Visual Characteristics of Flashing Roadway Hazard Warning Devices

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Previous investigations of the visual characteristics of flashing light sources, for the most part, have been made at low-energy levels at or near a visual threshold by means of extended sources. Although the results of these investigations have proved useful, they are not directly applicable to the design of portable battery-operated warning lights where conditions are somewhat different. These devices are usually first seen as nearby point sources under suprathreshold conditions. New data have been developed which relate to the important physical characteristics, such as flash duration and wave form, that directly affect the perceptual clues provided by such warning devices.

The effect of duration and wave form on the effective intensity of point sources of flash energies of 0.1 candlepower-seconds (red light) has been investigated by performing intensity matches between two modulated sources, one of which has a fixed duration and peak intensity. At this flash energy, which was chosen as being significantly above a visual threshold for a dark-adapted eye and as being readily obtainable by currently manufactured devices, flashes that have durations longer than 50 milliseconds require more energy to have an equal visual effect than flashes of shorter duration. This result is highly important to the conservation of battery energy.

Other factors that influence the design of battery-operated units (for example, flash rate, flash energy, and placement of units) are discussed.

● THE PURPOSE of this work was to study most of the visual characteristics of flashing light sources that might affect their effectiveness in attracting attention and to relate the findings to the design of battery-operated portable roadway hazard warning devices.

The major physical factors considered in this study were: flash duration, maximum intensity, wave form, flash rate, and the energy content of the flash. The important psychological factors were: apparent intensity as a function of flash energy, visibility threshold for detection of the presence of light, and the effect of flash duration on the ability to judge the position of the source.

PROCEDURE

Literature Survey

A survey of the existing literature of the effective intensity of flashing lights was made to determine if there were sufficient information available to answer the major questions involved in the design of portable roadway hazard warning lights.

Two serious limitations were discovered in the previous investigations. First, most of the studies were made with flashes that were at a visual threshold and were not directly applicable to the present problem, which involves suprathreshold visual conditions. Second, the energy required to produce the flashes was not restricted, whereas with battery-operated devices the energy consumption is highly important, because this determines battery life.

