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GUIDELINES FOR ENHANCEMENT OF VISUAL CONSPICUITY OF THE TRAILING END OF TRAINS

John B. Hopkins

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16. Abstract

This report summarizes a comprehensive study of potential means of reducing the probability of train-train collisions through enhancement of the visual conspicuity of the trailing end of trains. The basic function requirements and constraints for such devices are set forth, followed by a review of relevant past research. The form and parameter values of the warning system found to incorporate the best combinations of practicality and effectiveness are specified; in essence the systems consists of clear xenon flash-tube beacons mounted on opposite sides of the car at the roofline, flashing simultaneously.

Experimental use and observations of the system are described, and detailed recommendations are included.

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PREFACE

The work described in this report was performed in the context of an overall program at the Transportation Systems Center to provide a technical basis for the improvement of railroad transportation safety. The program is sponsored by the Federal Railroad Administration, Office of Research, Development, and Demonstrations. The program supports Government activities designed to promote greater safety in railroad freight and passenger service.

The work reported here has benefited greatly from the interest, information, and cooperation of numerous people at railroads, suppliers, and other Government laboratories. Among the many TSC staff members who have made significant contributions are A. Newfell, responsible for hardware acquisition, installation, and test, and D. DeVoe, preimarily concerned with human factor considerations. A Lavery was responsible for overall direction and review of the project.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

EXECUTIVE SUMMARY

During the last two years the Federal Railroad Administration has sponsored research with the objective of enhancement of the visual conspicuity of the trailing end of trains. The objective is reduction of train-train collisions. Research has included examination of the overall problem, selection of a preferred warning/marking system, behavioral and durability testing, and assessment of the technology.

A review of the results of these activities, supplemented by special studies as required, now permits determination of guidelines as to the optimal form such warning systems should take. There are three primary criteria: high conspicuity, uniqueness, and provision of range information. These can best be met through the use of a pair of clear xenon flash tube beacons, mounted on opposite sides of the car roofline, flashing simultaneously at a combined rate between 45 and 75 flashes per minute. The effective intensity (defined by the Blondel-Rey equation) is to be greater than 400 candela (not exceeding 800) at night, and 4000 in daytime.

It is estimated that the basic installation cost is $250, divided between hardware and labor. The annual cost, including maintenance and amortization, should be approximately $20-$35. Conservative (but highly approximate) estimates of system effectiveness yield a potential benefit/cost ratio of approximately 3.

1. INTRODUCTION

When a passenger train is overtaken and struck by a second train, the resultant toll of casualties can be as great as for a major airplane crash. The effectiveness of signal systems, crew performance, and operating rules have made such events rare in the United States. Nonetheless, the fact that such accidents can and do occur occasionally makes it highly appropriate to seek means of further reducing this hazard. A number of approaches, some involving considerable expense and technical complexity, can be followed, and in situations involving high traffic density and short headways, these may be warranted. However, this report addresses the problem on a more fundamental level. It is reasonable to assume that no train operator ever deliberately collides with a preceding train - accidents of this type result from a failure to realize sufficiently early the need to apply brakes. That such errors occur is not surprising when one considers the very great distances required to stop high speed or heavy trains - in excess of one mile in some cases.

The difficulties of achieving safe train separation merely by visual contact have always been recognized, and have led to development of the signal systems and operating practices which have long been in use. However, a brief or minor human, electrical, or mechanical failure is never impossible, and there can be no question as to desirability of taking all reasonable steps to enhance the likelihood that a stopped or slowly moving train will be perceived as early as possible by the operator of any following train.

This concept is well established; marking and lighting of the trailing end of trains - particularly those carrying passengers - is relatively common. However, the adequacy of many currently-used systems is open to question, particularly under adverse conditions of visibility. The focus of this study is a brief review of existing literature and technology relevant to enhancement of the trailing-end conspicuity of trains, leading to recommendation of the most effective and practical means of implementing this conventional concept.

The subject of improvement of visual conspicuity, particularly by means of special lights, has been studied in the past in a wide variety of contexts. Examples include aviation (navigation aids, obstacle indications, and collision avoidance), maritime activities (warnings, buoys, location of accident survivors), and automotive applications (vehicle marker and indicator lights). In a related area, the Federal Railroad Administration has been exploring the topic of enhanced locomotive conspicuity since 1969, with reference to the prevention of grade crossing accidents. Beginning in late 1972, the Transportation Systems Center, under FRA sponsorship, has studied and reported upon the general trailing-end visibility subject. Taken as a whole, this provides a sufficient background to permit a rapid definition and selection of those techniques which have the greatest promise of providing effective protection. This report will utilize this information within the special context of revenue passenger rail vehicles and operations.

