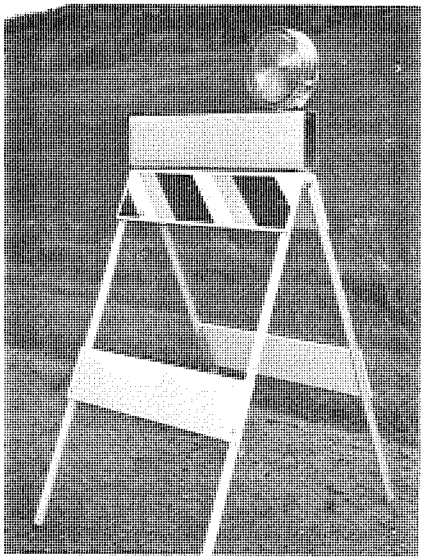


Figure 23. Delineation lighting field test site.

Steady-Burning Lights

1) Steady-burning (yellow and yellow) - continuously lighted yellow lights on both sides

2) Steady-burning (red and yellow) - red lights on right side

3) Steady-burning (green and yellow) - green lights on right side

4) Steady-burning (white and yellow) - white lights on right side.

Variations of the above systems were filmed using 50-ft and 100-ft spacings and also with only one line of lights.

Each film sequence of a single delineation system consisted of a scene as viewed from the driver's eye position as the vehicle passed between the delineation lights.

Theory

Because these films were to be presented for panel evaluation in the laboratory, consideration had to be given to the psychological scaling problem. The appropriate type of psychological scaling depends on factors peculiar to the stimulus (the physical cause of a visual sensation), memory persistence, abstractness of stimuli (e.g., delineation quality was considered more abstract than light intensity), and similarity of stimuli. It was considered that the subjective rating of delineation systems was a sufficiently complex and abstract task to require scaling techniques specifically designed to ease rating difficulty.

Ordinarily, this scaling technique can be accomplished through the use of graphic rating scales. They are highly efficient and can measure interval scale judgments provided observers can rate stimuli accordingly.

When observers rate abstract concepts such as delineation, however, it is not clear that observers can sufficiently differentiate degrees of delineation as required by the graphic rating scale techniques. For this reason, the analysis was based on a modification of Thurstone's pair comparison method (5) which requires the observer to decide only the rank order of two stimuli based on the property to be rated. The comparison method is useful when it is desired to scale difficult judgments given by either an individual or a panel of judges of size N. In its traditional form, the method requires that all pairwise combinations of the total, T, items (stimuli) to be judged be presented to the panel. After the presentation of each pair, each member of the panel registers his preference. In the present study, preference judgments were required for pairs of lighting configurations exhibiting different or possibly equal, degrees of delineation. All preferences from all panel members are then combined to form the desired scale[5].

While the method of pair comparisons simplified the scaling task, it did not, by itself, solve the problem of memory. Because delineation stimuli are abstract and difficult to differentiate, their sequential presentation makes memory fading a potentially large source of experimental error. Thus, while an observer may be able to form a judgment on each delineation stimulus by itself, he will find it difficult to compare it with future stimuli when this comparison depends upon memory. Therefore, it was decided to present each stimulus pair simultaneously, rather than sequentially, by showing two film reels on two projectors at the same time.

Frame-by-frame matching assured complete synchronization of the two films. The films were projected one above the other such that the lines of lights and center of the roadway were aligned vertically. This made it easier for an observer viewing the two films to move his eyes from one scene to the other. An experiment with side-by-side projection proved more confusing to the observers.

Each film reel consisted of the following sequences:

1) Daylight overview of the lights showing the route around the hazard, from a stationary vantage point, to familiarize observers with the purpose of the delineation.

2) Daylight view from vehicle moving through route, to acquaint observers with the procedure of the forthcoming pair comparisons.

3) Black film to adapt observers to darkness.

4) Lead-in sequence, consisting of view from a moving vehicle passing another car at night. This permitted observer accommodation to the driver's viewpoint and adaptation level.

5) Numeral (red on black background) alerting observers that the first pair comparison was approaching; appropriate numerals for each succeeding comparison.

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[5] See Appendix "Scaling Technique" for detailed discussion.

6) Pair comparison sequence in smooth transition from the previous sequence showing vehicle moving through a delineated route at night, edited such that both sequences begin and end simultaneously.

7) Nineteen repetitions of Sequences 4, 5, 6, and 7, such that each type of delineation lighting system appeared with all others in computer randomized order.

Two projectors in electrical tandem showed the two motion picture reels to 108 observers. The observers were licensed drivers selected at random from Department personnel. They ranged in age from 18 to 64 years; their visions were corrected to approximately 20/20 Snellen.