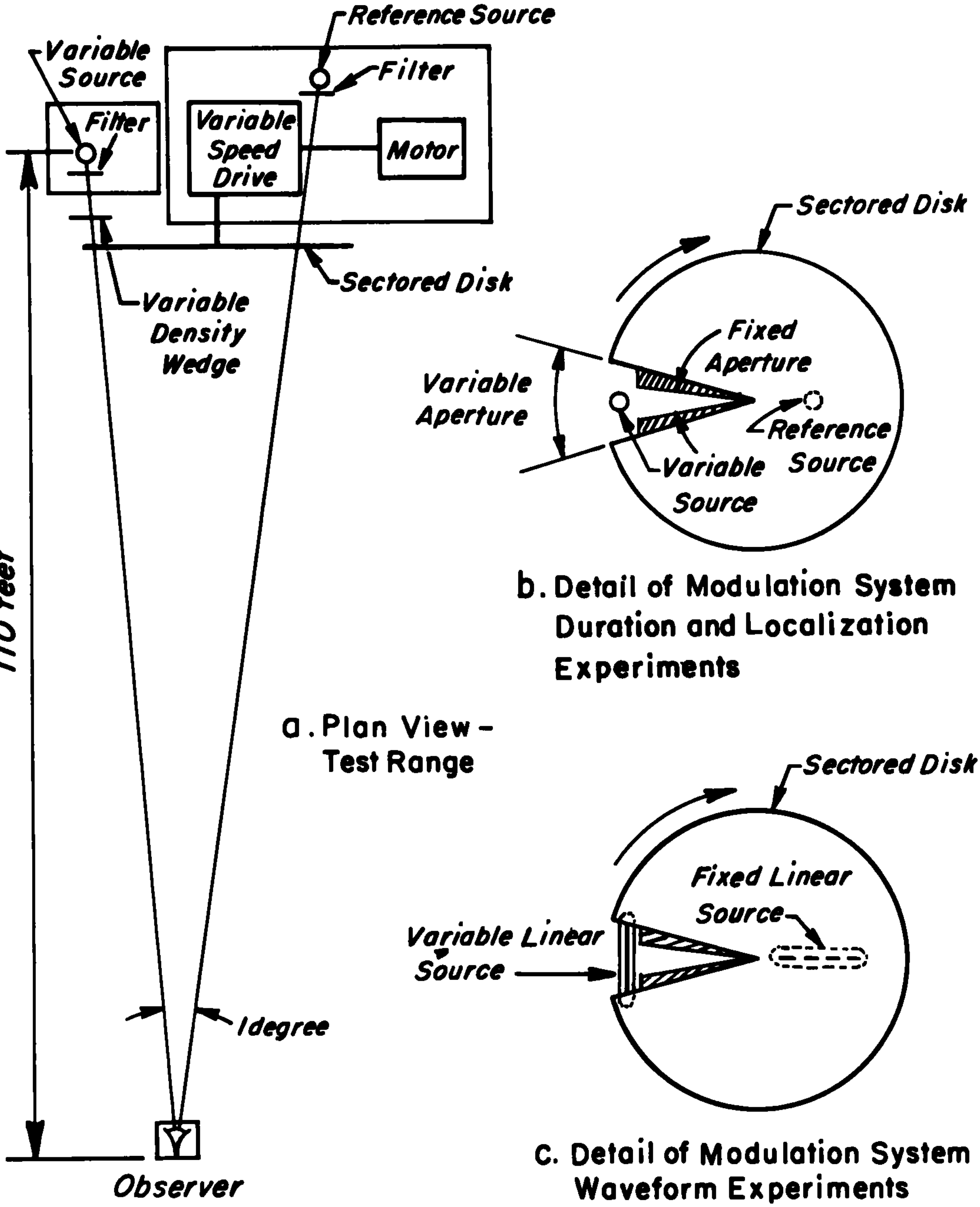

Figure 1. Layout of experimental equipment.

Experimental Work

Because of the limited application of previous research on flashing lights to this particular problem, it was necessary to conduct a series of experiments with the lighting conditions as nearly as possible like those that a motor vehicle operator might encounter at night when approaching a hazard. The environmental factors were approximated as closely as possible. For instance, one requirement was a long, totally dark-

ened test area. The laboratory room used as the experimental test range had a clear length of 110 ft (Fig. 1). It was also desirable to use realistic sizes and colors of lights.

Other investigations had indicated that the size of a light source studied was an important factor in threshold measurements. The smaller sources produced more sharply defined effects which could be interpreted for sources of larger area. For example, referring to Figure 6, the studies on single nerve fibers by Hartline (1) produced a sharp break in the resulting curve (Curve 3). Sources of larger extent studied by Blondel and Rey (2) produced more gradual effects as shown by Curve 4. Further studies by Graham and Margaria (3) and Karn (4) substantiated the gradual sharpening of the curve with a decrease in source area but they found no change in the critical duration at which the transition takes place.

It was reasoned that if the foregoing held true for threshold conditions, then the use of small sources for supra-threshold conditions could be expected to produce useful data which could be extended for sources of larger area as, for example, Curve 2 in Figure 6. The smallest sources used in these experiments were approximately ⅛ in. in diameter and subtended an angle of 20 sec at 110 ft. This size is less than the minimum angle of resolution, therefore the source acted as a point of light. This condition approximates a 4-in. diameter warning unit seen at 1,000 ft.

The color of the test sources was a red similar to that used on some existing warning lights. This color was chosen for two reasons: first, red is the color usually encountered under actual conditions, and second, the peripheral retina is relatively insensitive to red light, so there is little or no distraction caused by scattering of light in the eye. Observations during a portion of the experiments using a white source confirmed this, as the scattered light was distracting.

It is felt that the results shown in this report are applicable to other colors since Rouse (5) has found that the "time-intensity" relation is independent of color.

A square wave form was used in most of the experiments (except for the section on wave form) because of the ease in computing the total energy in the flash and for reproducibility in the event that a cross check is desired.

The experimental program was set up to obtain data on the following variables:

1. Total luminous energy per flash;
2. Duration of flash;
3. Wave form of flash;
4. Flash rate; and
5. Localization in space.