2. REQUIREMENTS AND CONSTRAINTS

A number of requirements must be met by any active visual warning system if it is to be both practical and effective. These are listed below.

1. Alerting Effectiveness. The intended observer - the engineer or other crew members of a following train - may be assumed to be alert, with primary attention in the direction of the potential collision object; however, in many cases he will have no expectation of the possible presence of any such hazard, and he may be looking for other types of signals, landmarks, etc.

2. Information Content. There are many bright steady and flashing lights often found in the visual environment. A preceding train may be a relatively unexpected sight. A viable trailing-end marking system must be highly characteristic so that identification will be rapid and accurate. It must be highly conspicuous, regardless of time of day, weather, and surroundings. Finally, it is most important that the observer be able to obtain a good measure of distance, which will also provide an indication of closing rate.

3. Absence of Deleterious Effects. Under some circumstances, such as operation near a second train on a parallel track, a train crew might be exposed to a warning system for a lengthy period. A similar situation could arise for motorists on a road paralleling tracks. It is most important that there be no circumstances under which vehicle operators be seriously discomfited, confused, or disoriented by such an experience.

4. Low Cost. The potential "population" to be protected includes all passenger-carrying rolling stock - approximately 7000 vehicles. Given the low rate of occurrence of the type of accident of concern here, the costs of

both installation and maintenance must be very low if this means of protection is to represent an optimal expenditure of safety resources. Related to both cost and safety is the need for a high degree of equipment reliability.

3. REVIEW OF RELEVANT RESEARCH

In 1972, FRA sponsored a task force study of the most effective and practical means of enhancing the conspicuity of the trailing end of trains, in order to reduce the possibility of train-train collisions.* It had five elements: (a) definition of a usable number of categories of target, background, and ambient conditions which include the great majority of situations actually encountered; (b) estimation of the stimuli required for each category to increase significantly the detection probability for typical observers; (c) examination of all potentially feasible visibility aids in terms of these criteria; (d) determination of estimated costs, lifetime, and power consumption of techniques which appear promising in terms of effectiveness; and (e) delineation of alternative systems, consistent with one another, comprising a hierarchy of effectiveness and cost. The devices suggested as optimal include large areas of fluorescent material arranged in a distinctive pattern, retro-reflectors at each corner, and flash lamps of moderate intensity.

The passive systems - fluorescent panels and reflex-reflectors - provide effective marking under many conditions, but require either ambient light, or illumination located near the observer. They are primarily relevant to the case of marking vehicles which do not have electrical power available. However, xenon flash lamps are more effective under all circumstances, as the passive systems are not required (except for partial redundancy) when such lights are used. In the case of passenger-carrying rolling stock, power is always available.

The flash lamps - xenon strobe units - were recommended to be clear (uncolored), mounted on the upper corners of the car, and flashed simultaneously at a rate of 45-75 flashes per minute. The fixed location and simultaneous flashing provides a signal which is

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*This is reported in "Enhancement of Train Visibility," September, 1973, Report No. FRA-ORD&D-74-15, NTIS Accession Number PB-223899/A5.

both unique and informative - the spacing provides a clear indication of range, and aids in estimation of closing rate. Calculations showed that an effective intensity of 3800 candela would provide a light intensity 50 times greater than the FAA standard detection threshold at a distance of 1/4 mile, in air permitting 5-mile visibility.

Field observations of this system were carried out by TSC on the Boston & Maine Railroad in February, 1973. A Buddliner was appropriately marked and equipped, (see Fig. 1) and followed by a second Buddliner from which observations were made. The test was run in daylight, in the morning and early afternoon of a clear day. The strobe lights had an effective intensity of approximately 4000 candela during most parts of the test. With no haze and the sun high in the sky, all observers immediately detected the test car at a distance of three miles, the maximum length of tangent track available. In several instances in which the test car was almost totally obscured on curves, a single strobe (with its characteristic color (white), flash rate, and short pulse duration), was readily identified. (For comparison, a fluorescent red flag used by a flagman was discernible at approximately .7 mile.) With the test car headed into the sun (still fairly high in the sky), and a substantial back-lit haze, the strobes (at 2000 candela effective intensity) were first detected by most observers at 1.4 miles; they were highly conspicuous at .5 mile.