The nine delineation stimuli selected required $\frac{9 \times 8}{2}$ or 36 film pairs for the observers to judge. While 36 is not a particularly large number for the panel to view, it would have resulted in a fairly large film duplication cost. In order to reduce this cost, a slight modification in the pair comparison procedure was made. The original group of nine stimuli was divided into two groups of five, with steady-burning common to both. This resulted in $\frac{2 \times 4 \times 5}{2} = 20$ comparisons, or about one-half the film duplication cost. Results of these comparisons, scaled so that the most preferred and least preferred have scale values of 100 and 0, respectively, are shown in Table 8.

TABLE 8
OBSERVER PREFERENCES - DELINEATION SYSTEMS

Rank	Delineation System	Value
1	Steady-burn (white and yellow)	100.0
2	Steady-burn (red and yellow)	81.4
3	Steady-burn (green and yellow)	76.3
4	Steady-burn (yellow and yellow)	72.1
5	Synchronous alternating (yellow and yellow)	45.8
6	Synchronous (green and yellow)	34.9
7	Synchronous (yellow and yellow)	32.1
8	Sequential (yellow and yellow)	11.1
9	Random (yellow and yellow)	0.0

Analysis of these preferences did not follow the conventional Thurstone procedure. A modified procedure suitable for incomplete data matrices (as in the present case, since not all 36 comparisons were made) was developed.

Conclusions

Table 8 contains the results of the laboratory study of delineation lighting by the modified pair comparison method. The study is based on the comparison judgments of 108 observers divided into groups of about 15 (due to limitations imposed by viewing conditions). The order of stimuli presentation as well as the position of each film (above or below comparison film) was randomized among groups only.

The combination of steady-burning with yellow lights on the left and white lights on the right was rated best, while the random flashing lights were rated the worst. These were assigned arbitrary values of 100.0 and 0.0, respectively.

The values in Figure 24 associated with each delineation lighting system have no absolute meaning but the relative differences between the rating values representing the lighting systems are significant. For example, it is significant that there is a large difference between the worst steady-burning light (yellow lights on both rows) and the best flashing light (synchronous alternating) as compared to differences between almost any two flashing light systems or between any two steady-burning light systems. It appears that, for delineation purposes, any of the experiment's steady-burning light systems, regardless of color, is quite preferable to any of the flashing light systems.

It also appears that the color of steady-burning lights matters little except that the system with the white lights on one side and the yellow lights on the other side is clearly preferred over the other color combinations of steady-burning lights. The preference by the observers may be due to the higher intensity of the white light than either the yellow, green, or red lights. Indeed, a few observers remarked that they had based their choice on intensity rather than color[6]. The actual intensity difference between the

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[6] Most hazard warning light clear lenses tested had $T_s = 96$ percent ($T_{air} = 100$ percent), while the transmittance of yellow lenses averaged approximately 68 percent.