EQUIPMENT

Sources

Two types of sources were used in the investigation, "point" and "linear." The point sources were obtained by means of 6-volt, 32-cp automotive headlamp bulbs that were entirely shielded except for a ⅛-in. opening. The linear sources were 110-volt, 25-watt, GE 25 T 10 tabular incandescent bulbs, shielded so that only 2 in. of the filament in the direction of the observer were visible. Red filters were interposed between the sources and the observers (Fig. 1).

Modulator

The modulation of the light sources was achieved by means of a variable-opening, sectored disk that was driven by a ½-hp AC motor through a Vickers variable-speed hydraulic transmission. Two sources could be alternately modulated by the same disk by placing each diametrically opposed along the radii of the disk. Hence, many combinations of flash rate and flash duration could be selected. The 2-ft 6-in. diameter of the sectored disk permitted a separation of 1 deg (2 ft at 110 ft) from the observer between the two sources being modulated by the same disk.

Detector

The flashes were monitored by a photoelectric system employing a color-corrected, RCA 1 P 21 photomultiplier tube whose output was fed into a Du Mont 403 Oscilloscope. The traces were recorded by means of a Du Mont oscilloscope camera, Model 353, having a Polaroid back. The system enabled the precise monitoring of the flash duration, instantaneous intensity, and repetition rate as the x-axis was calibrated by the line frequency to read in time units and the y-axis was calibrated by an incandescent standard lamp to read directly in candlepower (Figs. 2 to 5).

Power

The pair of light sources used in each series of experiments was each independently supplied with power. In the case of the automotive lamps, one lamp had a fixed 6-volt DC supply and the other a variable AC supply controlled by the observer. One of the linear sources had a regulated 120-volt AC supply and the other a variable supply controlled by the observer. The photomultiplier tube in the detector was supplied by a well-stabilized high-voltage DC supply.

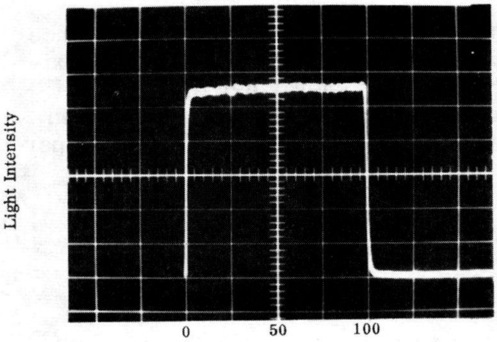

Figure 2. Typical square wave shows response of photomultiplier-oscilloscope system. Finite rise time is due to source size (1/8-in. diam).

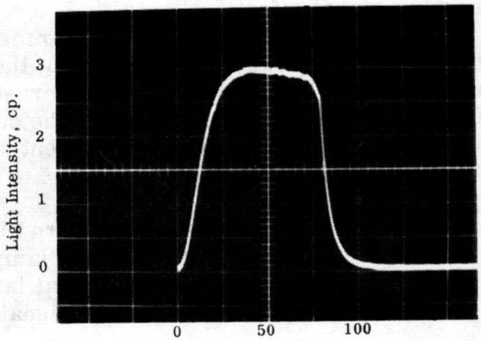

Figure 3. Incandescent source with transistorized electronic flasher. Approx. square wave modified by thermal inertia of light-weight filament. Flash energy 0.068 cp-sec (red), 0.20 cp-sec (amber).

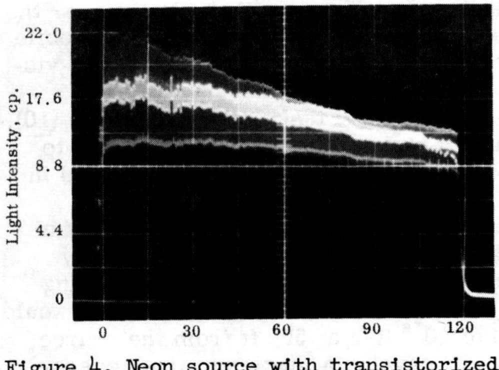

Figure 4. Neon source with transistorized electronic flasher. Flash energy 1.4 cp-sec.