In February, 1974, a more comprehensive test was carried out by TSC with the cooperation of the Southern Pacific Transportation Co. Five systems were considered, under both day and night conditions, including the sizes of strobe lights similar to those used on the B&M test (both with high and low intensity modes) and a variety of red incandescent lights, both flashing and steady. The test car is shown in Figure 2. A large number of observers attended this test, including experts in safety, railroad operations, and human perception and behavior. The basic conclusion was that strobes with effective intensities of 4000 candela daytime, and 400 candela at night, were highly conspicuous and distinctive at distances up to 3 miles and had no undesirable side effects.

Figure 1. Buddliner as Used In February, 1973 Test (B&M)

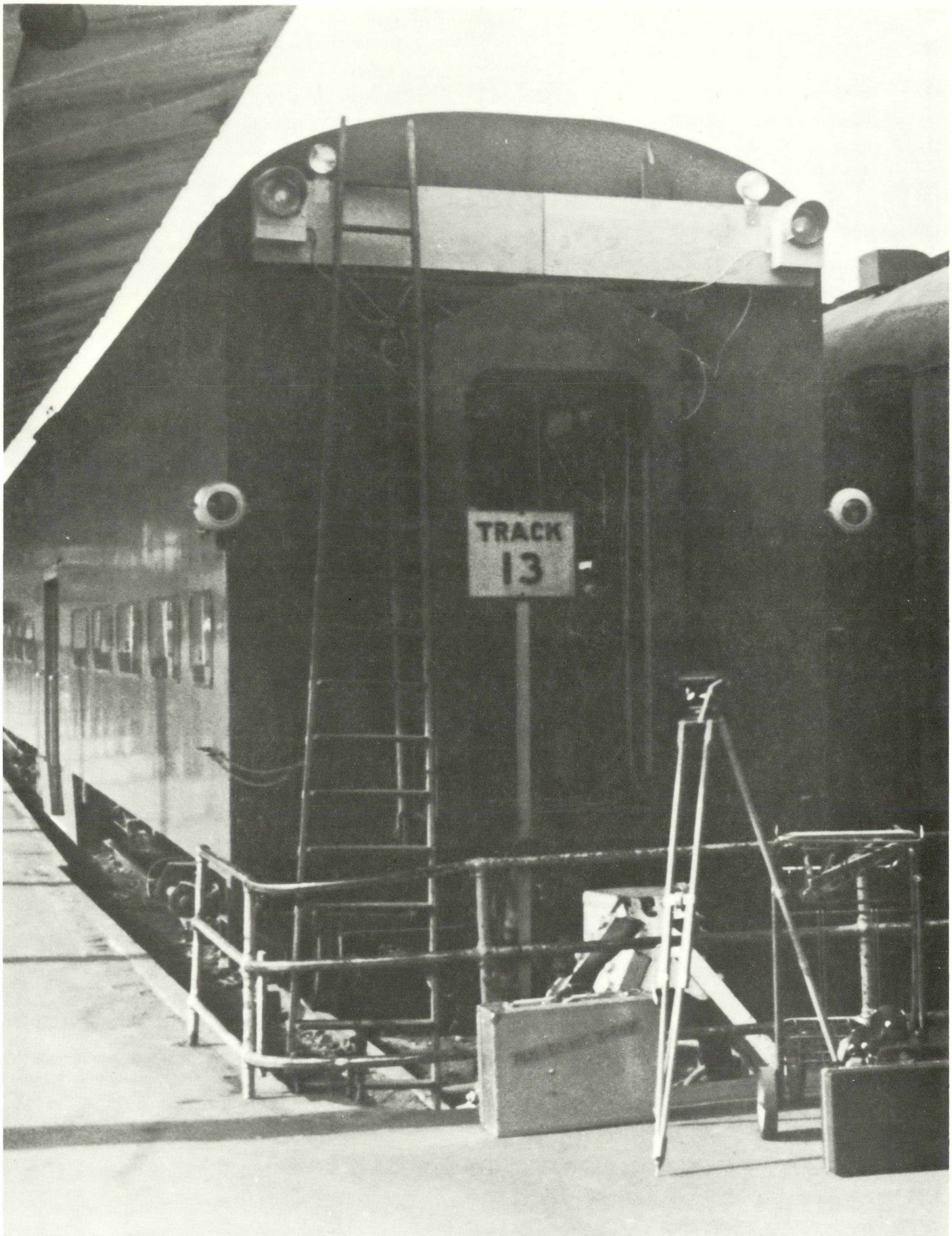

Figure 2a. Passenger Car Equipped for February, 1974 Test (SP)

