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16. Abstract <p>This document includes a general review of innovative conceptual and technical approaches to train-activated motorist warning systems for use at railroad-highway grade crossings, and also contains a specific report describing a study directed toward the generation, analysis and evaluation of innovative concepts. The review includes a discussion of communication-link systems, radar train detection, locomotive-mounted transmitters and several other concepts. The basic application constraints of safety, reliability, resistance to serve environments and low cost are used as the basis for evaluating the merits of the alternative concepts.</p> <p>The special study reported here explores the communication-link concept in detail, with particular emphasis on train-detection techniques. The use of microprocessor technology is advocated, along with substantial changes in motorist warnings. Volume II consists of 96 pages.</p>					
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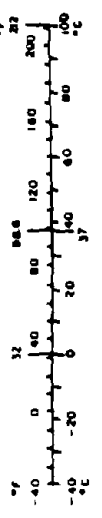
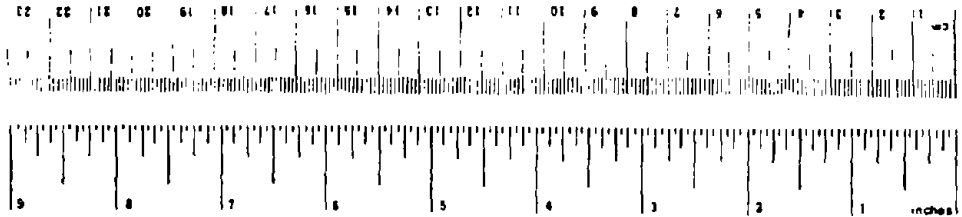
PREFACE

The work described in this report is 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.

This volume contains an overview of the subject of grade crossing motorist warning systems, followed by a concept generation and evaluation study carried out under contract. Volume II consists of the report resulting from a second parallel contract. The executive summary for both volumes is contained in Volume I.

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures				Approximate Conversions from Metric Measures			
Symbol	When You Know	Multiply by	To Find	Symbol	When You Know	Multiply by	To Find
LENGTH							
in	inches	2.5	centimeters	cm	centimeters	0.04	inches
ft	feet	30	centimeters	in	inches	0.4	inches
yd	yards	0.9	meters	m	meters	3.3	feet
mi	miles	1.6	kilometers	km	kilometers	0.6	miles
AREA							
sq in	square inches	6.5	square centimeters	cm ²	square centimeters	0.16	square inches
sq ft	square feet	0.09	square meters	m ²	square meters	1.2	square yards
sq yd	square yards	0.8	square meters	km ²	square kilometers	0.4	square miles
ac	square miles	2.6	square kilometers	ha	hectares (10,000 m ²)	2.6	square miles
MASS (weight)							
oz	ounces	28	grams	g	grams	0.035	ounces
lb	pounds	0.45	kilograms	kg	kilograms	2.2	pounds
	short tons (2000 lb)	0.9	tonnes	t	tonnes (1000 kg)	1.1	short tons
VOLUME							
fl oz	fluid ounces	30	milliliters	ml	milliliters	0.03	fluid ounces
cup	cups	0.24	liters	l	liters	2.1	pints
qt	quarts	0.95	liters	qt	quarts	1.06	quarts
gal	gallons	3.8	liters	gal	gallons	0.26	gallons
cu ft	cubic feet	0.03	cubic meters	m ³	cubic meters	38	cubic feet
cu yd	cubic yards	0.76	cubic meters	yd ³	cubic yards	1.3	cubic yards
TEMPERATURE (exact)							
F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	C	Celsius temperature	9/5 (after adding 32)	Fahrenheit temperature



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EXECUTIVE SUMMARY

In recent years a number of studies have been carried out by the Department of Transportation with the objective of achieving reduced cost and greater effectiveness in train-activated protection equipment at railroad-highway grade crossings. One major element of the overall program has been generation and examination of innovative system concepts which, by their nature, have proven too speculative and long-term to warrant investment of very limited industry research funds. This report contains a general overview of the area, drawing upon numerous past investigations and suggestions, combined with two recently-completed contractor reports describing specific studies relating to this topic. Concepts considered in the overview portion include communication-link systems, radar train detection, track circuit reflection techniques, locomotive-mounted transmitters, train-indicator equipment, malfunction indicators and motorist warnings.

In general, the fundamental requirements of high reliability, great tolerance to environmental extremes, virtually fail-safe performance, and reasonable cost are found to be serious obstacles to the applicability of many of the concepts proposed. Additional research and development will be required (with possible concomitant increases in estimated system costs) for the most promising concepts to determine their true safety and cost effectiveness.

