GRADE CROSSING SAFETY
Studies & Reports

PB 244551/AS
Mirabella

REPORT NO. FRA-OR&D-75-71

GUIDELINES FOR ENHANCEMENT OF VISUAL CONSPICUITY OF TRAINS AT GRADE CROSSINGS

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MAY 1975

FINAL REPORT

Prepared for

U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL RAILROAD ADMINISTRATION
Office of Research and Development
Washington DC 20590

TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No. FRA-OR&D-75-71	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle GUIDELINES FOR ENHANCEMENT OF VISUAL CONSPICUITY OF TRAINS AT GRADE CROSSINGS		5. Report Date May 1975 6. Performing Organization Code
7. Author(s) John B. Hopkins and A.T. Newfell		8. Performing Organization Report No. DOT-TSC-FRA-74-15
9. Performing Organization Name and Address U.S. Department of Transportation Transportation Systems Center Kendall Square Cambridge MA 02142		10. Work Unit No. RR502/R5335 11. Contract or Grant No.
12. Sponsoring Agency Name and Address U.S. Department of Transportation Federal Railroad Administration Office of Research and Development Washington DC 20590		13. Type of Report and Period Covered Final Report June 1972 - Nov. 1974 14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

This report summarizes a comprehensive study of potential means of reducing the probability of train-motor vehicle collisions at railroad-highway grade crossings through enhancement of the visual conspicuity of locomotives. Passive techniques are reviewed, and requirements and constraints upon active systems are described. Past research is reviewed, followed by derivation of functional specifications and discussion of practical operating considerations. Operational tests of devices deemed most appropriate to the application are described, with detailed recommendations.

The preferred system consists of clear ("white") xenon flash-tube beacons mounted on opposite sides of the locomotive cab roof, flashed alternately, used in conjunction with amber incandescent lamps outlining the locomotive.

17. Key Words Conspicuity Enhancement Grade Crossing Protection Train Visibility		18. Distribution Statement DOCUMENT IS AVAILABLE TO THE PUBLIC THROUGH THE NATIONAL TECHNICAL INFORMATION SERVICE, SPRINGFIELD, VIRGINIA 22161	
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No. of Pages 56	22. Price

Form DOT F 1700.7 (8-69)

PREFACE

The work described in this report was performed as part of an overall program of the Transportation Systems Center to provide a technical basis for the improvement of grade crossing safety. The program is sponsored by the Federal Railroad Adminsitration, 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 individuals at railroads, suppliers, and other Government laboratories. The assistance of the Boston & Maine, Bangor & Aroostook, Atchison, Topeka and Santa Fe, and Union Pacific Railroads, has been particularly appreciated. TSC staff members who have made especially significent contributions include A. Newfell, responsible for equipment acquisition, installation, and operational testing, and D. DeVoe, primarily concerned with human factor considerations. The project was under the overall direction of J. Hopkins; management of TSC grade crossing protection program is the responsibility of R. Coulombre.

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EXECUTIVE SUMMARY

During the last five years the Federal Railroad Administration has sponsored a number of research projects with the objective of enhancement of the visual conspicuity of trains. In most cases, the particular concern has been reduction of accidents at railroad-highway grade crossings. Past research has included examination of the overall problem, development of a variety of prototype warning systems, 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. Two primary functions are involved: alerting (getting the attention of the motorist), and informing (providing information as to the nature of the possible hazard). It has been judged preferable to separate the realization of these functions. For alerting, a pair of clear xenon flash tube beacons is recommended, mounted on opposite sides of the locomotive cab roof, flashing alternately at a combined rate between 1-1/2 and 3 flashes per second. The effective intensity (defined by the Blondel-Rey equation) is to be between 400 and 800 candela for a single-intensity system. If automatic switching between separate day and night modes is provided, intensities of 800 to 4000 cd (day) and 100 to 400 (night) are recommended. The lights are to be flashed, at a minimum, from 30 seconds prior to the locomotive's reaching the crossing until 30 seconds after (or until the entire train has crossed, whichever is shorter); continous operation while the train is in motion is preferred.

At night, a clear indication to the motorist of the nature of the object is to be provided by a series of outline lights, of the type commonly used on large commercial vehicles. Amber in color, they are to be mounted on the front corners of the locomotive and along the upper edges and side frames at 12' to 20' intervals, for a distance of at least 40'.

It is estimated that the basic installation cost will be less than $500, evenly divided between hardware and labor. The annual cost, including maintenance and amortization, should be approximately $50. Conserative estimates of system effectiveness yield a potential benefit-cost ratio greater than 10.

1. INTRODUCTION

The specific causes of the estimated 12,000 annual train-vehicle collisions at rail-highway grade crossings are poorly understood and defy quantification. The information which exists is largely statistical rather than behavioral. For example, accident data clearly reveal the benefits of installation of train-activated warnings. However, this source can provide only limited guidance in the development of new warning systems. The alternative, at present, is to utilize a combination of intuition, experience with related situations, and the professional judgement of those with relevant expertise. Such a course can be effective in suggesting the preferred form for a particular warning concept, and has been followed here. However, it must be noted that this approach permits only approximate estimation of potential system effectiveness.

Reduction of accidents at railroad-highway crossings can be sought in many ways, the most common of which is installation of train-activated motorist warning devices at the crossings. However, economic analysis suggests that the great majority of grade crossings are characterized by such low train and vehicle traffic densities, and concomitant low accident probability, that it is impossible to justify the expenditures required for active devices - those resources can provide a better safety return elsewhere. In addition, a substantial number of accidents occur even at locations with such protection, implying the need for additional measures. Since it is reasonable to assume that very few motorists deliberately drive into a train or in front of a locomotive, one must conclude that a key element in most accidents is a failure either to see the train or accurately to judge its arrival time. Indeed, in 7 of the 13 grade crossing accidents investigated under the NHTSA Multidisciplinary Accident Investigation program the driver reported failure to see the locomotive. This suggests the importance of determining the most effective means of enhancing the visual conspicuity of locomotives. Such a view is reinforced by the numbers involved: there are well over 400,000 public and private crossings, compared to approximately 27,000 locomotives.

This is not a new concept. Some railroads have long used locomotive-mounted beacons. One of the earliest activities of the FRA in the grade crossing research area was a study of the subject. Since that time, under FRA sponsorship, further conspicuity-aid research has been carried out at the National Bureau of Standards, TSC, and the Naval Ammunition Depot at Crane, Indiana. Integration of the results of these comprehensive activities is now possible, permitting definition of the optimal form that locomotive visual warning systems should take.

Passive markings - painting of the locomotive with large areas of bright, contrasting colors - has been extensively treated previously,[1] and will merely be summarized in the following section, with some additional comments. The remainder of this report will be devoted to research findings concerning active (lighting) systems, which appear to offer substantial safety benefits (particularly at night), but which have required more elaborate and comprehensive analysis and test for determination of an optimal form.

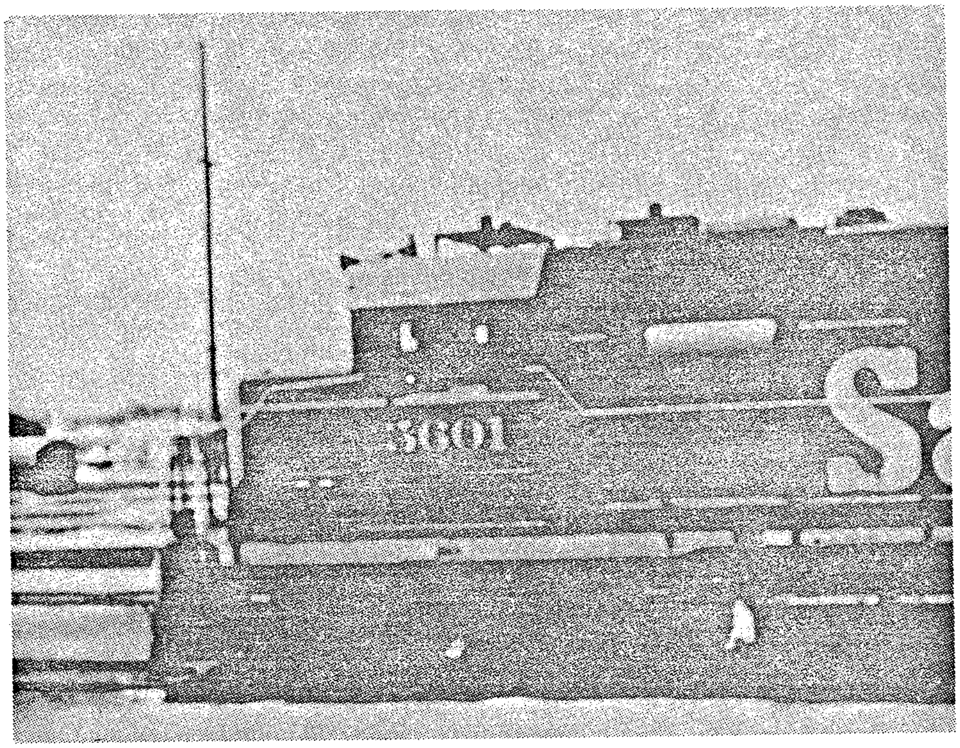
2. PASSIVE VISUAL ALERTING SYSTEMS

Improvement of the visual conspicuity of locomotives by means of distinctive painting was examined in 1970 under FRA auspices by Aurelius and Korobow of Systems Consultants, Inc.[1] Their basic recommendation was that locomotives be painted in two strongly contrasting colors, with minimum solid-color area dimensions of at least 3-1/2 feet vertically and 5 feet in length, with special attention to the nose and rear of the unit. They point out that maximum overall effectiveness is to be expected if the two colors contrast strongly, both in hue and brightness. Their studies indicated that yellow or fluorescent yellow/yellow orange, with a contrasting red, blue, or black basic background color, are preferred. Figure 1 indicates the type of improvement possible.

The comments of Reference 1 concerning fluorescent materials are worth special attention. In the course of related studies TSC researchers have noted the very high conspicuity of fluorescent yellow/orange materials, particularly under adverse circumstances. This property has caused their wide use in many safety applications. Although the durability of such materials is significantly less than conventional paints, a lifetime of 2 to 3 years appears attainable with modern treatment. As noted by Aurelius and Korobow, application of flourescent color might be accomplished through use of large panels which could be easily cleaned and replaced when necessary.

The use of retroreflective materials on the side of freight cars to reduce night hazards, particularly relevant for low traffic-density rural crossings used by long trains, has often been suggested, and is practiced by some railroads. The subject has been analyzed by FRA[2] and compulsory use was found to offer a poor safety return for the resources required, and to raise complex liability issues.

A more recent TSC review of accident statistics indicates that approximately 50 vehicle occupants are killed and 150 injured each year in nightime accidents in which a motor vehicle strikes a train



a. Old Paint Scheme

b. New Paint Scheme

Figure 1. Improvement of Conspicuity Through Painting

behind the locomotives, at a crossing with passive protection only. (This would appear to be the accident population of primary relevance to reflectorization.) According to FRA/FHWA estimates, this would imply an annual societal cost of the order of $10 million. A review of currently-available technology appropriate to this application - retroreflective tape and paint, plastic reflex reflectors, etc. (Figure 2) - suggests that marking carried out as a part of normal car painting and labeling should be possible at a cost of $.50 to $1.50 per car for materials, with a lifetime estimated at five years (paint, tape) or $3 to $5 for an estimated 10-year device. (Note that the reflector to be used here is inherently much less expensive and critical in location than are ACI labels.) Although these estimates are imprecise, they imply a total annual cost of the order of $500,000. This figure, which is considerably below previous estimates, suggests the likelihood of a benefit-cost ratio greater than unity. Utilization of reflective paint for required labeling and other markings appears to be an especially efficient technique, although other devices might well prove competitive or superior in practical applications.

Two further points should be noted. First, a reflectorization program may be expected to yield substantial benefits even at relatively low levels of implementation. Even if only one-third to one-half of the freight car fleet is so marked, a motorist would have a high probability of seeing warning reflectors at or near the crossing. Second, a particular railroad might operate under special circumstances which could make likely a far greater safety benefit. For example, a relatively captive fleet of cars, operated in long trains at low speeds over many passively protected crossings, might suffer substantially fewer vehicle-strikes-train collisions if reflectorized.

