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IMPROVEMENT OF THE EFFECTIVENESS OF MOTORIST WARNINGS AT RAILROAD-HIGHWAY GRADE CROSSINGS

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16. Abstract

Flashing red incandescent lamps have formed the primary motorist warning device at grade crossings for several decades, in spite of technical constraints that inherently limit the overall effectiveness possible. Tightly focused beams, necessary to obtain high intensity at low power consumption, make perceived brightness highly dependent on precise alinement, which is difficult to achieve and expensive to maintain. In this report an examination of appropriate literature and existing standards reveals preliminary requirements of function and desirable qualities for such motorist warnings. A consideration of relevant lighting technology shows that significant improvement is possible through the use of xenon flashlamps in standard crossing mountings. The quiet flash of the xenon unit appears to be more effective, with little deviation from the applicable standards, what motorists are used to, and conventional equipment. This study includes a discussion of optimal specifications, relevant technology, field tests, and related topics including system credibility and the use of highway traffic signals.

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PREFACE

The work described in this Report was performed as part of an overall program at the Transportation Systems Center to provide a technical basis for the improvement of railroad-highway grade crossing safety. The program is sponsored by the Federal Railroad Administration, Office of Research and Development.

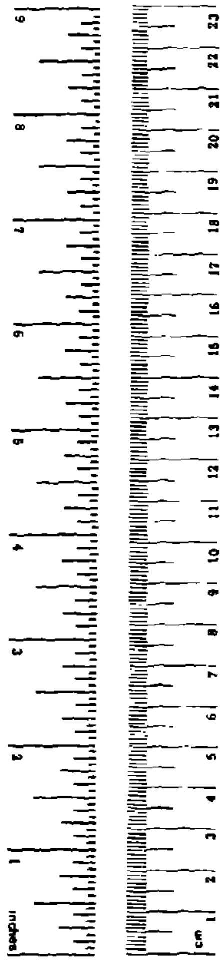
A major portion of the research was formulated and carried out by Professor F. Ross Holmstrom, University of Lowell, under Contract DOT-TSC-589. A substantial portion of this report consists of materials prepared by Professor Holstrom in performance of that contract. The overall project was conceived and directed by J. Hopkins, TSC, and E. White of TSC had major responsibility for acquisition, design, and construction of equipment; laboratory measurements; and field installations.

The project has benefited greatly from the cooperation and assistance of numerous individuals in the railroad, signal supply, and xenon lamp industries. Some of those to whom the authors feel particularly indebted include Emil Kraus, Union Pacific Railroad; Hiram Childers, Bangor & Aroostook Railroad; John Cartier, Providence & Worcester Railroad; and Frank Fotta, Boston & Maine Railroad; all of whom have been most helpful in matters relating to practical application and installation of experimental systems. In addition, much valuable information concerning xenon flash lamp technology has been provided by John Olsen, Whelen Engineering Company; and also by GTE Sylvania Lighting Division; Yankee Metal Products; and SDI, Inc. Ronald Pike, Safetran Systems Corporation provided much very useful information concerning the design and operating characteristics of roundels, and made available in a very timely manner the experimental light-red roundels used in this program.

METRIC CONVERSION FACTORS

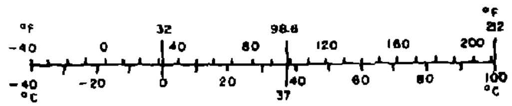
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
in	inches	2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
	AREA			
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
	MASS (weight)			
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
	VOLUME			
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
	AREA			
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
	MASS (weight)			
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
	VOLUME			
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
	TEMPERATURE (exact)			
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



CONTENTS

Section		Page
	EXECUTIVE SUMMARY	x
1.	INTRODUCTION	1
2.	CHARACTERIZATION OF GRADE CROSSING SAFETY FACTORS AND TECHNOLOGY	3
	2.1 Relevant Characteristics	3
	2.1.1 Intersection Visibility	3
	2.1.2 Vehicle Characteristics	4
	2.1.3 Traffic Characteristics	4
	2.1.4 Motorist Perceptions (Intersections)	5
	2.1.5 Motorist Perceptions (Vehicle)	5
	2.1.6 Motorist Warnings	6
	2.1.7 Motorist Response To Warnings	7
	2.1.8 Nature of Accidents	8
	2.2 Grade Crossing Motorist Warning Technology	8
3.	REALIZATION OF IMPROVED SYSTEMS	19
	3.1 Requirements	19
	3.2 Compatibility With Existing Practices	19
	3.3 Functional Requirements	20
	3.3.1 Intensity	20
	3.3.2 Pattern	21
	3.3.3 Flash Rate	22
	3.3.4 Flash Duration	22
	3.3.5 Color	22
	3.3.6 General	25
	3.4 A Technical Basis For Improvement	26
4.	XENON-FLASHLAMP HARDWARE AND OPERATING CHARACTERISTICS	27
	4.1 Flashlamp	27
	4.2 Light-Pulse Characteristics	27
	4.3 Overall Flashlamp System Configuration	33
	4.4 Alerting Effectiveness Of Flashing Lights	35
	4.5 Relative Power Efficiency	42
5.	EXPERIMENTAL XENON-FLASHLAMP GRADE CROSSING WARNING SYSTEMS	45
	5.1 Background	45
	5.2 Basic System	45

CONTENTS (CONT'D)

Section		Page
	5.3 Power Supply Mounting........................	49
	5.4 Xenon-Flashlamp Installation..................	49
	5.4.1 Providing Power For Flashlamp Systems..	58
	5.4.2 Roundels..............................	61
	5.5 Illumination Patterns Of Lights In Housing....	61
	5.6 Sychronization................................	66
	5.7 Subjective Observations Of Effectiveness......	70
	5.8 Cost..	70
	5.9 Summary And Conclusions From Experimental Studies.......................................	71
	5.10 Elaborations And Special Benefits.............	72
6.	GENERAL CONCLUSIONS CONCERNING XENON FLASHLAMPS AT GRADE CROSSINGS...................................	74
7.	OTHER POSSIBLE SYSTEM IMPROVEMENTS.................	75
8.	POSSIBLE FURTHER RESEARCH..........................	83
9.	REFERENCES...	84

ILLUSTRATIONS

Figure		Page
1.	Conventional Grade Crossing Flashing-Light Assembly....	10
2.	A Flashing Light Pair Mounted On A Pole At Wayside.....	12
3.	Standard AAR (Association Of American Railroads)-Approved Incandescent Flashing Light Housing...........	13
4.	The Beam Pattern (Horizontal and Vertical) Of A Standard Incandescent-Lamp Grade Crossing Unit Without Roundel In Place...	14
5.	Beam Patterns Of Incandescent-Lamp Grade Crossing Unit Equipped With "Long-Range" Roundel.....................	16
6.	Front And Back Of The Roundel Used To Obtain Beam Patterns...	17
7.	Standard C.I.E. (Commission Internationale De L'Eclairage) Curve for Sensitivity of Human Eye.....	23
8.	Typical Xenon Flashlamp................................	28
9.	Sylvania Model R4321A Xenon-Flash Tube.................	29
10.	Current, Voltage, And Light Intensity Vs. Time For A 20-J Xenon Flashlamp.................................	31
11.	Basic Parts Of A Xenon-Flashlamp System................	34
12.	Ratios Of Effective To Average Intensities For Xenon Flashlamps And Incandescent Flashing Lights............	41
13.	Xenon Flashlamps In PAR-64 Sealed-Beam Enclosures......	46
14.	Xenon-Flashlamp Power Supply For Powering Two Flashlamps..	47
15.	Xenon-Flashlamp Power Supply Mounted In A Crossarm Terminal Box..	50
16.	Sheet Metal Enclosure (Arrow) Mounted High Up For Protection From Vandalism.............................	51
17.	Pole Mounting Of Cast Metal Box.......................	52
18.	Large Sheet-Metal Box Used As An Expedient For Housing Flashlamp Power Supply................................	53

ILLUSTRATIONS (CONT'D)

Figure		Page
19.	Beam Patterns of a Grade Crossing Unit Equipped With "Long-Range" Roundel and Light-Stippled Xenon Flash Tube Sealed-Beam Unit	54
20.	Sealed Beam 8 in.Flashlamp Unit Mounted In Standard 8 in.Housing	55
21.	Sealed-Beam Flashlamp Unit Being Installed	56
22.	Grade Crossing To Which Xenon Flashlamps Have Been Added	57
23.	Permanent Installation Of Xenon Flashlamps In Conjuction With Incandescent Flashing Lights At A Grade Crossing	60
24.	Beam Patterns Of Incandescent Flashing Light And Xenon Flashlamp	63
25.	Relative Intensity Vs. Distance From Crossing	65
26.	Relative Intensity Vs. Distance From Crossing; Lights Misaimed By 1 Degree Vertically, 1 Degree Horizontally.	67
27.	Various Alternative Flash Synchronization Patterns	69
28.	Highway Intersection Warning	76
29.	Railroad Grade Crossing Warning	76
30.	European Passive Crossing Warning	76
31.	European Active Crossing Warning	76
32.	Railroad Crossing Traffic Light	78
33.	Crossings Marked By Both Conventional Traffic And Railroad Signals (Note Automobile Near Intersection).	80
34.	Crossings Marked By Both Conventional Traffic And Railroad Signals (Note Train Approaching Intersection).	81

ABBREVIATIONS

ABBREVIATIONS	DEFINITION
cd	Candela
Hz	Hertz
nm	Nanometers
cd-sec	Candle - seconds
V	Volts
Vdc	Voltage direct current
lm	Lumens
ms	Millisecond
J	Joules
μ-sec	Micro-seconds
Vac	Voltage alternating current
W	Watt
m	Meter
cp	Candlepower
C.I.E.	Commission Internationale De L' Eclairage
I eff	Effective intensity
I avg	Average intensity
AAR	Association of American Railroads

EXECUTIVE SUMMARY

Approximately one-quarter of the public railroad-highway grade crossings in the United States are equipped with train-activated flashing lights. These systems typically are found to reduce accidents from 60 percent to 70 percent. Since nearly one-half of the accidents occur at these crossings, potential safety benefits of enhancing the effectiveness of such warnings are considerable. The study reported here begins with an examination of the situations faced by a motorist approaching a grade crossing, compared with the case for normal highway intersections. Principal conclusions emphasize the importance of alerting effectiveness and definite identification as a grade crossing.

Grade-crossing flashing-light equipment currently in use is described, with emphasis upon the technical and other constraints which underlie design and construction. Attention is then given to the achievement of improved systems. Existing literature and logical analysis are used to generate preliminary functional and performance specifications which any system must meet: intensity, flash rate, flash duration, color, beam pattern, etc.

Experience in other fields--space, aviation, highway, marine, etc.--suggests the special relevance and applicability of xenon flash-lamp technology to this application. This type of equipment efficiently produces a highly alerting short-duration flash, and is characterized by simplicity and durability. Adaptation to conventional mounting hardware was found to pose no major problems, and laboratory measurements showed expected favorable performance. This equipment is described in detail.

Experimental installations of such equipment have been carried out in cooperation with three railroads. In each case, the xenon strobe lights supplemented, rather than replaced, existing flashing lights. A number of system configurations have been utilized and these are fully described in the report, with recommendations as to preferred forms. In general, results obtained have been highly promising, with a highly alerting aspect achieved in relatively simple fashion and at low cost.

1. INTRODUCTION

Reduction of the number of collisions occurring at railroad-highway grade crossings is a continuing objective of all levels of Government and the rail industry. In recent years, many activities have been carried out: public information programs, improvement of warning systems, development of methodologies for effective allocation of resources, research into all aspects of the problem, and new installation for upgrading of train-activated motorist warning devices. During this period, the annual number of grade-crossing casualties has steadily declined. Yet, the death toll remains near 1,000 per year, representing more than one-half of rail-related accidental fatalities, and the quest for even greater safety continues.

Recent studies have indicated that one solution to the problem is accelerated installation of active protection; it has been estimated that new or upgraded equipment at 20,000 to 30,000 more crossings (out of a total of 225,000 public crossings, 175,000 now are only passively protected) could further reduce collisions by as much as 50 percent.[1] Conventional grade-crossing flashing-light systems have generally been found to reduce accidents from 60 to 75 percent, with even better results when augmented by automatic gates. Yet, these systems still provide much opportunity for improvement. Over one-third of present fatalities occur at the 50,000 crossings marked by train-activated flashing lights. In general, the primary causes of these collisions appear to be motorist inattention, carelessness, misjudgment, inebriation, etc. However, the fact that active warnings do have a strong positive effect implies that even these factors can be overcome. The challenge which this report addresses is development of means of enhancing the effectiveness of currently used motorist warnings in a realistic manner, within the framework of existing technology and practices. There is no question that automatic gates can achieve a very high level of safety effectiveness. Indeed, the only way in which significant improvement might be sought for gates is through reduction of life-cycle costs, encouraging more widespread installation, and this subject has been addressed in another study.* However, the substantially lower cost of flashing lights alone, and the large number already in use, make it highly appropriate to examine means by which their effectiveness can be enhanced. Although present and future research into motorist behavior and accident causation may ultimately lead to highly innovative devices, which markedly surpass the safety now attainable, the time required for that process, as well as the uncertainty of the outcome and the seriousness of the current problem, make it imperative that short-term equipment improvements, preferably suitable to retrofitting of existing crossings, be sought. The research described in this report addresses this subject.

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*A. St. Amant et al., "Potential Means of Cost Reduction in Grade-crossing Automatic Gate Systems," Report DOT-TSC-FRA-76-14,I, in preparation.

2. CHARACTERIZATION OF GRADE CROSSING SAFETY FACTORS AND TECHNOLOGY

2.1 RELEVANT CHARACTERISTICS

Improved grade crossing motorist warnings, if sought in a systematic manner, must be based upon a comprehensive understanding of the nature of the problem. Unfortunately, there has been very little direct study of accident causation at railroad-highway intersections, so this foundation must be generated by inference from experience, logic, and knowledge of related situations. Traditionally, for a variety of reasons, grade crossing warning systems have been treated to a large degree as a subset of the railroad signal system, with relatively little consideration given to traffic-engineering principles. On the other hand, there has been much discussion and some actual installation, but little evaluation, of entirely conventional warnings, such as "STOP" signs and traffic signals at railroad crossings. However, the view taken in this study is that despite obvious similarities, and a need for basic compatability, the grade crossing is a very special type of highway intersection, which imposes special requirements and constraints upon the warning systems used. In the pages immediately following, the more important special characteristics of grade crossings will be delineated in some detail, and conclusions relevant to design and selection of warning systems will be developed. The special factors to be discussed are: Intersection visibility, Vehicle characteristics, Traffic characteristics, Motorist perceptions (intersection), Motorist perceptions (vehicle), Motorist warnings, Motorist response to warnings, and Nature of accidents.

2.1.1 <u>Intersection Visibility</u>

Intersections of roadways are generally relatively obvious, with the size, and consequent effect on a road on the visual environment, generally proportionate to the speed and density of traffic using it. The need to apply caution when approaching a major artery is normally perceived well in advance, through informational and traffic-control signs, curbs, presence (or absence) of brush, trees, buildings, fences, street lights, utility poles, cross-traffic, etc. While these elements can be present at a railroad-highway crossing as well, they will generally play a substantially less evident role, and the probability that the motorist will fail to note the impending intersection will be greater for the rail case. Further, the characteristics of a grade crossing may offer little guidance as to the degree of hazard, appearing almost the same for 60, as for 10 MPH trains, or for traffic densities of one train per week or one per hour.

2.1.2 Vehicle Characteristics

A highway vehicle--even a large, high-speed tandem-trailer truck--has a substantial capability for altering both speed and direction, even in a relatively short distance. Cars and most trucks are sufficiently short that a driver perceiving an imminent collision has a reasonable chance of slowing and/or swerving to pass behind them. None of these elements apply to typical rail traffic, for which stopping distances are limited by wheel/rail adhesion and the characteristics of train-braking systems. A fast-moving freight train of average size normally can be slowed only negligibly in a distance of several hundred feet, and evasive maneuvers are, of course, impossible. Thus, given a collision-course situation, avoidance depends entirely on the motor-vehicle operator, and will not be possible at all after a certain point.

2.1.3 Traffic Characteristics

Even if not directly visible, a highway intersection tends to be detectable by the movement of cross traffic. Indeed, since hazard may be expected to increase with traffic density, the inherently more dangerous intersections will also be more likely to provide this type of visual indicator. On the other hand, even a very heavily used railline is not likely to exceed one or two trains per hour, and in the highly prevalent single-track situation, railroad rules and signal systems will prevent trains from being within several minutes of one another. Thus, the only train the motorist has any chance of seeing is the potential collision object.

2.1.4 Motorist Perceptions (Intersections)

Under normal circumstances, a motor-vehicle operator will traverse far more highway intersections than grade crossings, and actual or potential traffic conflicts are likely to make him far more aware of them. Thus, motorists tend to cope with intersections at a nearly automatic level, carrying out necessary surveillance and avoidance actions almost without conscious effort. Grade crossings, on the other hand, are encountered much less frequently, and observation of trains at or near them may be a relatively rare event for many vehicle operators. Thus, a person might be expected to develop very different sets of assumptions and habits for the two cases: a feeling of hazard and a need for caution at highway crossings, and a very low level of concern over railroad crossings. This conclusion tends to be supported by the casual observation that motorists tend to slow down, turn heads, etc., to a much greater degree at uncontrolled highway intersections than at passively marked crossings. Indeed, a recent survey revealed a disturbing degree of erroneous assumptions held by many drivers concerning grade crossings.[2] Some 15 to 35 percent in various locations were under the impression that all crossings are equipped with train-activated motorist warnings, others believed that passive crossings were used only be occasional, slow trains. Relatively few had exhibited head-turning behavior, even at "blind" crossings. Over 40 percent estimated the average time interval between signal activation and train arrival to be over one minute.

2.1.5 Motorist Perceptions (Vehicle)

As suggested above, for many motorists it is a relatively uncommon event to encounter a train at a grade crossing or anywhere else. It might be expected that people will, therefore, be less adept at estimating size, speed, and arrival time of an approaching train than for a car, truck, or bus. At night, the single locomotive headlight, even if oscillating, provides little information as to range and closing rate, again in contrast to the relatively standard spacing of vehicle headlights. It was noted above that rail vehicles can neither turn nor (in most cases) stop. Yet, it seems not unreasonable that many motorists may tend to extrapolate from their far more frequent experiences with large highway vehicles, and assume that the train not only can stop or reduce speed, but that it will if necessary to avoid a collision.

2.1.6 Motorist Warnings

In general, the train-activated motorist-waring systems used at grade crossings have been developed by the railroad signal-engineering community with relatively little interaction with traffic engineers. Warning devices have been developed in a relatively pragmatic evolution. Unlike highway signals, grade-crossing systems have been subjected to several particularly severe constraints which have had direct impact upon the information conveyed to the motorist. The potentially catastrophic consequences of system failure have generated a dedication to fail-safe design, interpreted in this case, to require activation of the warnings in the event of virtually any system failure. One inherent consequence of this is a necessary bias toward unwarranted activation, or "false alarms"-- cases in which component failure, electrical surges, vandalism, etc., cause activation--possibly for an extended period of time, with no train present. This (safe) failure mode is considerably less common with traffic signals.

The importance of providing a fail-safe warning has led railroads to utilize a dual-power system, typically in the form of batteries to operate the system should commercial A/C power fail. This has generated a great concern for minimizing power consumption, a system constraint which will be discussed in more detail at a later point. One consequence of this and other factors is that no equivalent of the highway green light--an indication that the system is operating and the way is clear--is provided. In other words, a totally "dead" system, with or without a train approaching, presents to the motorist exactly the same aspect as a working installation under safe conditions. Also for simplicity and other reasons, a crossing does not provide the functional equivalent of an amber light, indicating that those far enough away to stop should do so but others can safely cross.

2.1.7 Motorist Response to Warnings

The signals at highway intersections are generally referred to as traffic-control devices. It is reasonable to assume that motorists in general perceive that an intersection is ahead, that hazard exists, and that it is prudent to seek to ascertain the presence of either active or passive traffic-control devices. Active warnings generally proclaim their presence by a flashing or continuous light.

None of these factors can be assumed at a grade crossing. The presence of a railroad-highway intersection may not be noted until it is quite close, and the situation may be poorly understood. As indicated above, many motorists have a highly imperfect knowledge concerning grade crossings, and sometimes, make unwarranted and dangerous assumptions.

Further, drivers normally come to associate a set of characteristic expectations with intersection traffic signals. They are aware that red lights normally change to green within a relatively short time and that there is a certain chance of being apprehended by law-enforcement officials for defying the signals. A potential collision hazard is often obvious. Very rrequently, the flow of cross traffic physically prevents passage. Thus, stopping at red traffic lights becomes an established habit. At grade crossings, on the other hand, experience may often have led to an expectation that either no train is coming, or that there is at least likely to be a quite sufficient time for a safe and leisurely crossing. There is also the possibility of a wait of several minutes while the train passes. In other words, the motorist may well perceive the message of the warning to be ambiguous or possibly fraudulent, with a significant penalty (a lengthy delay) with no corresponding benefit if one "plays safe."

2.1.8 Nature of Accidents

The very limited deceleration capability and great mass of a train tend to produce accidents of far greater severity than is the case for vehicle-vehicle collisions; a grade-crossing accident is approximately 30 times more likely to produce a fatality than one between highway vehicles.

The lengthy review, which may be felt to belabor the obvious, is intended to provide convincing support for several general conclusions concerning grade-crossing safety:

a) The motorist is less likely to be aware of the crossing than of a normal highway intersection; hence, a high degree of alerting effectiveness is necessary.

b) Both the situation and the hazard at a crossing are significantly different from those at crossroads; hence, the warning must be immediately and unequivocally identifiable as associated with a crossing.

c) There is inherently more ambiguity about the accuracy and meaning of a signal's message, and less motorist understanding of appropriate required actions.

The third conclusion relates primarily to issues such as driver education and train-detection technology, rather than to the motorist warnings themselves. However, the first two points are directly relevant to design of the signals. Two characteristics are clearly crucial: a high degree of alerting effectiveness; and a distinctive, readily recognized aspect.

The view taken in the above discussion has been primarily theoretical. However, useful insights and understanding are also obtainable through consideration of the history, evolution, and technology of the warning systems currently in use. The following pages provide such a review and analysis.