Consideration of innovative motorist warnings is constrained by the importance of motorist familiarity with existing signals. Thus, improvement in this area is most likely to occur within the basic framework of conventional signals; i.e., where the warning is conveyed to the motorist through a conventionally perceived medium (a gate, flashing light, etc.). This does not preclude innovative means of producing the conventional signal aspect.

In order that a comprehensive survey and concept-generation effort may be assured, two similar contracts, each involving approximately one man-year of effort, were awarded. The objective in each was selection, evaluation, and analysis of promising innovative concepts. The final reports of each contractor form the major portion of this document.

Cincinnati Electronics Corp. of Cincinnati, Ohio, examined numerous concepts of relevance to all aspects of crossing warning systems. The approach they found preferable was a communication link concept, in which a train is detected by a specific sensor at the end of the crossing approach, and that information is communicated to the crossing-located control circuitry. A magnetic sensor based upon the Hall effect (creation of a potential difference across a semi-conductor or conductor when exposed to a magnetic field) was suggested as preferable to other means such as piezo-electric crystals, magnetoresistors, radar, breaking of a beam of light, and induction loops. Their preference for the communication link was VHF transmission. An option suggested for use when parallel power lines or railroad pole lines are present is the traditional carrier system, in which modulation is superimposed upon the 60 Hz AC or existing coded signals. A solid state micro-processor control subsystem is proposed, providing relatively constant warning time and freedom from unnecessary activations in cases for which two or more sensing/transmitting points are used in the "approach circuit". In principal, failsafe operation can be achieved, although realizing this attribute in the train detection process will be a challenging task.

Cincinnati Electronics reviewed a number of possible motorist warnings, generally based upon existing concepts and technology. Red flashing strobe lights are recommended for indicating train presence, with horizontal amber flashing lights as a malfunction indicator. Train-activated advance warnings are proposed, possibly radio-controlled from the crossing, utilizing amber lights. Use of an "engineer warning signal" is also suggested with three possible modes: steady illumination (system activated for train);

flashing (system continuously activated by malfunction); and dark (system dead). Cost analysis indicates a potential for modest cost savings.

Tracor-Jitco, Inc. of Rockville, Maryland was the other contractor involved in this study. Three potential improvements were judged worthy of further exploration. Principal among them is a new form of track circuit which relies on the characteristics of the track as a transmission line. Through the use of correlation techniques, the elapsed time from origination of a transmitted signal at the crossing to receipt of the reflection can be measured to provide a precise indication of where the termination or reflector is. A train serves as just such a reflector. Velocity and direction of the train can be obtained through successive differentiations of location with respect to time, so that constant warning time can, in principle, be obtained. Preliminary analyses indicate a possibility of some cost reduction.

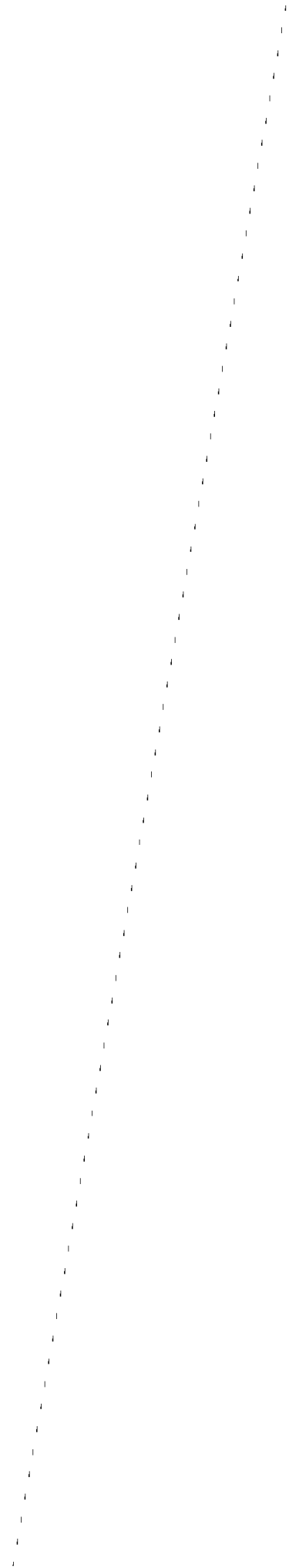
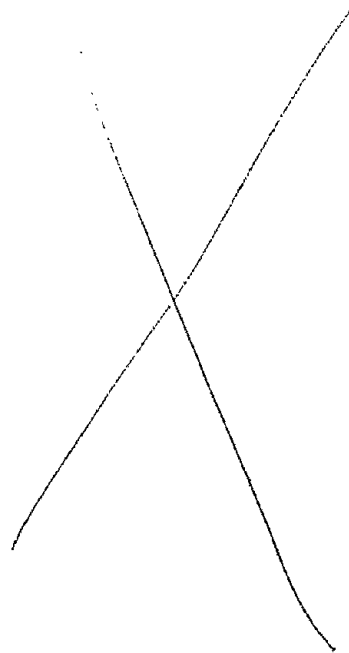
Traco-Jitco also proposed use of two techniques now being applied in other highway applications. "Open Graded Asphalt Friction Course" is a recently-developed porous mixture of asphalt, sand, and aggregate which, when placed in an inch-thick layer on an existing road, provides for rapid drainage of water, greatly reducing stopping distances under heavy rainfall conditions.