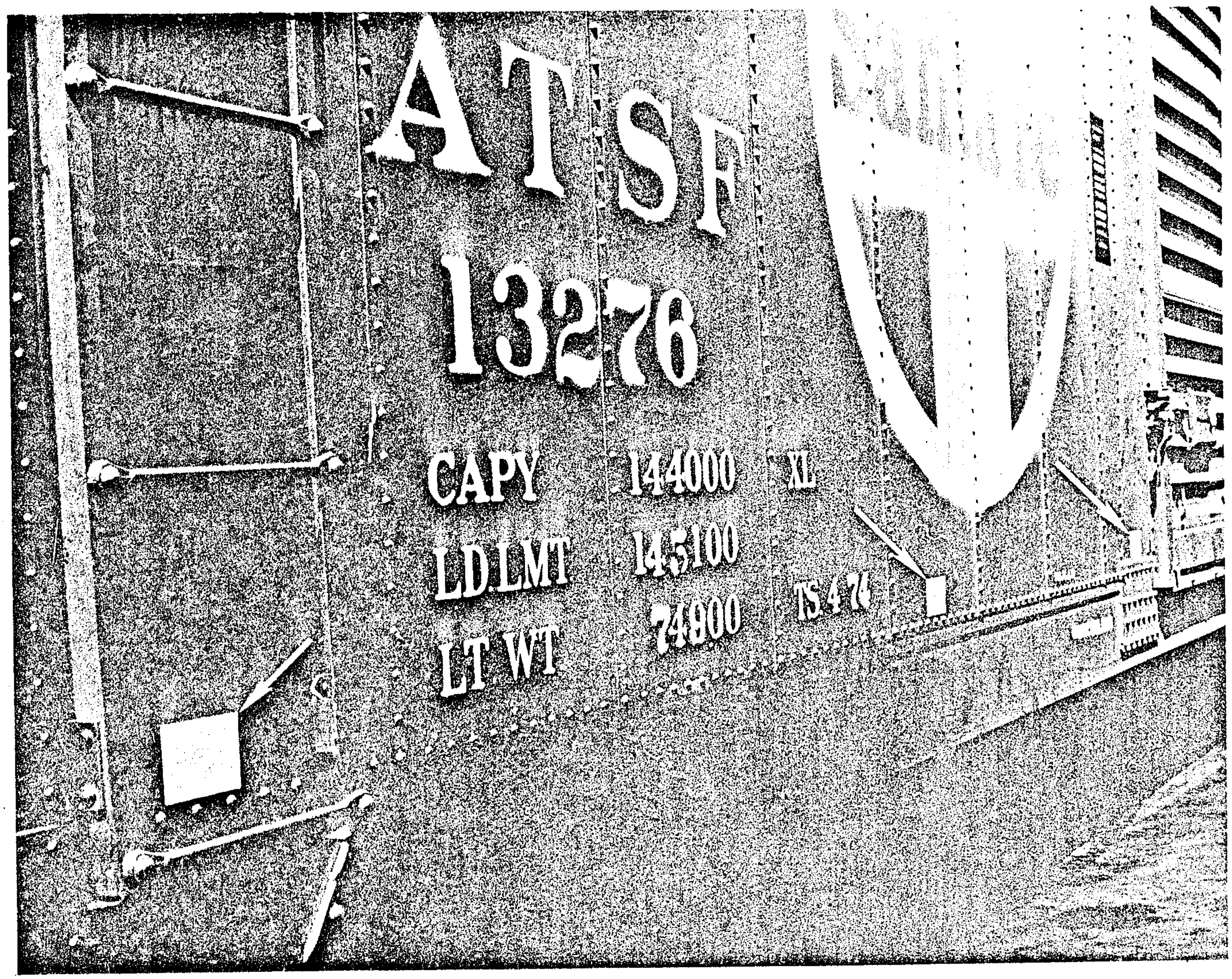


Figure 2. Illustration of Use of Reflectorized Tape on Rolling Stock

3. REQUIREMENTS AND CONSTRAINTS FOR ACTIVE SYSTEMS

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

1. Alerting effectiveness. It is highly desirable that the system maximize, within other constraints, the degree to which the attention of motorists is drawn to the locomotive, even when preoccupied or inattentive.

2. Information Content. Many bright steady and flashing lights are found in the visual environment. Trains at grade crossings are a relatively unexpected sight for many motorists. A viable warning system must be sufficiently characteristic of locomotives that identification will be rapid and accurate; and this trait should be largely independent of the relative angle and speed of approach, time of day, weather, and surroundings.

3. Deleterious Effects - Motorists. It is possible that motorists and others might be exposed to the warning system for significant periods of time, as when on a road paralleling a track. It is most important that there be no circumstances under which vehicle operators would be seriously discomfited, confused, or disorientated by such an experience.

4. Deleterious Effects - Train Crew. Even if an alerting system were operated only in the vicinity of crossings, the result in urban areas could be continuous activation. Although the crew would not normally be directly exposed, they would be working in an environment constantly illuminated by the system. It is a necessity that this neither be annoying nor make their task in any way more difficult. It is equally important that no difficulties be created

for the crews of a train approaching another train, nor for caboose-located crew members charged with continual observation of the train.

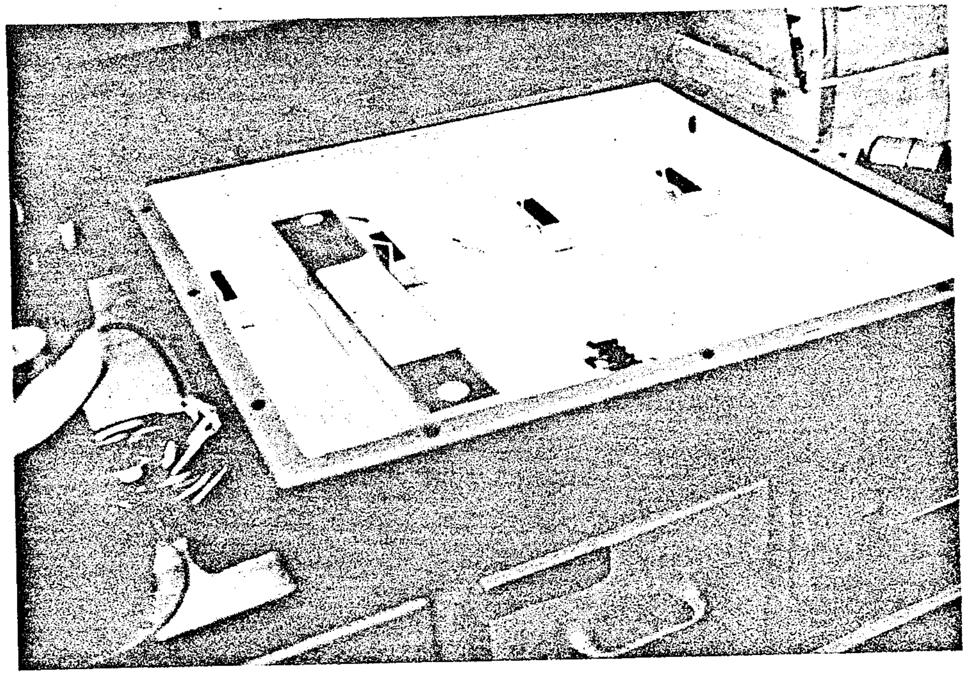
5. Low Cost. Although significent safety benefits can be anticipated, it is unlikely that mere enhancement of visual conspicuity can provide a dramatic reduction in crossing accidents. Thus, such an approach will be viable only if implementation costs are low. This applies to initial costs, equipment lifetime, and maintenance requirements, and tends to imply the desirability of simple approaches.

6. Reliability. Although to some degree inherent in low maintenance costs, system reliability must also be emphasized in terms of safety. A dark locomotive, particularly when motorists have become accustomed to the presence of illumination systems, could represent some degree of hazard. Railroad liability considerations further reinforce the importance of reliable performance.

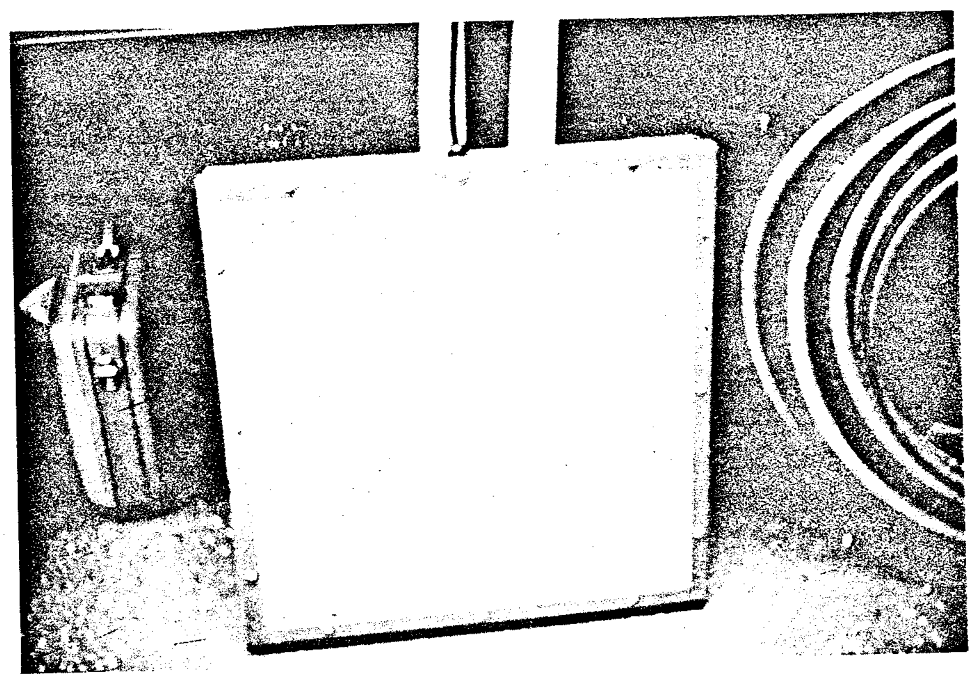
4. REVIEW OF RELEVANT RESEARCH ON ACTIVE SYSTEMS

In 1970-71, under FRA sponsorship, Systems Consultants, Inc. carried out a study reported under the title "The Visibility and Audibility of Trains Approaching Rail-Highway Grade Crossings."[1] In addition to analysis of the relevant literature and the geometry of the train-motor vehicle conflict, the section of this study concerned with visibility was based upon tests of two types: conventional beacons mounted and observed on a captive locomotive passing a grade crossing; and illuminated side and front panels, simulated on a model, photographed, and the transparencies displayed to a number of subjects. These tests, while lacking in rigor, indicated that of the roof units tested, only a pair of emergency vehicle xenon strobe lights were "effective" (this was undefined) in daylight. (All of the rotating beacons and strobes were deemed "effective" at night.) The projected model photographs also indicated potential value for illuminated side panels several square feet in area. (No outline lights were considered.) It was noted in this study that the very narrow beamwidth of conventional headlights - even of the oscillating variety - rendered them virtually irrelevant to the alerting function under consideration except for vehicles stopped near the crossing. The final recommendation was for use of a pair of roof-mounted xenon strobe lights, flashed alternately.

During 1971-72, FRA supported extension of this work at the National Bureau of Standards. In this study a number of devices of various types were designed and fabricated. In addition to special dual-color strobes, these included 3' x 3' panels of white transluscent material, illuminated from behind both by continuously-lit fluorescent lamps and xenon flash tubes (Figure 3); and a "bicolor radial beacon" (BRB), consisting of an incandescent roof lamp with a vertical filament, housed within a structure of alternating vertical red and clear (transparent) filters, Figure 4. The purpose of the latter device is to provide a changing aspect



a. Open



b. Closed

Figure 3. Side-Panel Light (Fluorescent/Xenon)