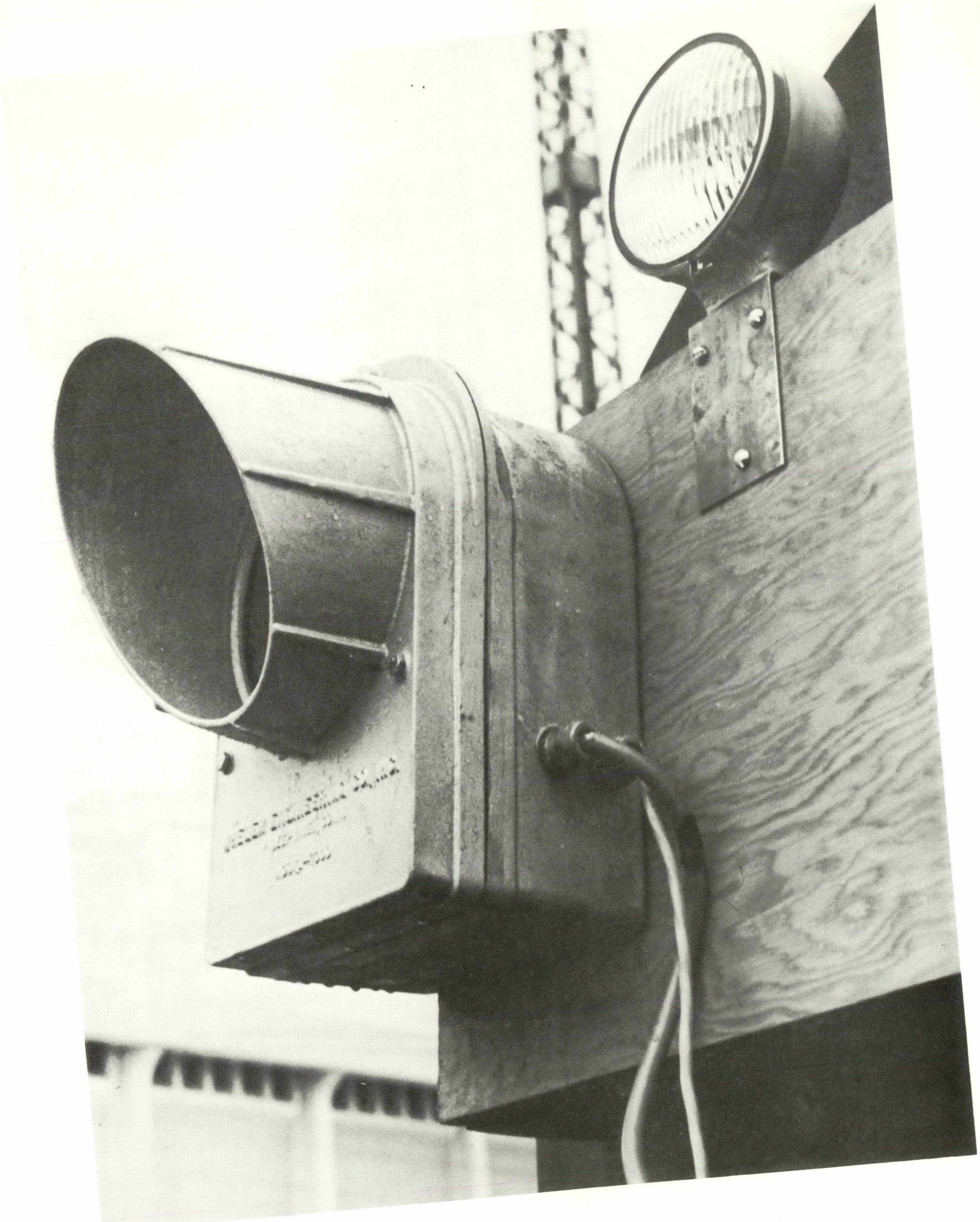

Figure 2b. Strobe Lights Used In February, 1974 Test (SP)

(4000 candela at night was found disturbing, particularly when viewed from a "chase car" on a parallel highway.) All red lights, in addition to having lower conspicuity under some conditions, were subject to confusion with wayside block signals, grade crossing signals, and other lights in the environment. The importance of a light location high on the car was clearly seen; this minimizes the obstructive effect of rolling terrain.