The other relevant technology is "Optionally Programmed Traffic Signals" -- the use of special optical techniques to obtain a very sharp cutoff of beam from a traffic light so that motorists in different locations will see different aspects. The main purpose would be to provide an initial amber light for vehicles near the crossing, which still can cross safely, but a red light for motorists further back.

A number of interesting and intriguing possibilities have resulted from these contract research efforts. The technical feasibility, practicality, safety, and costs of these concepts will require careful examination to determine whether further research and development in this area is appropriate.

PART I
OVERVIEW

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1. INTRODUCTION

1.1 BACKGROUND

Extremely high levels of performance and reliability are absolute requirements placed upon the equipment associated with train-activated motorist warning systems used at railroad highway grade crossings. As a consequence, such hardware is generally costly, and certain functions -- such as constant warning time, or independence of railroad property -- may be either expensive or impossible to attain within the technology and system concepts now used. The speculative nature, great cost and lengthy period of development and test required for convincing demonstration of new approaches, in what must be a safety-oriented, conservative marketplace, tightly constrained by liability considerations, have created little or no incentive for suppliers to attempt more than evolutionary advances. The considerable technical advance during recent years -- AFO, motion sensing, improved lights, application of solid state technology, etc., -- is a tribute to the skill and ingenuity of the industry, but has been carried out almost entirely within the framework of existing concepts and practices. More recently, the Federal Railroad Administration, acting under the authority of the Railroad Safety Act of 1970, has undertaken to explore more speculative, high-risk research topics which, for economic reasons, have not been addressed directly by industry -- the area which will here be referred to as "innovative system".

A rigorous definition of "innovative" is not easily achieved, and is unnecessary for present purposes. The term will be used here primarily to describe system concepts or technology not currently applied to grade crossing protection. In general, this will imply consideration of areas not covered by existing AAR and FRA standards, or possibly in conflict with them.

Such work was initiated at the Transportation Systems Center in 1970,^{1,2} which has conducted continuing general research activity in this area since that time. Current efforts directed toward improved warning effectiveness and cost reduction

through acceleration of evolutionary advances and direct application of existing technology to conventional concepts are described in other reports.^{3,4,5}

In order that the FRA grade crossing research program be truly comprehensive, it was judged appropriate to include as a major element a solicitation to private industry to uncover, generate, analyze, and evaluate truly innovative concepts for improved grade crossing safety. A competitive procurement was issued, with emphasis placed on ability to apply new and creative thinking, broad interdisciplinary technical expertise, and rigorous engineering analysis to the problem. No special emphasis was placed upon specific background for experience in grade crossing safety, so that fresh thinking would be encouraged. Two parallel contracts were awarded, with the objective of increasing the likelihood that effective solutions would be generated. The successful vendors were Cincinnati Electronics, of Cincinnati, Ohio, and Tracor-Jitco, located in Rockville, Maryland. The major portion of this document consists of the final reports resulting from these two studies; the other is contained in Volume II. Each represented approximately one man-year of effort. The studies included achieving familiarity with grade crossing safety and technology, selecting criteria for evaluation of concepts, and generation and analysis of new types of warning systems. Obviously, this was a very sweeping objective for the available resources, and the depth of analysis possible was therefore somewhat limited. Also, both firms were basically unfamiliar with existing technology, which provided a freshness of viewpoint, but which also restricted the degree to which each concept could be explored. Thus, many of the judgements and conclusions presented in their reports (Part 2 and 3) must be seen as preliminary, subject to modification through further study. For example, no significant failure-mode analysis could be carried out within the scope of their efforts, and this is at the heart of any judgement of acceptability and practicality. Important characteristics such as surge protection, power consumption, and general tolerance to a harsh environment could only be analysed in a preliminary manner, if at all.