2.2 GRADE CROSSING MOTORIST WARNING TECHNOLOGY

The basic train-activated flashing lights now found at many railroad-highway grade crossings, either alone or in conjunction with automatic gates, have been in use for over 50 years. Although many improvements have occurred in both performance and construction, the aspect presented to the motorist has become standardized: two incandescent lamps, mounted in reflectors behind red lenses, horizontally aligned at a spacing of 30 in (0.76 m), against a 20 in (0.5 m) circular black background, flashed alternately at a rate of 35 to 55 flashes per min for each lamp (Figure 1). Indeed, the history of this basic pattern can be traced back through the electromechanical wig-wag signal to the motion of a man swinging a red lantern.[3]

Such warnings have generally been found to reduce the occurrence of grade crossing accidents from 60 to 80 percent.[4] They are now to be found at an estimated 41,600 of the 220,000 public crossings in the United States, accompanied by automatic gates in approximately 9000 cases. Through the years, and particularly in recent times, the railroad-supply industry has advanced the technology of these lights substantially. In addition to improved mountings and reflectors, lenses, incorporating more efficient beam patterns and fabricated from nearly unbreakable polycarbonate materials, have been developed. Higher-intensity bulbs are now offered, with special reflectorization available, and now, quartz-halogen lamps are also on the market.

These changes have generally contributed to greater brightness and improved beam patterns. However, all have occurred within a framework which has severely limited major innovation. It is the purpose of this section to review the nature and consequences of these constraints.

Perhaps the most fundamental limitation on conventional warnings is the very low-power consumption permitted. It is generally considered necessary (and often legally required) that grade-crossing protective systems operate from batteries for periods of one to seven days in the event of any failure of commercial power or power-system components (such as fuses). This constraint, coupled with the large number of lights commonly used at a crossing (typically four pairs; often three or four

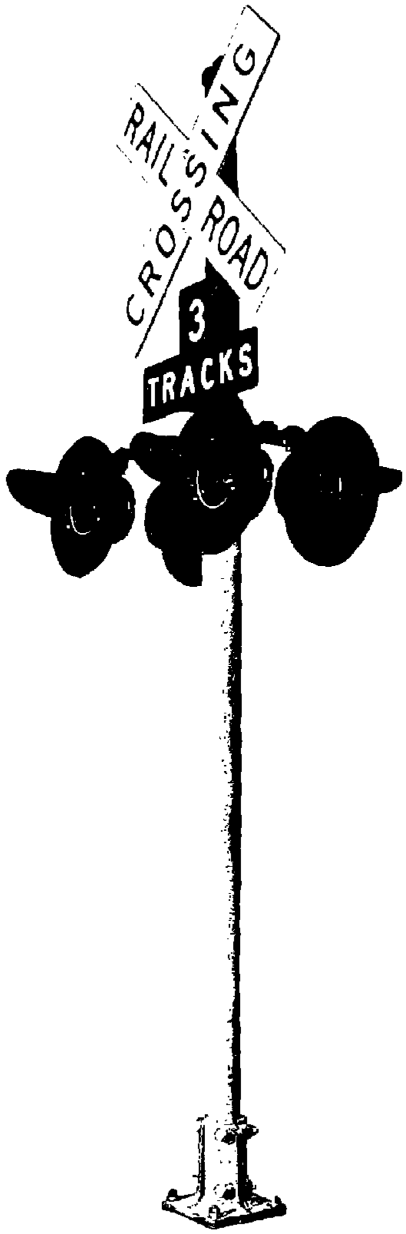

FIGURE 1. CONVENTIONAL GRADE CROSSING FLASHING-LIGHT ASSEMBLY

times that), has led to use of 11-w bulbs for many years, with 18 w now standard, and 25 w coming into wide use. When these wattages are compared to the 60- to 150-w ratings of bulbs used in highway traffic signals, it becomes obvious that adequate intensity can be obtained only through tightly focusing the light produced into a narrow beam. This is the course which has been followed, with special roundel (lens) design providing a diversion of a limited quantity of light in certain directions to include motorists not located within the main beam. Each light consists of a housing either 8 or 12 in. in diameter, containing a high quality spherical-mirrored reflector, a bulb rated at 11, 18, or 25 w, and a red glass or plastic beam-forming roundel. Quartz-iodine bulbs rated at 16 and 36 w are currently also available. The standard design voltage is 10 for a lamp filament, although less voltage is often used in practice to prolong filament life. This practice has a decidedly deleterious effect on light output, which is approximately proportional to the third power of voltage. Without the roundel in place, the quality of the reflector and compactness of the filament are typically capable of providing a conical beam of less than 4 degrees between 10-percent maximum intensity points or approximately 2 degrees between 50-percent intensity points.

Figure 2 shows a typical flashing-light pair mounted by wayside. Note that each light is equipped with a 20-in. diameter black background and a black hood. Figure 3 shows the internal arrangement of reflector and lamp in a housing. Figure 4 shows a beam pattern measured without the roundel in place.

The purpose of the roundel is to filter all but the red light out of the beam to produce a pure red hue, and to shape the remaining light into the desired beam shape. It should be noted that typically used roundels are of such a deep red that the transmittance is only between 0.1 and 0.2. Therefore, the shaping of the beam must be performed scrupulously to avoid wasting any of the remaining light. Modern practice calls for a beam with an intense central portion for long-range alerting of the motorist, plus a lower-intensity fan-shaped beam with some downward scattering

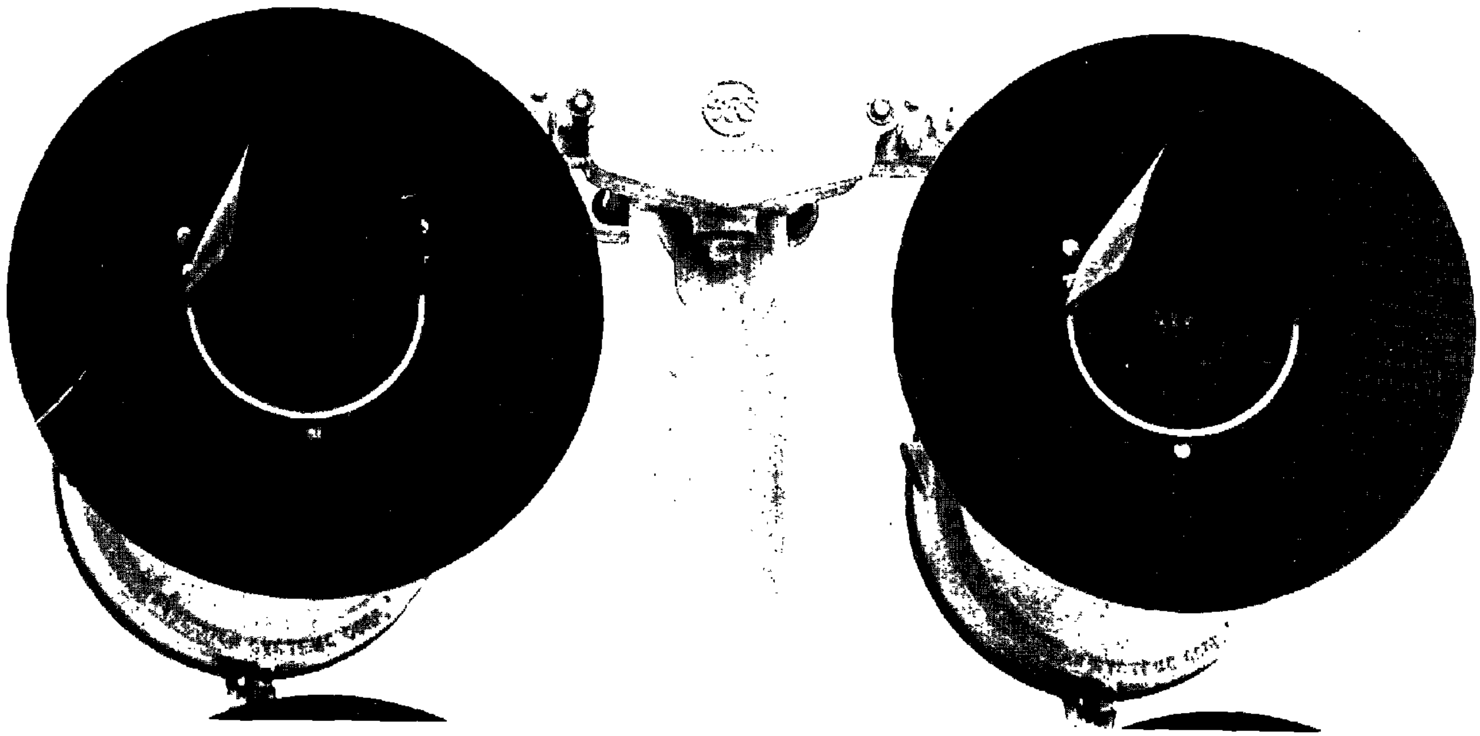

FIGURE 2. A FLASHING LIGHT PAIR MOUNTED ON A POLE AT WAYSIDE
Note the 20 in. diameter black backgrounds used to enhance conspicuity of lights.

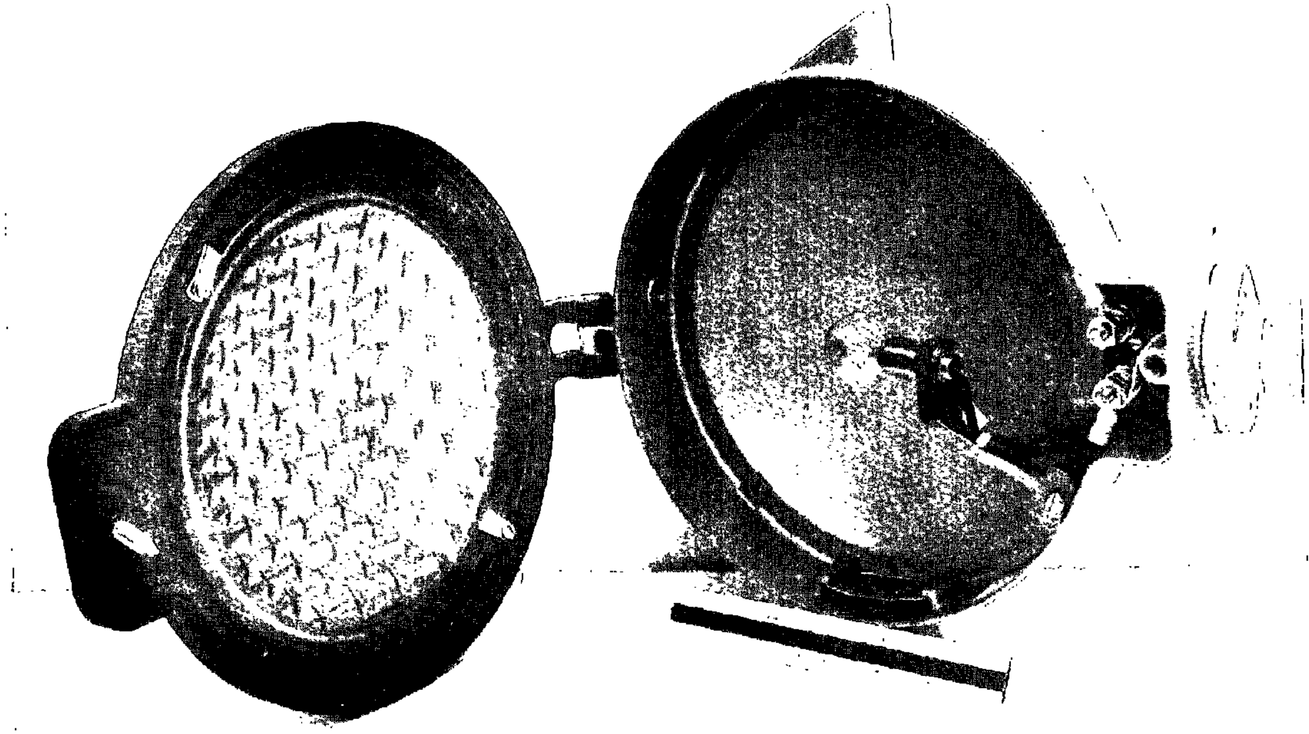

FIGURE 3. STANDARD AAR (ASSOCIATION OF AMERICAN RAILROADS)-APPROVED INCANDESCENT FLASHING LIGHT HOUSING Note Reflector and Bulb. Roundel is Mounted in Hinged Front Cover.

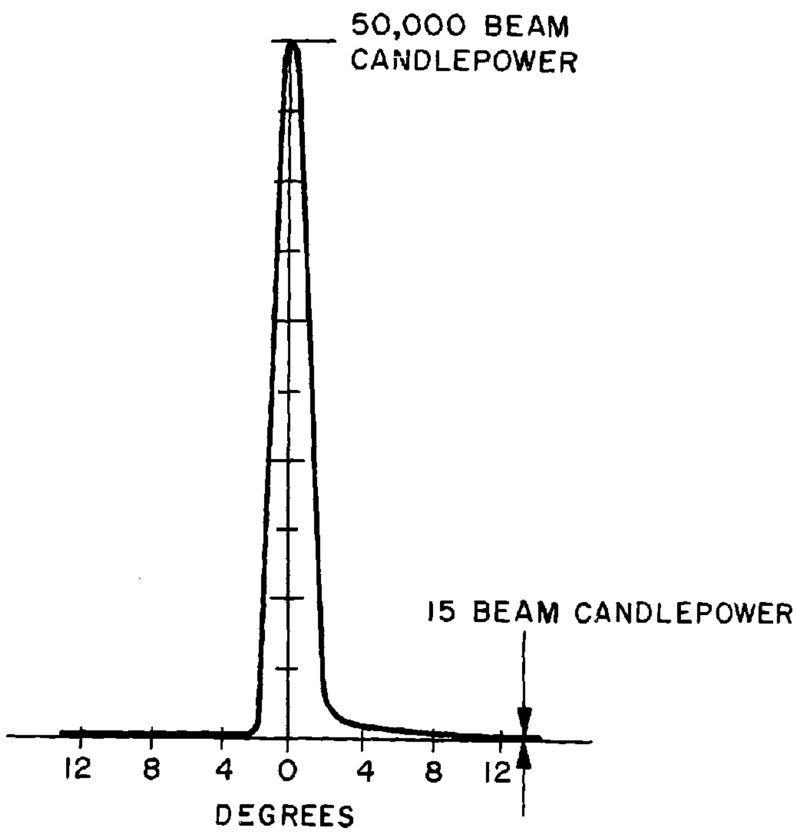

FIGURE 4. THE BEAM PATTERN (HORIZONTAL AND VERTICAL) OF A STANDARD INCANDESCENT-LAMP GRADE CROSSING UNIT WITHOUT ROUNDEL IN PLACE

to provide indication to motorists very close to the lights, which are typically mounted a number of feet above eye level. The beam pattern is formed by distributing zones covered with ribs of varying depth and beads over the internal surface of the roundel. Figure 5 shows a typical beam pattern obtained with a "long-range" roundel. Figure 6 shows two 8-in. diameter roundels. In the roundel on the left, a long-range central beam, sometimes called the "hot-spot," is obtained by having an annular region of 1- to 2-in. width at the outer rim of the roundel which is only very lightly ridged.

The technical development of light housings, mirrors and roundels has been a result of trying to optimize the use of an inherently underpowered light source--the low-wattage bulb. The use of such bulbs in turn has been predicated on the fact that flashing-light systems must be capable of operation for periods of a day to a week on emergency battery power when line power fails. It should be pointed out that under ideal conditions of cleanliness, adjustment, voltage and aiming, the performance of a modern light unit is surprisingly good, with a central beam of over 1,000 candle-power (cp) peak intensity. It is clearly visible at a distance of 1,000 ft near noon on a bright day, and has side and lower beams visible at shorter distances at angles to the side and below right up to a crossing.

Considered in terms of effectiveness as a motorist warning device, serious limitations arise from the requirements for tight focusing. The problems are both inherent and practical. In the former category is the challenge of providing an adequately intense light to all positions which a motorist might occupy. Even the use of two or three pairs of lamps, aimed to provide overlapping coverage of the entire approach path, often appears to be marginally adequate. Further, a driver might easily focus his attention upon a pair of lights other than the one appropriate to his position, and be inadequately warned. This difficulty has tended to increase in recent years, as lights have been located farther from the road--both vertically (with

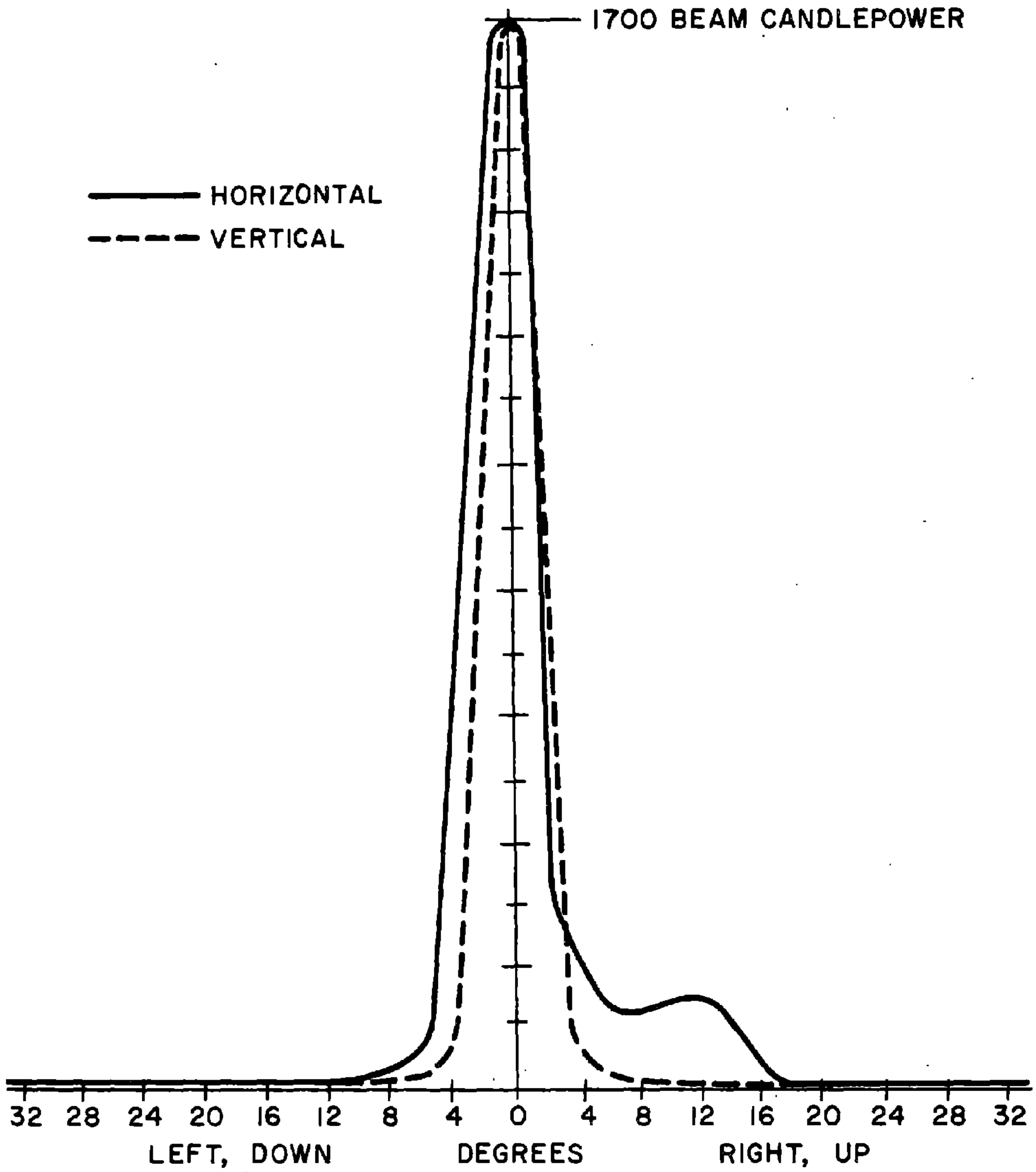

FIGURE 5. BEAM PATTERNS OF INCANDESCENT-LAMP GRADE CROSSING UNIT EQUIPPED WITH "LONG-RANGE" ROUNDEL. This Roundel Produces a "Zonal" Pattern--the Asymmetrical Bump on the Right-Hand Side of the Curve is to be Positioned on the Road Side of the Light. The Incandescent Light was an 18-W Bulb. The Intensity Wattage is for a Continuously Burning Incandescent Bulb. Effective Peak Intensity for one Flash/Sec is I_{eff} = 1300 bcp.

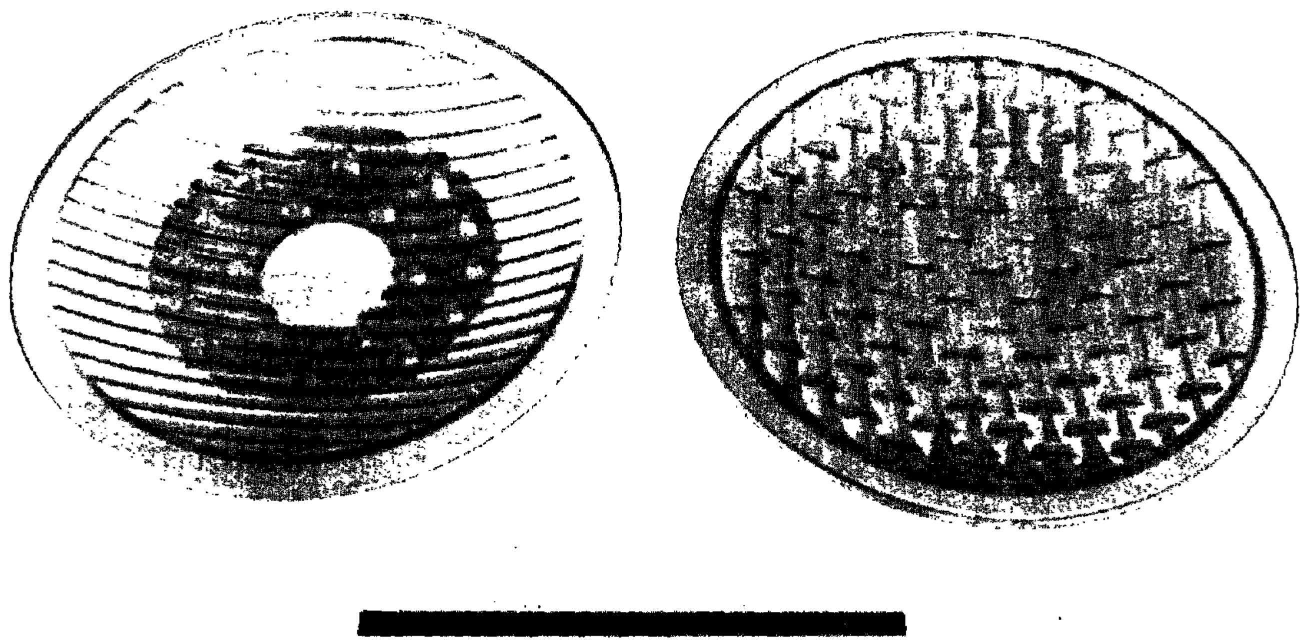

FIGURE 6. FRONT AND BACK OF THE ROUNDEL USED TO OBTAIN BEAM PATTERNS. (See Figure 5.)

cantilevers) and horizontally (beyond highway shoulders). This difficulty is a primary cause of the common (but incorrect) impression that grade-crossing lights are inherently less bright than conventional highway-traffic signals.