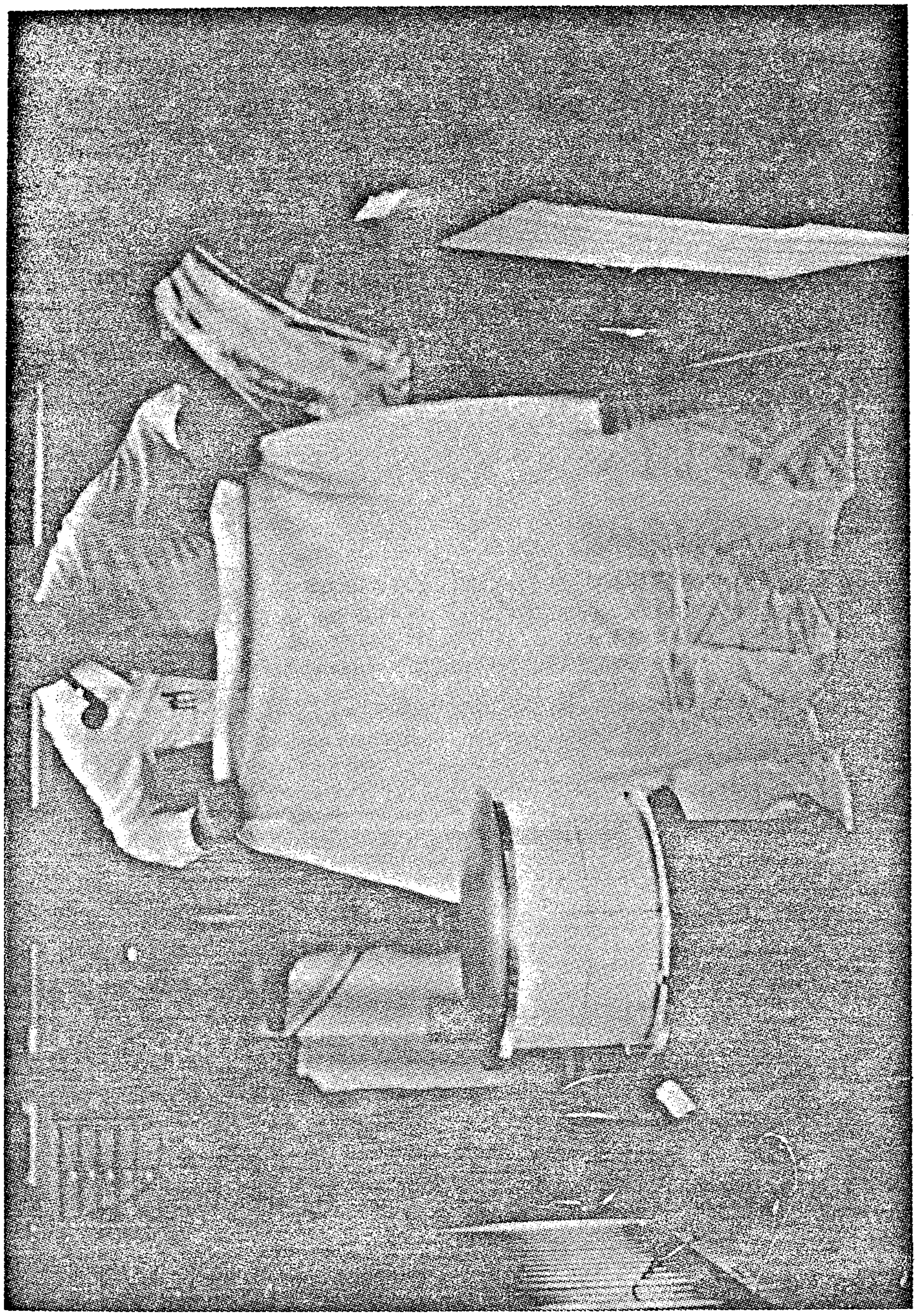


Figure 4. Bicolor Radial Beacon

(alternating red and white light) to a stationary observer when the source is moving. Several other devices and configurations were also considered by NBS and found unlikely to be effective, or unacceptable for other reasons.

In 1973, the Transportation Systems Center, acting for FRA, contracted with the Research and Development Department, Naval Ammuniton Depot, Crane, Indiana, to provide a preliminary evaluation of five candidate alerting and warning light systems: BRB, fluorescent/strobe-illuminated panels, dual (red/white) strobes, standard emergency-vehicle xenon strobe lights, and truck-type marker/delineator lights.[4] All systems were installed on a captive locomotive (Figures 5 and 6), and tested with experimental subjects under controlled circumstances to determine whether any devices had marked advantages in facilitating accurate estimation of train arrival time. (The standard locomotive headlight was also considered.) No significant differences in this respect were found. However, observers were generally agreed that the standard xenon emergency-vehicle lights, fired alternately 2-1/2 times per second, were the most conspicuous. (These units - the same model thought to be effective even in daylight by Systems Consultants, Inc. - had an effective intensity of approximately 600 candela.) The locomotive headlight and the panels were given low ratings. Train crews in the experiments found the outline lights useful in determining locomotive position at night. Mild objections were expressed concerning the effect of both strobe lights when working around the locomotive at night. The BRB was found to be objectionable, largely as a result of the striped pattern it projected, which flickered when the locomotive was moving. In addition, its alterting effectiveness was found to be relatively limited. In addition to the inherent weakness that a motorist on a collision course with the locomotive (constant bearing angle) would perceive no flashing effect, internal reflections and bulb limitations were such that the simulated "flashing" effect was relatively mild, with both "flash" duration and period substantially longer than is optimal for an alerting device.

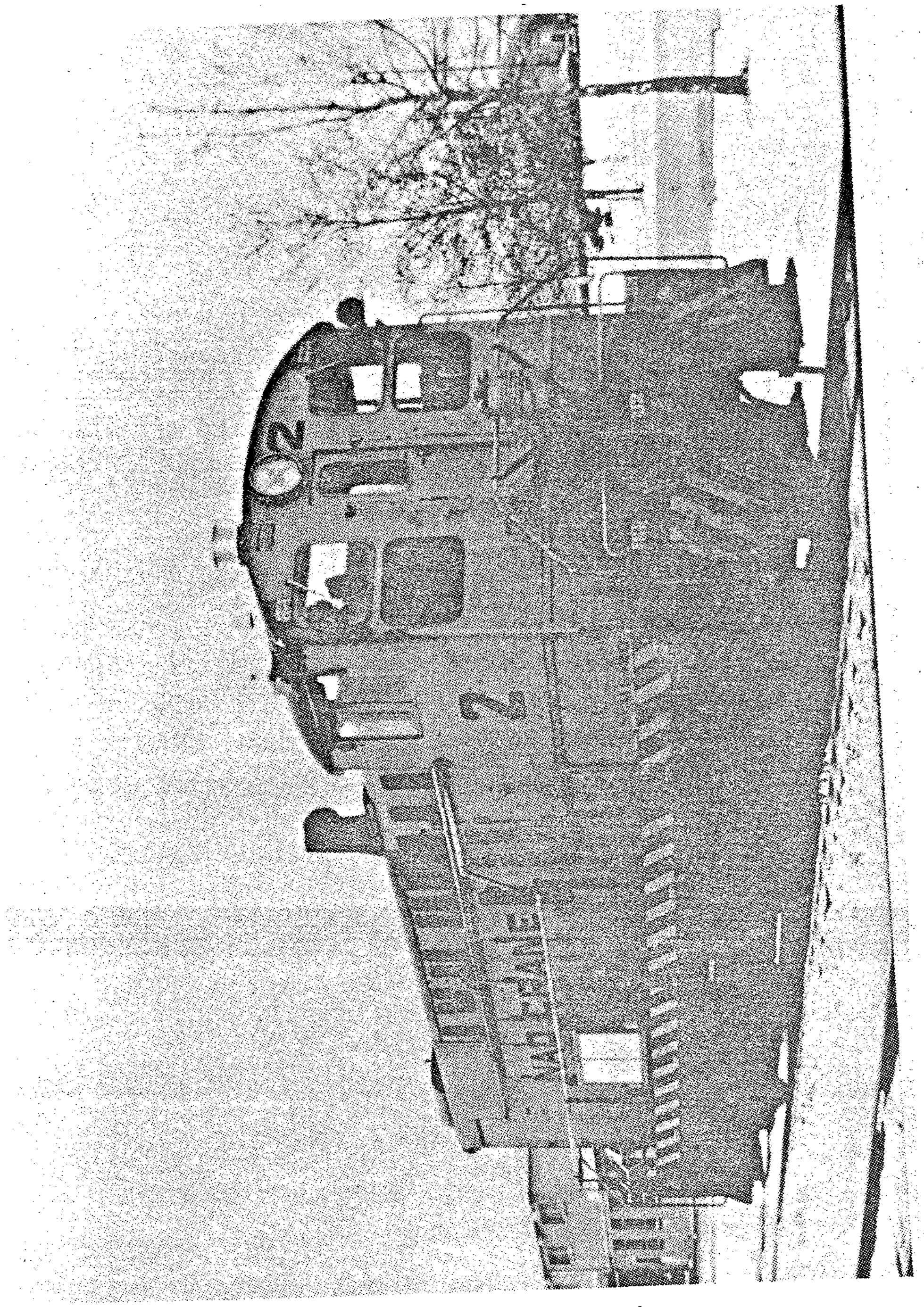


Figure 5. Locomotive Equipped with Test Devices (Day)

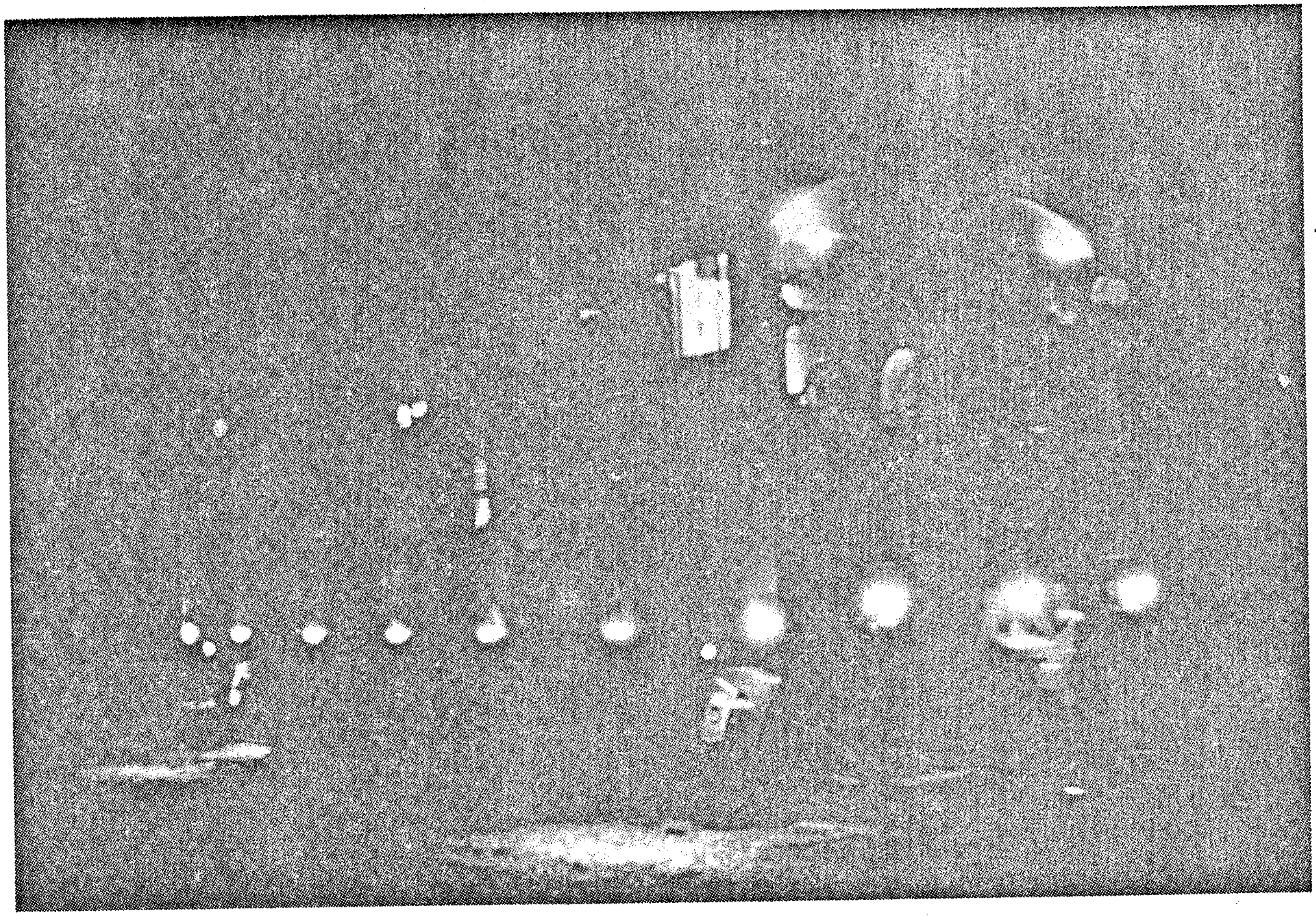


Figure 6. Locomotive Equipped with Test Devices (Night)

The illuminated panels showed no special effectiveness, and are made less attractive as a warning device by size, vulnerability to damage, expense (at least 5 3'x3' units required), and a low mounting position which increases the likelihood of obscuration by shrubbery, etc.

The weakness of the dual color xenon lamps (white, flashed alternately, in the daytime; red, flashed simultaneously, at night) is inherent; since the motorist may see different warnings under different circumstances the important effect of motorist familiarity is degraded. Confusion is possible particularly at dawn and dusk, when either mode may be in use. Since no clear benefit to a dual system was identified in the tests, or on other grounds, and the cost is significantly greater, this approach has been judged less desirable than the simpler xenon beacon system.

Testing of these various devices has also been carried out by the Chessie System and the Richmond, Fredericksburg and Potomac Railroad Company, during 1973 - 1974. No formal reports have been made public, but their findings are understood to be similar, with a preference shown for xenon lights.