Similarly, alternative concepts for motorist-warning devices can be given meaningful analysis and evaluation only in terms of a fuller understanding than now exists concerning accident causation and driver behavior. Nonetheless, it is felt that these studies are of real value in delineating the range of possibilities which exists, and in assessing the limited benefits attainable.

It is the primary purpose of this document to present the findings of these investigations, and - in this overview - to combine them with results of several previous studies to provide general conclusions arising from consideration of the totality of these studies.

It is to be emphasized that the conclusions and recommendations contained in the Cincinnati Electronics and Tracor-Jitco reports are the views of those organizations, and do not necessarily reflect the opinions or policies of the Department of Transportation or any part thereof.

1.2 SCOPE AND OBJECTIVES

Although the scope of this work includes investigation of all aspects of grade crossing equipment, the emphasis has, in practice, fallen largely on train detection and control system aspects, with relatively little effort in innovative motorist warning devices. This arises due to the great importance of motorist familiarity and nationwide standardization of the visual aspect presented to the driver. Accordingly, research to date in this area has been in a relatively conventional framework - utilization of Xenon lamps in flashers, alternative gate arm materials and structures, etc. The major exception to this pattern is the exploration of in-vehicle warning systems recently carried out jointly by FRA and NHTSA.⁶ Locomotive-mounted systems, such as alerting beacons and impact attenuation structures will not be discussed here. This report will concentrate primarily upon crossing-located, train-activated motorist warning systems.

In considering the possibility of system improvement through technical or conceptual innovation, one must be particularly careful to avoid change for the sake of change. An approach that is different is not automatically better and may well have significant inherent disadvantages. In the work to be described here, specific objectives guide the formulation and evaluation of projects:

- 1) Reduced life-cycle cost -- This comprises design, installation, scheduled maintenance, emergency repairs, upgrading, etc., and would include extending the maintenance interval, achieving a greater mean time between failures, etc.
- 2) Increased functional capability -- Possible examples include enhanced ability to provide a uniform warning time and deal with variable-speed train movements, discrimination between system failure modes and train presence, and motorist warnings which automatically adjust as ambient conditions (light levels, visibility, etc.) change.
- 3) Removal of existing non-technical constraints -- The primary example in this category is development of detection systems independent of the tracks.

The viability of innovative concepts is determined by rigid constraints of reliability, safe failure modes, and tolerance of an extremely severe environment. These factors make achievement of low cost and improved performance (compared to existing systems) very difficult. Further, the generation and evaluation of innovative concepts must in large part be based upon (1) the experience, wisdom and insights that come only from extensive experience in grade crossing safety and conventional technology; and (2) the substantial research carried out by FRA, FHWA, NHTSA, TRB, States, AAR, individual railroads, grade crossing equipment suppliers, other interested parties. Indeed, many research projects

directed toward evolutionary advances in current systems, or carried out within that framework, offer much that is also useful in addressing innovation.

Finally, the innovation concepts discussed here must be recognized as being, at best, many years from application to actual grade crossings. If a truly innovative approach ultimately does prevail, it may be one very different from those we have now identified here. Yet, despite the very challenging and speculative nature of this effort, it forms a natural part of any comprehensive research program in grade crossing safety. The objectives indicated above all relate to factors which now restrict crossing safety. Approximately 1000 deaths a year, with a major portion occurring at crossings with train-activated warnings, make clear that the problem is real. The answers lie in many types of research in addition to technological -- driver behavior, institutional factors, train-mounted systems, warrants for protection, etc. However, grade crossing safety in the future will only be markedly greater if a start is made now, and if no possibility is excluded without careful consideration.

2. REVIEW OF INNOVATIVE CONCEPTS

In order that the specific studies reported here be considered in proper perspective, this section will provide a brief review of the major concepts identified in these studies, as well as others which have been proposed from time to time. The topic will be addressed primarily in terms of technical feasibility, practicality, and potential safety or economic benefits.

The relatively high level of interest in recent years in grade crossing safety and research has brought with it many suggestions for means of improvement. Frequently, these ideas reflect a misunderstanding of the relevant technology, functional system requirements, acceptable economics, or accident causal factors. These notions can often be dismissed relatively quickly, and will not be discussed here. However, a number of concepts have been uncovered or generated for which more thorough consideration is warranted. The following discussion will review several of the more interesting of these, to the degree that they fall within the general subject area addressed by this report.