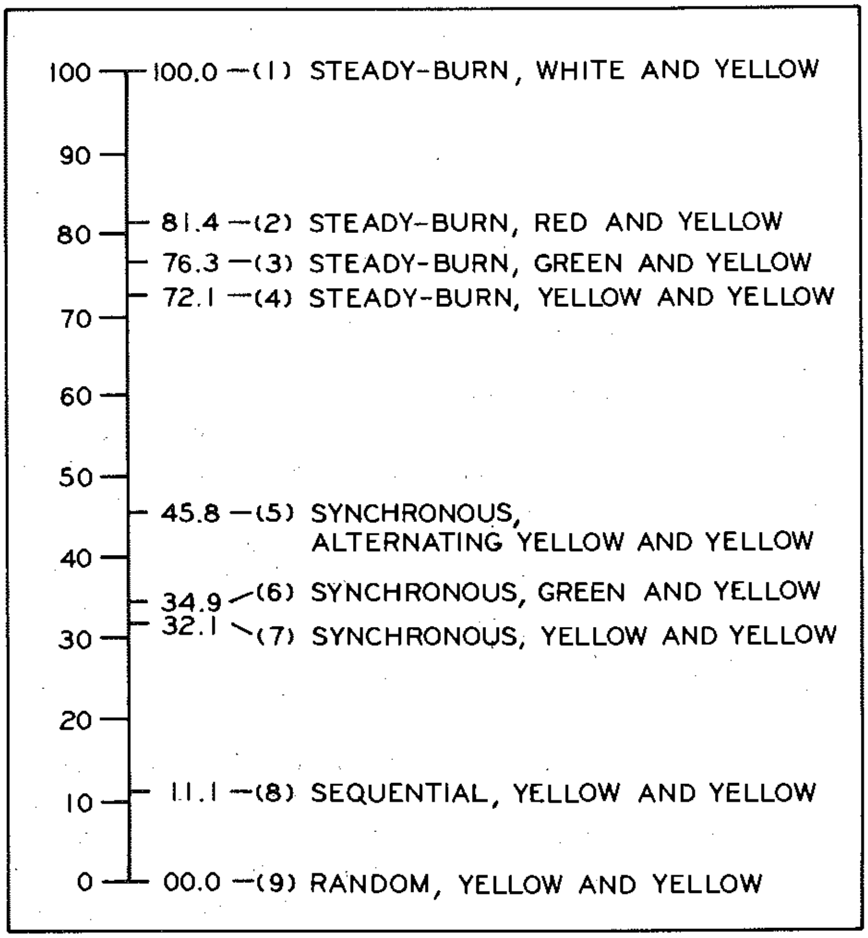

Figure 24. Delineation lighting system - Thurstone scale.

white and yellow lights was greater than was apparent in the films since the limited color film latitude precluded showing the full dynamic range of intensity observable by the eye.

Several who indicated that the red-yellow system was a superior delineation system did not select it over the other color combinations because red meant 'stop' to them. It is possible that the red-yellow system would have ranked much higher had not several observers rejected this system because of connotations of 'stop' or road closure having been associated with the color red.

Pair comparisons of delineation lighting systems with one line of lights only on the right side of the road and lighting systems having lights on both sides elicited little preference from five observers for either system. In addition, a comparison study showing 25, 50, or 100-ft separations between barricades for steady-burning lights revealed a preference for the 25-ft separations.

Recommendations

It is recommended that steady-burning lights be used for delineation. In addition, it is preferable that lights with clear lenses, that is, white lights, be used on at least one side of the road. Even though the color yellow is strongly and traditionally associated with caution, it was assumed that white lights on both sides of the roadway might be better since the resulting greater intensity of the lights may offset the advantage of the color contrast between white and yellow. Some comparisons of yellow and yellow delineation lighting systems with similar green and yellow systems in Table 8 and Figure 24 show that the benefits of color differences between the rows of lights is very slight, e.g., compare ranks 3 and 4, or ranks 6 and 7. However, should explicitness of delineation or discrimination between sides of the roadway be desired, a two-color combination of white for one row of lights and green for the other row is recommended.

If some sort of warning value is desired in addition to the delineation, the warning feature could be retained by using alternating synchronous flashing lights, i.e., simultaneous flashing of all lights on one side of the road, followed by a simultaneous flash from all lights on the other side of the road. The experimental results favored the alternating synchronous flashing lights to the other types of flashing light systems. Observers indicated that where both sides were synchronized, i.e., both sides flashing at the same time, there was a moment of darkness in each cycle where there was no delineation, creating an observer reaction of uneasiness with respect to proper guidance around the hazard.

FIELD STUDY

As originally proposed for this project a field test of delineation lighting was necessary for substantiation of the laboratory results. This test was designed to determine the preference for the configuration of lights which would most readily guide a driver around a hazard. Since this test was run concurrently with the hazard warning light field phase, the same observers, the same general test area, and the same type of test was used. Again the lights were barricade-mounted and 25 lights were used on both sides of the routes through each test site. As shown in Figure 21 four sites were available, one site on each ramp of the Holt Rd, US 127 interchange. Four different light configurations, one on each side, were prepared as follows:

1) Random Flashing, i.e., 6-v warning lights operating at 60 flashes per minute with a 25 percent 'on' time. This light conformed to Michigan Department of State Highways and Transportation specifications in effect at the time of the test.

2) Synchronous Flashing, i.e., 6-v warning lights operating at 60 flashes per minute with a 25 percent 'on' time. All lights on one side of the route flashed on and off at the same time. Lights on one side were not synchronized with the other.

3) Sequential Flashing, i.e., 6-v warning lights flashing at 60 flashes per minute with 25 percent 'on' time. Lights on one side flashed in a sequence of the first, then the second, the third, etc. This circuit failed and was finally deleted from the test.

4) Constant Burning, i.e., 6-v battery-operated units with the lamp burning constantly. This light conforms to the present Michigan Department of State Highways and Transportation specifications, and to the ITE Standard for Steady-Burning Barricade Lights (Type C).

The test was designed so that the observers would drive through the four test sites and select the best and the worst delineation light. The worst was to be removed and the observers would again select the best and the worst. Since the sequential flash circuit failed, only one pass through the test area was necessary. Data from 20 observers was obtained and only their best and worst choices are shown in Table 9.

TABLE 9
OBSERVERS PREFERENCE DATA

Light Type	Considered Best By	Considered Worst By
Random Flashing	2	13
Synchronous Flashing	4	7
Constant Burning	14	0

Obviously the constant burning light was preferred by most of the observers and it is significant to note that none of the observers considered this light the worst. There was considerable interest in the synchronous flash configuration.