Of comparable importance in practice is the great sensitivity of such a device of misalinement. Whether through misplacement of the bulb, faulty aiming of the assembly, use of an inappropriate roundel, or physical movement through accident or malicious vandalism, very little deviation is required to degrade seriously the effectiveness of the warning. The railroad environment makes particularly difficult the attainment and maintenance of optimal conditions. Extremes of weather, continual vibration, sabotage, etc., all make probable that the lights will deviate somewhat from proper aim, and thus, will not achieve full design effectiveness.

The preceding discussion is intended to provide both an overall framework for developing and evaluating innovative approaches, and an understanding of the context into which they must fit. In terms of the warnings themselves, alerting effectiveness and distinctiveness, are seen to be major goals to be achieved in a manner compatible with existing technology and capable of benefiting motorist familiarity with the highly standardized devices now in use.

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* This situation has been analyzed by V.L. Lindberg, as reported in Railway System Controls, Januarary 1971, p. 24-30.

3. REALIZATION OF IMPROVED SYSTEMS

3.1 REQUIREMENTS

It is here appropriate to attempt to establish necessary and desirable quantitative performance specifications. For improved systems, however, if this is to be more than an academic exercise, technical objectives must be determined within a relistic overall framework. As suggested previously, constraints of practicality require a broad compatability with both existing crossing warnings and general traffic control principles.

3.2 COMPATIBILITY WITH EXISTING PRACTICES

Conventional protection is well defined by Cox and by the Association of American Railroads.[5,6,7,8] If one were to attempt to work entirely within these specifications, little improvement would be possible since they have developed as a codification of existing technology and practices. However, acceptance of the major part of these standards raises no problems. The use of alternately flashing, horizontally alined red lights is nearly unique to the crossing application, and enjoys widespread motorist recognition. Thus, present details of component dimensions and location can readily be accommodated in developing an alternative system.

In addition to retaining current motorist recognition, compatibility with existing engineering and construction practices is highly important. Recent analysis indicates that the number of crossings likely to warrant new installation to active protection is substantially smaller than the number which already have it, and at which approximately 40 percent of deaths now occur. Thus, the potential benefits of improved devices will be sharply limited unless upgrading and retrofitting is relatively simple and inexpensive.

It is equally important that grade-crossing warnings be as consistent as possible with all other motorist-warning and traffic-control devices. Thus, the Institute of Traffic Engineers standards for traffic signals can provide useful guidelines as to color, beamwidth, and intensity.[9] In more general terms, the manual on Uniform Traffic Control Devices includes a substantial body of information as to location and use of traffic controls, certain elements of which are particularly pertinent.[10] Data from references 5 through 10 will be utilized as needed in the following discussion.

3.3 FUNCTIONAL REQUIREMENTS

3.3.1 Intensity

The fundamental quantitative specification needed for warning lights is intensity. This is not a simple matter. The brightness required for "adequate" warning depends upon the individual's physical and emotional characteristics, the ambient light level, and the entire visual context. This problem has been treated by others, and the results of Cole and Brown for traffic signals in general have been adapted for this study.[11] Their basic finding is that the source intensity I_o (candela) (cd) appropriate to a viewing distance d(ft), with ambient illuminance L_b (ft-Lamberts), is given by the expression

$$I_o = 6.37(L_B + 2.92)d^2 \times 10^{-7} \quad \text{(cd)}.$$

As an example, "normal daytime conditions" (L_b = 2919 ft-L, or 10,000 cd/m^2) imply I_o = 200 cd to be necessary for a viewing distance of 330 ft (100 m). Background illuminance can, at times, reach three to four times this value. Further, the intensity required, if one seeks to alert as well as inform, can increase this value. However, this equation provides a useful starting point and is readily modified if necessary. (Under night conditions, it is important that intensity not be so great that motorists are bothered or hampered in their actions. Tests in a different but related research activity indicate that a level of 200 to 500 cd is likely to be acceptable for an observer 20 to 50 ft (6 to 15 m) from the lights.[12, 13])

3.3.2 Pattern

The perceived brightness at the eye of the motorist depends upon the lamp and intensity of beam shape, the location and aim of the light, and the observation distance. The illumination pattern must be such that as a motorist approaches the signal by moving out of the brighter central part of the light beam, the resultant decrease in brightness will be compensated by the reduction in viewing distance, so that the Cole-Brown criterion can continue to be met. Further, this must be true for a variety of possible light locations and viewing points; it would be highly impractical to require a large number of roundels or optical systems for different cases, or, under such circumstances, to expect that the correct one would always be used. In addition, substantial margin is required to allow for some degree of misalinement and the likelihood of curving or undulating approach roads.

There are two basic situations to be covered: roadside installation, and cantilever mounting above the traffic lanes. In the former case, both driving lane(s) and shoulder may be wide or narrow, so that the light may be displaced horizontally from the vehicle path by an amount which could easily range from 10 to 35 ft (3 to 10 m). The vertical spread is of less concern because of the common mounting height of approximately 8 ft (2.4 m). However, it must accommodate vehicles from sports cars (driver eye height 40 in (1 m) to large trucks, (eye height in excess of 100 in (2.5 m) . Grades on the approach road, particularly when undulating rather than constant, can have a marked detrimental effect.

For cantilever-mounted lights, vertical spread can be a severe problem: with a typical mounting height of 18 ft (5.5 m), the angle at which a driver views the lights can change substantially as he approaches, especially if grades are involved. This difficulty is normally alleviated by the use of additional short-range lights, but the subject of this study is a system which, like traffic lights, require no such compensation.

3.3.3 Flash Rate

Experience in a variety of similar applications (marine, aviation, and highway) and recent research concerning railroad applications indicate that the combined flash rate (with alternate flashing) should be at least 90 per min (1.5 Hz), with 120 per min (2 Hz) preferred.[13,14] Practical considerations militate against values higher than 3 to 4 Hz and rates between 6 and 12 Hz can have seriously disturbing effects on some individuals and should be avoided. (Current practice calls for a combined flash rate of 70 to 110 Hz flashes per min.)

3.3.4 Flash Duration

For a given intensity level, the energy required to produce a pulse is proportional to the duration of the pulse. This suggests the desirability of using very short intense pulses in cases for which low power is important. However, the perceived brightness of flashes which are markedly shorter than the response time of the eye(.2 sec) is basically determined by total flash energy alone, so that no further benefits are obtained for shorter flashes. Numerous studies of this very complex topic confirm that the power efficiency, with which a given perceived brightness level can be obtained, increases with decreasing duration, down to approximately 0.2 sec. Little improvement is found below that interval.

3.3.5 Color

The total amount of light perceived by the human eye depends upon the intensity of light energy emitted by a source, the distribution of that light energy throughout the spectrum, and the exact manner in which the emitted light is weighed by the spectral sensitivity characteristics of the human eye. Figure 7 shows a graph of the sensitivity of the normal human eye as a function of wavelength. Note that the human eye is more sensitve to yellow-green light than to any other color and it is markedly less sensitive to red. The deeper the red, the less sensitive the eye

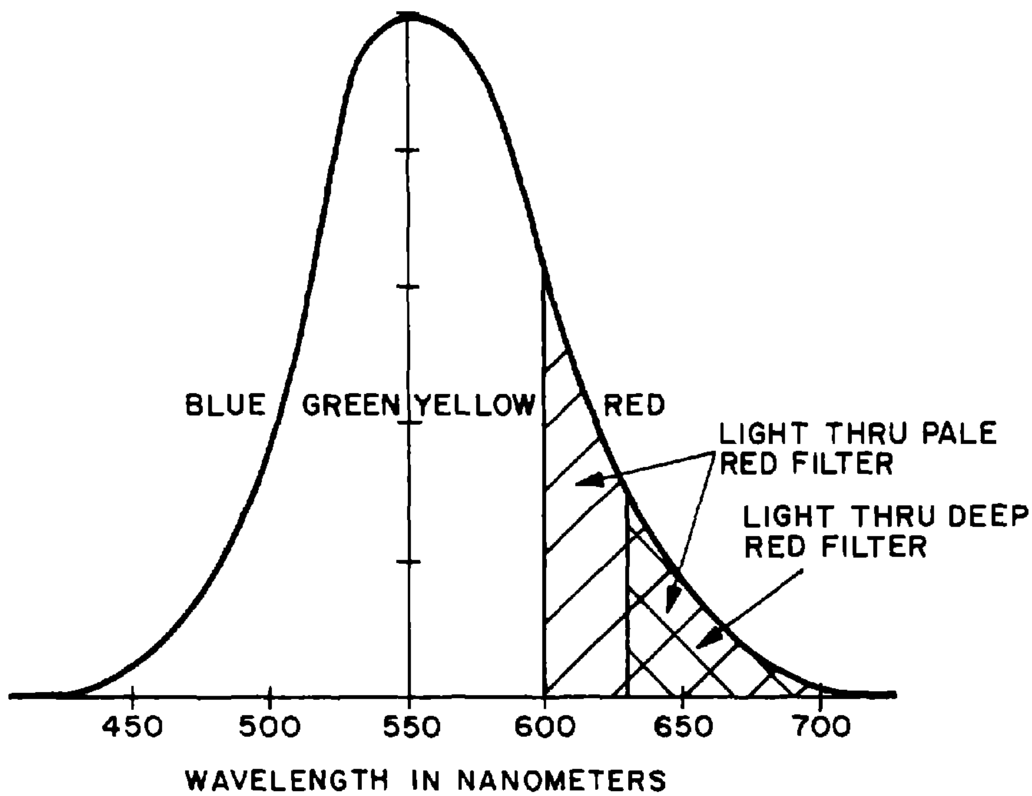

FIGURE 7. STANDARD C.I.E. (COMMISSION INTERNATIONALE DE L'ECLAIRAGE) CURVE FOR SENSITIVITY OF HUMAN EYE. Area Under Total Curve Represents Perceived Brightness of Source of White Light. Area Under Smaller Crosshatched Portions Represents Perceived Brightness Following Filtering of White Light Through Pale-Red and Deep-Red Filters.

is. Red filters commonly are made by adding a dye to the plastic or glass lens material that absorbs all light of wavelength shorter than some certain cutoff wavelength. The shade of red light coming through, then, depends upon the characteristics of the light source and the cutoff wavelength of the filter. It is approximately correct to say that the average hue of the light coming through is the perceived hue, as long as all the light lies in the yellow-green to red range.

In the railroad industry, emphasis has been placed on producing red lights of very distanct red appearance to avoid any possibility of a red light being mistaken for one of any other color. In view of the statistical variation in color perception from observer to observer, and manufacturing tolerances required for glass lenses, the practice has been to use very deep reds. As can be seen in Figure 7, the result is that most of the light available is filtered out. One distinct disadvantage of this approach is that a significant portion (two percent) of the male population suffers from red-deficient vision. While recently observing experimental flashing-light systems being tested by a large western railroad, one of the authors who has color deficient vision was unable to see the lights at a grade-crossing flashing at a distance at which a normal observer ordinarily could. The lights in question had roundels of the traditionally deep red. The same difficulty was not encountered with experimental lights using roundels of a lighter red. It is believed that using a lighter shade of red roundel provides an advantage of added brightness to a normal observer that more than compensates for any possible confusion in color that could arise, and provide far greater benefits to the observer with red-deficient vision.

One important aspect of a grade-crossing flashing light is its informational aspect. In part, this is provided by the color of the light, just as the color of a highway intersection signal light either indicate stop or go. However, early warning of approach to a grade crossing is also an important consideration, and there is an advantage to be gained in catching the unsuspecting motorist's eye at maximum possible range. At the grade crossing, once the motorist's attention has been obtained, the pattern of the flashing lights together with the presence of crossbucks should be sufficient to indicate to the motorist just why the lights are flashing, and, therefore, what action should be taken. Thus, use of a relatively pale or orange shade of red appears to be the preferred course of action.

In accordance with this reasoning, the roundel color utilized in most of the research reported here has been one passing light of 620 nanometers (nm) average wavelength, with color chart coordinate of y = 0.308. This shade is at the pale end of the allowed AAR grade-crossing red spectral range and provides approximately twice the transmission for normal viewers as do filters whose shade lies in the middle of the AAR range (620 to 633 nm; or from y = 0.308 to 0.288). For reference, Institute of Traffic Engineers standards allow a maximum y-value of 0.308 for traffic signals, and Society of Automotive Engineers limit for motor-vehicle taillights go to y = .330.

3.3.6 General

Little elaboration need be given the obvious practical requirements--installation costs and power consumption comparable to present systems, or less, minimal maintenance needs and commercial availability without extensive development. Particularly for experimental or initial installation of an innovative system, a number of special constraints or considerations apply. Standard railroad hardware and installation practices should be used wherever possible. The visual appearance of the unactuated crossing should not be significantly altered. New motorist warnings should be installed only in addition to existing devices to capatalize on their fail-safe properties and motorist familiarity with their visual characteristics. In general, installation procedures should strike a reasonable balance between ease and economy of installation and protection from vandalism and the environment.

3.4 A TECHNICAL BASIS FOR IMPROVEMENT

The key to synthesis of a meaningful advance is the requirement for a short-flash duration. Since it is not practical to cycle an incandescent bulb at the pulse durations desired because of filament heating and cooling times, an alternative is needed. Electro-mechanical devices, such as rotating beacons, can provide the desired effect. However, considerations of cost, complexity, and maintenance requirements, as well as synchronization and easy adaptation to existing systems, all combine to make this an unpromising approach.

On the other hand, short-pulse beacon applications in space, marine, aviation, highway, and--more recently--railroad rolling stock have made increasing use of xenon flash-tube (capacitive discharge) lamps.[12,15,16] In such lights, the energy stored in a capacitor ($1/2CV^2$) is released--primarily as visible radiation--by electrical discharge across a xenon-filled gap. The process is readily initiated by an applied "trigger" signal, so that precise timing and synchronization are possible; duration is typically less than .001 sec. Application of this technology to grade crossings was examined in the mid-1960's by Scott and Moe.[17] They carried out field installations using a burst of xenon flashes in place of each conventional flash. However, the multiplicity of flashes and limitation of dark-red lenses made it impossible to obtain satisfactory intensity within the power consumption then considered permissible. In recent years, E. Krause has installed xenon lights to supplement conventional flashers in a variety of forms at a large number of operating grade crossings, with generally good results.[18] This work has clearly demonstrated the basic feasibility of the concept, particularly as lighter reds and higher-power-consumption incandescent lights have come into use.

4. XENON-FLASHLAMP HARDWARE AND OPERATING CHARACTERISTICS

4.1 FLASHLAMP

A xenon-flashlamp system basically consists of the flashlamp or flashlamps, energy storage power supply, and trigger circuit. The flashlamp is a sealed glass or quartz envelope containing xenon gas, which in the type of application covered here is at approximately 1 atmosphere pressure. Figure 8 shows a diagram of a typical flashlamp. An anode electrode and a cathode electrode inside the envelope are attached to feed-through conductors. A trigger electorde is typically provided for the purpose of initiating ionization of the xenon gas, so that it will conduct a pulse of current and discharge an energy-storage capacitor connected between anode and cathode. The trigger electrode can be inside of the envelope, but it is generally sufficient to locate it on the outer surface of the envelope since a high momentary electric field induced by an abrupt voltage pulse between trigger electrode and cathode is sufficient to cause triggering of the flash. The envelope of the flashlamp can be either a straight or coiled tube. (In grade-crossing applications, a coiled tube is used so that the production of light can be concentrated near the focus of a parabolic reflector.)

The power handling and light-producing capacity of a xenon-flash tube depends upon electrode design, arc length, gas pressure, and cooling arrangements. As an illustrative example, the Sylvania R4321A flash tube in Figure 9 has an internal gas pressure of (approximately 1 atmosphere), and it can be operated continuously at one 30-J flash per sec, producing approximately 60 candle-sec (cd-sec) per flash.

4.2 LIGHT-PULSE CHARACTERISTICS

When the energy-storage capacitor is charged up from a d/c voltage source to a voltage in the 300- to 500-v range and a high-voltage pulse in the 4,000-v range is applied to the trigger electrode, the gas in the flashlamp becomes conducting and an arc

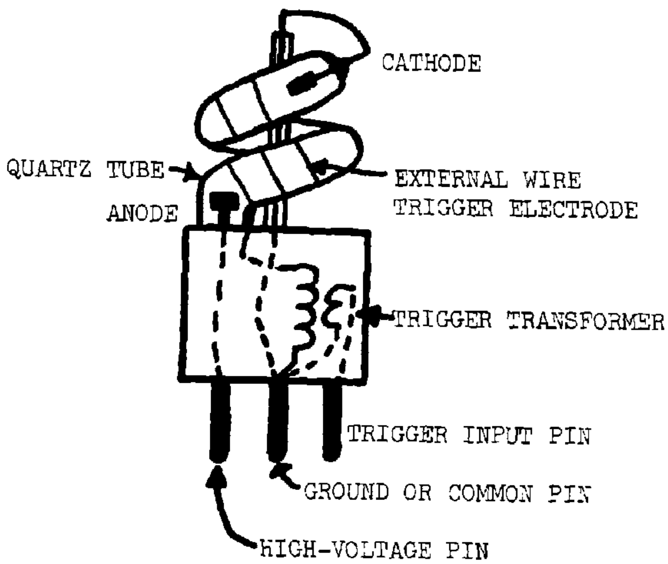

FIGURE 8. TYPICAL XENON FLASHLAMP. Flashlamp is shown Approximately Actual Size.

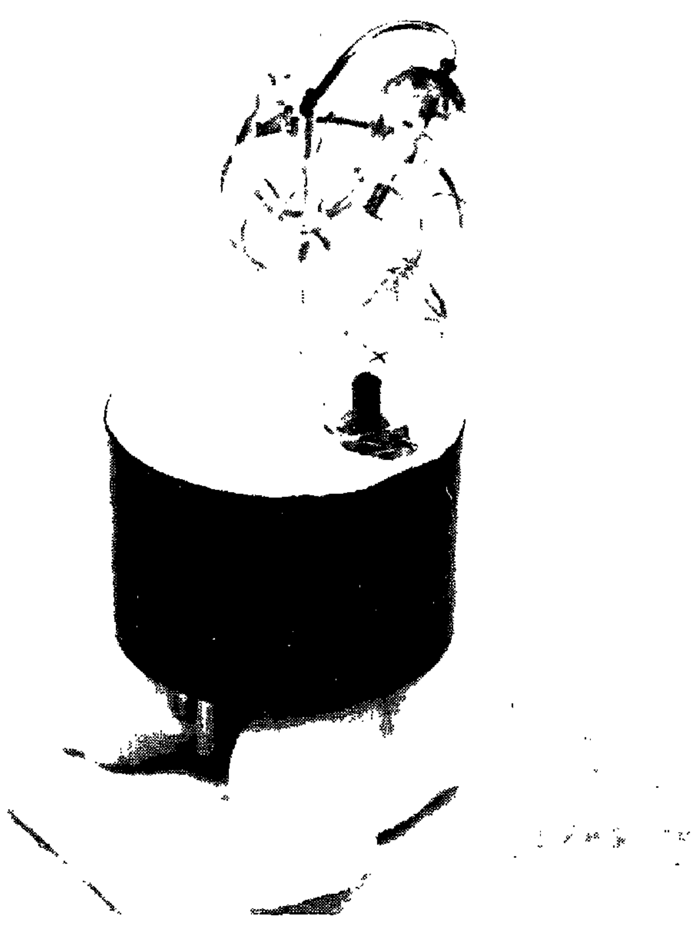

FIGURE 9. SYLVANIA MODEL R4321A XENON-FLASH TUBE. Tube is Rated at 60 Flashes Per Min. at 30 J Per Flash With Guaranteed Lifetime of 500 h of Continuous Operation.

discharge results. The stored charge on the capacitor is discharged in a very short period of time, on the order of a fraction of a millisecond (ms), causing the gas in the flash tube to attain a temperature of approximately 6,500°C. The hot incandescent gas emits a flash of white or bluish-white light before cooling very rapidly because of thermal radiation and thermal conduction to the envelope of the flashlamp.

The total amount of light energy released in one flash depends upon the initial stored electrostatic energy in the energy-storage capacitor. In grade-crossing applications, total electrical energy consumed per flash of approximately 20 joules (J) has generally been used, using a 250 uf energy-storage capacitor charged to 400-v just prior to discharge, according to the relation

$$W_{stored} = CV^2/2.$$

Figure 10 shows typical waveforms for voltage, current, and instantaneous light output from a typical 20-J flashlamp. Note that the flash of light produced is of very short duration--much less than the resolving time of the human eye. What is important is not the fact that the peak intensity is 150,000 cd (1 cd = 1 cp), but rather that 23 c-sec of total light energy are emitted in a very brief time.