A highly relevant study was carried out by TSC in 1972-73. Directed toward enhancement of train trailing-end visibility, and consequent reduction of the probability of train - train collisions, it touched on a number of topics closely related to the grade crossing situation. The results are contained in a September 1973, report, "Enhancement of Train Visibility."[5] That study included theoretical examination of required intensities, lamp characteristics, etc., for effectiveness at a range of at least 1/4-mile, even under adverse weather, and recommended use of a pair of clear xenon flash-tube lights. Field observations under various circumstances were carried out in February 1973, on the B&M Railroad, Figure 7, and confirmed the effectiveness of such units for the intended purpose. A more elaborate test/demonstration was implemented with assistance of the Southern Pacific Transportation Co. in February 1974, Figure 8, and provided detailed information

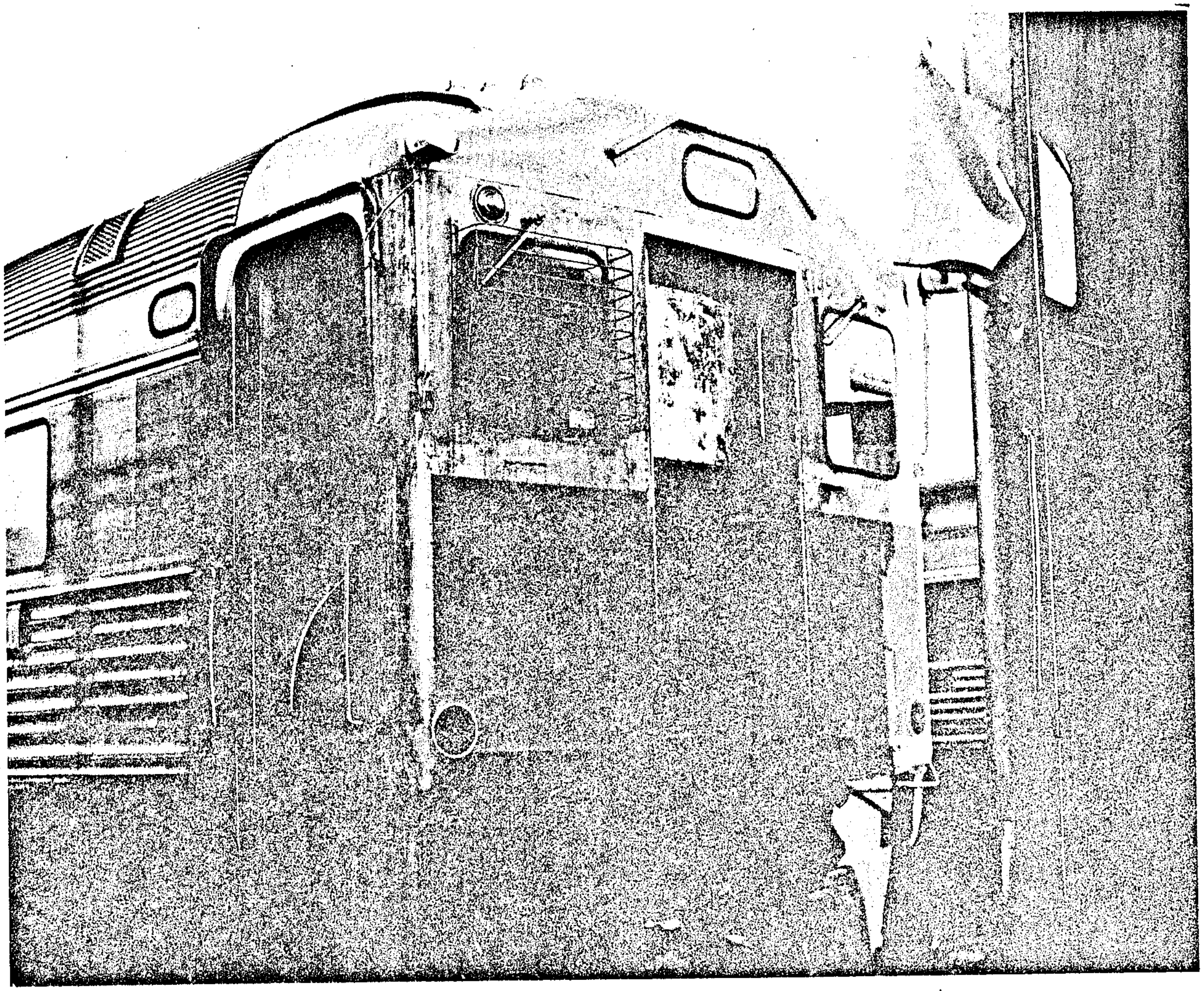
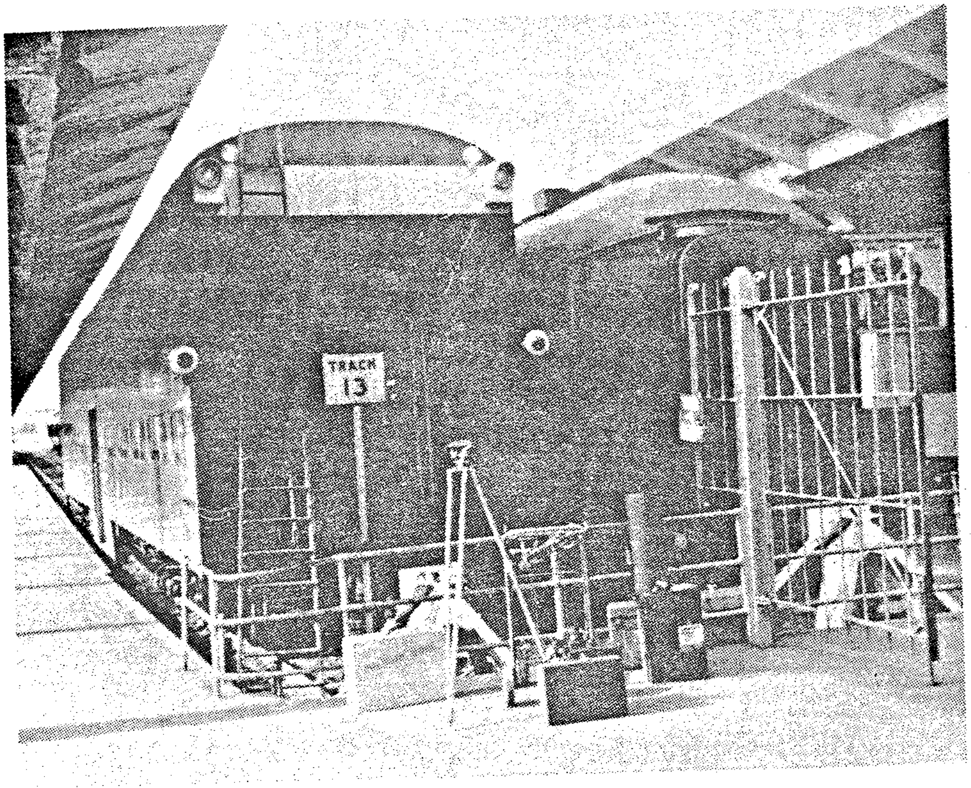
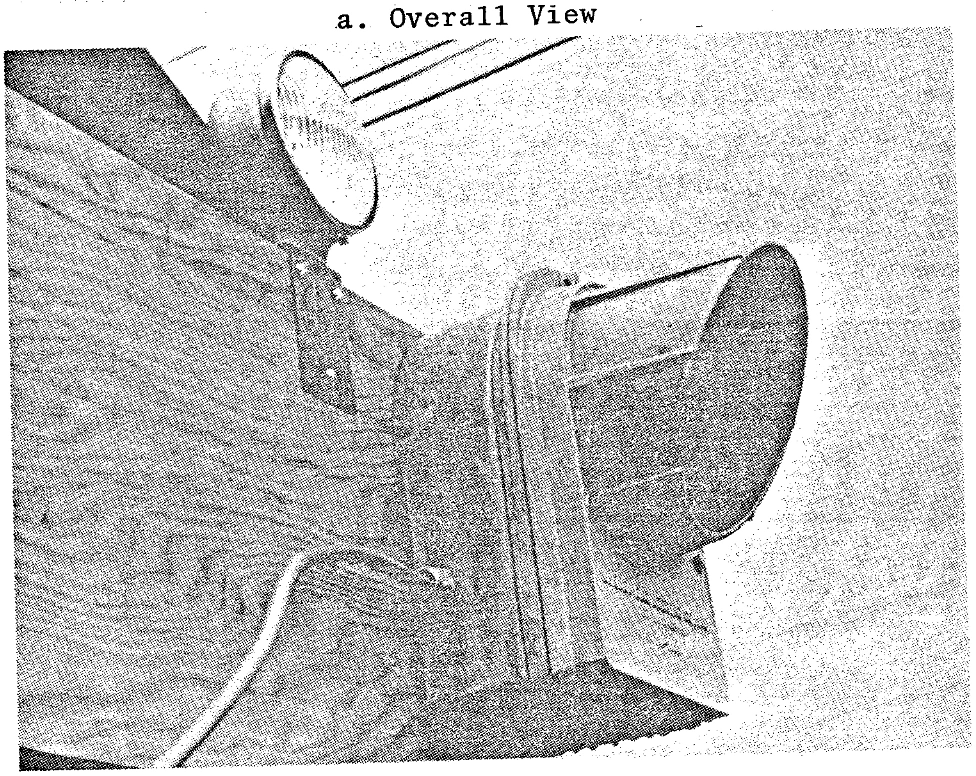


Figure 7. Test of Trailing-Ends (B&M)

Figure 7. Test of Trailing-Ends (B&M)



a. Overall View



b. Detail

Figure 8. Test of Trailing-End Lights (SP)

concerning both the high conspicuity, and the absence of adverse effects upon both crew and wayside observers, for xenon flash tubes of moderate intensity (400 candela effective).[6]

The experience obtained through use of rotating beacons and xenon strobes on emergency and maintenance vehicles is instructive. The high conspicuity of strobes, in particular, is familiar to most motorists. The effectiveness, durability, and driver acceptability of such units under adverse circumstances has been well established by the Maine Highway Department, which uses them not only on the roofs of snowplow trucks, but also mounted on the tips of sidewing plow blades. Similarly, the universal use of outline lights on large commercial vehicles and automobiles testifies to their value in conveying information as to vehicle characteristics.

Thus, although there do not exist quantitative measures of effectiveness or crew acceptability relevent to this particular situation, there is a very substantial body of highly relevant information available, sufficient to provide the foundation for firm recommendations as to an optimal system.

5. CONCLUSIONS FROM PAST RESEARCH

A number of conclusions can be drawn from analysis of the past research results and system requirements discussed above. Illuminated panels are judged to have serious deficiencies in several areas, including warning effectiveness, cost, durability, and resistance to vandalism. The BRB is relatively expensive, appears to be of limited alerting effectiveness, and was disturbing to train crews. The conclusion drawn from thorough examination and evaluation of past studies is that the simplest, most practical, and potentially most effective active visual warning system is a combination of flashing lights (to alert the motorist) and outline lights (to inform).

The standard locomotive headlight, whether stationary or oscillating, is extremely bright, but it has the crucial limitation of narrow beam width; moreover, it can provide no basis for estimation of range, motion, or specific rate of approach, and gives little or no clue as to its identity - the motorist is as likely to be confused as alerted. On the other hand, special warning lights have long been in common use on motor vehicles. Flashing incandescent lamps, rotating beacons, and xenon flash tubes can be found on police cars, fire trucks, ambulances, maintenance vehicles, tow trucks, etc. In all cases, the basic function is to attract the motorist's attention to the possible existence of some special circumstance or hazard. This is exactly the function of locomotive warning lights. Similarly, both trucks and cars now make wide use of outline lights to provide observers with information as to the nature and size of the vehicle. Experience with these devices, augmented by special analytical and behavioral studies, is sufficient to permit specification of optimal systems. (Although both flashing and steady lights are also often used in numerous other alerting functions - particularly in marine and aviation safety - the direct applicability of the motor vehicle case makes unnecessary detailed discussion of other, less relevant cases.)

6. GUIDELINE FUNCTIONAL SPECIFICATIONS

6.1 FLASHING LIGHTS

This section presents only a brief summary of the more pertinent results obtainable from the literature on human visual perception of flashing lights and test and analysis carried out by TSC. Five resulting system characteristics are of special importance: flash rate, duration, intensity, color, and configuration.

6.1.1 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 alerting effect is greatest for a flash rate of approximately 1-1/2 to 3 flashes per second. At lower rates, effectiveness decreases, and higher frequencies, particularly in the range of 6 to 12 flashes per second, can be highly disturbing and disorientating to observers.

6.1.2 Flash Duration

It has long been established that the alerting effectiveness of flashing lights increases 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.

6.1.3 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 can be defined 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

Past analyses[1,3] have shown that the principal need for motorist warning occurs at a train-vehicle seperation of less than 1000 feet, and commonly under 500 feet. Both theoretical considerations[5] and experimental observations[6] indicate that for day use, with margin for severe conditions, effective intensities as great as 4000 candela are desirable. However, effectiveness nearly as great under most conditions may be anticipated for intensities as low as 400 to 800 cd. At night, beacons with intensities in the range of 100 to 400 cd are highly conspicous, and serious annoyance problems for either crews or motorists are unlikely below 800 to 1000 cd under most circumstances.