A highly relevant parallel study has been under way for several years: determination of the optimal means of enhancing visual conspicuity of locomotives as seen by motorists approaching grade crossings. (In that case the assumed viewing distance is substantially less - generally only a few hundred feet - and the alerting function is of greater importance than the information aspect.) In addition to the study of literature of human factors research, hardware, and related applications, that effort has resulted in the installation of strobe lights on four Bangor & Aroostook Railroad locomotives, for use during normal operations. A variety of observations have been made, all confirming the high conspicuity of the devices and the absence of any undesired effects. When used in a railroad environment, under daytime conditions of heavy snowfall, 600 candela strobes were clearly visible at approximately 1100 feet, a distance at which the shape of the locomotive could barely be seen. (No observations were made at greater distances under these conditions.)

4. DETAILED FUNCTIONAL SPECIFICATIONS

The literature reviews, analyses, and tests described in the previous section strongly support selection of flashing lamps as the most effective and practical means of increasing the conspicuity of the trailing end of trains. In this section detailed optimal system characteristics will be summarized.

1. Flash Rate. Flashing lights have been found to be markedly superior to steady beacons for applications of this type. It has generally been found that, for lights of specified intensity, the ease of identification is greatest for a flash rate of approximately 1 flash per second, or 60 per minute. At significantly lower rates, effectiveness decreases, and higher frequencies, particularly in the range of 6 to 12 flashes per second, can be highly disturbing and disorienting to observers.

2. Flash Duration. It has long been established that the alerting effectiveness and distinctiveness of flashing lights increase as flash duration decreases, down to durations of approximately .1 sec. Below that length, effectiveness is only a function of total energy radiated. Thus, a basic specification is that each flash be shorter than .1 sec. This is substantially less than is achieved with the incandescent lights commonly used by railroads, and thereby provide a relatively unique signal in that environment.

3. Intensity. Because of the relationship between flash duration and alerting effectiveness, and the variation of light intensity during the pulse, short-flash lights are generally characterized in terms of "effective intensity," which is a measure of the steady intensity necessary for equivalent conspicuity (point source, seen at threshold). Mathematically, this is calculated by the Blondel-Rey equation,

$$I_e = \frac{1}{.2 + (t_2 - t_1)} \int_{t_1}^{t_2} I\ (t)\ dt,$$

where

I_e = effective intensity (candelas)

$I\ (t)$ = instantaneous intensity (candelas)

t_1 = time at beginning of flash

t_2 = time at end of flash

$(t_2 - t_1)$ = flash duration

Both theoretical considerations and experimental observations indicate that for the range of interest (1/4 to 1 mile) an effective intensity of 400 to 600 candela provides highly effective illumination at night, at twilight, and on dark days. (For dark nights, effective intensities as low as 40 to 60 candela would be adequate, but these values are much too low for other conditions.) For day use, intensities as high as 4000 to 6000 candela may be necessary to provide high effectiveness in conditions of strong backlighting or other reduced visibility situations. However, values greater than 1000 candela can be objectional to crews and others at night.*

4. Color. Primary information to facilitate identification and correct interpretation of the lights is to be conveyed through the combination of configuration, flash rate, and flash duration, with color of reduced importance.

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*Xenon strobe lights are often described in sales literature in terms of peak candlepower (equivalent to candela); numbers in excess of 1,000,000 are often quoted. This peak intensity, however, is not an adequate means of characterizing light intensity. The eye responds not to an instantaneous brightness, which may last for only microseconds, but to the total light energy received over a time long compared to the flash duration - of the order of .1 second. Meaningful specification must therefore be in terms of the time-integral of the intensity, or, preferably, with use of the "effective intensity" concept, defined above.