Since the human eye tends to integrate received light over a time interval of approximately 0.2 sec, making any light flash of a duration much less than 0.2 sec, appear to be about 0.2 sec long, a figure of <u>effective intensity</u>, I_{eff}, of a single light flash can be obtained by dividing the total integrated light intensity in a flash by 0.2 sec, to obtain

$$I_{eff} = \frac{\int_{o}^{\infty} I(t)dt}{0.2} \text{ effective cd.}$$

Thus, the effective intensity of a single flash of a 20-J xenon flashlamp producing 23 C-SEC of light energy or integrated intensity is

$$I_{eff} = 23/0.2 = 115 \text{ effective cd.}$$

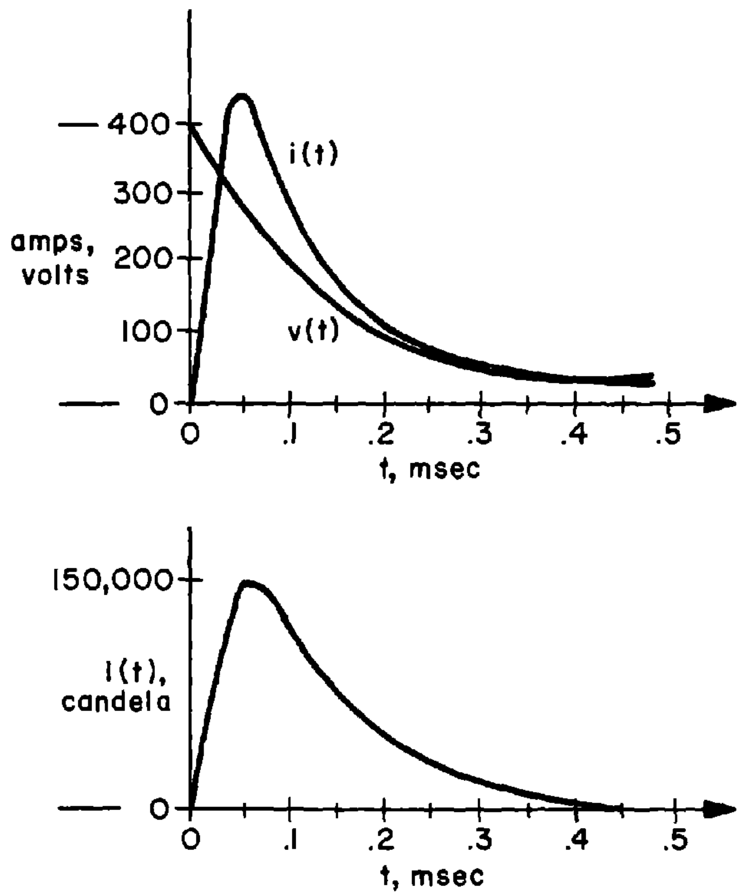

FIGURE 10. CURRENT, VOLTAGE, AND LIGHT INTENSITY VS. TIME FOR A 20-J XENON FLASHLAMP.
Top Curves: Current i(t), and Voltage v(t).
Bottom Curve: Instantaneous Light Intensity I(t).

The subject of "effective intensities" of flashing lights is discussed further in a later section of this report. To orient the similarities and differences of xenon flashlamps and tungsten-filament lamps, it is indicated here that an unfocused standard 18-w tungsten-filament railroad signal lamp produces 15 cd of light output.

One important operational advantage of xenon flashlamps over incandescent lamps is their lifetime and failure characteristics. Over the flashlamp's lifetime, the intensity of emitted light slowly diminishes because of deposition of electrode material, sputtered off the electrodes on the interior wall of the tube. The lifetime is dependent on the choice of electrode materials used, construction features of the tube, and energy input per pulse. However, the tube will continue flashing practically indefinitely since there is no mechanism of catastrophic failure as there is in a tungsten-filament incandescent lamp. A relatively inexpensive flashlamp such as the Sylvania R4321A (shown previously in Figure 9) has a rated lifetime of 500 hours (hr) for continuous operation at a rate of one 20-J flash per sec. (The rated lifetime is defined as the time for light output to drop to 50 percent of original output.) In test installations at lower power levels, light output has been found to degrade much more slowly; lifetimes of thousands of hours have routinely been obtained. At a grade crossing, where operation will normally occur for well under an hour per day, a useful life of at least several years should be the typical experience, with almost total freedom from complete failure.

A further operational advantage of xenon flashlamps over incandescent lamps is that the intensity of light output can easily be changed simply by changing the energy of electrical pulses into the flashlamp. This is most conveniently done by changing the value of energy storage capacitance. To a good approximation, light output is directly proportional to power. In some applications of xenon flashlamps, such as on railroad locomotives, it is believed desirable to use a higher intensity during the day and a lower intensity at night. The most reliable way to do this is to use two separate power supplies--one with a large energy storage capacitor and one with a small one--connected to the flashlamps. Only one power supply is energized at a time, and intensity can be switched by switching low-voltage power rather than by switching high-voltage power from a capacitive source. This scheme could be directly used for grade crossings if it were felt to be desirable or necessary.

4.3 OVERALL FLASHLAMP SYSTEM CONFIGURATION

Figure 11 shows an overall flashlamp system of the type that has been employed at grade crossings. The xenon flashlamps are coiled tubes with external trigger electrodes in the form of wire mesh. To permit lower voltages to be used for trigger pulses, a 20:1 step-up pulse transformer is mounted integral with each flashlamp. Trigger pulses of approximately 200-v with fast rising leading edges fed to the primary of the trigger transformer are sufficient to cause triggering of flashes.

The simplified diagram of the power supply shows that the secondary voltage of the main power-supply transformer is rectified, and then, impressed across the energy-storage capacitor. Primary power can come from a variety of sources and three of the most common possibilities are shown schematically. A/C power of 115 vac (voltage alternating current) 10 to 12 vac and be fed directly to the primary windings of the main transformer for step-up to the required secondary voltage. As an alternative, 10 to 12 vdc (voltage direct current) can be fed through an inverter circuit to the main transformer for step-up to the required secondary voltage, or use of an additional bridge rectifier and transformer permits normal operation from 115 vac line power and emergency operation from 12 vdc standby power.

Triggering is controlled by a trigger circuit which can be either free-running at a specified rate, or which can be itself controlled by an electrical signal from another source. In some grade-crossing applications to date, free-running flashlamps have been employed. In other grade-crossing applications, the voltage waveforms across the existing tungsten-filament signal lamps have been used to synchronize the xenon flashlamps to the incandescent lamps.

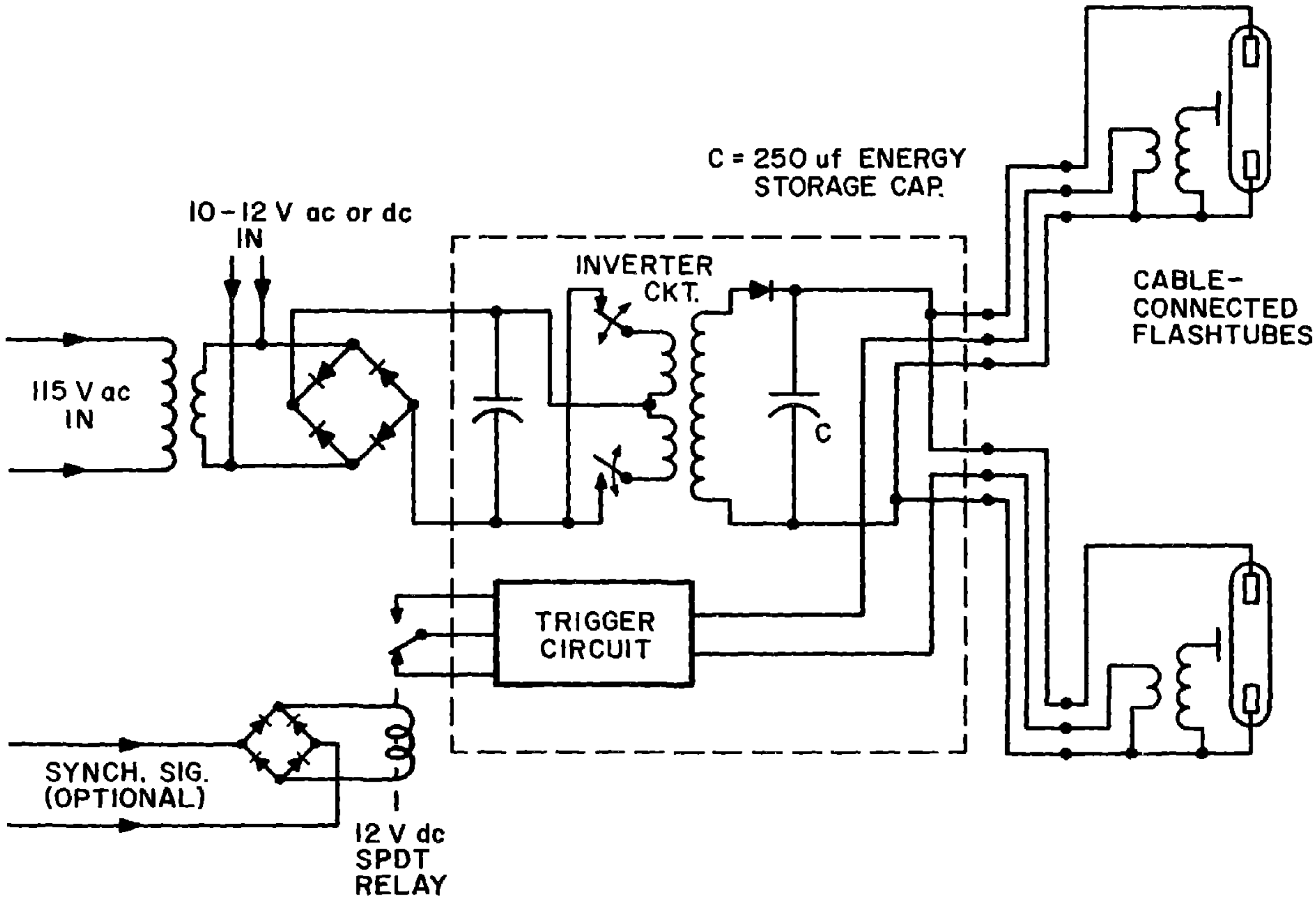

FIGURE 11. BASIC PARTS OF A XENON-FLASHLAMP SYSTEM. System Can Operate From 115 vac (Volts Alternating Current), or from 10 to 12 vac or vdc The Two Xenon Flashlamps Flash Alternately. Optional Synchronizing Relay Operates From Low-Voltage a/c or d/c Signal From Flashing Incandescent Lamps.

The triggering circuit can consist of any means of providing a low-current pulse of a few volts amplitude to the gate lead of the SCR (Silicon Controlled Rectifier) electronic switch each time it is desired to flash a flashlamp. For a free-running pair of alternately flashing lights, it is convenient to use a multivibrator circuit together with some digital logic gates that alternately pulse the flash lamps. To synchronize flashlamps to tungsten-filament incandescent lamps, it is convenient to use a relay with the coil energized by the filament voltage. More sophisticated techniques, such as light-actuated switches, could be used as well with the light being produced by the tungsten-filament bulb. However, this method would have the disadvantage that the trigger signal would be lost if the bulb were to burn out. Filament voltage is bridge-rectified, so that the d/c synchronizing relay can be operated with either a/c or d/c filament voltage.

Trigger signals are applied alternately to the flash tubes. Because of the fact that the spontaneous arc breakdown voltage from anode to cathode is many times greater than the anode-to-cathode voltage sufficient to cause a flash upon impression of a trigger pulse, the energy-storage capacitor can be left permanently attached to both flashlamps of a pair, and only the one receiving a trigger pulse will fire. Because of the long-voltage recovery time of the energy-storage capacitor's charging circuit and the current-voltage characteristics of the arc discharge in a flashlamp, the flashlamp arc self-extinguishes at the end of a flash, and another flash will not occur until application of another trigger pulse.

4.4 ALERTING EFFECTIVENESS OF FLASHING LIGHTS

Flashing lights at grade crossings perform two basic functions. First, they gain the motorist's attention and warn the motorist that something potentially dangerous or unusual is happening. Second after the motorist's attention has been gained, the positioning of the flashing lights, the alternating flashes, the color, and the general surroundings serve to indicate that the motorist is approaching a railroad grade crossing and a train is coming.

For a given amount of power available, different flashing-light characteristics are required to optimize attention-getting potential than are necessary to optimize signaling or informational potential. For signaling, when it is presumed that the observer's attention has been obtained, long flashes of light suitably coded and colored, are preferable. The long duration allows the observer to accurately perceive the color, size, location, and time characteristics of the light flashes--all of which convey information. However, for maximum attention-getting power, available light energy must be concentrated into very short intense bursts of light that offer the greatest contrast with the ambient illumination. It is more difficult for an observer to accurately determine the color, size, and location of very short bursts of light , but on the basis of equal light energy output, short bursts are far more effective attention-getters than long-duration flashes of lower peak intensity.[19]

This approach can provide intense flashes that rise above the threshold of detectability, whereas the same light energy if continuously released at a constant average rate would continuously fall below the threshold for detectability.

The point has previously been made that one of the most important functions of a grade crossing flashing light is to alert the motorist and gain his or her attention. Often this is done when the motorist is some distance from the crossing and is not looking directly at the crossing lights. On broad busy streets, where overhead cantelever-mounted crossing lights are mounted high enough to clear large trucks, a motorist paying attention to automobile traffic might not even be aware of the existence of lights when they are not flashing. Thus, when these lights start to flash, they must gain the attention of an unsuspecting, unaware motorist, whose attention is focused elsewhere, sometimes only seen out of the corner of the motorist's eye. After the motorist's attention has been gained under these threshold conditions, it becomes reasonable to assume that the alternate flashing, the positioning of lights, existence of crossbucks and possibly gates, and often the tracks themselves, all serve to signal and motorist that his or her attention is being called to an active grade crossing, and that one must stop. A flashing light intense enough to provide alerting effectiveness to an unsuspecting person can be a fairly effective signal as well. However, a flashing light that is solely optimized for signaling an alert observer may completely fail to gain the attention of an unsuspecting individual in a brief amount of time.

Blondel and Rey were among the first investigators to study the alerting effectiveness of flashing lights of various flash durations at the threshold of visibility.[20,21] Early in the century, these workers investigated the comparisons in intensity necessary for observer detection between lights flashed with varying flash lengths and steadily burning lights.

Blondel and Rey found that a good empirical relationship between the actual intensity I of a light flash whose intensity varies throughout the flash, and the intensity I_{eff} of a steadily burning reference light that had equal threshold detectability is

$$I_{eff} = \frac{\int_{t_1}^{t_2} I(t)\,dt}{0.2 + (t_2 - t_1)},$$

where the total flash length is $(t_2 - t_1)$ sec.

What this relationship implies is that for light flashes much longer than 0.2 sec, the same light intensity measured in photomic units (lumens per square meter or candelas)($\ell m/m^2$ or cd) is required during the time the flash is on as is required in the continuous case. On the other hand, for light flashes much shorter than 0.2 sec, what matters is the total light energy released or the integrated intensity (ℓm-sec/in 2 or c-sec). Specifically, where I_{eff} is the detectable threshold intensity level of a steadily burning light, and I_{peak} is the peak level of a square pulse of light of duration t_{on} sec, the relationship between the detectability of the flashing light and the steady light at the threshold of detectability of each is

$$I_{eff} = \frac{I_{peak}\ t_{on}}{0.2 + t_{on}}.$$

Blondel and Rey worked only with intervals between flashes of 3 sec, but their results apply equally well to longer durations between flashes or to isolate single flashes. An interesting comparison can be made between alerting effectiveness of a 0.001-sec flashlamp flash and a 0.5-sec flash from a tungsten-filament lamp in the case where ($I_{peak}\ t_{on}$) is the same in both cases. We have immediately

$$\frac{I_{eff\ 0.001\ sec}}{I_{eff\ 0.5\ sec}} = \frac{0.2 + 0.5}{0.2 + 0.001} = \underline{\underline{3.5}}\ .$$

Thus, the ultra-short flash uses the available light energy 3.5 times more efficiently in providing alerting effectiveness.

The Blondel-Rey equation has been generally accepted as the standard method for defining and determining the "effective intensity" of flashing lights, even though it is specifically applicable to lights flashing at a rate of one flash every 3 sec or longer, or to isolate single flashes.[22,23,24]

A number of investigators have subsequently investigated the interval between flashes, the flashrate, as well as the flash duration in determining alerting effectiveness of flashing lights. Williams and Allen have shown that a good empirical fit to data coverning flash durations from ultra-short flashes to flashes of 1.6 sec duration, and off-times from 0.025 to 3.2 sec is provided by substitution for the Blondel-Rey constant of 0.2 sec, the factor [25]

$$a = 1/\left(\frac{1}{0.2} + \frac{1}{t_{off}}\right) = \frac{0.2\ t_{off}}{0.2 + t_{off}}\ .$$

Then, the expression for effective level of light intensity of a periodically flashing light of constant intensity while on is

$$I_{eff} = \frac{I_{peak}\, t_{on}}{a + t_{on}} .$$

Since the peak intensity is related to the average intensity by the relation

$$I_{peak} = I_{avg} \quad \frac{t_{on} + t_{off}}{t_{on}} ,$$

we can express the effective intensity in terms of the average intensity and the total period of the flash $t_{tot} = t_{on} + t_{off}$ as

$$\frac{I_{eff}}{I_{avg}} = \frac{t_{tot}(0.2 + t_{off})}{0.2\ t_{tot} + t_{on} t_{off}} .$$

It is this approach of Williams and Allen that has been used in this work.

For a case very near to that of grade-crossing flashing lights, where t_{on} and t_{off} are both approximately 0.5 sec, t_{tot} is approximately 1 sec, we obtain $(I_{eff}/I_{avg}) = 1.56$. In other words, using a flashing light with 0.5-sec on, 0.5-sec off, flash pattern provides the alerting effectiveness of a continuously burning light consuming 1.56 times as much power; or, the flashing light uses 1/1.56 = 64 percent as much power for equal alerting effectiveness.

Applying the same relation to the case of a xenon flashlamp where t_{on} is a fraction of 1 ms and is negligibly short and $t_{tot} \approx t_{off} = 1$ sec, we obtain a value of $(I_{eff}/I_{avg}) = 6.0$. Therefore, the xenon flashlamp flashing once per sec provides the alerting effectiveness of a continuously burning lamp emitting light energy at a rate six times greater. In other words, the xenon flashlamp provides equal alerting effectiveness as a continuous lamp while using only 1/6 = 16.7 percent of the optical power of the continuous lamp.

Note that at a flash rate of one flash per sec and equal average power, the ratio of I_{eff} for the xenon flashlamp to that of the incandescent lamp of 50 percent duty cycle is

$$\frac{I_{eff\ xenon}}{I_{eff\ incan.}} = 3.85.$$

Thus, at this flash rate, the xenon flashlamp uses available light energy 3.85 times more efficiently than does the incandescent flashing light.

Figure 12 summarizes the relationship between effective and average intensities of flashing lights as a function of flash rate for two cases--that of ultra-short flashes characteristic of xenon flashlamps, and that of a 50 percent duty cycle characteristic of incandescent lamps. It is seen in Figure 12 that for both types of operation, the alerting efficiency steadily increases as the period t_{tot} increases. However, in grade-crossing applications, a motorist only has a limited amount of time in which to perceive a flashing light, and must be subjected to a number of flashes in that time period for effective warning to be provided. Therefore, some upper limit on repetition period must be set.

Because of the heating and cooling times of incandescent-lamp filaments, it is not practical to operate incandescent lamps at a rate in excess of one flash per sec. When faster flash rates are used, the filament does not entirely cool down during the off time or heat up during the on time, and the contrast between on and off periods tends to be lost. In the case of the xenon flashlamp, it is the human eye itself that sets an upper limit on useful flash rate. As the flash rate increases beyond the flicker-fusion frequency, the light appears to be continuously lit, and the amount of perceptible flicker becomes less and less. Under conditions of low background illumination and high-flash energy, the human eye perceives an afterglow of up to 0.3 sec--a phenomenon entirely caused by the eye and the nervous system, since the production of light by the flashlamp totally ceases after a time on the order of 1(ms) millisecond.[19,26]

A recent study in a related field, which included an extensive literature search, concluded that the most conspicious frequencies range from 1 to 3 Hz, with 2 to 3 Hz preferred.[13] On the other hand,

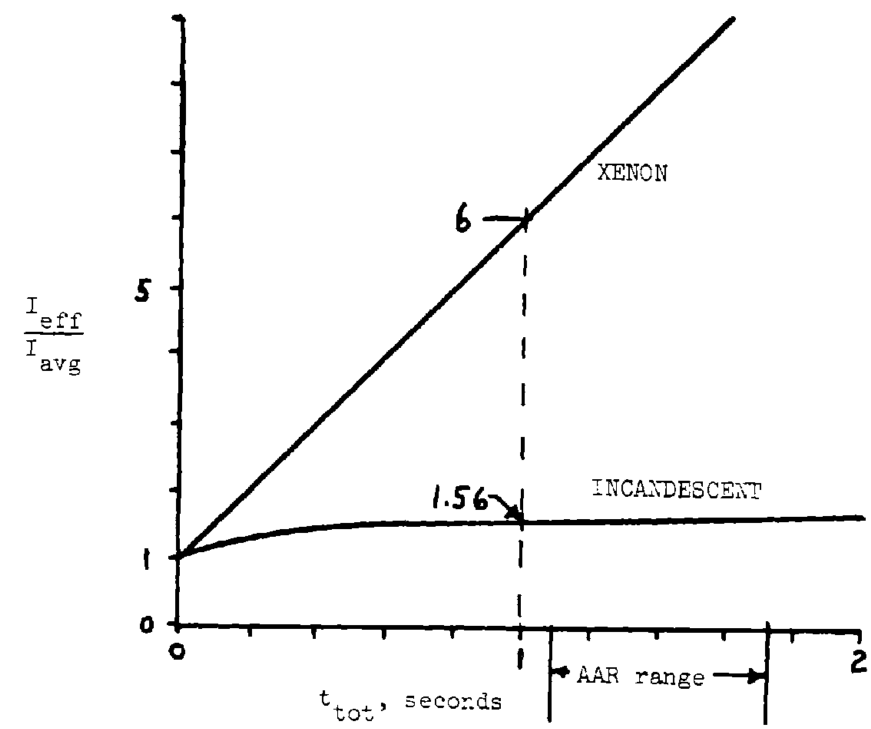

FIGURE 12. RATIOS OF EFFECTIVE TO AVERAGE INTENSITIES FOR XENON FLASHLAMPS AND INCANDESCENT FLASHING LIGHTS. For the Xenon Flashlamps, a Negligibly Short Flash Duration is Assumed. For the Incandescent Flashing Lights, a 50 Percent Duty Cycle is Assumed.

numerous references discuss a variety of potential adverse behavioral reactions associated with higher frequencies in the range of 5 to 10 Hz. Although few individuals are likely to suffer from these effects, there appears to be no loss of effectiveness in avoiding the problem entirely by restricting safety systems to frequencies below 5 Hz (300 flashes per min).

It is possible to use a burst of individual flashes spaced so closely together that the eye integrates them into one flash of steady light approaching an incandescent-light flash in appearance. Indeed, this was the approach taken by Scott and Moe, who used such an approach in adapting xenon flashlamps for grade crossings.[17] This approach does benefit from the greater efficiency of the xenon flashlamp in turning electrical energy into visible light, on the greater and more easily controllable luminous output of xenon flashlamps. However, such operation is not as efficient in providing alerting effectiveness as when the available electrical power is used to produce intense isolated single flashes of light.