Motion pictures were taken while driving a camera car through the delineation test sites. A limited number of viewers of the resulting films expressed preferences similar to the observer-field preferences.

Intensity effects were not included in the delineation tests and the effects of placement were not considered.

Results from the delineation phase of the field test indicate that steady-burning lights should be used for delineation. Flashing lights should be used as necessary to provide advance warning and warning at a hazard, but steady-burning lights should describe the traffic route around the hazard or through a hazardous area.

It is interesting to note that delineation lights operated and used as suggested above would conform with the recommendations of the Manual for Uniform Traffic Control Devices (1971).

SUMMARY OF CONCLUSIONS

SUMMARY OF CONCLUSIONS

Hazard Warning Lighting

The basic requirements of lights and lighting for hazard warning and delineation have been studied and the characteristics of lights fabricated for such applications investigated. The laboratory study of hazard warning lights was conducted with 24 observers representing a cross-section of driver ages. The observers pushed a button on a steering wheel rim in response to a flashing yellow light which appeared among several other lights, such as vehicle turn signals, tail-lights, headlights, an intersection flasher light, and billboard sign lights. The lights were to scale in a simulated roadway setting. Each observer was positioned 40 ft from the roadway setting in order to obtain a simulated 1,000-ft viewing condition.

In addition to the task of searching for warning lights, observers were also required to maintain a given speedometer reading by means of an accelerator pedal linkage. The test warning lights were to scale and were designed to produce six different illuminances at the eye for each combination of flash rate and 'on' time. Two flash rates of 50 and 100 flashes per minute were used and 17 'on' times of 5 to 90 percent of the flash cycle were used.

The experimental results clearly demonstrated that a flashing light had greater attention value than a steady-burning light as measured by observer reaction time. When the 'on' time was maintained at 20 percent, with the test lights operating in an effective illuminance range of approximately 10×10^{-6} to 140×10^{-6} ft-c at the eye; the results showed an average 200 millisecond faster response time for a rate of 100 flashes per minute than for a rate of 50 flashes per minute. This was a substantial improvement since the mean response time to 50 flashes per minute was approximately 850 milliseconds (0.85 sec). No other rates were examined because the incandescent lamps were not capable of sustaining rates much higher than 110 flashes per minute at the relatively short 'on' times and other research has shown that rates of 40 flashes per minute or less have little attention value. Results of a laboratory pilot study showed little difference in response time for lights flashing at 70 and 50 flashes per minute.

Statistically, reaction time for both rate and 'on' time were highly significant at the 0.001 level, carrying the expectation that approximately 99.9 percent of the average response times would be expected to fall within the same limits if the experiment were repeated. It was noted that the majority of observers detected flashing lights during the second flash regardless of 'on' time, rate, or intensity. Therefore, detection time was shortened because the second flash at the 100 flashes per minute rate appeared 600 milliseconds sooner than the second flash at the 50 flash per minute rate.

The shorter response time associated with the faster rate may indicate a much greater difference in detection time in an actual traffic situation where the driver is not as alert or is not searching for warning lights as were observers in the laboratory study.

In a field study of 6-v (ANSI 1850 lamp) and 12-v (ANSI No. 957 lamp) warning lights, the 6-v and 12-v lights were compared, and then only the 12-v lights were compared. These flashers had 'on' times of 25 and 10 percent and flash rates of 60 and 100 flashes per minute. Combinations of rate and 'on' time were compared while viewing pairs of warning lights. Twenty observers drove between two sets of duplicated warning lights at 40 mph. Based on a primarily subjective first impression about 70 percent of the observers preferred the 12-v light to the 6-v light. With the two sets of 12-v lights operating at the same flash rate, approximately 90 percent of the observers chose the lights with the 25 percent 'on' time over the light with the 10 percent 'on' time. When comparing lights of equal 'on' time, observers chose the light with the 100 per minute flash rate over the light with the 60 per minute flash rate about 70 percent of the time. Thus the field study substantiated the main findings of the laboratory study.

These findings do not affirm the recommendations for 'on' time (8 percent for Type B, High-Intensity) and for flash rate (55 to 75 flashes per minute) in the Federal Manual of Uniform Traffic Control Devices, 1971, p 310.

We also note here that interviews with drivers disclosed that the "short" flashes in use (presumably 10 percent or less) inhibited localization of the warning light or hazard.

Delineation Lighting

In a laboratory study involving 108 observers, and again in a field study with 20 observers, the steady-burning delineation light proved distinctly superior to various types of flashing light delineation systems. This coincides with the Federal MUTCD, 1971.

GENERAL RECOMMENDATIONS

Warning Lights

1) Flash rate should be between 95 and 105 flashes per minute.