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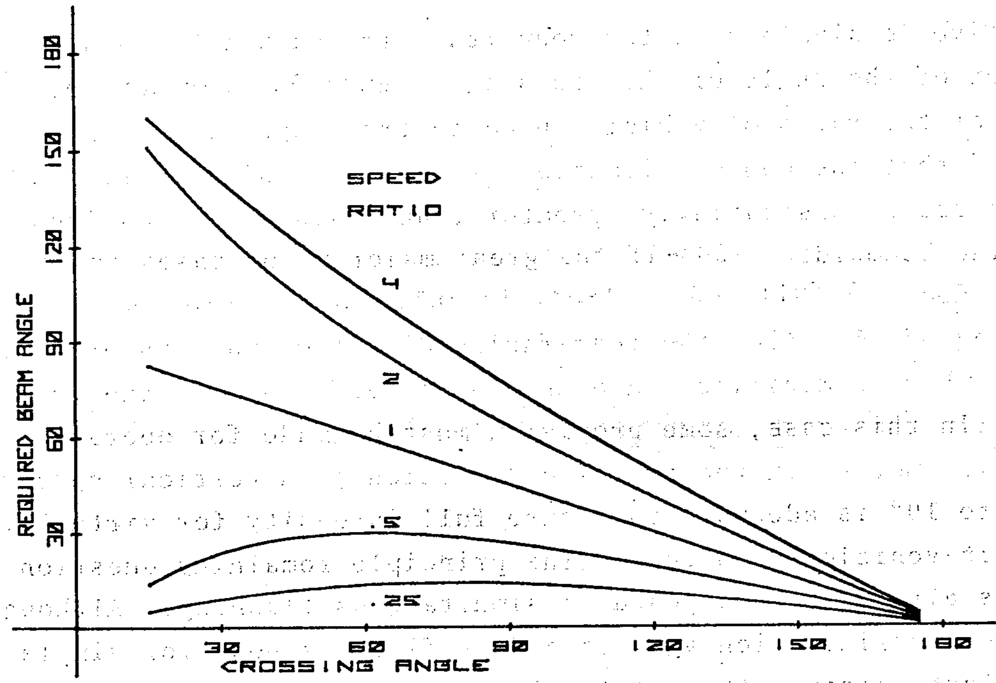
*Xenon strobe lights are often described in terms of peak candlepower (equivalent to candela), which may easily exceed 1,000,000. This is not an adequate means of characterizing light intensity. The eye responds not to an instantaneous brightness, which may last for only microseconds, but to the total light energy received over a time of the order of .1 second - a long period compared to the duration of the flash. Meaningful specification must therefore be in terms of some form of the "effective intensity" concept, defined above.

6.1.4. Color

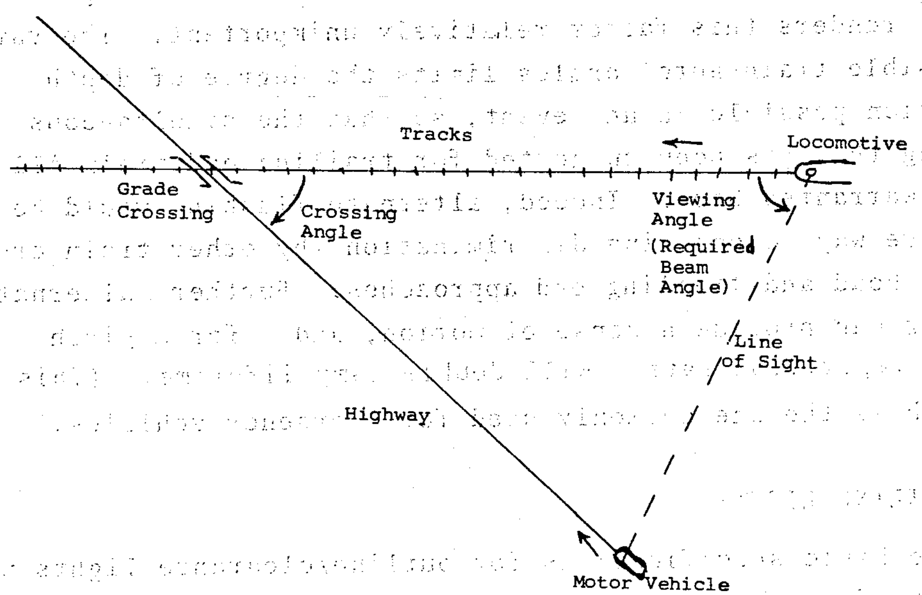
The primary purpose of the flahing lights is to attract attention. Information concerning the nature of the potential hazard should be available from other cues, including outline lights, headlights, and in daylight, the locomotive itself. Although red and amber suggest themselves through the connotation of danger, and amber has often been used in this application, their use in a railroad environment is subject to possible confusion with both wayside signals and the general environment. As a general rule, collision-avoidance lights in both aviation (aircraft and tall obstructions) and marine (ship and navigational hazard) applications are white, with colored lights used only to convey specific information, such as configuration or orientation. Also of great importance is the selection of a color which will stand out sharply against such common (and difficult) backgrounds as a setting or rising sun, which typically produces an orange/red sky. Cases such as this imply the strong desirability of a high color-temperature (very "white") light. Furthermore, for relatively high-intensity, short-pulse, point sources of light, color can be difficult to perceive, and therefore offers no reliable connotation. Since any coloration tends to reduce radiated intensity (amber attenuates brightness by approximately 50%, red by 75% to 85%) use of such shades must either reduce effectiveness or require greater expense for lamps and power supplies of appropriate greater basic brightness.

6.1.5 Configuration

In terms of visibility from all viewing angles, redundancy, clearance, and range discrimination it is desirable to have two lights rather than one, located high on the locomotive, on opposite sides. Mounting the lamps on the roof of the cab will preclude the crew being exposed to direct observation of the light and minimize obscuration by wayside obstacles. In order to assure visibility ragardless of vehicle approach angle, a wide horizontal beamwidth is necessary. Figure 9a shows calculated values of the angle at which the motorist will view the



a.



b.

Figure 9. a. Required Beam Angle as a Function of Crossing Angle, for Various Ratios of Vehicle Speed to Train Speed
b. Geometry of a

locomotive (equivalent to the required half-beamwidth) as a function of the angle of the crossing Figure 9b, for several values of the ratio of vehicle speed to train speed. It will be noted that the common situation of acute crossing angle and vehicle speed substantially greater than train speed requires very wide beamwidth -150°-if the great majority of cases is to be included. A full 360° (±180°) is fully acceptable, but shielding of ±30° from the rear-facing direction may, in practice, be desirable to minimize annoyance or interference to the train crew. (In this case, some provision must be made for operation of the locomotive in the opposite direction.) A vertical spread of ±5° to 10° is adequate to assure full intensity for virtually all train-vehicle encounters. The principle remaining question concerns alternate as opposed to simultaneous flashing. Although position discrimination against a dark field is poor for single short-flash beacons, the relatively short viewing range involved and the normal presence of other visual cues (including outline lights) renders this factor relatively unimportant. The variety of possible train-auto angles limits the degree of depth perception possible in any event, so that the simultaneous flashing that has been suggested for trailing-end train illumination is not warranted here. Indeed, alternate flashing would be an effective way of ensuring discrimination (by other train crews) between head and trailing-end approaches. Further, alternate flashing can provide a sense of motion, and - for a given overall repetition rate - will double lamp lifetime. (This approach is the one commonly used for emergency vehicles.)

6.2 OUTLINE LIGHTS

The basic specifications for outline/clearance lights used on trucks form the basis of recommendations for the locomotive case. Amber lights are used on the forward portions of such vehicles, with red indicating the rear. Since there is no value - and possible confusion - in attempting to define the "rear" of the locomotive, amber is recommended throughout.

Further, the possibility of operating either end forward would lead to unnecessary complication if two colors were used. SAE Standard J592c specifies a minimum brightness of .62 candela over a viewing angle of $\pm 45°$ in the horizontal plane and $\pm 10°$ in the vertical plane. These angles are also suitable to the locomotive case, although a somewhat greater brightness is warrented in the more hazardous situation under consideration here. The basic function of such lights is to outline the main body of the locomotive, and it is difficult to define further the exact locations. There is little purpose to lights less than 4' off the ground, since they will easily be obscured. Except where significant problems occur, marker lights should be located at front corners, along the top, and along the side frame, for a distance extending back at least 40' from the front of the locomotive. The lights should be spaced uniformly. A separation of not less than 12' appears to be unnecessary, and greater than 20' would limit the effectiveness. Since it is typically desirable to be able to operate the locomotive with either end forward, it will normally be appropriate to choose spacings consistent not only with locomotive construction, but also such that spacing is approximately uniform for its entire length. It may, in some situations, be necessary to shield the outline lights so that they do not shine directly into the cab; however,this should easily be achieved without violating the $\pm 45°$ horizontal beamwidth.

7. OPERATIONAL CONSIDERATIONS

7.1 PERIOD OF OPERATION

Crossing-located protection is typically activated 20 to 30 seconds prior to arrival of a train. A similar minimum requirement is appropriate to train-mounted devices. Operation should continue for a period following passage of the locomotive across the highway, to alert notorists who might fail (at night) to see the train. It has often been suggested that lights could be activated simultaneously with the horn, and this appears to be a useful approach. However, in many urban situations, sounding of the horn has been curtailed by noise abatement ordinances. Connection to the bell control might therefore be used. In any event, the lights - once activated - should continue to flash from a time at least 30 seconds prior to crossing until 30 seconds after passage. By far the simplest method, particularly in areas with many crossings, is continuous in-motion operation outside yard areas. This could also have some possible benefits in alerting trespassers (pedestrians, snowmobile riders, etc.), of whom more than 500 are killed every year. An additional benefit of continuous operation is avoidance of placing an additional burden on the engineer, who already has responsibility for operation of horn and bell, in addition to controlling the train. (However, TSC human factors specialists recommend that it be possible for the train crew to extinguish the strobe lights if any special circumstances require this action.) Tests conducted by the Atchison, Topeka and Santa Fe Railroad in cooperation with TSC (described a following section) have been based upon utilization of the headlight switch, so that the flashing lights operate any time that the headlight is on. Outline lights should run continuously, and are likely to increase safety in yard operations as well.

7.2 MULTIPLE-INTENSITY OPERATION

The conclusions described in Section 6 regarding desirable intensities under various conditions imply that a single intensity value in the range of 400 to 800 cd is basically adequate in terms of conspicuity. This would provide a simple and inexpensive realization, and represents an acceptable, if minimal, system. (This is the approach generally followed for emergency and maintenance highway vehicles.)

However, the relatively low cost of including two or more intensity levels can permit practical benefits worth the modest expense. At night, reduction of intensity to the range of 100 to 400 cd should eliminate virtually all possible annoyance to crew members, with no significant reduction in effectiveness. This would also permit use of a significantly higher day intensity (at some increase in system cost), which is particularly desirable for difficult situations such as looking into a rising or setting sun, even though this would be too bright for night use. Under this approach, a "day" mode of at least 800 cd is recommended, with up to 4000 cd preferred. If a two-level system is selected, it is important that the changeover be automatic, triggered by reduction of ambient illumination below a set level.* (This is to avoid imposition of any unnecessary additional decision-making responsibility upon the engineer.) Any such system should, however, include a manual override for special cases, including the possibility of malfunction of the automatic control.

In addition, there could conceivably be times when even 400 cd might be considered annoying. Typically, these would be occasions when no grade crossing is imminent, and the lights could safely be turned off. However, this requires discretionary action by the engineer - an unnecessary burden and an invitation to dispute in the event of any accident. This possibility is readily (and inexpensively) treated by addition of a third, very low intensity - approximately 50 to 100 cd - which could be used if necessay, in yards, canyons, tunnels, and while passing other trains.

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*The change-over from "day" to "night" intensity should occur for ambient illumination in the range of 1.0 to 20 lumens/meter^2, as discussed in Reference 6.

The 400 cd nominal value proposed above for night operation necessarily includes a substantial margin for poor conditions of visibility, so that even if the "dim" position were inadverently used at a grade crossing it would normally be sufficient. In summary, then, one would have a three-position system "DAY" (800 to 4000 cd), "NIGHT" (100 to 400 cd), and "DIM" (50 to 100 cd), with the Day/Night transition carried out automatically, with switches available for special conditions.

In all cases, practicality requires that lights with nominal design intensities near the recommended maximum levels be installed. This will provide tolerance for accumulation of dirt and degradation of system components.

In one class of service, multiple-level operation is strongly indicated. In the case of passenger trains, there arises a serious potential hazard not only for the vehicle occupants, but also for the possibly large number of people on the train.[7] The substantially greater hazard of this situation, in addition to the higher probable speed (and thus greater distance at which visual detection is necessary) appears to warrant two-level operation, with "day" effective intensity of 2000 to 4000 candela.