It should be noted that the prevailing environment has a profound effect on the absolute level of light required for detection by a human observer as do factors of side and forward vision and attention and inattention of the observer.[27,28] It is generally believed however, that the effect of flashinglight patterns on the quantity of light required for detectability is approximately the same under all conditions. Thus, the previous equation for I_{eff}/I_{avg} is fairly accurate, independent of environment, even though a far greater I_{eff} is required for detectability in bright daylight than is required at night for instance.

4.5 RELATIVE POWER EFFICIENCY

The spectral characteristics of light produced by tungsten-filament lamps and xenon flashlamps differ. The standard temperature for operation of a tungsten-filament lamp that is specified in railroad applications is 2854°K, whereas the color temperature of the hot xenon gas in the flashlamp is approximately 6000°K. The higher effective temperature makes the xenon flashlamp a more efficient means of turning electrical power into light than the incandescent lamp. Measurements performed under similar conditions on a commercial xenon flashlamp and on a standard 18-w commercial tungsten-filament lamp showed that the tungsten-filament lamp produced 0.85 c/w, whereas the xenon flashlamp produced 1.15c-s/J, or 1.15 c/w average. This value includes a flashlamp power-supply efficiency of 50 percent--typical of an inexpensive commercial unit. A power-supply efficiency of 75 percent, obtainable at slightly greater cost, would yield 1.73 cd-sec/J.

However, the higher color temperature of xenon flashlamp light also means that the intensity of light produced is greater at shorter wavelengths than it is at longer wavelengths. Xenon-flashlamp light is most intense in the blue portion of the spectrum, falling in intensity through the red end, whereas incandescent light is most intense in the red, falling in intensity through the blue. Therefore, a red filter, as required for the grade-crossing application, subtracts out a proportionally greater amount of xenon-flashlamp light than incandescent light. (The AAR light-red roundels used in this program transmit 25 percent of tungsten-filament light, but only 15 percent of xenon-flashlamp light.)

When light production, spectral characteristics, and psychological factors are all taken into account, the performance (for providing alerting effectiveness) of a tungsten-filament lamp flashing once per second at a 50 percent duty cycle compared to that for a xenon flashlamp with 50 percent efficient power supply flashing once per second is as indicated in Table 1. (The base figures for average cd/w for the tungsten and xenon light sources are in good agreement with values obtained by other investigators.)[29]

It can be seen that for applications of this type, xenon flashlamps are predicted to produce more than three times more effective light than is provided by a tungsten-filament light of the same power consumption. With use of a 75 percent-efficient power supply, xenon lamps are nearly five times as effective.

TABLE 1. OVERALL PRODUCTION EFFICIENCIES OF RED LIGHT FOR XENON FLASHLAMPS AND FOR TUNGSTEN-INCANDESCENT LAMPS

	Xenon* Flashlamp	Tungsten-Incandescent** Lamp
$a = \frac{I_{avg}}{P_{lamp}}$ = cd/w into lamp	2.3	0.85
$b = \frac{P_{lamp}}{P_{pwr\ supply}}$ = power supply efficiency	0.5	1.0
$c = \frac{I_{avg\ red}}{I_{avg}}$ = red filter transmission	0.15	0.25
$d = \frac{I_{eff\ red}}{I_{avg\ red}} = \frac{I_{eff}}{I_{avg}}$	6.0	1.56
$a \times b \times c \times d \times = \frac{I_{eff\ red}}{P_{pwr\ supply}}$	1.03 eff cd/w cd/w	0.33 eff
Ratio = $\frac{\text{eff cd/w for xenon}}{\text{eff dc/w for tungsten}}$ = 3.13		

*Xenon flashlamp is a Sylvania R4321A flashlamp operated at 20 J per flash, 1 flash per sec.

**Incandescent lamp is a standard 1.8 amp, 10 v, 18 w railroad signal lamp, operated at rated power.

5. EXPERIMENTAL XENON-FLASHLAMP GRADE CROSSING WARNING SYSTEMS

5.1 BACKGROUND

Motorist-warning systems based upon the xenon-flash-lamp technology described in the preceding section have been installed experimentally at a number of grade crossings already protected by conventional incandescent flashing lamps. The purpose has been solely to determine technical feasibility and practicality, and to resolve questions concerning optimal system configuration, the far-more-complex studies necessary to establish safety effectiveness have not been undertaken. Although the installations described here are those carried out by TSC in cooperation with several railroads, this research has benefitted substantially from prior experimentation and numerous installations carried out independently by the Union Pacific Railroad.

5.2 BASIC SYSTEM

The hardware used is basically that described in section 4, with several variations. Figure 13 and 14 show photographs of system components. The style of flashlamp previously shown in Figure 9 mounts in an octal socket, with the trigger transformer potted into the base of the flashlamp. Figure 13 shows a sealed-beam flashlamp enclosure having an outer diameter of 8 inches that can be easily mounted behind the roundel of a standard 8-inch grade-crossing signal-lamp housing. The trigger transformer in this case is cemented to the rear of the reflector and the coiled flashtube is mounted approximately at the focus inside of the permanently sealed outer envelope composed of reflector and lens. Figure 14 illustrates a power supply for driving a pair of flashlamps. This power supply operates from 12 vdc and uses an inverter circuit.

Table 2 summarizes the operating data for a two-flashlamp system of the type that has been employed at numerous grade crossings.

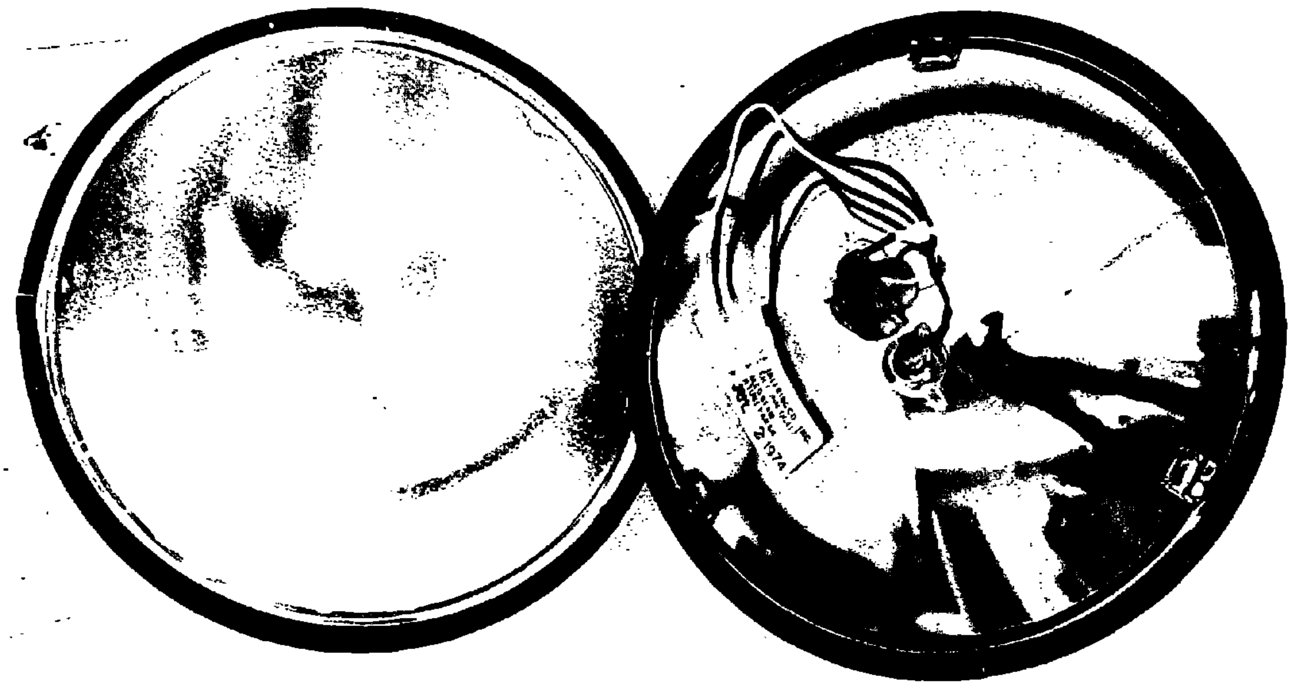

FIGURE 13. XENON-FLASHLAMPS IN PAR-64 SEALED-BEAM ENCLOSURES. These Flashlamps Have a Tube Similar to That of the Flashlamp 4a Mounted at the Focus of the Reflector. The Trigger Transformer is Cemented to the Back.

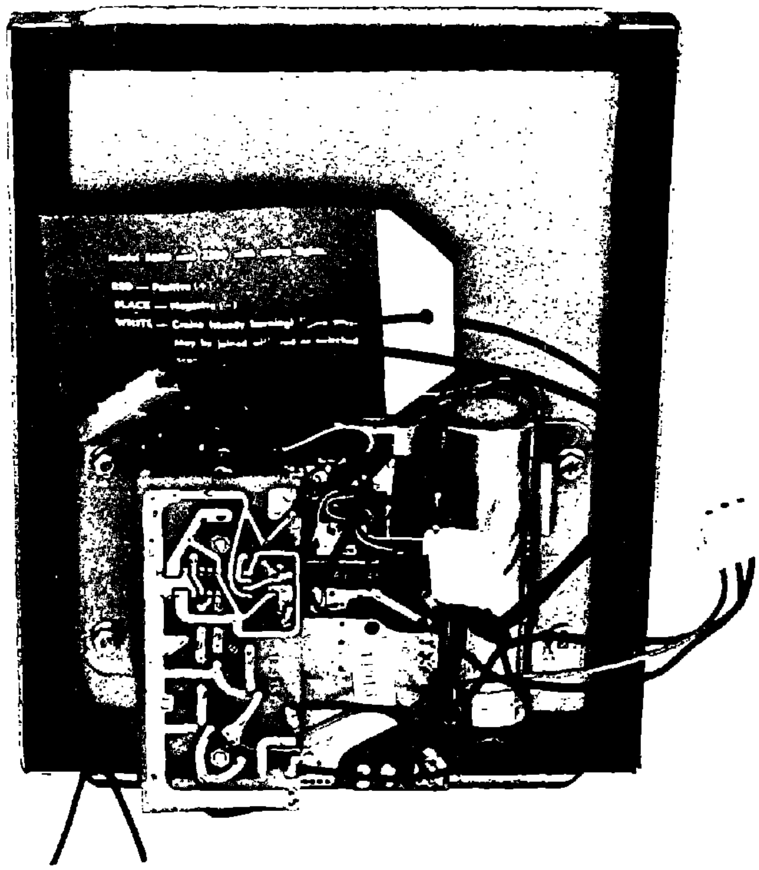

FIGURE 14. XENON-FLASHLAMP POWER SUPPLY FOR POWERING TWO FLASHLAMPS.
Power Supply is Shown Fastened to Lid of 8 in.x 10 in. box.

TABLE 2. CHARACTERISTICS OF A TYPICAL HIGH-INTENSITY XENON - FLASHLAMP SYSTEM CONSISTING OF POWER SUPPLY, CONNECTING CABLES, AND TWO FLASHLAMPS THAT ARE FLASHED ALTERNATELY

Basic operating voltage range	10-12 vdc
Power requirements	10 to 12 vdc; or 10 to 12 volts rms at 60 Hz, that is full-wave rectified by self-contained bridge rectifier
Flash rate	60 flashes per min. each lamp; 120 flashes per min. total
Energy discharged into flash-lamp/per flash	20 J
Current drawn from 10-12 vdc source	6 amp dc average
Percentage ripple on current drawn	100 percent unless filtering is used on power input leads
Electrical efficiency of power supply	Approximately 60 percent
Flash risetime from triggering to peak intensity of light output	50 μ-sec typically
Flash decay time from peak intensity to 50 percent of peak intensity	100 μ-sec typically
Integrated light intensity per flash	23 dc-sec
Effective intensity of a single flash (given by Blondel-Rey equation)	115 effective cd
Effective intensity of a single flashlamp flashing at 1 flash/second (given by Williams and Allen's results)	138 effective cd

5.3 POWER SUPPLY MOUNTING

To minimize power loss in the high-current, high-voltage, short-duration pulses to the xenon flashlamps, the cables to the flashlamps from the power supplies must be fairly short. It is desirable that these cables be no longer than approximately 10 feet. For that reason, the flashlamp power supplies must be mounted at the poles on which the flashlamps they feed are mounted.

Figure 15-18 show photographs of various ways in which mounting can be done. Figure 15 illustrates a flashlamp power supply assembled in a shape that allows it to be fitted into the terminal box on the crossarm supporting the flashlamps. Unfortunately, the fit is so tight that this method was considered to be impractical for experimental field installation. Figure 16 shows the use of a weathertight sheetmetal box that is inexpensive and easy to install. It is relatively easy to punch the necessary holes for leads in this box and it is small enough to provide flexibility of mounting location on the pole. Figure 17 shows use of a standard cast-metal terminal box of a size that is fairly convenient to mount and provides greater protection from vandals than the lighter sheet-metal box. Figure 18 illustrates the use of a larger enclosure which proved convenient in one mental field installation.

Of the methods of mounting the power supply described above, use of the small cast-metal terminal box shown in Figure 17 appears to be preferable. It is somewhat more trouble to mount than the sheet-metal box and its larger overall dimensions diminish the degree of flexibility for choosing a mounting position on the pole. However, the resulting ruggedness and resistance of vandalism more than compensate for the drawbacks.

5.4 XENON-FLASHLAMP INSTALLATION

Two methods have been used to date for mounting xenon flash-lamps. One method is to use a separate flashlamp plugged into a socket mounted inside of a standard signal-lamp housing. The disadvantages of this method are that each different type of lamp housing requires a different socket-mounting technique, and

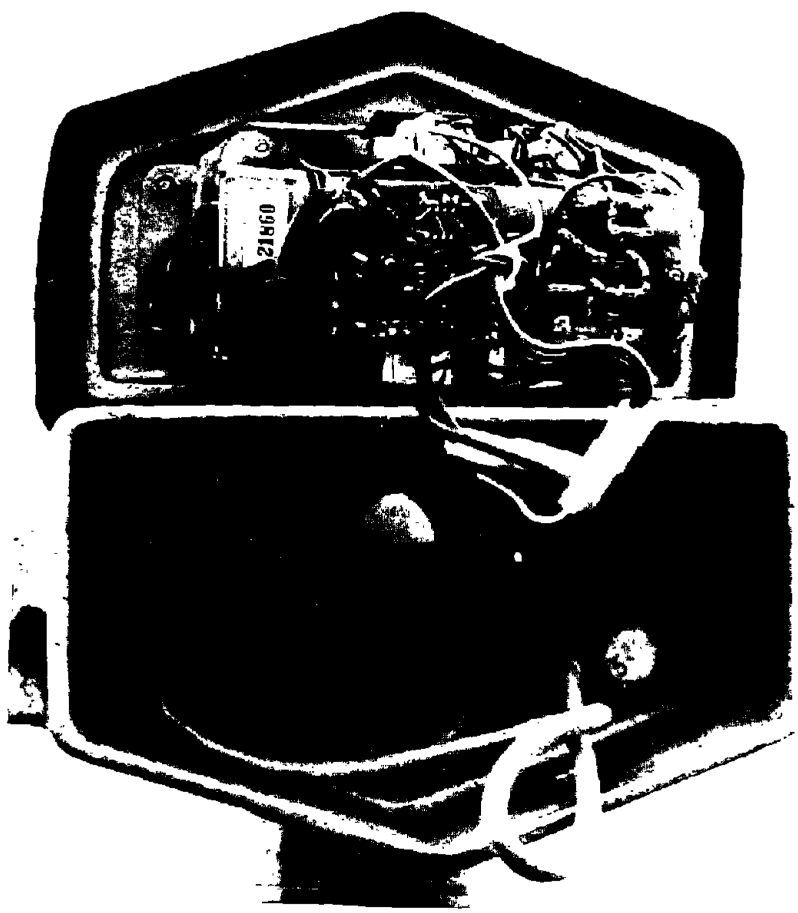

FIGURE 15. XENON-FLASHLAMP POWER SUPPLY MOUNTED IN A CROSSARM TERMINAL BOX

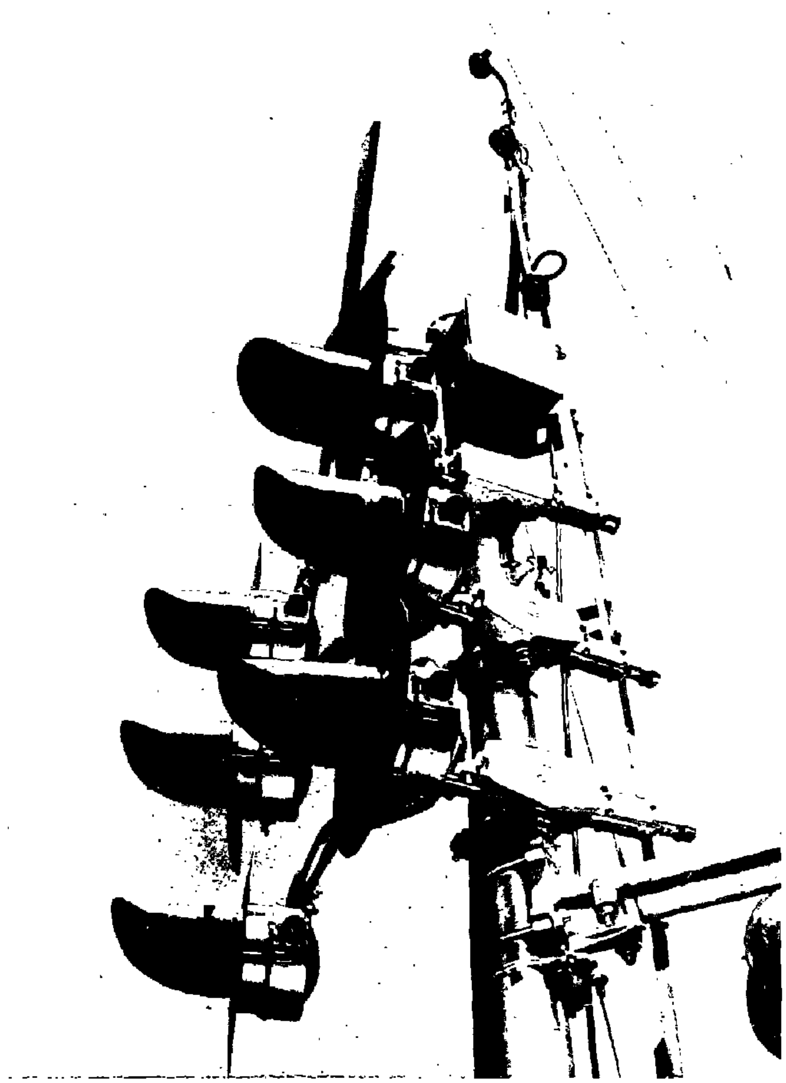

FIGURE 16. SHEET METAL ENCLOSURE (ARROW) MOUNTED HIGH UP FOR PROTECTION FROM VANDALISM. Xenon Flashlamps are at Top of Mast. The Two Lower Crossarms Both Support Incandescent Lights.

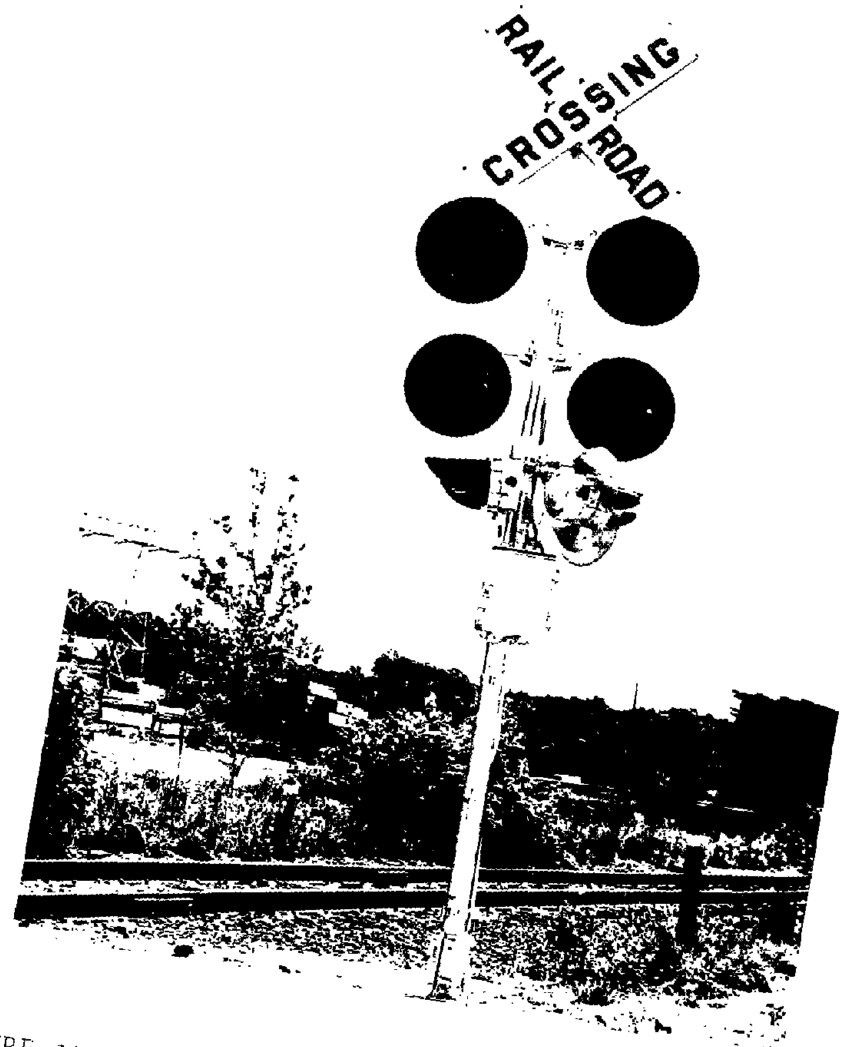

FIGURE 17. POLE MOUNTING OF CAST METAL BOX. Xenon Flashlamps are at Top of Mast, With Original Incandescent Lights Mounted in Original Position Underneath.