2) 'On' time should be not less than 15 percent and not greater than 25 percent, with a 20 percent recommended minimum.

3) Effective intensity should be a minimum of 20 to 40 candela for a 1,000 ft warning distance (or a combination of intensity and distance to yield 20 to 40 x 10^{-6} ft-c at the eye). These recommendations are intended to establish minimum warning light performance at all times while the light is in use for hazard warning.

Delineation Lighting

1) Steady-burning lights should be used for delineation.

2) The color of the light for delineation shall be equivalent to traffic signal yellow, but for better delineation, the left and right rows of delineation lights should be different colors.

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APPENDIX

DELINEATION LIGHTING LABORATORY STUDY
SCALING TECHNIQUE

For each of the $\frac{T(T-1)}{2}$ pair comparisons, there will be X panel members who feel that one lighting configuration (say, A) delineates best of the pair, and N - X panel members who prefer the other (say, B). Thus, $\frac{X}{N}$ and $\frac{N-X}{N}$ are the proportions of panel members preferring configuration A over B, and B over A, respectively. These $\frac{T(T-1)}{2}$ proportions form a TXT matrix, P. Because the observers will disagree on the exact delineability value of each configuration, it is assumed that the population scale of configurations is such that each is distributed about a mean value designated as the scale value (S). Further, if it can be assumed that these distributions are normal with common variance σ, the P matrix can be transformed to a Z matrix by use of a table of normal deviates (Figs. 25 and 26). For example, if 50 percent of the panel preferred A to B, and 50 percent B to A, the distribution of configuration scale values is assumed to be similar to that shown in Figure 26.

In this case, the points A and B would coincide on the scale. If, however, the proportion preferring A to B was 80 percent, the presumed distribution of preferences would be similar to the one shown in Figure 27.

The shaded area of the normal curve represents the 20 percent who prefer B to A, while the unshaded part represents the 80 percent who prefer A to B. The midpoint (or for our purposes, the arithmetic mean) of this distribution is not located at zero, but at some distance (Z) away. A proportion of 0.80 corresponds to a Z of +0.6903 for a normal distribution of unit variance. (As long as the variances of the individual stimuli are equal, the exact value is of no concern since there will always be a linear transformation of the scale which corresponds to stimulus distributions of unit variance.)

It is this Z matrix which serves as the basis for Thurstone scaling[7].

As noted in the text, consideration of film duplication costs for 36 film pairs resulted in reducing the number of comparisons to 20. Analysis of these preferences did not follow the conventional Thurstone procedure.

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[7] Usually, the columns of the Z matrix are summed (if the matrix is complete with not 0.0 or 1.0 proportions). The sums are then accumulated to build the scale.

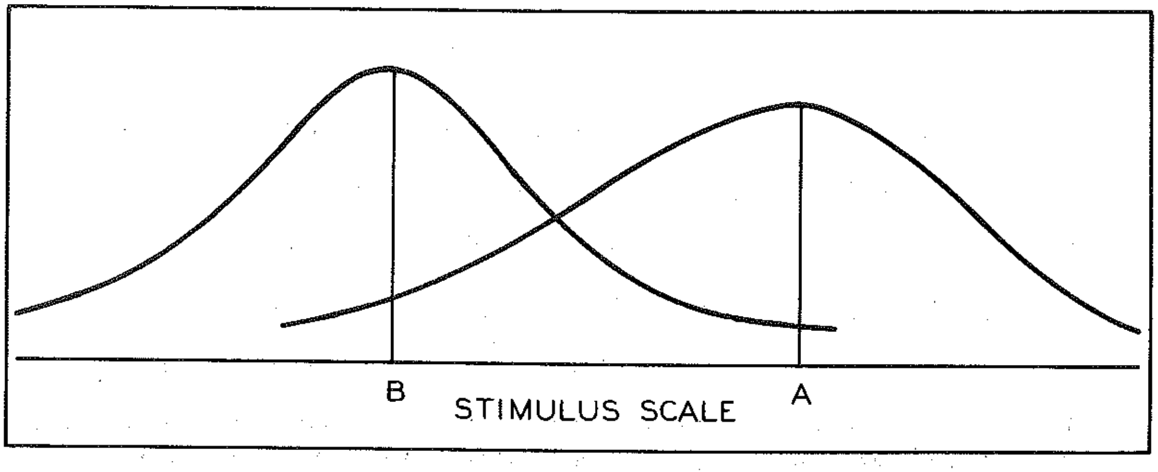

Figure 25. Population scale values of stimuli A and B.