8. APPROPRIATE TECHNOLOGY

The basic specification concerning flash characteristics could be met with either a xenon flash tube or a rotating incandescent lamp of sufficiently narrow beamwidth. (A stationary flashing incandescent bulb cannot achieve the short duration and high repitition rate required.) Several considerations lead to a strong preference for the xenon flash tube. A beacon involving physical motion is inherently more complex, more prone to mechanical failure, and generally more expensive. Indeed, informal comments from railroad personnel indicate serious dissatisfaction with the expense, performance, and maintenance requirements of such devices. Expense of the xenon lamp is largely in the electronic flasher circuit, for which very high reliability can be obtained. Incandescent bulbs can be higher in cost, since their lifetime is typically far shorter than the 5000 or more hours which can be expected from a xenon beacon. (This is usually sufficient for at least one year between bulb changes.) Further, xenon tubes tend to fail through gradual bulb darkening, with diminished light output, rather than the abrupt and total failure associated with filament breakage. Synchronization of two rotating assemblies to provide the recommended alternating flashing effect would pose substantial problems and increase cost. Finally, the great sensitivity of incandescent lamp brightness to supply voltage adds further complication to assurance of within-specification operation. Figure 10 shows a pair of emergency vehicle strobes which have been found to be entirely suitable.

Empirically, xenon strobes have shown very good durability in related applications, whereas rotating assemblies, used continuously, are reported to present maintenance problems. (Note that this problem is often less severe for emergency-vehicle use, where operation is usually brief and intermittant.)

Outline lights of the type typically installed on large trucks appear entirely satisfactory for this application. Fitting of different

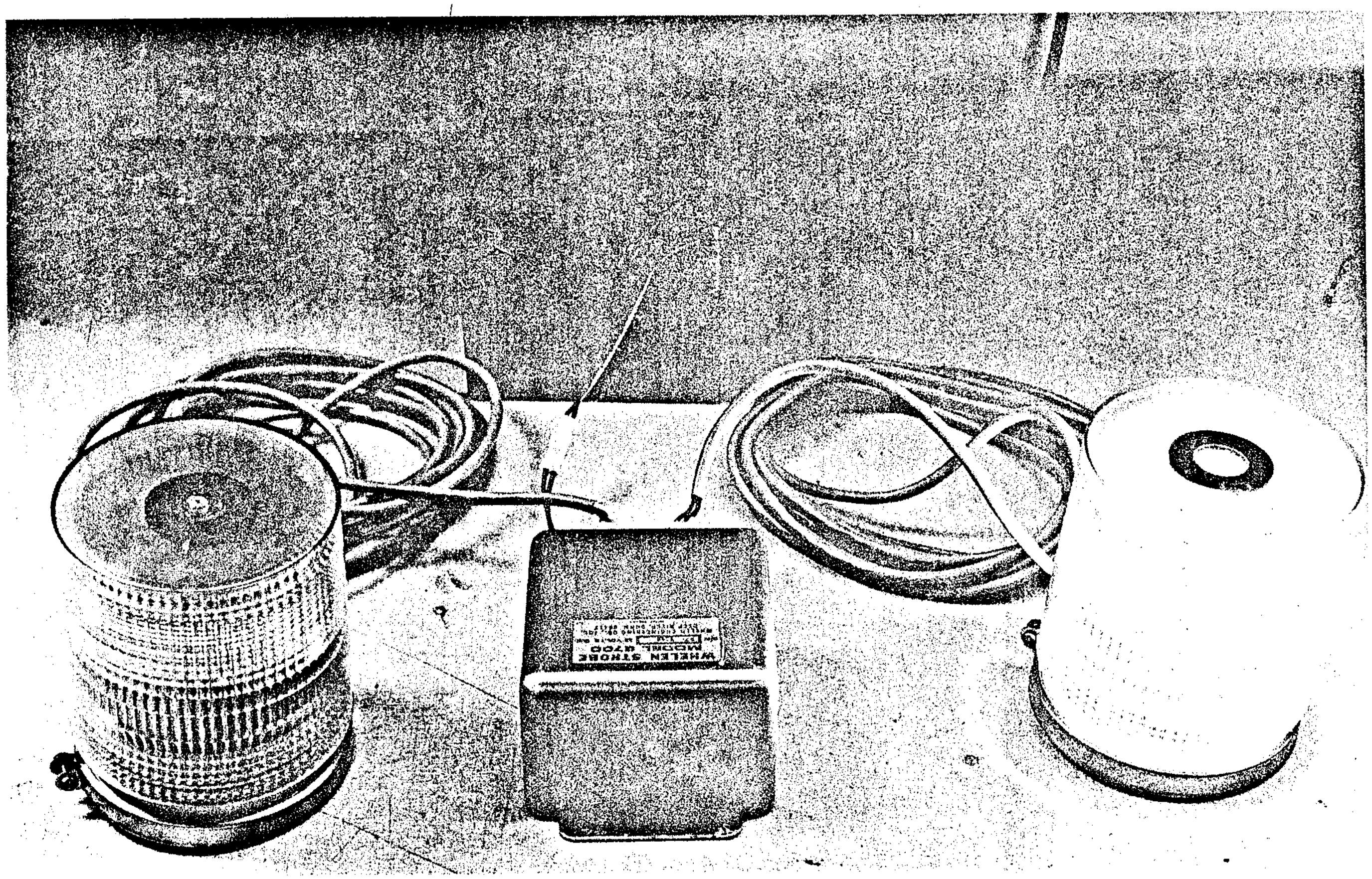


Figure 10. Xenon Flash Lamp Assembly

bulbs may be desirable for operation at standard locomotive voltages. Power consumption is strongly dependent upon beam pattern and optical efficiency, but should be no more than a few watts per lamp, which is readily supplied from existing terminals. 64 V bulbs are available for standard truck fixtures. A typical light assembly is shown in Figure 11. Alternatively, use of an inverter, with 12V bulbs, may provide lower life-cycle costs.

Cost of installation of the xenom beacon/outline light combination, based upon a number of actual test installations, is estimated at $500 per locomotive, broken down as follows:

Xenon flash tube beacons	$200
Marker lights	50
Installation labor	250
	500

The annual expense associated with these devices, including both maintenance and amortization is estimated to be approximately $50.

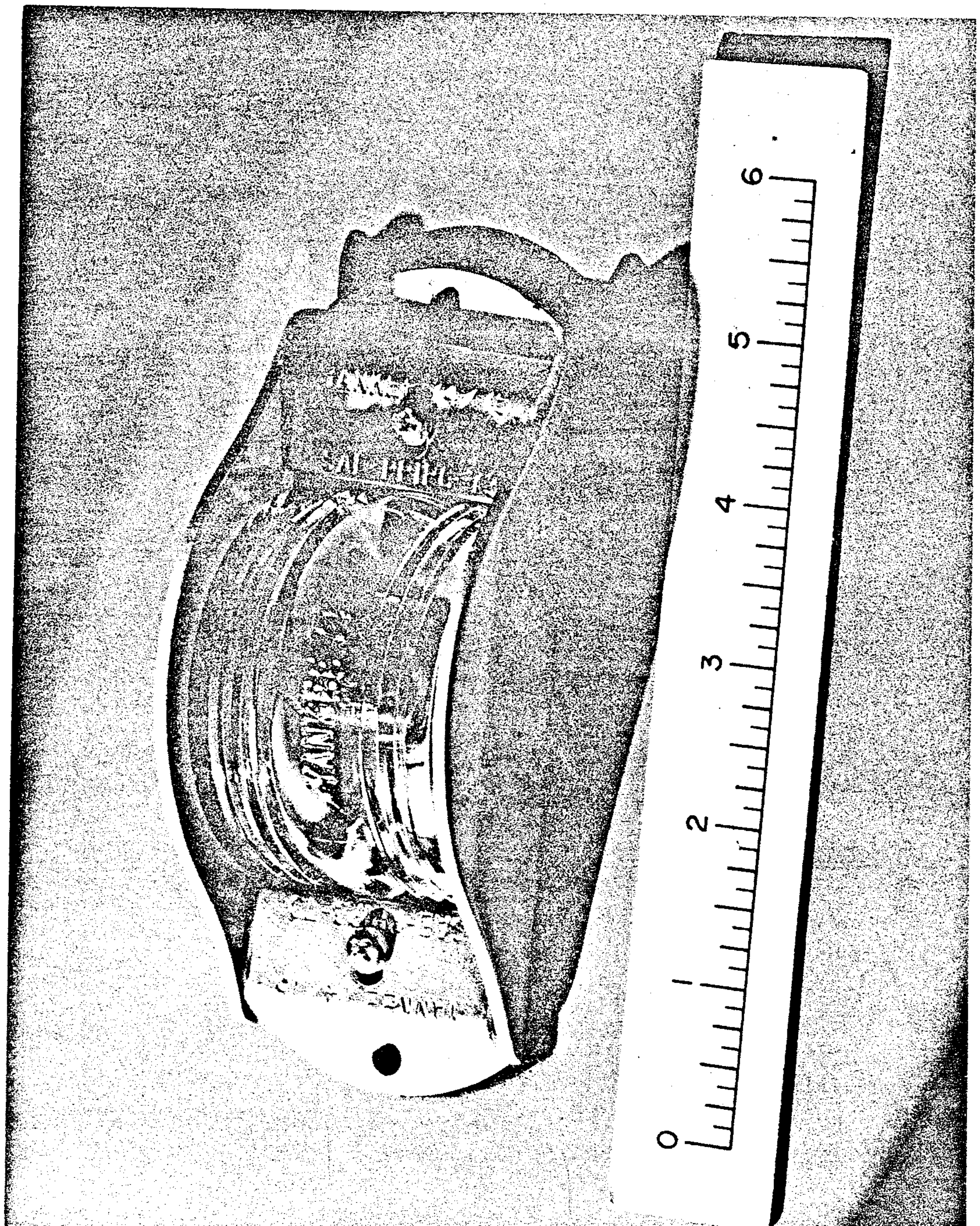


Figure 11. Outline Light

9. BENEFIT/COST CONSIDERATIONS

Uncertainty in the potential effectiveness permits only estimation of cost effectiveness. Approximately 20% of grade crossing accidents are reported as occurring at passively protected crossings in darkness. This would, à priori, be assumed to be the category most relevant. FRA/FHWA figures show 12,000 accidents annually, with an average societal cost of $40,000.[8] Thus, passive/dark accidents represent an annual cost of the order of $100,000,000. On the other hand, if one assumes 80% of the locomotive fleet to require such devices (the remainder being used only in yards or never as lead units) the annual cost (at $50 per locomotive) would be approximately $1,000,000. Thus, such a system would return benefits equal to costs even if only 1% effective (i.e., if 1% accident reduction is accomplished) at passive crossings at night, with no benefits elsewhere. In fact, effectiveness of 5% to 10% seems not unreasonable, and significant benefits at actively protected crossings and in daytime are also probable. If, for example, accident reduction is 5% for passive crossings at night, 2% day, and 2% at night for crossings with automatic protection, 1% day; one would anticipate an overall accident reduction of 2.4%, with a resulting benefit cost ratio of 11.4.

10. ELABORATIONS ON THE BASIC CONCEPT

Many variations and elaborations are possible. Although effectiveness cannot readily be determined, some of these might prove preferable to the system recommended. However, substantial further behavioral studies and tests would be necessary to establish the benefits, and most would entail significantly higher costs. Examples include use of a flash rate proportional to train velocity, and use of sequentially triggered flashes from a line of lights to provide an enhanced sense of motion. No attempt will be made to enumerate or evaluate the possibilities in this area. However, it must be noted that once a motorist has become aware of an approching train, several hundred feet away or less, there is little more that can be done for him. His judgement of closing rates, vehicle performance, and acceptable risk will determine the outcome, as is true of virtually all vehicle - vehicle encounters. Thus, it is difficult to make a case for going beyond devices designed simply to attract attention (flashing lights) and inform as to the nature of the possible hazard (outline lights). The task of providing substantive evidence as to the enhanced effectiveness of any more elaborate (and costly) system lies with its proponents, and further investigation would require far greater understanding of driver behavior at crossings than is now available.

With little increase in basic complexity, one could provide an "emergency" mode, to be used at the discretion of the train crew, which would be characterized by a high effective intensity (5000 to 10000 candela), and an increased flash rate. (A repetition frequency of 5 to 10 flashes/sec might be quite effective in such situations, although not suitable for general use.) However, intensity must be increased through addition of relatively expensive capacitors, required in proportion to brightness, so that system cost would be increased very substantially for a capability very seldom used. Thus, this variation also implies a questionable benefit/cost situation.

It would be a useful addition to arrange that the lights be operated only when the locomotive is actually in motion, but the incorporation of this feature would be viable only in cases of easy availability of an electrical signal associated only with such motion.

11. OPERATIONAL TESTS

The use of xenon flash lamp beacons in aviation, marine, and highway applications provides considerable assurance as to effectiveness, durability, and absence of adverse behavioral effects. However, recommendation of specific techniques must be based upon practical verification of analytical results in actual railroad operations. A number of relevant tests have been carried out in the course of this program, and are described below.

In August 1973, two pairs of standard emergency vehicle xenon beacons were installed on a locomotive of the Boston & Maine Railroad, in cooperation with TSC, to obtain information concerning durability. In order to avoid delays associated with liability considerations, the lights were taped to prevent visible illumination (see Figure 12). These lights have been operated continuously, in both yard switching and branch line movements, 24 hours/day ever since and have been checked every two weeks. As of June 1, the lights were still in service, having completed approximately 7000 hours of basic operation. This test has provided impressive data concerning basic durability.