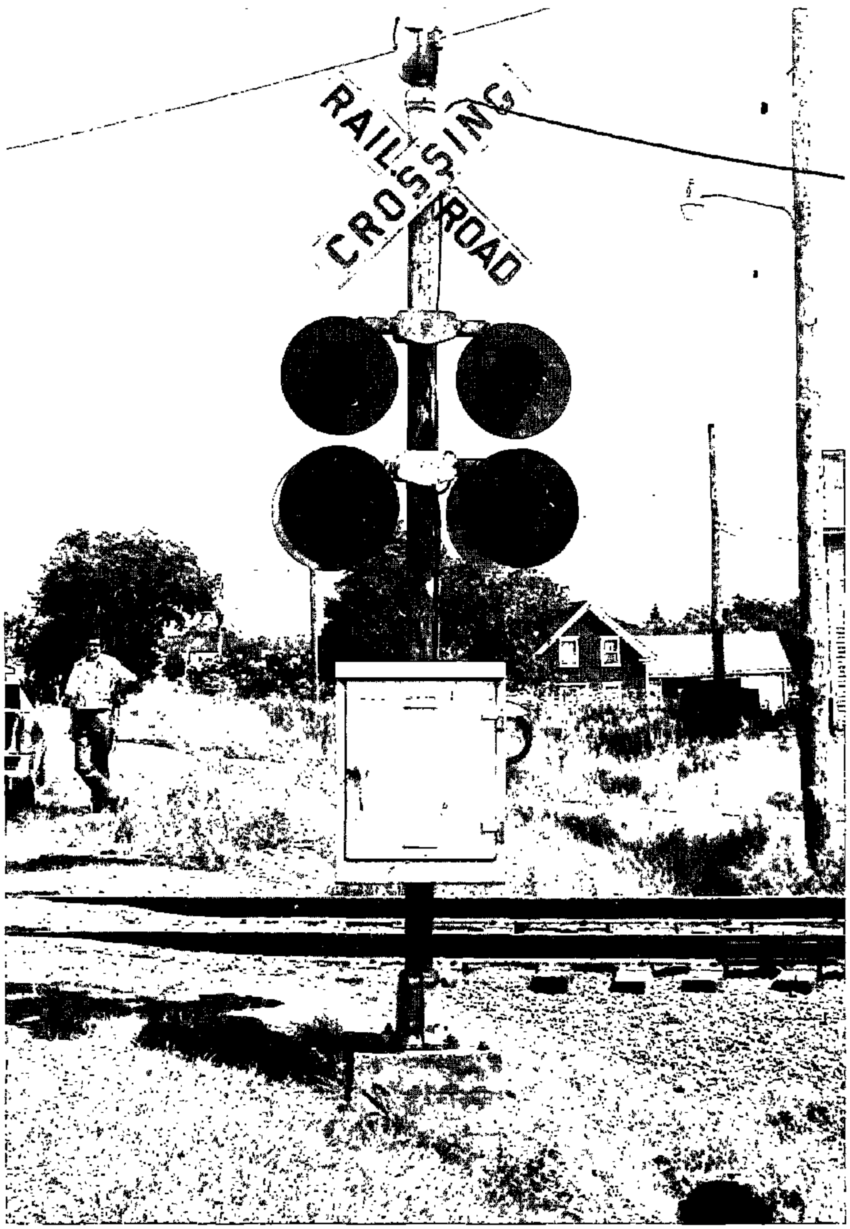

FIGURE 18. LARGE SHEET-METAL BOX USED AS AN EXPEDIENT FOR HOUSING FLASHLAMP POWER SUPPLY. (Note the 115-Volt Lines Bringing Power to Power Supply Running Overhead to Top of Pole. Xenon Flashlamps are Shown Mounted Above Original Incandescent Lamps.)

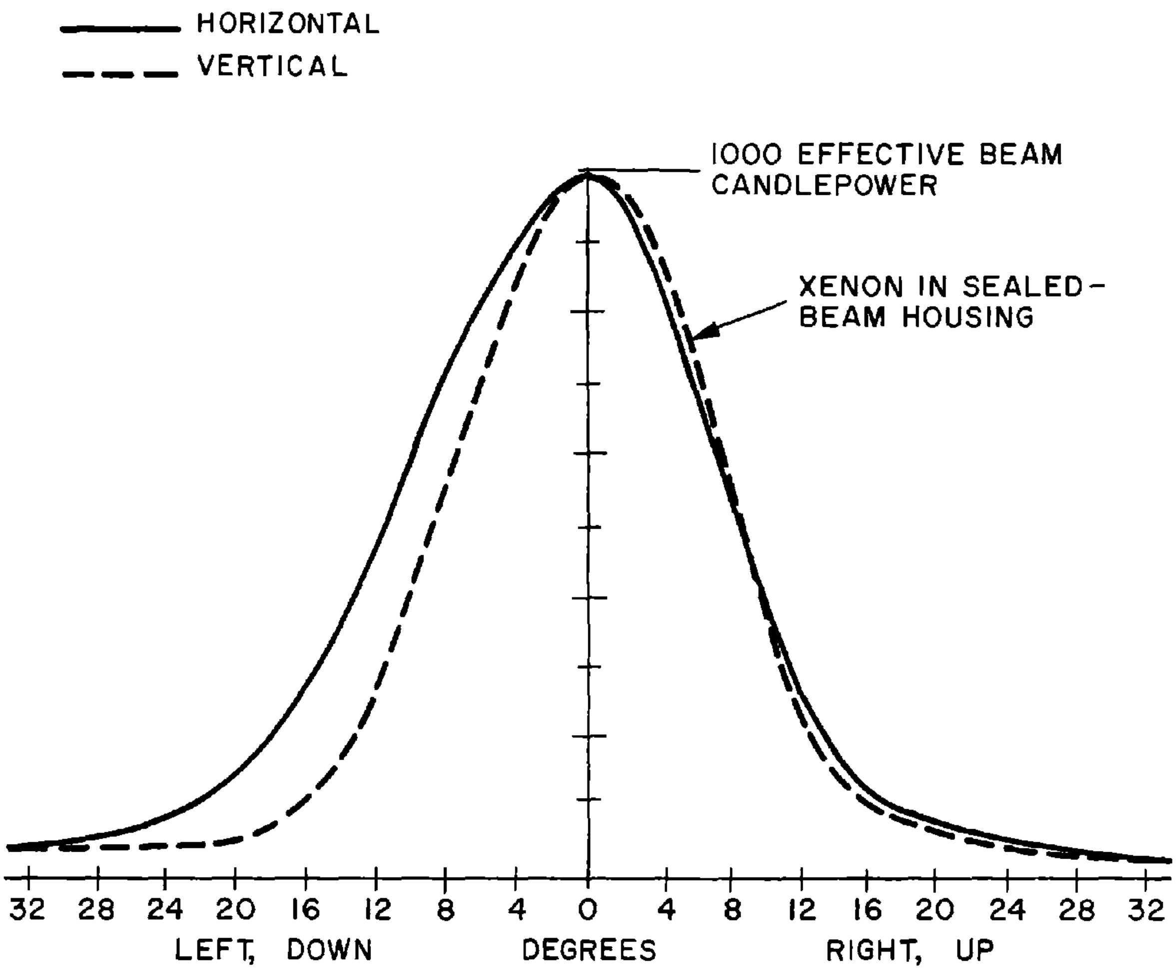

FIGURE 19. BEAM PATTERNS OF A GRADE CROSSING UNIT EQUIPPED WITH "LONG-RANGE" ROUNDEL AND LIGHT-STIPPLED XENON FLASH TUBE SEALED-BEAM UNIT. [This Roundel Produces a "Zonal" Pattern--the Asymmetrical Bump on the Right-Hand Side of the Curve is to be Positioned on the Roadside of the Light. The Xenon Flashlamp was Pulsed at 20 J Per Pulse. The Intensity Figure is for an Isolated Single Flash From the Flash Lamp. Effective Peak Intensities For One Flash/Sec is I_{eff} = 1300 bcp and I_{eff} = 1200 bcp For the Xenon.] (Compare to Figure 5 for Incandescent Lamp.)

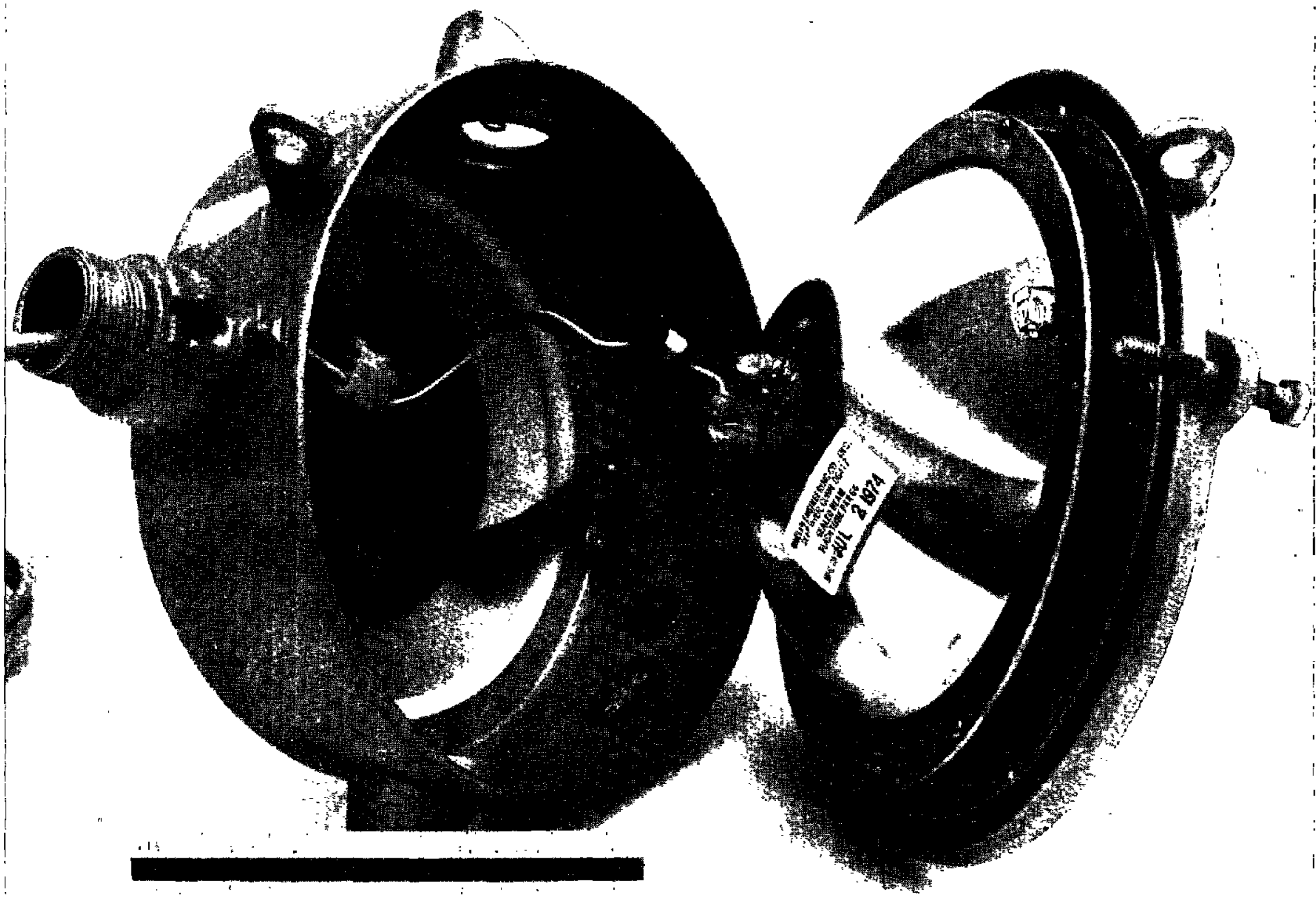

FIGURE 20. SEALED-BEAM 8 in. FLASHLAMP UNIT MOUNTED IN STANDARD 8 in. HOUSING

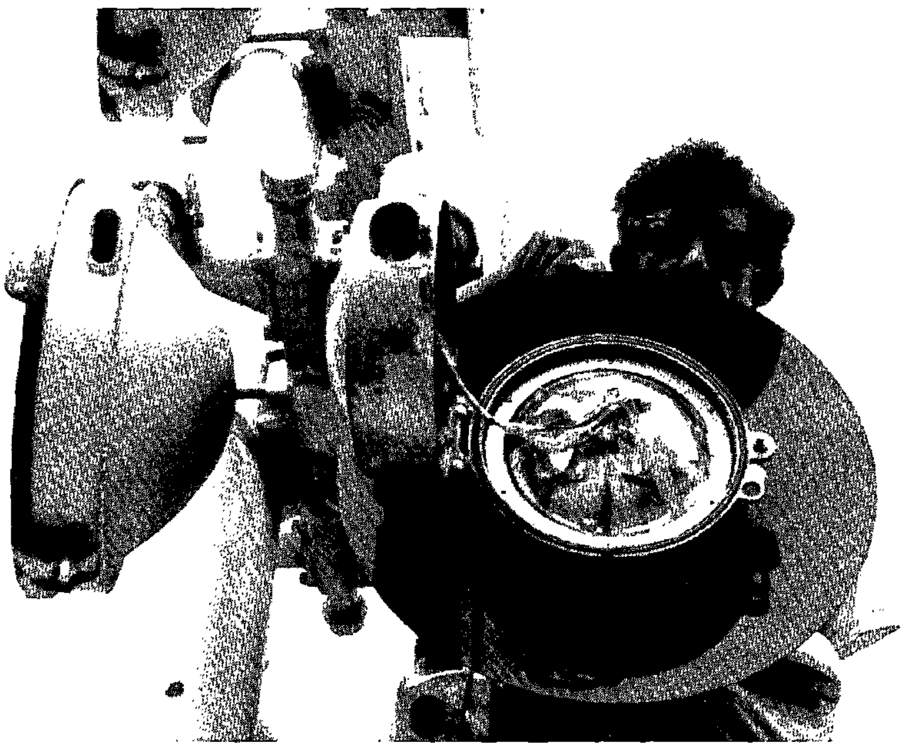

FIGURE 21. SEALED-BEAM FLASHLAMP UNIT BEING INSTALLED

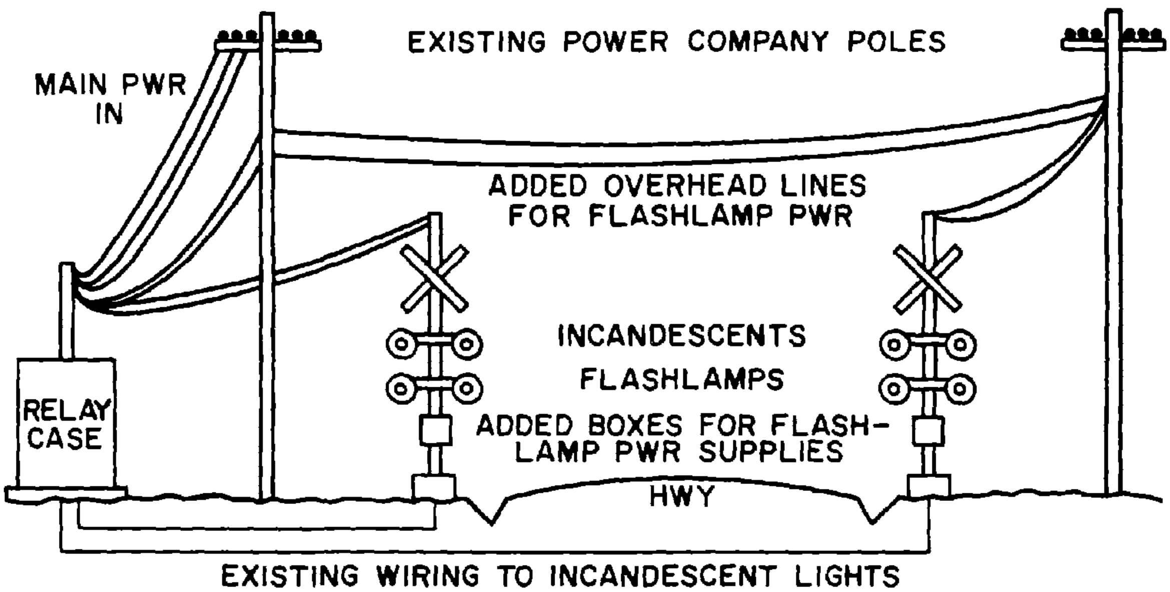

FIGURE 22. GRADE CROSSING TO WHICH XENON FLASHLAMPS HAVE BEEN ADDED. Additional Power Feedlines are Run via Existing Power Poles to Save Cost of Burying Them. Synchronization Interconnections are Made on Flashing Lightpoles.

precision is required in mounting the socket to assure that the flashlamp, when plugged in, will be at the focus of the reflector.

The method that has been found to be the most practical is the use of flashlamps in their own sealed-beam reflectorized housings of 8-inch diameter. They consist of a sealed-beam lamp housing with a helical flash tube (approximately like that of the lamp of Figure 9) mounted inside in place of the tungsten filament. The front diffuses the light passing through, producing a beam that is quite symmetric about the centerline--more so than that obtained without the stippled lens, and an appearance of a uniformly illuminated disc of light when viewed from a distance. The lens has been attached to the reflector with epoxy glue, providing a good enough seal to insure against any degradation of the reflecting surface with age. The particular lamp (shown in Figure 13) is of a type used for flashing runway approach lights. Figure 14 shows the pattern obtained from such a light. Since the natural beamwidth of the light alone is far greater than that of the roundel, the roundel just acts as a red filter when used with this light and does not change the beam pattern, contrary to the case for incandescent lamps. These lamp units can be placed directly against the roundels and clamped in place with the roundels as shown in Figure 20 and 21. This method works with any of the deeper lamp housings such as the WABCO, GRS, Western-Cullen, or deep Safetran, but not with shallower units. There is some variation in the pattern of the retainer ring needed for each type of lamp housing, but the rings are inexpensive and easily fabricated from sheet aluminum.

5.4.1 Providing Power for Flashlamp Systems

At a number of experimental installations done jointly by railroads and DOT, it was most convenient to provide 115 vac power to the xenon flashlamp power supplies, as shown in Figure 22. In one case, 115 vac power lines were run overhead to the poles where the flashlamps were mounted.

In another case, it was more convenient to bury the powerlines in trenches paralleling existing conductors. In a third case, 115 vac conductors already installed for carrying power to gate-mechanism heaters were utilized. In all cases, relaying is provided so that power is only applied to the flashlamp power supplies when crossing flashlamps are activated. In the experimental installations described above, it was not deemed necessary to provide for operation of the xenon flashlamps on emergency power. All of these installations did use a synchronizing relay for synchronizing the incandescent flashing lights and xenon flashlamps.

The xenon-flashlamp systems installed by the Union Pacific Railroad utilize 10v ac/dc power supplies that are powered directly in parallel with the incandescent flashing lights, as shown in Figure 23. In this type of installation, emergency dc power is automatically provided to the xenon flashlamp systems when main ac power fails, just as it is to the incandescent flashing lights. This type of installation requires greater emergency power capacity to supply the 6 amps at 10-12 vdc required of each flashlamp power supply driving a flashlamp pair. (The Union Pacific installations do not use synchronizing relays, and their xenon flashlamps are operated at an independent rate of approximately 80 flashes per minute.)

Another option would be to add a separate small emergency power supply to serve only the xenon flashlamp systems. Emergency power supplies could be pole-mounted where 115 vac power is brought to the poles, or one emergency power supply could be added separately at the main relay case for all the xenon flashlamps at a crossing. To date, the authors are not aware of any installations of add-on emergency power such as these being made.

No one to date has reported inclusion of comprehensive lightning protection for the solid-state flashlamp power supplies. For permanent installations this must be done, using the multi-stage surge suppression techniques that are becoming common in the industry for protection of solid-state gear.[30]

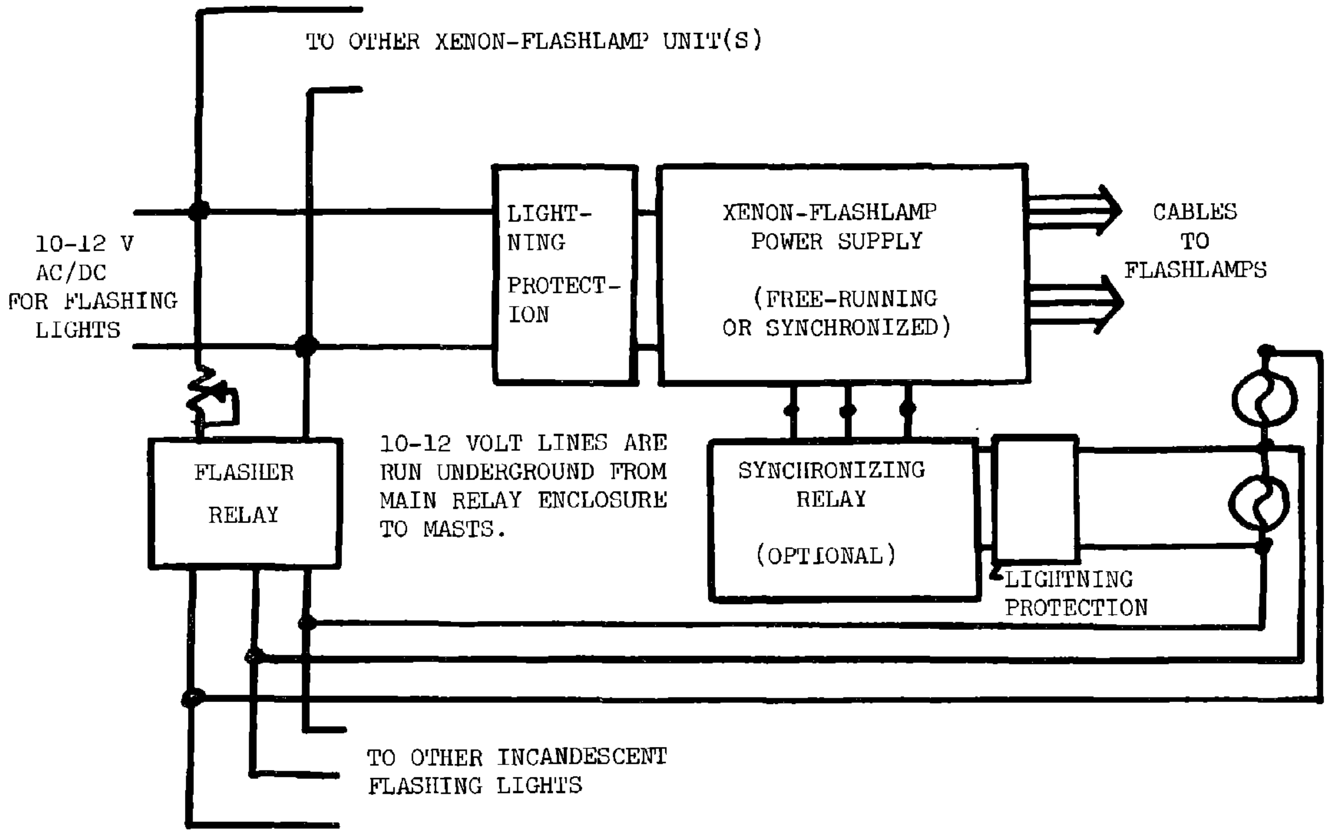

FIGURE 23. PERMANENT INSTALLATION OF XENON FLASHLAMPS IN CONJUNCTION WITH INCANDESCENT FLASHING LIGHTS AT A GRADE CROSSING

In permanent installations, where it is desired to limit the voltage drop to one volt in the lines bringing low-voltage power to the flashlamp power supplies, heavy-gage wire will have to be used. Conductors must have crossection equivalent to No. 9 AWG for runs up to 50 feet, or double that for runs up to 100 feet.