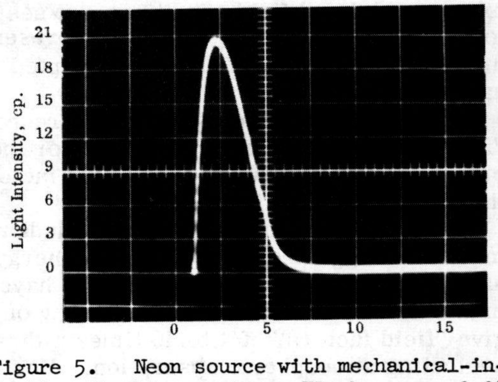

Figure 5. Neon source with mechanical-inductive flashing system. Flash energy 0.06 cp-sec.

TEST RESULTS

Energy Content

The important subject of energy content is probably the most difficult one to treat in the laboratory. One of the main difficulties involved in the determination of the minimum required luminous energy per flash is the choice of the state of visual adaptation or the range of adaptations to be considered. The adaptation level of the motor vehicle operator at night ranges over a wide distribution of values and is usually difficult if not impossible to determine with available techniques. The visual threshold and the minimum intensity that can be perceived are directly related to the level of adaptation. Assuming one could arrive at a reasonable choice of adaptation level, one would still be faced with the decision of determining how far above threshold the flash energy should be. The relationship between signal intensity and its effectiveness is not known. In other words, if a signal intensity is 50 times threshold intensity, it is not necessarily 10 times more effective than a signal at 5 times threshold, nor 50 times more effective than a threshold signal.

It is generally agreed that the brightest lights in a field of view command the most attention and that flashing lights have more attention value than non-flashing lights. With so many extraneous flashing sources in a driver's purview, it is desirable that critical warning lights should be among the brighter ones encountered. Thus, the choice of flash energy is reduced to a compromise between economic feasibility and maximum signal effect.

As an indication of some of the sources having a similar flash rate and appearance with which the roadway hazard warning lights have to compete, the following approximate values of flash energy are of interest. The luminous energy per flash may be defined as the integrated area under the candlepower versus time curve and is given in cp times seconds. Roadway-abutment and division-strip warning lights used on per-

Light Source	Flash Energy
Red passenger car turn signal	12 cp x sec
Red truck turn signal lamp	40 cp x sec
Red intersection signal lamp	40 cp x sec
Yellow intersection signal lamp	340 cp x sec

manent hazards fall withing this range of values. The foregoing represent "on-axis minimum values" using 60 flashes per minute as the rate and assuming a square wave of light output with a 40 percent effective "on" time for the incandescent sources.

The literature on the visibility of flashing lights is meager insofar as the minimum necessary luminous energy per flash is concerned. Minimum perceptible values (threshold) have been roughly determined for various sizes of source, viewing distances, states of dark adaptation, color of light, time for seeing, and location in the field of view (2-9). These data show an enormous range from 3×10^{-10} to 9×10^{-7} ft-c at the observer's eye as the minimum perceptible values (threshold) for the wide variation in experimental and field conditions. It seems reasonable to assume that a value near the top of the range (say 10^{-6} ft-c) is representative of a threshold value for an automobile driver who is only partially dark adapted and may not have his full attention on the visual task.

In other recent studies relating threshold values of visual tasks to performance (10), "field factors" have been developed for the required changes in threshold contrast to provide adequate values. The "field factors" for many tasks have been established in the range of 5 to 50 times threshold.

Considering all of these factors, judgment must be exercised in the selection of a minimum suggested luminous flash energy for a portable battery-operated roadway hazard warning device. The authors have examined devices that are currently being manufactured and have evaluated many of them for luminous flash energy. These would give "field factors" of 4 to 40 times a threshold of 10^{-6} ft-c at 500 ft from the source, neglecting atmospheric absorption. Most units will develop a maximum flash energy in the range of 0.10 to 1.0 cp x sec with red light.

With red light, more color contrast is available with the usual sources in the field of view at night so it has become accepted practice in automotive lighting design (11) to use a ratio of 1:2.5 between red and amber for equal signal effect.

Therefore, for roadway hazard warning devices the minimum suggested values for the luminous energy per flash are 0.10 cp x sec/flash for red and 0.25 cp x sec/flash for amber colored units. Admittedly these are arbitrary but they represent values at least several times threshold and they are available in the better quality portable roadway warning devices that are in current production.