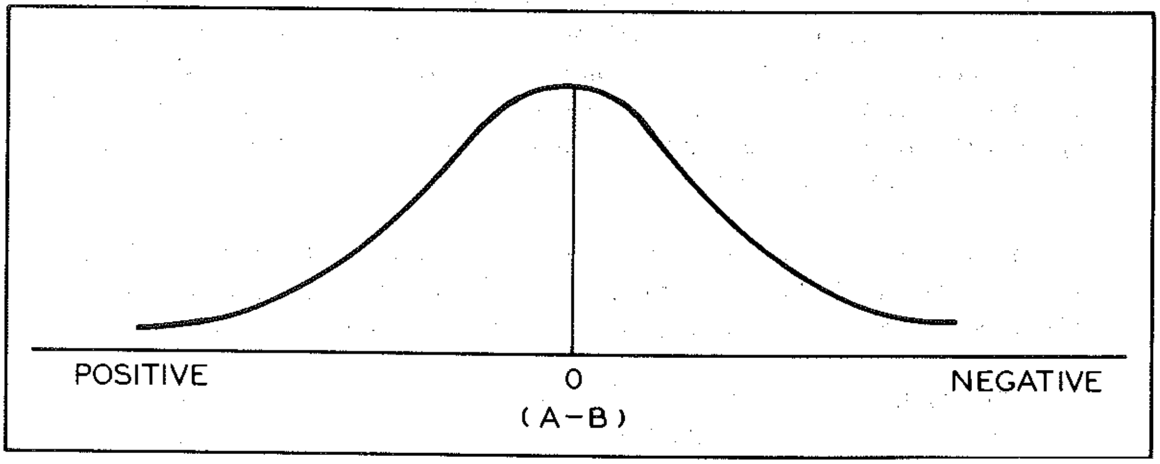

Figure 26. Distribution of individual scale difference (A-B) where A is preferred to B by 50 percent of the panel.

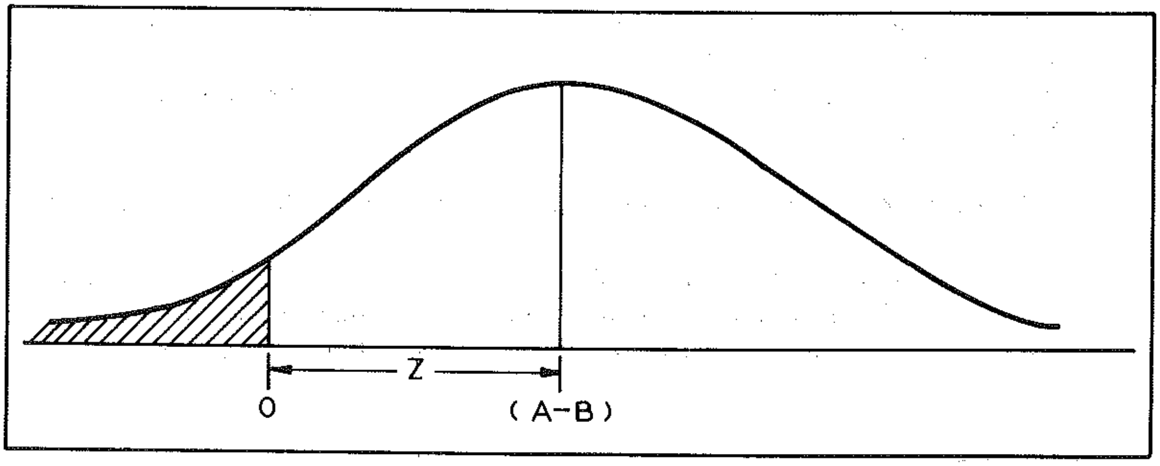

Figure 27. Distribution of individual scale difference (A-B) where A is preferred to B by 80 percent of the panel.

Therefore a modified procedure was developed which was suitable for incomplete data matrices. This procedure evaluates a Z matrix (based on a standard normal curve) constructed from a proportion matrix based on a pair comparison schedule.

The algorithm used is a modification of Thurstone's method, but the basic scaling method is similar in that intervals between adjacent stimulus estimates (scale positions) are accumulated (35). The procedure performs a series of regressions on the Z matrix in an iterative manner that continues until no further scale estimate revision is required. Briefly, each stimulus defines a Z scale by virtue of comparisons with all other stimuli. Thus, one can construct at most, T scales. The procedure used combines the T scales into a single composite. When two of the T scales are plotted against each other, one gives the X-coordinate and the other the Y-coordinate for each stimulus position. If, for example, scale 2 is considered independent and scale 4 dependent, an equation of the form $Y - AX + B$ can be formed using simple linear regression techniques. This equation will closely approximate the scale positions plotted on the graph. If we set Y to zero in the obtained equation, and solve for X, the result is the X-intercept -- a revised estimate of the position of stimulus 4 on scale 2. This is a better estimate of the position because all of the positions on both scales were used to determine it. After applying this procedure to all of the possible $\frac{T\ (T - 1)}{2} = 36$ scale combinations, the result is a new Z matrix with revised scales as columns. This procedure can be repeated as many times as is necessary to maximize the average correlation coefficient. Limited experience has shown that less than ten iterations are necessary to converge r^2 to 1.0000.