In order to expand the durability testing to main line operations, and to obtain "real-world" information concerning crew response to use of such lights, the Bangor & Aroostook Railroad installed xenon strobes provided by TSC on three locomotives (one GP-9 and two F-3's). Details of these installations can be seen in Figures 13 through 15.

Since the installation in March 1974, these locomotives have operated a combined total of approximately 5000 hours (as of August 10, 1974). Initial response has been highly favorable. Both train crews and operating management are agreed as to the enhanced conspicuity of the locomotives. Crews have reported no adverse effects, even when operating in fog or blowing snow. A number of comments have been received from private citizens, all of a favorable nature. Although such observations cannot be considered totally

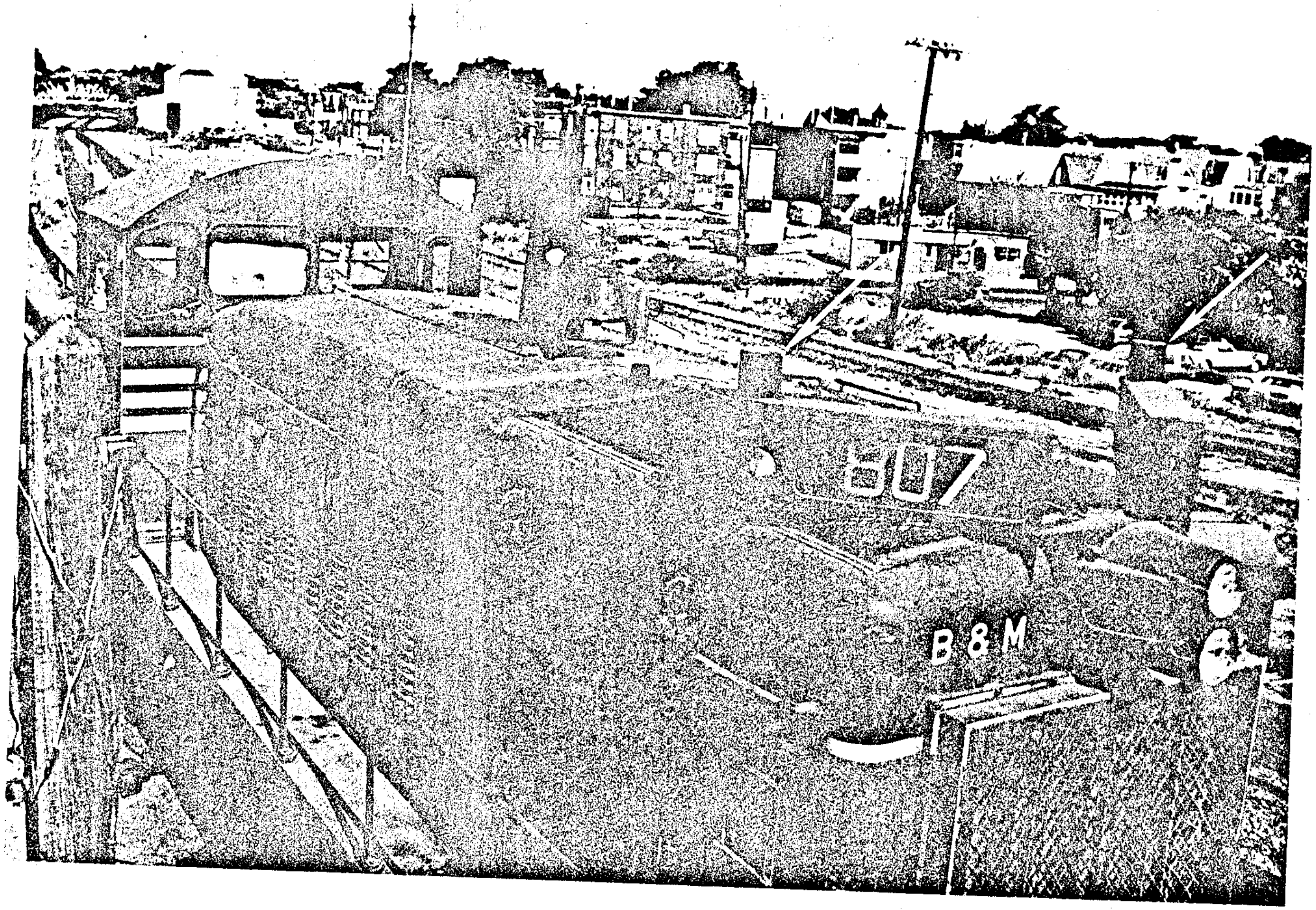
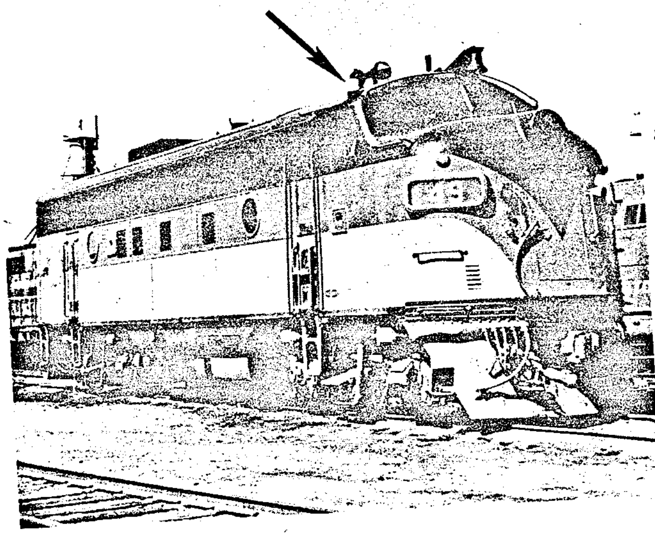
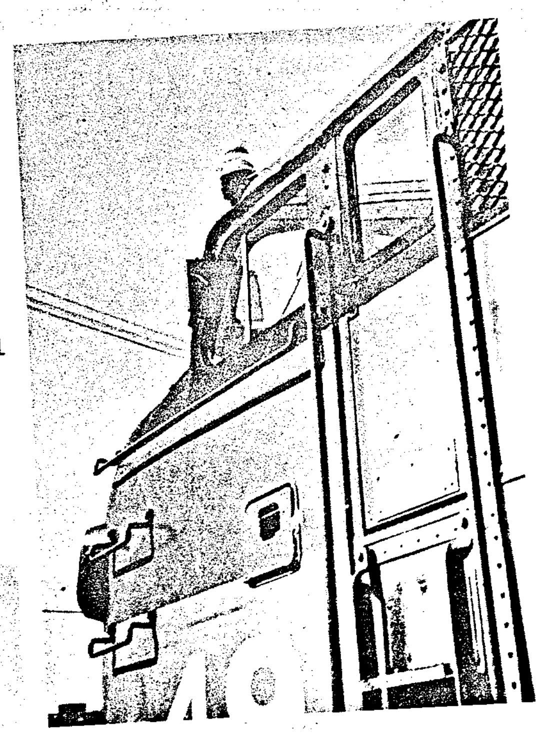


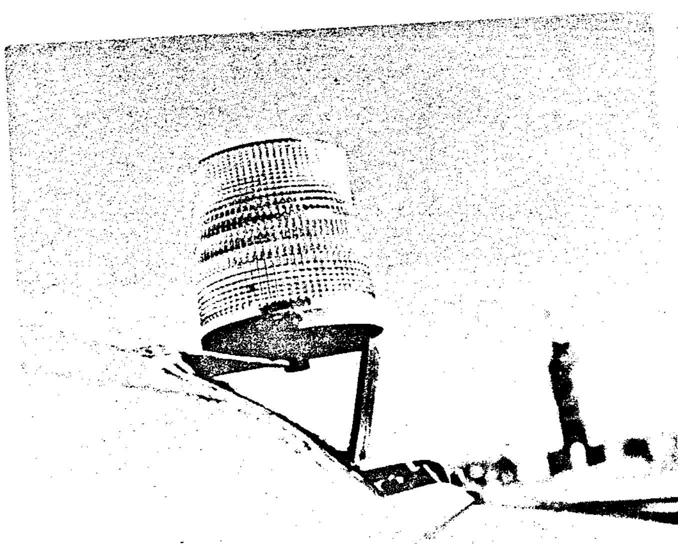
Figure 12. Test of Lamp Durability (B&M)



a. Overall View

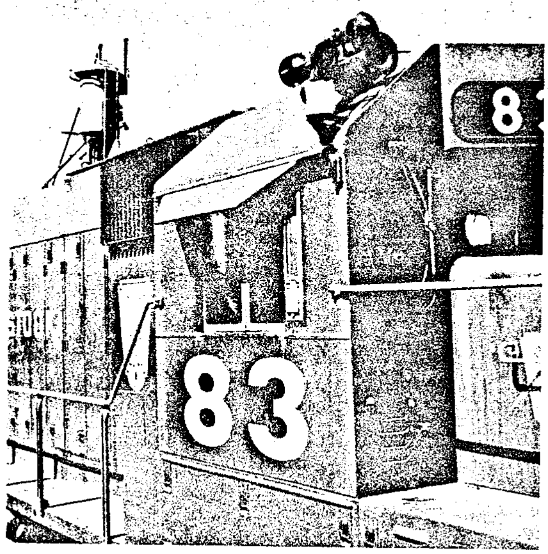


b. Detail

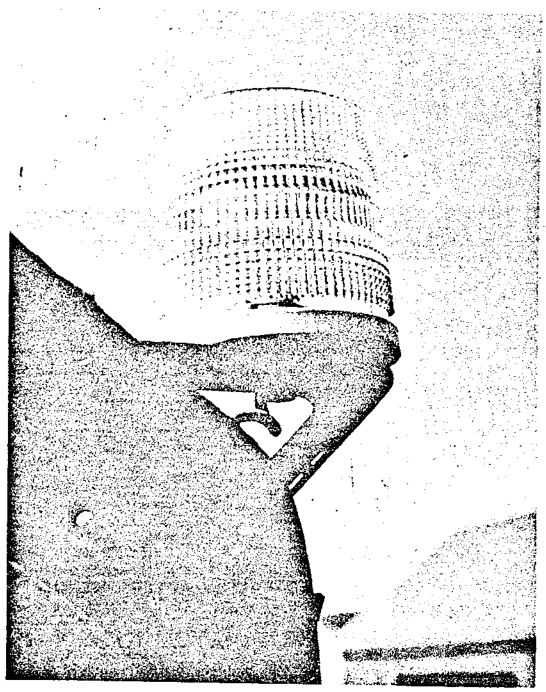


c. Closeup

Figure 13. Xenon Lamp Mounted on BAR F-3 Locomotive



a. Overall



b. Detail

Figure 14. Xenon Lamp Mounted on BAR GP-9 Locomotive.

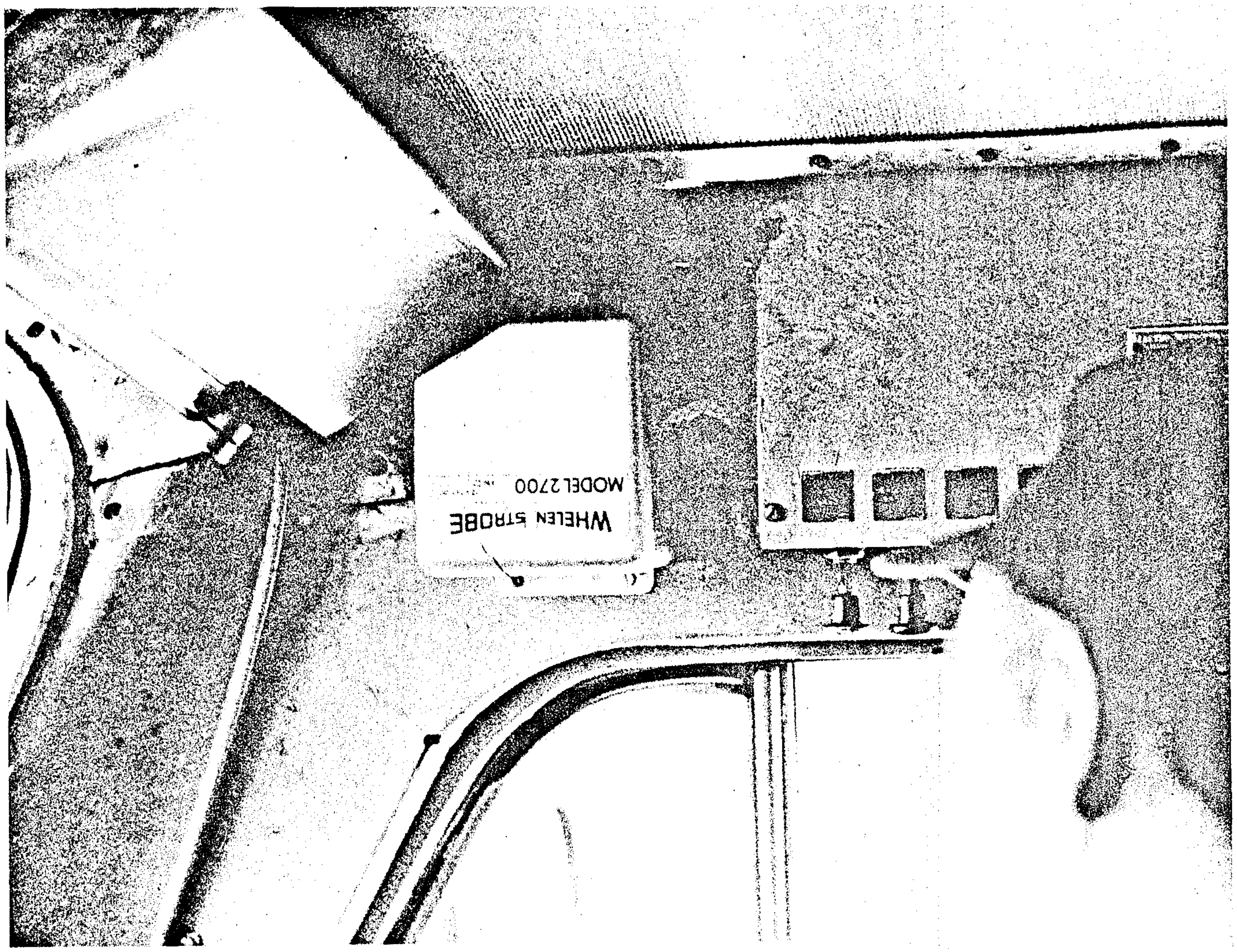


Figure 15. Interior View of BAR F-3 Installation

objective, train crews have reported numerous instances of improved motorist behavior, which they attribute to the new lights. Members of both the Maine Dept. of Transportation and the Maine State Police have expressed favorable reactions to use of such beacons.