Factors such as attenuation by fog or the glare due to oncoming headlamps have to be considered. A decision also has to be reached as to how much money one is willing to invest in battery power to cover all contingencies and to what extent one should try to cover them.

These minimum values should be the in-service maintained luminous energies and should be available at all points within a central cone extending to 5 deg around the photometric axis of the device. The specified light distribution should be in substantial agreement with automotive rear signal lights as recommended by the Society of Automotive Engineers (12).

Duration of Flash

The subjects were seated 110 ft from the sources in a darkened room and viewed the flashes binocularly (Fig. 1). Two point sources were placed on opposite sides of a sectored disk axis on a horizontal diameter. The left source could be attenuated by means of a remotely controlled variable density wedge. The two sources were at unequal distances from the center of rotation of the disk, so the angular size of the opening through which the sources were viewed could be made unequal (Fig. 1). There was only one opening in the sectored disk so that the two sources were presented alternately. The disk was driven at a speed of 60 rpm so that 120 alternate flashes per minute were presented. This speed was judged by most observers to be the most comfortable one at which to make the measurements.

The right source was held constant at 10 cp and 10 milliseconds duration (0.10 cp x sec luminous energy) while the left source had its duration changed for each run and its candlepower adjusted by the subject until the alternate flashes appeared equal in subjective intensity or signal effectiveness, depending on which criteria the subject chose for his match. The two sources had the same color at all times.

Five observers made a total of 456 readings and developed the technique. Table 1 gives the averages of 144 additional readings by four other observers which are in substantial agreement to the previous 456 observations.

TABLE 1

INTENSITY MATCHES

Variable Duration (Left Source) (ms)	Matching Intensity (Left Source) (cp)	Matching Flash Energy (Left Source) (cp x sec)
10	10	0.10
20	5.1	0.10
33	3.4	0.11
41.5	2.75	0.11
45.5	2.4	0.11
50	2.45	0.12
55.5	2.3	0.13
62.5	1.96	0.12
71	1.9	0.135
83	1.8	0.15
100	1.8	0.18
250	1.1	0.27

The foregoing table gives the average setting by the observers of the candlepower of the variable source for different flash durations required to match the constant source. The right source remained constant at 10 cp and 10 milliseconds giving a flash energy of 0.10 cp x second. The energy of the matching flash is also given.

Table 1 indicates that it requires a gradually increasing amount of energy to match a 10 millisecond flash with a flash whose duration is gradually increasing. A log plot of flash energy versus duration shows more clearly at which point the energy required to match a 10 cp-10 millisecond flash begins to increase (Curve 1, Fig. 6).