A few comments should be made about the stability of the Z matrix under the regression procedure. The iteration process is fundamentally quite stable except when it is formed on the basis of too few subjects. For example, if there are only 10 subjects there are only 21 possible Z values. This condition can yield regressions with a very wide dispersion of scale difference estimates, some of which are highly inconsistent with the others. Constraints must be chosen very carefully. Experimentation with the different constraint settings was found necessary and it was decided that the modified Thurstone scaling should not be attempted with fewer than 40 subjects, and that from two to three times this number (e.g., 108) would effect a good compromise between scale reliability and experiment cost.

STATE OF MICHIGAN
DEPARTMENT OF STATE HIGHWAYS

TEST METHOD NO. T 6.31.01

TEST PROCEDURES
FOR
BATTERY-OPERATED WARNING FLASHERS AND LIGHTS

Description:

This test procedure is used for sampling and testing the following three types of warning flashers and lights:

1. Type A Battery-Operated Low Intensity Warning Flashers (12 volts).
2. Type B Battery-Operated High Intensity Warning Flashers (18 volts).
3. Type C Battery-Operated Steady Burning Warning Lights (6 volts).

Sampling:

The expected frequency rate of sampling warning units will be one unit for each 10 warning flashers, or fraction thereof, or for each 25 steady-burning lights, or fraction thereof, on the project.

Testing:

a. Housing - The structure and design characteristics of the housing, lens support assembly, and fastener devices will be visually inspected on the project during normal use of the unit.

b. Lens - Relative luminous transmission and lens color will be tested in the Laboratory in accordance with the method described in the 'Standard for Adjustable Face Vehicle Control Signal Heads," revised 1966, Institute of Traffic Engineers. Measurement will be made on the lens after cleaning.

c. Reflector Ring - The specific intensity of the lens reflector ring will be determined by mounting the unit on a suitable goniometer 100 feet from a photometer equipped with a vacuum phototube and a filter to provide a phototube-filter combination with a spectral response similar to the CIE standard observer luminosity function. The phototube will be positioned at a distance from a projection light source which will provide an equivalent observation angle of 0.2 degrees. Measurements will be made at the specified 0, 10, and 20 degree entrance angles. Left and right measurements at 10 and 20 degrees will be averaged.

The projected incandescent light beam will cover the lens with uniform illumination. The illumination will be measured at the lens with a foot-candle meter corrected to the CIE standard observer luminosity function. Specific intensity will be calculated by dividing the measured intensity, in candelas, of the lens by the illumination, in foot-candles, incident on the lens.

d. Maintained Intensity - Maintained intensity will be tested in the Laboratory and will be determined on units in the "as sampled" condition.

The maintained effective intensity of flashers and the maintained intensity of steady-burning lights will be determined by mounting the unit on a suitable goniometer 100 feet from a photometer equipped with a vacuum phototube and a filter to provide a phototube-filter combination with a spectral response similar to the CIE standard observer luminosity function.

For warning flashers, the output of the phototube will be displayed on an oscillograph or oscilloscope, thereby recording the intensity-time characteristics of the flashing light.

Measurements will be made at 75 ± 5 F with the lamp in the "as sampled" condition, but operating from a regulated DC source. Measurements will be made within the limits specified. The lens and reflector will not be cleaned. Flashers or lights reflectors will not be cleaned. Flashers or lights relying on lens rotation for directional adjustment as specified under the Specific Requirements for "Housing" will be tested with the lens rotated to the position of minimum intensity.

For warning flashers, the recorded intensity-time flashing light data and recorded data from a steady-burning lamp calibrated for horizontal candlepower will be used to determine the maintained effective intensity of all measured points in terms of the lamp operating at 10.5 volts for Type A units and 13.5 volts for Type B units. Effective intensity will be calculated in accordance with the "IES Guide for Calculating the Effective Intensity of Flashing Signal Lights," Illuminating Engineers, Vol. 59, November 1964, pp 747-753.

e. Dwell Time - For warning flashers, the dwell time will be tested in the Laboratory and will be determined from recorded intensity-time characteristics obtained as described in the maintained effective intensity test. Recordings of intensity-time characteristics will be taken at the specified rated and replacement voltages at the following temperatures: 150 F, 75 ± 5 F, and -20 F. The percent dwell time will be calculated by multiplying 100 by the time in which the intensity of a flash cycle exceeds 20 percent of its maximum and dividing the product by the time of a flash cycle.

f. Flash Rate - For warning flashers, the flash rate shall be the number of times per minute the flashing light reaches maximum intensity. In the Laboratory, measurements will be made from the recorded intensity-time characteristics obtained as described under the test for Maintained Intensity.

g. Battery Voltage - Battery voltage as an equivalent battery voltage at the lamp will be measured at the battery terminals. The voltage measured after 30 seconds under a total resistance load of 56 ohms will be considered the equivalent voltage. Battery voltage of a warning flasher or light shall be measured with a voltmeter having an accuracy of ± 0.5 volts, at 4.5 and 13.5 volts. The voltmeter shall be calibrated against laboratory standards at 4.5 and 13.5 volts as often as necessary to insure meter accuracy.