Experimental observations show that color of lights (particularly the distiction between white and amber) is difficult to perceive at large distances. Although red and amber might be suggested due to the connotation of potential hazard, their use in a railroad environment is highly subject to possible confusion with block signals, grade crossing lights, and non-railroad lighting such as is used in advertising and on motor vehicles. (It should be noted that clear lights are typically used in both aviation and marine applications.) Further, white lights - particularly those with the high color temperature of xenon flash tubes - are more readily distinguished from difficult background such as the setting or rising sun.

5. Configuration. In terms of visibility in rolling terrain and to provide maximum assistance to range discrimination, it is desirable to have two lights, located on opposite sides of the car (separated by a full car-width), mounted as high as possible - preferably at the roof-line. They are to be aimed straight back-parallel to the axis of the car. Allowance for hills and terrain implies a minimum beamwidth (defined as the angle at which intensity is reduced to 50% of its value at maximum) of $\pm 5°$ in the vertical plane, measured from the axis of the train.

The necessary horizontal beamwidth is determined by the degree of track curvature over which operations are carried out and the minimum distance at which effectiveness is required. The basic relationship between half-power beamwidth θ (radians), track curvature ϕ (radians), and distance D (feet) at which an observer will receive one-half the beam center intensity is

$$D = \frac{11460 \tan \theta}{\theta\sqrt{1+\tan^2\theta}}$$

For the cases of interest (small θ), and θ and ϕ expressed in degrees, approximated by

$$D = 200\ \theta/\phi$$

or

$$\theta = \frac{D\phi}{200}\ .$$

For example, a maximum track curvature of 2° and a required range of 1320 feet (1/4-mile) imply a minimum beamwidth of 13.2°. Although appreciable light intensity will be seen well outside the half-power beamwidth, reliance upon this factor compromises the margin available for bad weather conditions, visual clutter, and bright backgrounds. Thus, unless operations are restricted to low-curvature track, a horizontal beamwidth of at least $\pm 15°$ from the longitudinal axis of the train is recommended. In order that the lights be useful for range discrimination, simultaneous flashing is necessary; this also contributes to distinctiveness.

5. OPERATIONAL CONSIDERATIONS

5.1 VARIATION OF INTENSITY WITH AMBIENT ILLUMINATION

The intensity required for full effectiveness varies widely as existing illumination and viewing conditions vary. In the previous section, three possible cases were mentioned; more could be defined. Xenon flash lamps are readily varied in intensity, and automatic adjustment is not a problem. However, use of a large number of brightness levels complicates the power supply circuitry, increasing cost and reducing reliability. The experimental activities reported above make clear that only two levels are necessary to provide effective and acceptable performance. At night, an effective intensity of 400 candela is substantially more than necessary, but no deleterious effects have been noted. Although this level is usually highly conspicuous in daylight as well, difficult viewing conditions are often encountered. A major portion of high-traffic-density passenger-train movement occurs in urban areas, at times near sunrise and sunset. Both haze and smog are often to be expected, in some cases back-lit by a sun relatively low in the sky, implying that visibility will be poorest just when the greatest hazard exists. Thus, the higher effective intensity (4000 candela) should be used during daylight, to be switched to 400 candela for twilight or lower illumination. Figures commonly used for illuminance (incident light) at such times range from 20 lumens/m^2 for a very dark day, through 2 lumens/m^2 for "twilight," to .2 lumens/m^2 at "deep twilight." (1 lumen/m^2 = 10.764 foot-candles) It is recommended that the higher intensity (4000 cd) be used whenever ambient illumination (from the zenith) is greater than 20 lumens/m^2, and that only the lower intensity be used below 1 lumen/m^2. In the transition region, either is acceptable. (This large overlap is possible because of the wide dynamic range of the human eye, and avoids the need for precise - and expensive - measuring systems for automatic adjustment.)

5.2 RELATIONSHIP TO SIGNAL AND OTHER SAFETY SYSTEMS

Concerns have occasionally been expressed that the presence of such a warning system might diminish reliance upon signal systems and operating rules. However, it should be noted that the system recommended here is merely a variation on the current practice of providing some form of rear warning lights. Operating rules are frequently based upon visual sighting, and there should be no deleterious effects from improving the likelihood that such sighting can occur. Indeed, the logical conclusion of such objections is that trains should be camouflaged - surely an untenable position. In fact, train crews interviewed informally on this subject have been found to be favorably inclined toward any systems which make more precise their complex task of surveillance and information gathering. The range information inherent in the wide (and standard) light spacing is felt to be particularly valuable.