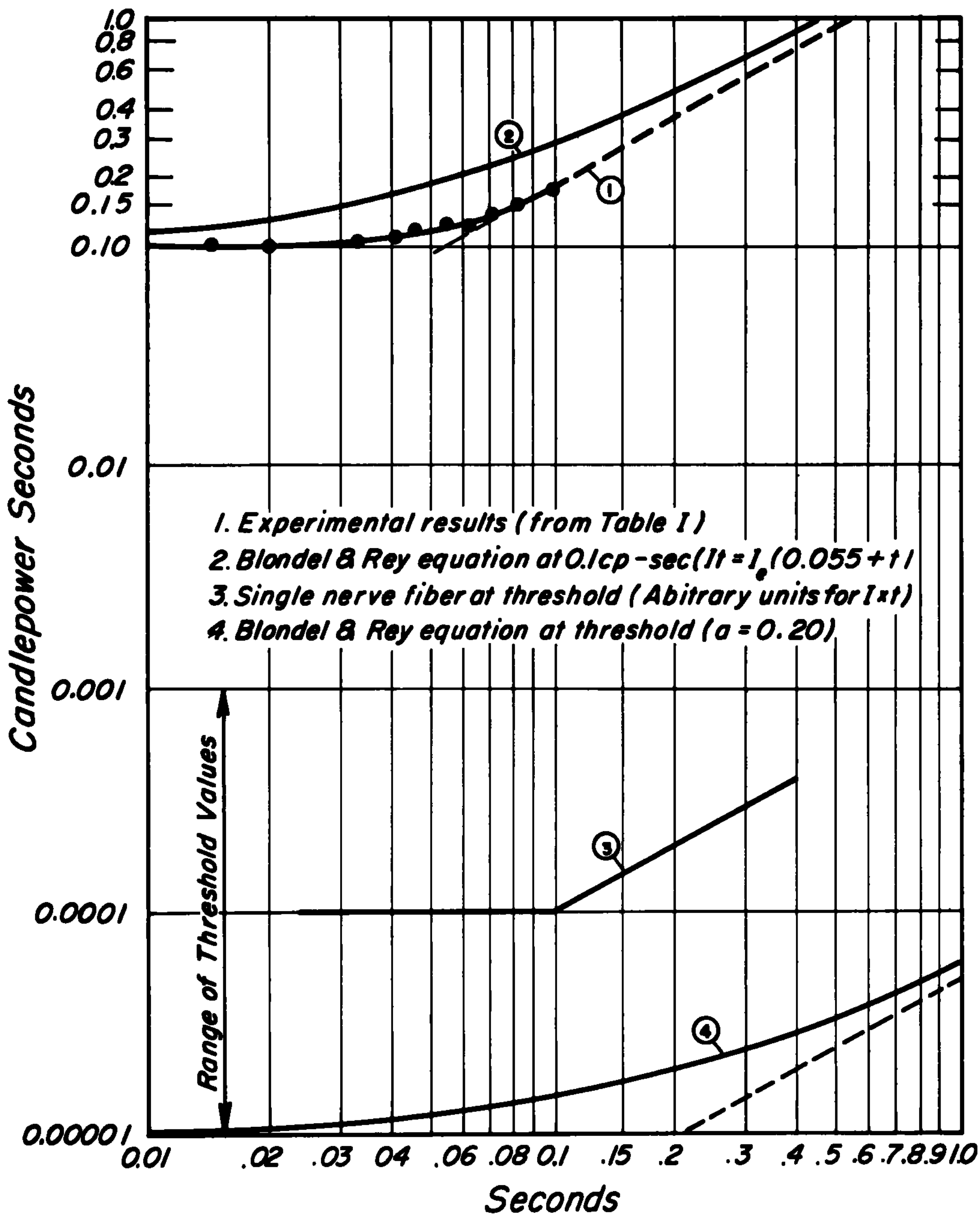

Figure 6. Flash energy vs duration of flash for equal effective intensity.

Also included in the graph are the lines indicating the results of previous work for a single nerve fiber and sources of large extent made at threshold condition (Curves 3 and 4). It can be noted that the curve for a single nerve fiber has a sudden transiton at 100 milliseconds. The first portion of this curve represents the condition wherein the photochemical process within the retina is predominating. The later portion of the curve is controlled by the characteristics of the nerve fiber and indicates a condition of saturation. Because the shape of the curve for supra-threshold conditions seems to tie in with the data for threshold conditions, it is believed that an extrapolation that approaches Curve 2 (Blondel and Rey) is valid for sources of finite extent under supra-threshold conditions. For example, a 4-in. warning lamp subtends an angle of 72 sec at 1,000 ft or a little more than three times the subtence of the "point" sources used in the experiments; therefore, one could expect that the transition in the neighborhood of 50 milliseconds would be a little more gradual or more nearly like Curve 2. In essence, the use of the "point" sources in these experiments (Curve 1, Fig. 6) is an effort to pinpoint more carefully the transition point on the curve of duration versus flash energy. Curve 2 was computed from the Blondel and Rey (2) equation $[I \times t = I_e(a \times t)]$, using a value of a = 0.055 in the manner of Toulin-Smith and Green (8). Curve 2 does not represent experimental points as do the points on Curve 1.

The data clearly show that when the flash energy is in the neighborhood of 0.10 cp x seconds, the flash duration should not be longer than 50 milliseconds if the energy must be conserved. At lower values of energy per flash the transition duration is closer to 100 milliseconds which is the limiting case under threshold conditions as determined by Blondel and Rey (2). At flash energies higher than 0.10 cp x sec, the transition duration could be expected to decrease to somewhat less than 50 milliseconds but not appreciably.