STATE OF MICHIGAN
DEPARTMENT OF STATE HIGHWAYS

SUPPLEMENTAL SPECIFICATION
FOR
BATTERY-OPERATED WARNING FLASHERS AND LIGHTS

6.31 (1a)

Description:

This specification covers the requirements for the following three types of warning flashers and lights.

1. Type A Battery-Operated Low Intensity Warning Flashers (12 volts).
2. Type B Battery-Operated High Intensity Warning Flashers (18 volts).
3. Type C Battery-Operated Steady Burning Warning Lights (6 volts).

Sampling and Testing:

Sampling and testing will be done in accordance with current MDSHT Test Procedures for Battery-Operated Warning Flashers and Lights, Test Method No. T 6.31.01, which is available upon request from the Department. The Contractor shall provide replacement units on the project for those sampled for testing. The units sampled for testing will be returned to the Contractor upon completion of testing.

General Requirements:

The warning flashers and lights shall be complete with fastener devices and fittings, permitting attachment to barricades, posts, and other construction devices.

Specific Requirements:

a. Housing - The housing and the lens support assembly shall be constructed in such a manner that their structural strength and rigidity will withstand in-service conditions. The optical head or the fastener devices for attaching the optical head or housing to the barricade, post, or other device shall permit sufficient directional adjustment to obtain the maximum warning effect for the motorist.

b. Lens - The lens shall conform to the requirements for the relative luminous transmittance and the chromaticity of the yellow color for a traffic signal lens as defined by the "Standard for Adjustable Face Vehicle Control Signal Heads," revised 1966, Institute of Traffic Engineers.

The lens for Type B units shall be not less than 7 inches in diameter.

The lens for the Type A and Type C units shall be not less than 6 inches in diameter and, in addition, shall have a 1/2-inch reflex reflector ring around its perimeter. The reflex reflector ring shall meet the specific intensity requirements specified in Table 6.31-1.

Table 6.31-1 Specific Intensity Requirements for Lens Reflector Rings

Entrance Angle, degrees	0	10	20
Specific Intensity,* candles/foot candle	18	14	7

* From an observation angle of 0.2 degree.

c. Optical Unit - The optical unit shall consist of a lens, a reflector, a lamp, and a lampholder. The number of lens faces permitted shall be in accordance with Table 6.31-2. The type of lamp used shall be as specified in Table 6.31-2, or equal.

d. Maintained Intensity - The maintained effective intensity for warning flashers and the maintained intensity for steady-burning lights shall not be less than the applicable intensity specified in Table 6.31-2, for each angle of light emission within a solid angle 9 degrees on each side of the vertical axis and 5 degrees above and 5 degrees below a horizontal plane through the light center. The maintained intensity will be determined on the units in the condition as sampled from the project.

e. Batteries - The units shall be operated from a battery source as specified in Table 6.31-2.

Batteries shall be replaced with new batteries when the voltage at the battery terminals after 30 seconds under a 56 ohm resistance load is less than the voltage specified in Table 6.31-2.

The voltmeter used for testing shall have an accuracy of ± 0.5 volts at 4.5 and 13.5 volts.

f. Flash Rate and Dwell Time - The flash rate and dwell time ('on-time') for each on-off cycle for warning flashers shall be as specified in Table 6.31-2.

The flasher shall meet these requirements within a temperature range of 150 F to -20 F. The flash rate and dwell time will be determined on a flasher in the condition as sampled from the project.

Table 6.31-2 Requirements for Warning Flashers and Lights

Unit Type	Lens Faces	Lamp Required	Battery Voltage		Maintained Effective Intensity	Maintained Intensity	Flash Rate per Minute	Dwell Time per "On-Off" Cycle
			Rated	Replacement				
Type A	1 or 2	No. 957*	12	10.5	4 candelas	--	55 to 75	10%
Type B	1	No. 1003	18	13.5	35 candelas	--	55 to 75	8%
Type C	1	No. 1850	6	4.5	--	2 candelas	Constant	Constant

* A No. 1408 lamp, or equal, may also be used until January 1, 1975.