TSC human factors specialists have carried out numerous observations and behavioral tests, including discussions with crews, on-board observations and structured experiments with naive subjects. Although the transition from such experiments and observations to estimation of the potential for accident reduction is highly uncertain, the general conclusion supported the hypothesis that the strobe lights produce a substantial increase in locomotive conspicuity, particularly at night, with no adverse effects on crews, motorists, or other observers. One one occasion the strobe lights were readily detected at a range of 1000 feet in heavy snow, with the locomotive otherwise invisible.

Information on use under rather different operating conditions have been obtained in continuing tests carried out jointly with the Atchison, Topeka and Santa Fe Railroad. In early May 1974, xenon beacons were installed on two SD-45 locomotives used exclusively on the "Super C" priority (piggyback) freight trains, which operate on a runthrough basis between Chicago and Los Angeles (see Figures 16 and 17). As of August 10, 1974, the two locomotives had compiled approximately 150,000 train miles (over 3000 hours) of operation. No maintenance has been required, and there is general agreement as to the enhanced conspicuity obtained with the flash-tube beacons.

In this case there was some adverse crew response. The primary concern was with reflections from very near surfaces - canyon walls or passing trains. There was also concern expressed about the potential for annoyance to train crews approaching beacon-equipped trains. Some apprehension was displayed regarding effects on crews working near a locomotive at night, in dark surroundings - as when throwing switches. The lights used in these tests had a single effective intensity of 800 candela, which is well above that required at night. The negative comments reinforced the desirability of using a multiple-intensity lamp, which would provide enhanced effectiveness at marginal increased cost, while ameliorating adverse affects in darkness.

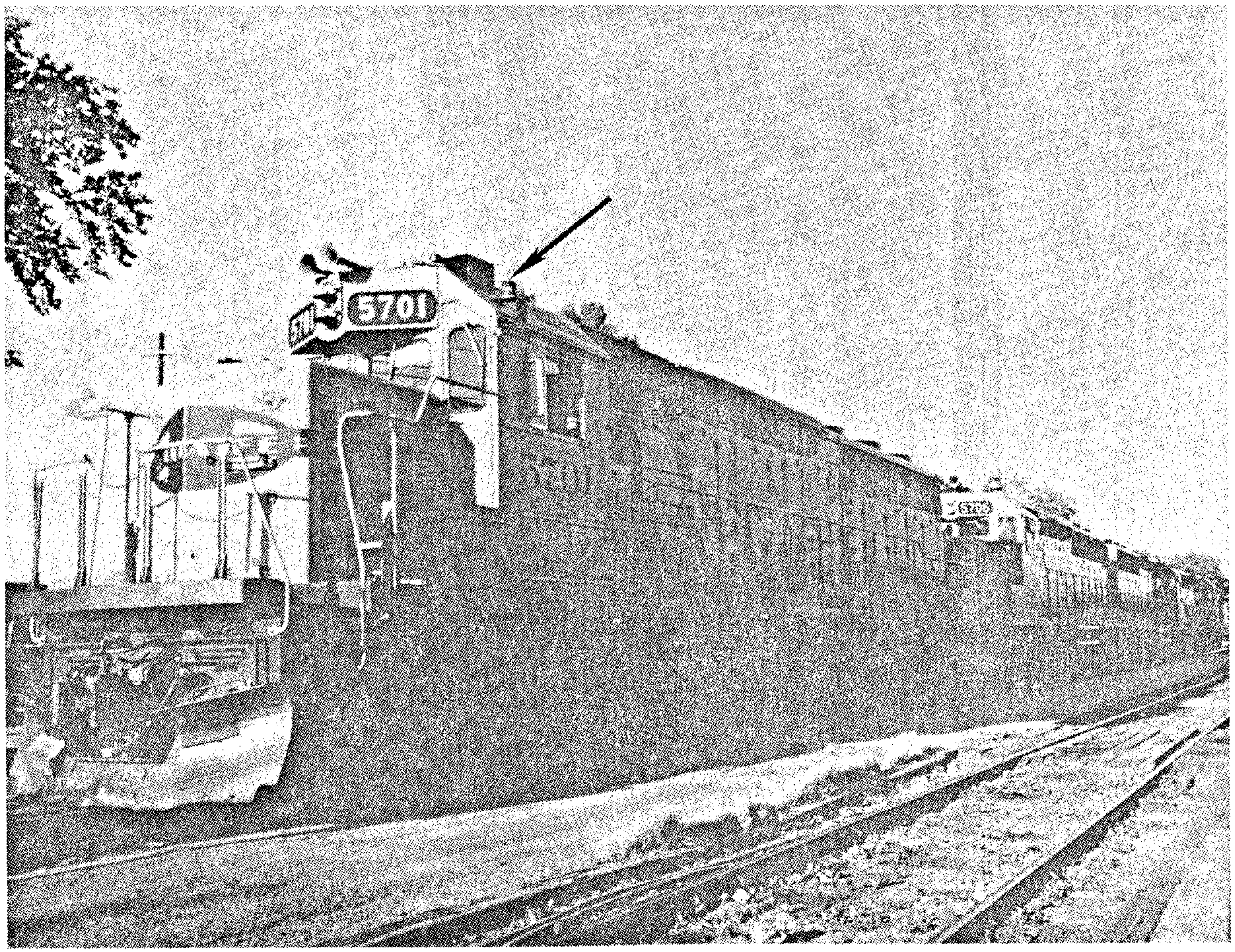


Figure 16. Xenon Lamp Mounted on ATSF SD-45 Locomotive

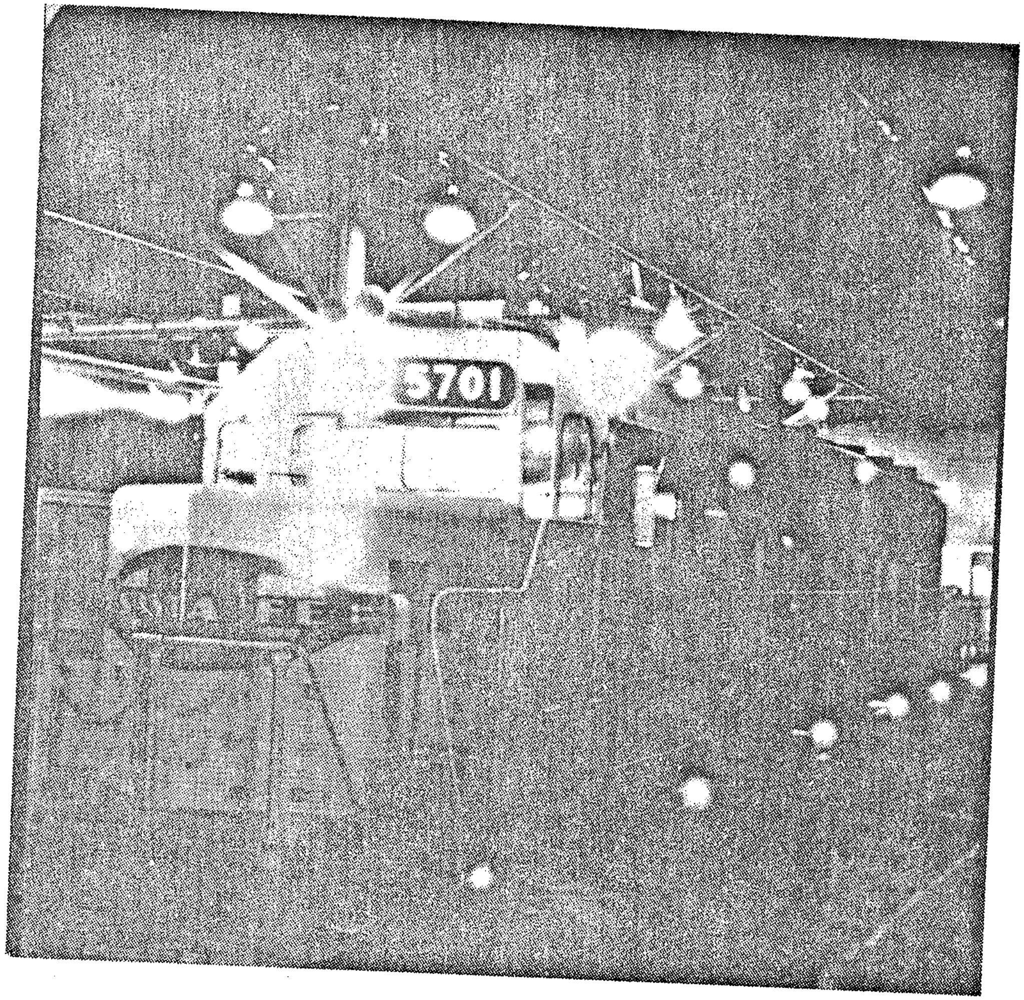


Figure 17. Outline Lamps Mounted on ATSF SD-45 Locomotive

One other source of complaint was upward radiation, which was bothersome to a towerman. This was relieved through painting over the top of the beacon; recall that only a $\pm 5°$ vertical beamwidth is recommended. Special problems of this nature, involving railroad employees whose work places them near eye-level with the beacons, can be dealth with through use of the DIM setting.

Although the outline lights were installed more recently, there appear to be no difficulties associated with their use, and comments by observers are highly favorable.

In October 1974, three-level systems (100, 400, 800 cd) were installed on two ATSF locomotives and have reportedly eliminated previous concerns. In November 1974 a similar system was installed on a SD-40 locomotive of the Union Pacific Railroad, and this also has proved satisfactory in general line-haul service. Indeed, crew members often use the Day intensity at night, particularly in areas they consider prone to crossing accidents.

12. SPECIFIC RECOMMENDATIONS

The following are minimum recommendations for active visual alerting systems for locomotives:

1. A pair of clear ("white") xenon flash tube lights flashing alternately, with a combined flash rate between 1-1/2 and 3 flashes per second, should be mounted on the locomotive cab roof. The beamwidth (in terms of the point at which intensity is reduced by a factor of 2 compared to the maximum value) should be 360° (isotropic) in the horizontal plane and at least $\pm$ 5° in the vertical. If only one intensity is used, the effective intensity (as defined by the Blondel-Rey equation) should be at least 400 candela and no greater than 800 candela. If two intensity levels are utilized, night intensity of 100 to 400 cd is preferred, with day intensity between 800 and 4000 cd. If this option is chosen, switching between levels must be automatic. A manual control must also be provided for use in exceptional situations. ("Day" is defined by incident illumination greater than lumens/m^2.) These lights are to be mounted on opposite sides of the cab roof, as close to the edges as practicable. They should be flashed, at a minimum, from the point at which locomotive is within 30 seconds of reaching a grade crossing until the entire train has passed, whichever is less. Continuous operation is recommended. Masking of the rear quardrant ($\pm$ 30° from the rearward direction) is acceptable where necessary.

2. Outline lights, amber in color, with steady intensity of at least 1.5 candela, should be mounted at the front corners and along the top edge and side frame of the locomotive, spaced at intervals no greater than 20' nor less than 12', extending at least 40' from the front of the locomotive. These are to be visible with the specified

intensity, over a vertical angle at least ± 5 degrees from the vertical plane perpendicular to the side of the locomotive.

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