Wave Form

In order to study the effect of wave form on the signal effectiveness, two linear sources were used. One source was oriented parallel to the sector edge and the other was oriented perpendicularly to the sector edge (Fig. 1).

Hence, a square wave was compared against a triangular wave. Table 2 gives the average results of 40 readings by four observers in which the intensity of the square wave was adjusted until it was equal in appearance to the triangular wave. It is to be noted that the energy contained in the triangular flash would just be equal to that contained in the square flash when both have equal peak intensities and the square flash has one-half the duration of the triangular flash.

TABLE 2

SQUARE AND TRIANGULAR FLASHES FOR EQUAL VISUAL EFFECTIVENESS

Wave Form	Duration (ms)	Peak Intensity (cp)	Flash Energy (cp x sec)
Triangular	28	10	0.14
Square	14	10.8	0.15
Triangular	82.4	3.5	0.14
Square	41.2	2.8	0.12
Triangular	124	3.5	0.22
Square	62	2.6	0.16

As long as the duration is less than the critical duration, it appears to matter little how the intensity is distributed in time and what combination of intensity and duration is used so long as the flash energy is constant. Other investigations (6) have shown this reciprocity to hold down to durations as short as a few microseconds. The results of this experiment confirm the findings of Table 1, namely, that it requires more energy

at durations longer than a given critical value than at shorter durations to cause a given sensation of subjective intensity. It is also interesting to note that it requires more energy for a match when the wave form is triangular than when it is square when one or both flashes are longer than the critical transition duration. This effect implies that for flashes longer than the critical duration the distribution of intensity should maximize the energy in the minimum duration. Hence, a square wave of intensity would be the best choice.

Flash Rate

It was not possible to set up an adequate experiment to determine the most effective flash rate, however, some observations can be made. An enhancement of the subjective intensity by a factor of approximately 2 was noted for flash rates of about 8-12 per second (Brucke Phenomena). Thus, for a doubling of the effective intensity at this higher frequency the battery power consumption would be multiplied about 8-12 times over a flash rate of 1 per second, hence, flash rates in this range were considered impractical for battery-operated devices. Studies by Gerathewohl (13) indicate that for sources with high visual contrast there is little visual difference between a flash rate of 1 per second and 4 per second, therefore, from the standpoint of maximum battery life, 1 flash per second would be the better choice.

No references were found in the literature to studies of flash rates slower than 60 per minute, thus, additional work is necessary to determine the effectiveness of flash rates slower than 60 per minute. Personal experience in tests made on automotive flashers by the authors indicate that approximately 40 flashes/minute is about the minimum value acceptable for high energy flashes in the order of 40 cp x seconds. At the present, one can only say that as the flash rate is decreased below 60 per minute, the aspect of the source changes from a localized flashing appearance to that of an indeterminant source slowly turning on and off without a high demand for attention.

Localization

The term localization is used here to signify the ability of the driver to judge the distance and position of the hazard with respect to the roadway. This ability of the driver is another important factor in the design of portable roadway hazard warning devices. It is important to know whether flash duration and repetition rate affect this ability and if so, in what manner.

The small amount of work to be found in the literature is negative (7). Observations during the conduct of the experiments on duration and wave form did not indicate any correlation between flash duration and localization.

A series of judgments were made in the following manner: In the first group the subject was asked to estimate the separation in distance units between two modulated sources that were equal in duration and intensity. The peak intensity of the flash was held constant throughout the first series and only the duration was varied. In the second group, the intensity was increased while the duration was decreased to maintain a constant effective intensity. The actual separation of the two stimuli was 2 ft.

The results indicate no correlation between the ability to judge the separation distance between two flashing sources and the duration of their flashes. However, the results are not sufficiently conclusive to disprove a correlation. Even when the two sources were burning steadily, there was no significant change in the judgment of the separation. Two steadily burning point sources isolated in space offer little information as to their physical separation (Tables 3 and 4).

The effect of pattern on localization has not been studied as a part of this report. Other investigators have stressed the importance of pattern and the rate of change of the pattern with speed as a major factor in visual judgments (14, 15). This factor should not be overlooked in the placement and number of roadway hazard warning devices used at a particular location.