A second point of concern is the possibility that confusion could be created between such warning lights and wayside block signals. The experimental tests reported above make clear that the strobe lights are particularly free from this problem. Such a weakness does appear to be a valid concern with both steady and flashing incandescent red lights, although experienced engineers typically are well aware of the location and characteristics of all block signals, and are adept at such discrimination. However, white lights are far less common in railroad signaling, and the very distinctive short-duration flashes of xenon strobe lights have been found to pose no problem whatsoever. (The simultaneous paired flashing also contributes to a unique effect.)

6. APPROPRIATE TECHNOLOGY

The basic specification concerning flash characteristics could be met with either a xenon flash tube or a rotating incandescent lamp of narrow beamwidth. (An incandescent bulb cannot achieve the short flash duration and high repetition rate required.) Several considerations lead to a strong preference for the xenon flash tube. A rotating structure is inherently more complex, more prone to mechanical failure, and likely to be more expensive. The expense of the xenon lamp is largely in the electronic flasher circuit, for which very high reliability can be obtained. Although the incandescent bulbs are lower in cost, their lifetime is typically far shorter than the 5000 to 10,000 hours which can be expected from a xenon beacon. (This is sufficient for one to two years between bulb changes.) Synchronization of two rotating assemblies to provide the recommended simultaneous flashing effect would pose problems and increase cost. Finally, the great sensitivity of incandescent lamp brightness to supply voltage adds further complication to assurance of within-specification operation.

Empirically, xenon strobes have shown very good durability in related applications, whereas rotating assemblies, used continuously, are reported to present maintenance problems.

Cost of installation of the proposed system is estimated at $250 per car end, broken down as follows:

Xenon flash tube beacons	$150
Installation labor	100
	$250

This assumes a standardized procedure has been established, and the operation is coordinated with other servicing. The annual expense associated with these devices, including both maintenance and amortization, should be approximately $35 per car end for a car normally in an end-of-train position. However, if cars are used randomly, the lights will have a much lower duty cycle, and maintenance costs will be substantially reduced. Thus, $20-$25 is likely to be a more accurate estimate for entire fleet.

7. BENEFIT-COST CONSIDERATIONS

Although costs can be estimated with reasonable accuracy, potential benefits are difficult to assess. Relatively few trailing-end passenger-train collisions occur. However, those rare events have catastrophic results. Normal statistical analysis is of relatively little assistance in this case. However, simple calculations can provide useful insight. If both ends of all 7000 passenger cars were to be equipped, the annual maintenance/ amortization cost would be of the order of $350,000, or $3.5 million over a ten-year period. Based upon NHTSA estimation of the societal cost of accidents, one collision with the toll of the October 1972 ICG crash in Chicago (45 killed, 344 injured) has a cost in excess of $10 million. Thus, prevention of only one such accident every ten years, with no "minor" benefits, would imply a benefit-cost ratio of approximately 3.

It should be noted that the costs could actually be substantially lower than indicated above. It should be possible to arrange operations such that many cars are not used in an end-of-train location. Further, use of detachable, battery-powered or plug-in lights might prove to be a significantly lower cost means of implementation. The cost of installation should also be significantly less if carried out as part of original construction or major car renovation.

8. SPECIFIC RECOMMENDATIONS

The review and study synopsized here leads to the following recommended visual marking system for rail passenger trains.

A pair of clear ("white") xenon flash tube lights, flashing simultaneously at a flash rate between 45 and 75 flashes per second, should be mounted on the trailing-end car of all passenger trains. The beamwidth (in terms of the point at which intensity is reduced by 50% compared to the maximum value) is to be $\pm 15^{\circ}$ in the horizontal plane and at least $\pm 5^{\circ}$ in the vertical. The effective intensity (as defined by the Blondel-Rey equation) is to be between 400 and 800 candela when ambient illumination is below 1 lumen/meter^2, between 4000 and 6000 candela when ambient illumination is greater than 20 lumens/meter^2, and between 400 and 6000 candela for ambient illumination between 1 and 20 lumens/meter^2. The lights are to be mounted so that each is within 1 foot of the roofline, with one no more than 1 foot from the right edge of the car, and the other no more than 1 foot from the left edge. (Measurements are to be from the center of the lamp lens.)