5.4.2 Roundels

The roundels that have been most widely used to date in experimental xenon flashlamp installations at grade crossings have been ones supplied by Safetran that produce light at the pale end of the allowed AAR red spectral range. The transmission of these roundels is approximately twice that of roundels whose shade lies in the middle of the allowed AAR red spectral range that extends from 620 to 633 nonometers. Doubling the brightness of signal lights seen by the motorist is done more readily by switching to these slightly lighter roundels than could be done by the alternate method of doubling light intensities, power supply capacities, and conductor cross sections.

5.5 ILLUMINATION PATTERNS OF LIGHTS IN HOUSINGS

The light produced by the light source in a grade crossing flashing unit is partly radiated in all directions, but the fraction of light that is radiated back toward the reflector is reflected forward to form an intense beam that has far greater intensity than the light source by itself. With a given light source producing a constant amount of light, the narrower the beam is, the more intense it will be, and conversely, the broader the beam is, the less intense it will be. A continuously burning 18-watt tungsten signal lamp bulb mounted in an 8-in. Safetran grade crossing signal lamp housing with the roundel removed will produce a conical beam with central intensity of 50,000 beam candelas. The beam produced is very narrow, having an angle between half-intensity points of less than 3 degrees (1.5 degrees from beam axis to half-intensity point). In use, beam intensity is reduced by filtering to achieve the proper color of red. Peak beam intensity is also reduced by defocusing the beam using a patterned roundel to direct light so that the proper coverage is obtained.

To get required intensities using tungsten-filament lamps, narrow beams are frequently used. Quite frequently, roundels are used that broaden the beam only horizonally. A course pattern of raised bumps is often placed on the surface of the roundel to scatter a small fraction of the light downward to provide illumination to a viewer close to the light. To achieve the range necessary on high-speed highways, long-range roundels are used in which the outer portion of the roundel is only very slightly patterned, thus producing a pencil beam that is only slightly broadened. One severe problem that is encountered when using such tightly focused beams is that aiming accuracy is critical. It is essentially a two-person job to initially aim a conventional light unit producing a very narrow beam. Proper aim is easily lost if the lamp unit or its supports are jarred, or if the lamp socket is moved even slightly during bulb replacement.

In comparison, the type of xenon flashlamp used in this program produces a very broad beamwidth, extending approximately 20 degrees between half-intensity points, and yet the peak intensity in the central portaion of the beam is approximately that of a conventional 8 in 18-w grade crossing signal lamp using a long-range roundel (see Figure 19). The increased horizontal and vertical coverage with essentially no sacrifice in central beam intensity is obtained in two ways: through increased efficiency in turning electrical power into effective illumination, and through increased electrical power. The xenon flashlamps used in this program along with their power supplies are 3.7 times as efficient at producing effective illumination, and they use 3.3 times the power of an 18-w tungsten-filament lamp.

Figure 24 shows a typical beam pattern of a xenon flashlamp mounted in a sealed-beam reflectorized enclosure, as shown in Figure 20. For purposes of comparison, the pattern obtained using a long-range "zonal" roundel in front of an 18-w tungsten-filament bulb in a standard housing is also shown.

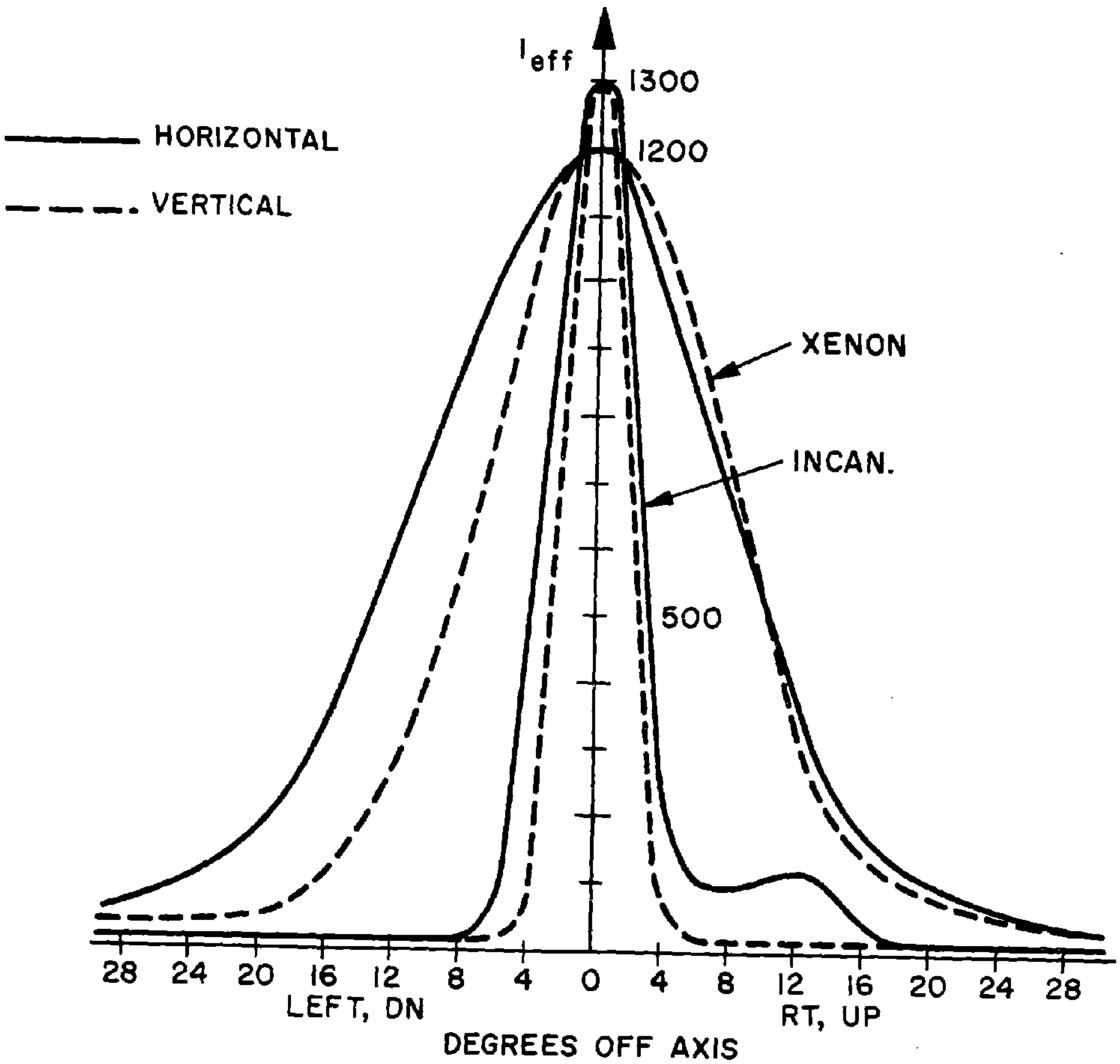

FIGURE 24. BEAM PATTERNS OF INCANDESCENT FLASHING LIGHT AND XENON FLASHLAMP. The 18-W Incandescent Light was Mounted in an 8 in, Housing and Used a Light Red Roundel of "Long-Range Zonal" Design. The Peak Intensity of 1300 Effective Beam Candelas When Operated at a One Flash Per Second Rate at 50 percent Duty Cycle is Equivalent to 1700 Instantaneous Beam Candelas For Continuous Operation. The Xenon Sealed-Beam Flashlamp Unit was Mounted Behind the Same Roundel and Operated at 20 J Per Flash. The Peak Intensity of 1200 Effective Beam Candelas When Operated at One Flash Per Second is Equivalent to Integrated Intensity Per Flash of 200 Beam Candle-Seconds.

In actuality, the same roundel was used as the color filter for the xenon flashlamp. Since the beam produced by the xenon flashlamp is so much broader than the defocusing pattern of the roundel, the roundel only serves to color the beam and not to defocus it further. The roundel was one whose color is at the pale end of the AAR spectral range. In order to give direct comparison of alerting effectiveness of the xenon flashlamp and tungsten-filament lamp, intensities are presented in units of effective beam candelas, assuming a flash rate of one flash per second, with a 50 percent duty cycle for the tungsten-filament lamp. The actual peak intensities at beam center measured were 1700 beam cd for the tungsten-filament lamp running continuously, and 200 beam cd-sec per flash for the 20 joules per flash xenon flashlamp. (A single isolated flash of 200 cd-sec has an effective intensity of 1000 cd.)

The increased beamwidth of the xenon flashlamp units should lead to greater effectiveness in the field due to much less critical aiming tolerances. It might also mean that cantelevers with far less rigidity than currently required could be used. Perhaps cantelevers of the type used for traffic signals could even be used, at far less expense than the massive structure needed for grade crossing flashing lights. This possibility could lead to considerable savings on costs of equipment and installation for new grade crossing protection.

To estimate the effect of the altered pattern on a motorist, calculations of received illumination as a function of observer distance from the crossing were made for a variety of lamp characteristics and flashing light locations. Figure 25 is an example. Intensity normalized to the criterion of Cole and Brown is shown as a function of distance from the crossing. A background illuminance of 30,000 cd/m^2 was assumed, which is equivalent to a very bright day: a value of unity in Figure 25 meets the Cole-Brown definition of adequate intensity. (Alternatively, one could interpret these curves as descriptive of normal brightness, with a criterion that crossing protection warnings should have three times the intensity of normal traffic control devices.)

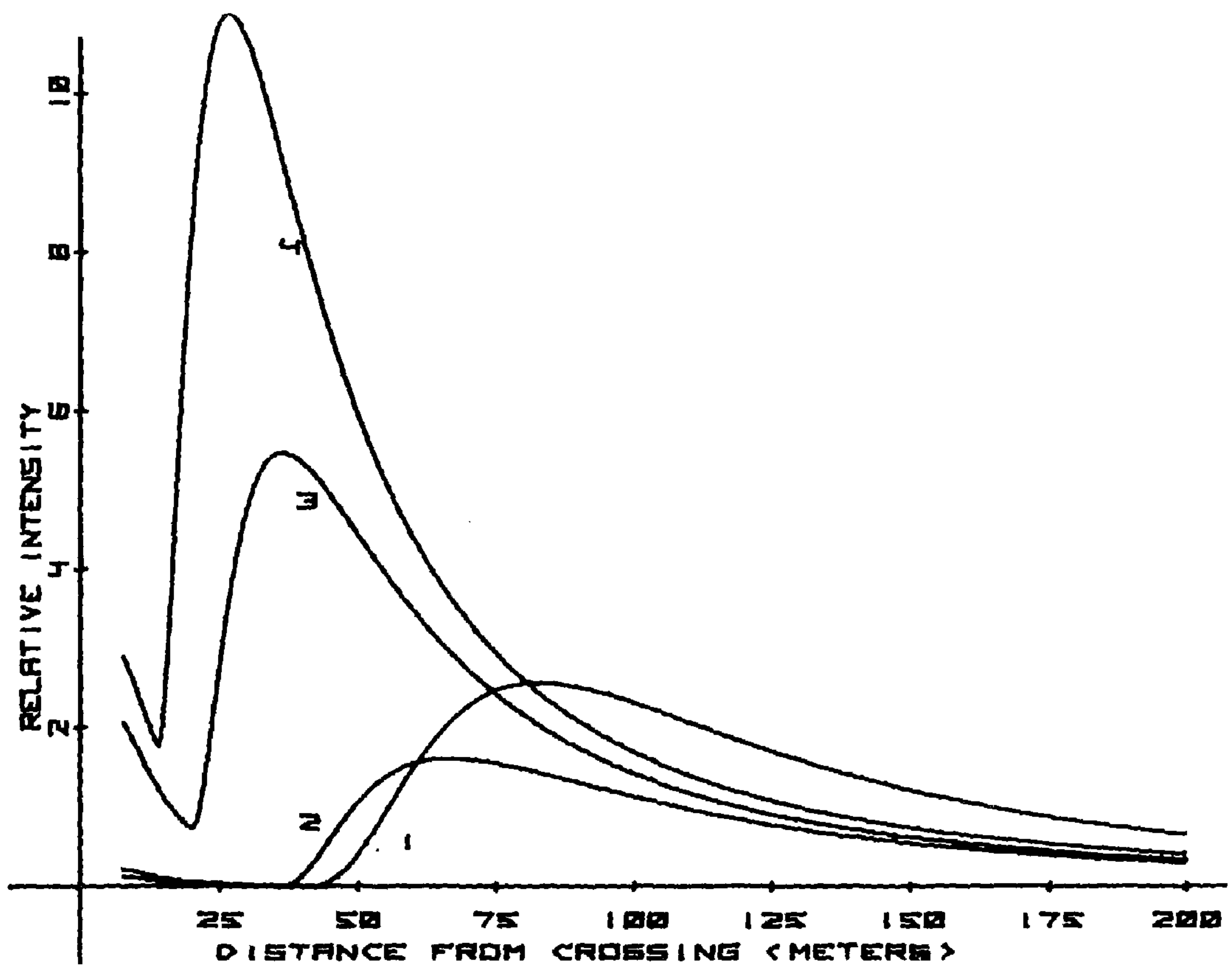

FIGURE 25. RELATIVE INTENSITY VS. DISTANCE FROM CROSSING
1: Conventional Light; Long-Range Roundel
2: Conventional Light; Standard Roundel
3: 12 in. Narrow-Beam Traffic Light
4: Xenon Light in Standard Flasher Head

In Figure 25 four cases are considered: a conventional grade crossing light, a "long-range" version, a 12-in "narrow-beam" standard traffic signal, and a xenon flash lamp in a conventional grade crossing assembly. These calculations are for a lamp location at the edge of an 11-ft (3.3 m) shoulder; similar results are obtained for cantilever-mounted lights. The basic result is clear: narrow-beam lights can provide good coverage at a distance, but once one drives out of the beam the intensity drops sharply. The wider beams generally sacrifice peak intensity, but the vehicle stays within them as the distance decreases, so that the square-law increase in received illumination strongly dominates the beam pattern effect until very near the crossing. (In practice, the near region is covered by use of a second pair of lights.) The sensitivity of the narrow-beam systems to proper aiming is illustrated in Figure 26; it repeats Figure 25 except that all lights are assumed to be aimed 1 degree high and to the right. The effect on the conventional crossing light is extreme detrimentals road undulations or curvature have similar effects.

5.6 SYNCHRONIZATION

Direct replacement of incandescent grade crossing lights with xenon units as described above is a simple process and offers the likelihood of substantially improved performance. However, it would be unwise and unrealistic to seek widespread use of devices having such a crucial role without a lengthy and comprehensive period of testing. Fortunately, these lights in no way conflict with existing systems, so that it is a relatively simple matter to <u>add</u> xenon lights to crossings now protected with conventional lights, above or below the existing assemblies. This permits refinement and optimization of all components under practical conditions, and allows evaluation of both technical and behavioral factors.

A question arising in combined installations is the time relationship between the xenon and conventional flashes. The simplest possibility (technically) is to attempt no deliberate

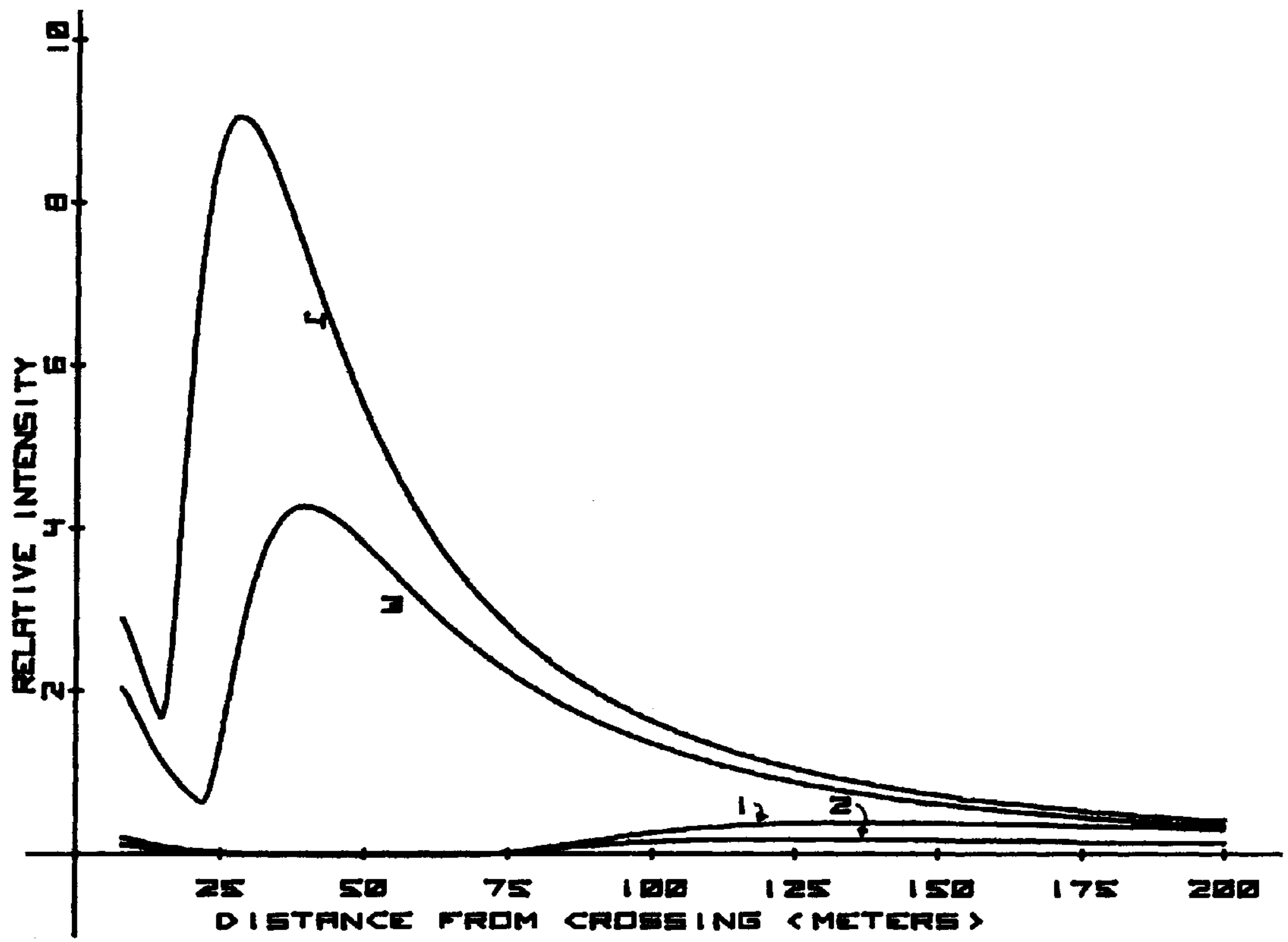

FIGURE 26. RELATIVE INTENSITY VS. DISTANCE FROM CROSSING; LIGHTS MISAIMED BY 1 DEGREE VERTICALLY, 1 DEGREE HORIZONTALLY. (See Figure 3.)

synchronization, so that the two types of lights will tend to go in and out of phase with one another. This quasi-random pattern can be quite attention-getting at some times, but raises serious questions in a motorist warning system. It can be argued that uniformity of aspect is a key to rapid identification and understanding on the part of vehicle operators, and that this is best achieved through assuring that the perceived pattern is the same every time it is encountered. This can be obtained only through synchronization, since different choices of xenon and incandescent flash rates may produce significantly different asynchronous patterns.

If a synchronous pattern is accepted as preferable, a wide range of choices remain. Several of the more attractive alternatives are presented in Figure 27. Each group of four squares represents a pair of xenon flashers above a pair of incandescent units; individual units are darkened to indicate the "on" state. In each case, a full cycle is shown - one flash of each incandescent lamp. (The tungsten lamps are on throughout a half-cycle; the xenon units fire only at the times pictured.) The different cases are described in terms of a ratio of xenon flashes per cycle to incandescent flashes per cycle ("2/2", for example); where appropriate, "in phase" or "out of phase" is noted. Many other possibilities exist. However, those involving more than two incandescent cycles to repeat have been found in practice to appear only marginally different from the asynchronous case.

The choice as to which flash pattern is to be preferred cannot yet be made; it is unlikely that different alternatives will have dramatically different effectiveness. The intuitive response of a small number of observers during preliminary studies has been a preference for the cases of Figures 6a and 6b; 6b provides an "X" pattern which is in keeping with the normal grade crossing symbol. The cases involving flash ratios substantially greater than unit (3/2; 4/2, etc.) require either a relatively slow incandescent flash rate or a high xenon rate, the latter being undesirable due to increased power consumption.