TABLE 3

JUDGMENT OF LINEAL SEPARATION OF TWO MODULATED LIGHT SOURCES WITH INCREASING DURATION AND INCREASING SUBJECTIVE BRIGHTNESS (PEAK INTENSITY = 10 CANDLEPOWER = CONSTANT)

Run No.	Duration (ms)	Subject JH (ft)	SM (ft)	DD (ft)	HG (ft)	KF (ft)
1	5	4	2	3	2	2.5
2	10	5	4	4	1.5	3
3	20	3	2	3	2	3
4	30	3	4	4	2	3
5	40	4	3	4	2.5	2.5
6	50	3	3	3	2.5	3
7	75	2.5	3	3	2	4
8	100	3	3	3	2	4
9	250	3	3	3	2	3
10	∞	3.5	3	2	2.5	2.4

TABLE 4

JUDGMENT OF LINEAL SEPARATION OF TWO MODULATED LIGHT SOURCES WITH DECREASING DURATION AND EQUAL SUBJECTIVE BRIGHTNESS

Run No.	Duration (ms)	Subject JH (ft)	SM (ft)	DD (ft)	HG (ft)	KF (ft)
1	200	3	1.5	3	2	3
2	100	2	2	4	1.5	3
3	50	3	3	3	1.5	3
4	25	3	4	4	1.5	4
5	16.6	4	4	4.5	1.5	4
6	12.5	3	4	2.5	2	3.5
7	10	3	3	-	2	3

CONCLUSIONS

1. For flashes of light that are to be above the threshold value of energy required for the detection of the presence of the light by a motor vehicle operator under normal conditions at night, an energy content of at least 0.10 candlepower-seconds of red colored light or 0.25 candlepower-seconds of amber colored light should be developed in the principal viewing directions (assumed to be within 5 deg of the photometric axis). These values are several times the minimum perceptible values for a representative state of adaptation of a motorist and are 100 to 1000 times the minimum perceptible values for a completely dark adapted eye. Moreover, they are several hundred times less than the energy in an automotive turn signal or a flashing traffic signal. At present there is no technique to use except experience in establishing the energy content of a flashing light to give an adequate warning signal. The better designed roadway hazard warning devices now manufactured will meet the above requirements.

2. The flash duration need not exceed 50 milliseconds total time. Any time less than 50 milliseconds will give a constant effective intensity for the same energy in the flash (cp x seconds = constant). Any time greater than 50 milliseconds will require more energy to give the same effective intensity for the flash.

3. The effective intensity of the flash is independent of the wave form when the dur-

ation is below 50 milliseconds, however, when the duration is above this value, the most effective wave form is that which most closely approximates a square-wave.

4. The flash rate need be no faster than 60 flashes per minute for an effective signal and could possibly be slightly slower than this value, but further study is necessary to determine this point.

5. Localization — no correlation between ability to judge separation distance and flash duration was detected. More work needs to be done on patterns of light and synchronization of flashes to convey distance information.

The two main requirements of a hazard warning system are to attract the driver's attention to prepare him for an unusual situation and to provide some clue as to the position and extent of the hazard.

The first requirement can be satisfied by a single flashing source that is of sufficient intensity and duration to be above the visual threshold. It may be advisible to combine the energy consumed in several weaker randomly flashing lights into one stronger light so that it might be more comparable in flash energy to some of the commonly encountered warning signals having luminous flash energy in the order of 40 candlepower-second.

The second requirement is best met either by providing ample illumination of the hazard to reveal its form and texture or by delineating the hazard by a group of light sources arranged in a meaningful configuration.

Possibly both requirements could be met by a group of flashing sources each of luminous energy in the order of 0.10 cp x second, that are arranged in a meaningful pattern and synchronized to flash simultaneously. Such a group, flashing in unison, probably would be as effective as a single higher intensity flashing source used in combination with a pattern of steady burning lights.

It is suggested that an absolute minimum of three random flashing lights should be considered for marking any roadway hazard and that these should be grouped within a visual angle of not more than 1 deg when the driver is 500 ft to the nearest unit and when the driver is in the most critical traffic lane on the road with respect to the hazard. The number and pattern of lights for marking any given hazard should receive additional study in order to arrive at suitable recommendations for field use.

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