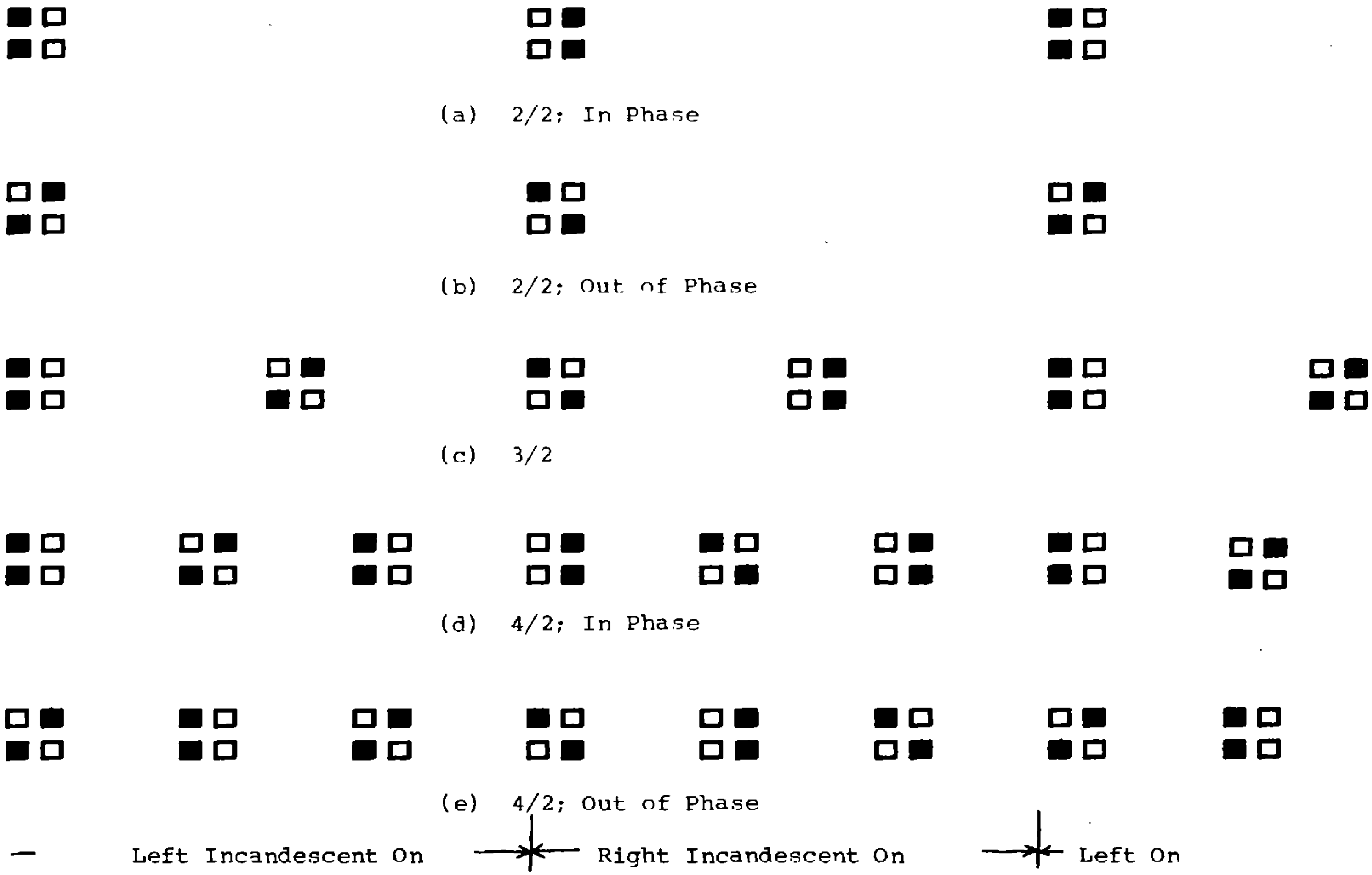

FIGURE 27. VARIOUS ALTERNATIVE FLASH SYNCHRONIZATION PATTERNS

5.7 SUBJECTIVE OBSERVATIONS OF EFFECTIVENESS

In an area as complex as grade crossing safety, theoretical analysis and laboratory measurements can be achieved only through extensive experience. As noted previously, the Union Pacific Railroad has carried out a substantial test program in recent years, including installation of xenon flash lamps in a variety of forms at grade crossings in 12 states. Although quantitative measures of effectiveness are not available, the intuitive response of most observers is that addition of the xenon lamps provides a dramatic increase in alerting effectiveness and visibility. No major equipment problems have been reported, although it is clearly desirable that components engineered specifically for the grade crossing application would be greatly preferred, and would reduce maintenance needs.

Results at TSC installations have generally been similar to findings reported by Union Pacific. Conspicuity is high and the effect of wider beamwidth is especially pronounced. An additional effect is noteworthy. When an observer's attention is directed not at the flashing lights, but near to them (a typical situation for the motorist), or when concentrating on a conversation, the short duration xenon flash appears to be far more attention-getting - an observation of obvious relevance to the grade crossing case.

5.8 COST

An immediate concern of anyone considering installation of a new warning system component is cost. Although firm figures have not been established TSC research has provided sufficient experience to permit reasonable estimates, based on 1974 dollars. The flasher heads and mountings, as well as the roundels, are standard railroad units, with a cost of the order of $100 per pair. The only additions are the sealed-beam xenon lamps and an appropriate power supply, likely to represent an expense of the order of $250 per pair when fully hardened for railroad service. A given retrofit situation may pose special difficulties, but for cases not requiring extensive rewiring for the heavier load, replacement of poles, etc., labor costs appear unlikely to exceed $500. Incorporation of such lights into a new installation should add little more than the equipment cost.

Installation expense is only one aspect of protection cost. Lifetime and maintenance must also be considered. The only element not identical or comparable to conventional systems is the xenon lamp, which can be expected to have a useful lifetime of 3000 to 10000 hours of activation. If this is achieved in the crossing application, one could expect many years of operation between changes. Crossing maintenance needs therefore should not be increased, and accurate aiming of lights could become significantly less important.

5.9 SUMMARY AND CONCLUSIONS FROM EXPERIMENTAL STUDIES

At this time, xenon flashlamps for grade crossings are still experimental. Years of field experience have not been gained in widespread operation of these units and the motoring public has not been generally exposed to them. For these reasons, the authors believe that in the immediate future, xenon flashlamps should only be installed to augment, but not replace, standard incandescent flashing lights. Preliminary indications are that high-intensity xenon flashlamps are highly effective when used at grade crossings. However, their reliability and serviceability have not been tested to the degree that is true of standard incandescent flashing lights. Even in these instances where xenon flashlamps will become accepted by the motoring public as the most noticeable warning device, the proven operating characteristics of incandescent flashing lights should be present as back-up.

The electrical performance of high-intensity xenon flashlamp systems installed at grade crossings has generally been good to date. However, to assure that overall grade crossing protective systems are not jeopardized, it is recommended for now that any leads interconnecting a xenon flashlamp system with the overall electrical system at a grade crossing be separately fused.

With the limited amount of experience gained to date, xenon flashlamps appear to offer significant advantages in altering effectiveness when used at grade crossings. The flashlamps and their power supplies appear to be rugged and reliable. After their special characteristics are accounted for, they are easily installed and easily serviced.

It appears that the short intense bursts of light emitted by xenon flashlamps provide greater alerting effectiveness than longer flashes from incandescent lamps, as predicted by vision psychologists. The greater efficiency in using electrical energy to produce light energy, the more efficient use of the light energy, and the greater power input capacity of xenon flashlamps all contribute to much greater overall alerting effectiveness than can be obtained with standing incandescent lamps.

The greater overall alerting effectiveness allows the use of far greater horizontal and vertical beamwidths, which results in much better overall coverage and freedom from tight aiming tolerances, while providing the same maximum central beam intensity realized with the newest long-range roundels and standard incandescent bulbs.

Experience gained from past and future installation of xenon flashlamps at grade crossings on an experimental basis should hasten their development to the point where they will become a useful standard item for increasing grade crossing safety.

5.10 ELABORATIONS AND SPECIAL BENEFITS

The greatly reduced need for precise alinement associated with xenon lamps can have dramatic benefits in connection with cantilever mountings, now coming into widespread use. The combination of wide highway lanes and shoulders, with very rigorous standards as to structural rigidity has required development of massive structures, adding greatly to the cost of protection installations. They are in sharp contrast with the mountings found satisfactory for normal traffic lights. There are two reasons for this: (1) the railroad units are designed so that a maintainer can walk out on the arm of bulb changes and aiming, and (2) the narrow beam pattern requires that there be no wind-induced movement. Replacement of conventional lights with xenon units would appear to relieve both requirements to the point that normal signal mountings could be used, with concomitant substantial cost savings.

Unlike an incandescent lamp, which requires a specific operating power for best performance, a xenon lamp can readily operate at a wide variety of energies, depending upon the capacitor used. Thus, a multi-intensity system can easily be implemented, in which the brightness of the lamps is automatically determined by ambient light. One could thereby accommodate the need for particularly high intensity when the light may be seen directly against the sun, and low intensity at night (to avoid dazzling the motorist).

6. GENERAL CONCLUSIONS CONCERNING XENON FLASHLAMPS AT GRADE CROSSINGS

The analysis, laboratory measurements, and field tests reported here strongly suggest that xenon flashlamps can be employed at railroad-highway grade crossings in a manner which can significantly increase the effectiveness with which motorists are warned of approaching trains. The primary benefit accrues through the increased alerting effectiveness and conversion efficiency associated with short-duration flashes, which in turn make possible utilization of a relatively broad beam pattern. Installation of such lights as supplements to existing protection is technically simple, economical, and should not have any serious liability implications.

Given optimization of equipment and a lengthy and comprehensive test of this concept, it may prove possible to reduce costs and power consumption through elimination of some or all of the incandescent lights. In addition, significant improvements are possible through reduction of the severe demands now made upon cantilever structures, and through simplified tailoring of the light intensity to both crossing location and ambient illumination.

A variety of practical realizations of xenon grade crossing lamps are possible, including combination in one assembly of both incandescent and xenon elements. (This is now done for certain highway warning lights.) Final determination of the preferred configuration is a matter of product engineering and driver-behavior evaluation.

7. OTHER POSSIBLE SYSTEM IMPROVEMENTS

The study reported here, as well as investigations by others, suggests that use of xenon flashing lights can offer a significant advance in the effectiveness of train-activated grade crossing protection. However, this topic does not exhaust the potential for improvement. The several respects in which grade crossing warnings differ from general practices for traffic control devices were indicated in Section 2. Certain conclusions concerning overall system configuration follow directly from that analysis with logic and general constraints immediately dictating the form that solutions might best take. These findings will briefly be described here.

From the viewpoint of an approaching motorist, the first major difference between grade crossings and highway intersections with active protection is the advance warning. In the purely highway case it is common practice to provide signs indicating "SIGNALS AHEAD" and symbolic signs showing a traffic light (Figure 28). In the railroad case, the standard advance warning sign (Figure 29) makes no distinction between passive and active crossings, even though quite different surveillance activity is required in the different cases. This is not inherently a difficult problem to deal with, requiring only that a reasonably simple set of warnings be adopted and standardized; a number of alternatives already exist.[28] In Europe, this distinction is commonly made as shown in Figures 30 and 31. In certain cases, particularly those characterized by high vehicle speeds and obscured crossings, active advance warnings appear to be desirable and pose no major technical problems, although these have been little utilized to date, and a standardized device has not yet been agreed upon.

The crossing-located warnings do relatively little to clarify the situation. At night, particularly for crossings with flashing lights only, the presence of those warnings may often not be apparent at times when no train is approaching. This is in sharp contrast to the case for highway-highway intersections with traffic signals, which generally show either a steady or flashing light.

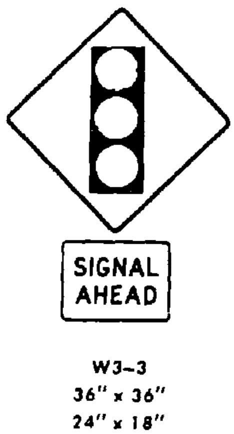

FIGURE 28. HIGHWAY INTERSECTION WARNING

FIGURE 29. RAILROAD GRADE CROSSING WARNING

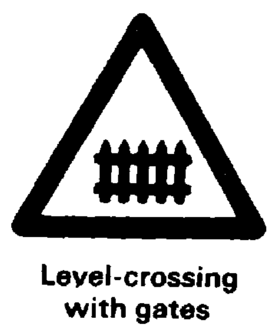

FIGURE 30. EUROPEAN PASSIVE CROSSING WARNING

FIGURE 31. EUROPEAN ACTIVE CROSSING WARNING

The obvious solution here is to provide a separate light unit which indicates the presence of the crossing, the functioning of the warning system, and the absence of trains. Such an approach is used in some other countries, and has been proposed for use in this country by R. Meyer.[32] His concept, illustrated in Figure 32, consists of addition of a third conventional housing below the standard pair of lights. When the system is functioning, but no train has been detected, this light flashes amber; it stays dark when the system is activated and the red lights begin to flash. It could be argued that this could substantially increase back-up power requirements, but it should be noted that no emergency power is necessary for the amber light; when the crossing is entirely dark, it should be seen by motorists as equivalent to a passive crossing, requiring appropriate caution. (This is, of course, the situation for traffic signals.) Alternatively, use of a small xenon flash lamp in this application could reduce the power consumption to only a few watts. Other variations might also be worthy of study, in terms of color, flashing or continuous operation, location, etc. However, it would appear that such a concept could significantly clarify the situation for many motorists.

Another concern is the dilemma faced by a vehicle operator who is relatively close to the crossing when the signals actuate. At a normal highway intersection, there is a steady amber for three to six seconds to indicate that a "stop" aspect is imminent, but that those sufficiently close may pass safely. No equivalent exists at grade crossings, and the resultant ambiguity raises the possibility of an undesirably wide spread of motorist response, some drivers carrying out severe braking, while others simply speed through a flashing red light--a poor habit to encourage. The grade crossing may, in fact, be likened to a highway intersection for which the green and amber signals have burned out, leaving only an often-unexpected red.

This problem could be dealt with in a manner analogous to the traffic signal case, as by using a steady amber light. For example, this could be combined with a normally flashing amber as described above. However, still more effective approaches may be

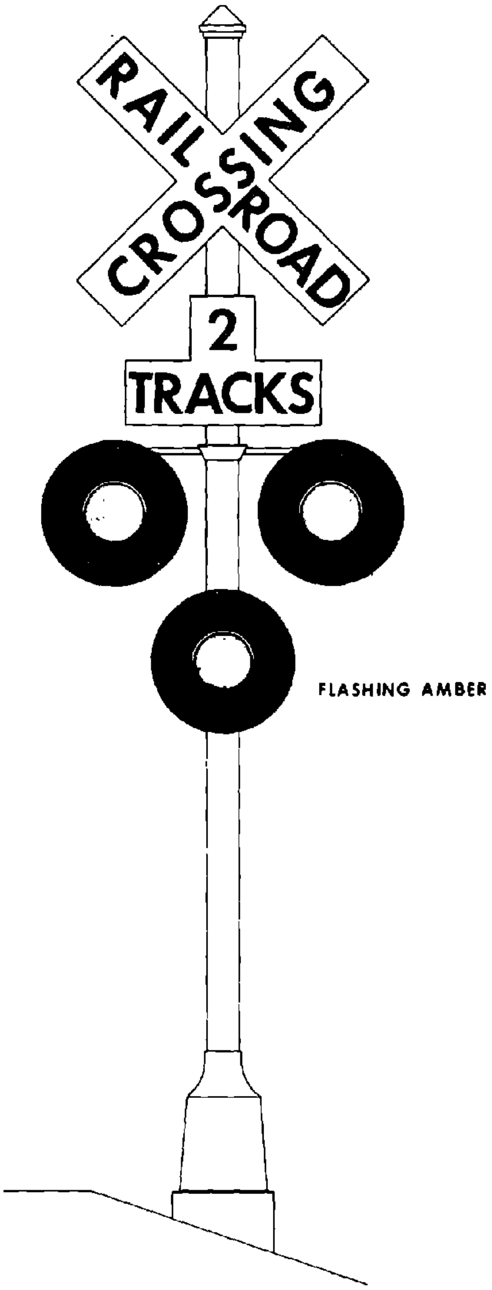

FIGURE 32. RAILROAD CROSSING TRAFFIC LIGHT

possible. Wilde and others have concluded that even in the purely highway case the sudden amber tends to generate indecision and variability in driver response.[33] Their proposed concept includes a train-activated advance warning which begins to flash prior to the crossing-located warning. It is intended that the system be timed and physically laid out such that motorists, who have already passed the active advance warning, can safely traverse the crossing, while those who have not reached it, and therefore see that it has been activated, are to initiate braking. (This concept does, however, assume the use of a constant-warning-time train detection.)

The use of conventional highway traffic signals at grade crossings has long been discussed. Indeed, one finds numerous crossings at which interconnected traffic signals are an intimate part of the warning system, possibly serving as the dominant control device in the eyes of most motorists (Figures 33-34). However, the question has yet to be resolved. The basic argument in favor of such devices is that they generally receive a high level of obedience at highway intersections. However, it is not clear whether this would be transferred to the grade crossing application; mixed results have been found in the analogous use of "Stop" signs. In addition, this does tend to diminish, rather than enhance, motorist perception of the nature of the potential hazard. The crucial question, which is basically independent of the warning device used, appears to be credibility. If motorists do not believe the signals, due to previously unnecessary or excessively long activation, in cases where there is, in fact, no hazard, their obedience to the signals tends to be weakened. Wilde and others address this question at some length, and their proposed system is intended to incorporate constant-warning-time activation to eliminate just this problem.[33] Without this characteristic, traffic signals appear unlikely to offer marked improvement. One has only to consider the behavior of motorists at a malfunctioning highway traffic signal--one permanently on red, or with an abnormally slow cycle. After a certain point, traffic begins to move through the red signal. If a particular signal becomes known to local

FIGURE 33. CROSSINGS MARKED BY BOTH CONVENTIONAL TRAFFIC AND RAILROAD SIGNALS (NOTE AUTOMOBILE NEAR INTERSECTION).

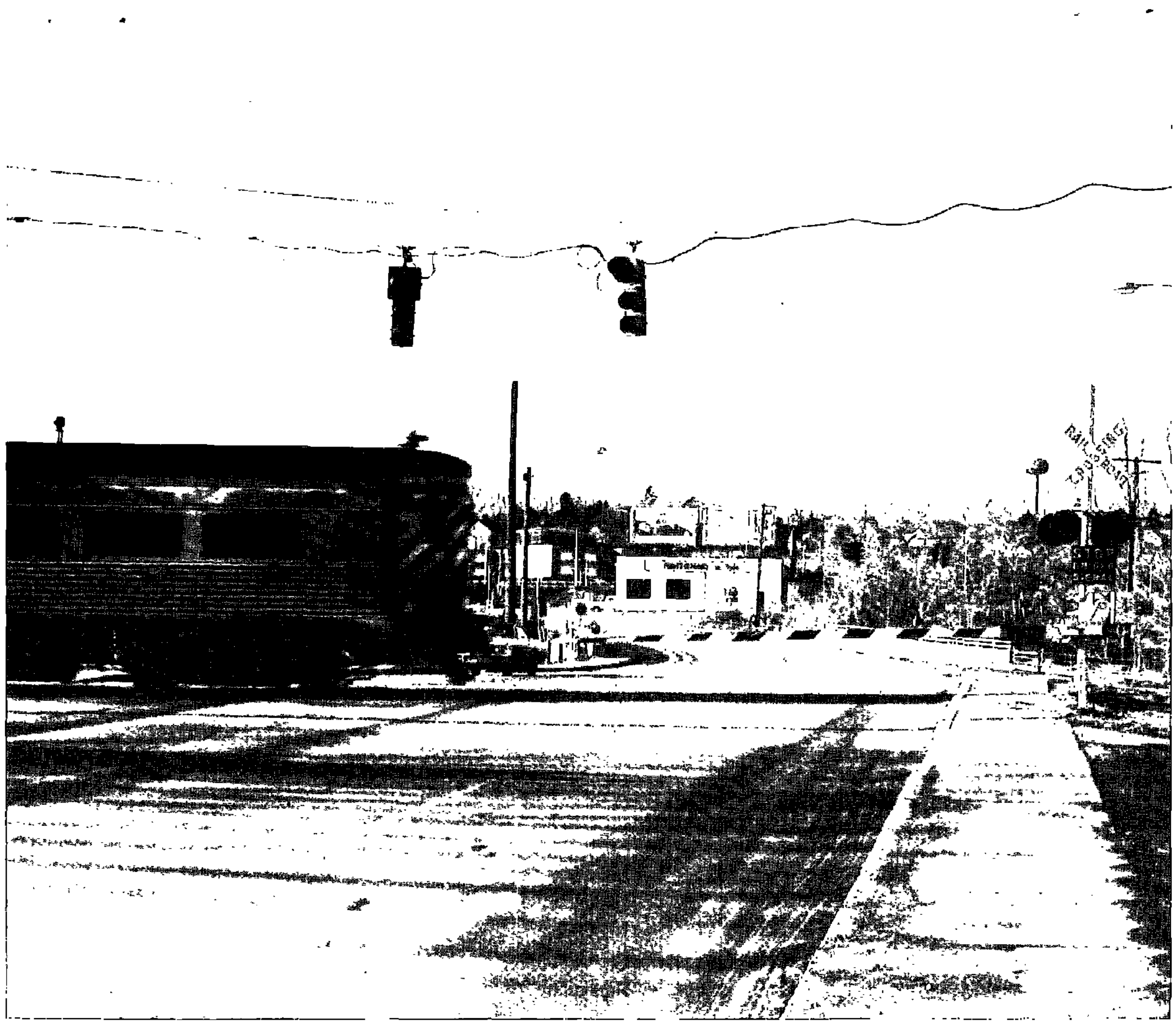

FIGURE 34. CROSSINGS MARKED BY BOTH CONVENTIONAL TRAFFIC AND RAILROAD SIGNALS (NOTE TRAIN APPROACHING INTERSECTION).

motorists as being prone to such problems, their behavior soon becomes a close approximation to that often observed at grade crossings. The usual behavior is that the signals are treated merely as an advisory indication, not taken seriously in comparison with direct observation of hazard. On the other hand, it seems reasonable to assume that the virtually guaranteed arrival of a train twenty to thirty seconds following activation can do much to establish the validity and importance of a grade crossing warning system.

8. POSSIBLE FURTHER RESEARCH

The application of xenon flashlamps and other devices suggested here require no further extensive research or development; a modest amount of product and application engineering should suffice. This appears to be well within the capabilities of private industry. The need for research lies in resolution of various design parameters (flash rates, intensities, synchronization, etc.); this type of activity is now in progress (FHWA Contract DOT-FH-11-8846). Possibly even more important is research that would provide clear insights into accident causation, which is now poorly understood. Only specific identification of the key motorist errors now being made can generate design of truly effective and efficient warning systems. For example, it is not at present possible to state whether accidents are typically produced by a failure to see the lights, mistrust or misunderstanding of their message, or observation and miscalculation of train rate of approach. Resolution of such questions, which could be sought in a variety of ways (statistics, controlled tests, crossing observation, interviews, etc.), would properly underlie further research into improved grade crossing warning systems. In addition, studies of particular topics which have long been recognized as important would be valuable: the effects of constancy of warning time, advanced active warnings, cantilever mounting of lights, crossing illumination, etc. The main thrust of such work should be to define more fully the probable safety benefits of each approach for various types of crossings and situations.

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