2.1 POINT DETECTION/COMMUNICATION-LINK (CHECK-IN, CHECK-OUT)

The track circuit systems used universally in the U.S. detect train occupancy at any point in the signal block. A possible alternative is detection of trains only at entrance and exit points, with that information then communicated to a central processing point. (This is a common European practice.) Examination of this concept in the past has been a major effort at TSC, and has become the focus of the Cincinnati Electronics (CE) Study reported here. The communication link aspect is relatively straightforward. Cables, whether buried or polemounted, are typically too expensive to be practical; however, numerous other methods are possible. Past TSC studies have explored the use of microwave telemetry, for which good power efficiency can be obtained by use of narrow beams. CE analysis leads to a preference

for VHF radio transmission, which is not limited to line-of-sight operation. It may be that each method has a role to play, depending upon circumstances; in any event, this affects only a small part of the system. (CE also recommends consideration of the traditional carrier system, in which information modulation is superimposed upon existing 60 Hz AC pole lines.)

The principal design constraint with this overall concept is selection of a train-detection device which meets all requirements of extreme reliability, fail-safe operation, low power consumption, long lifetime, invulnerability to severe environments, and low cost. A highly localized short-distance conventional track circuit could be used, but this would be expensive and would preclude the major potential advantage of the concept: elimination of track-based detection, thus making possible public assumption of responsibility for the warning system. At least one existing sensor appears adequate, but costs in excess of \$1000. A variety of physical principles might lead to a lower-cost device, but would require an extensive development effort, since this subsystem is at the very heart of safe system operation and must meet very rigorous standards.

Studies to date indicate limited potential for overall cost reduction via this avenue. Functional advantages compared to existing equipment might be obtained, but further investigation would be required for confirmation. Use of speed-sensitive train detectors might facilitate constant-warning time operation; but increased system complexity (and therefore cost) occurs if one seeks to duplicate the performance of existing motion-sensing equipment. The major potential strength of this concept lies in the possibility of achieving a system which would permit assumption of responsibility for the equipment and its operation by a public authority such as a highway department. (Current use of the track circuit involves railroads so intimately that total transfer of operational responsibility for train detection appears to be virtually impossible.) However, to obtain full benefits of a total transfer of responsibility, one would have

to consider retrofitting the nearly 60,000 crossings now equipped with conventional train-activated systems.

2.2 RADAR TRAIN DETECTION

The use of crossing-located radar has been a popular notion for some years, partially stimulated by nominally analogous uses in speed monitoring, small boat safety, and military perimeter surveillance. This concept was examined extensively at TSC, and found to have numerous weaknesses, particularly with regard to line-of-sight problems, fail-safe operation, and adequate performance at multiple-track crossings with more than one train present.² In addition, even partial satisfaction of these rigorous performance standards tends to escalate costs to an unacceptable level.

2.3 "TRACK RADAR"

Tracor-Jitco (TJ) found a new form of track circuit to be promising. It is significantly different from present track circuits in that it does not rely exclusively upon circuit characteristics or transmission line characteristics, but upon reflection of audio frequency electrical signals transmitted down the track. These reflected waves travel in the opposite direction to the transmitted waves, and are added vectorially to them. Through the use of correlation techniques the elapsed time from originating to receipt of the reflection can be measured to provide a precise indication of where the termination or reflector is. A train serves as just such a reflector. Another source of reflected wave is a broken rail; however, the wave from a broken rail is 180° out of phase with the waves reflected by the train. The virtue here lies in the fact that the system would not only detect broken rail, but would also identify the break as such. Velocity and direction of the train are obtained through successive differentiations of location with respect to time, so that constant warning time can, in principle, be obtained.

This system should be capable of automatic compensation for the changes in impedance and conductance which render present systems perversely nonlinear, changing daily as the nature of the track and ballast change with the weather. The potential advantages of this approach are substantial, with a possibility for a reduction from the cost and complexity of existing systems. On the other hand, the basic principle of operation is at present only theoretical, and the variability of typical track structures is likely to raise significant problems. The sophistication required of practical circuitry could render the potential of low cost difficult to achieve, although it still might offer advantages over existing constant-warning-time systems. Extensive further analysis and testing would be required to achieve meaningful estimation of the potential practicality and safety of this concept.

2.4 LOCOMOTIVE-MOUNTED TRANSMITTERS

Another frequently-raised issue is the potential viability of a system in which a locomotive can signal the crossing of its impending arrival. There are approximately eight times as many public crossing as locomotives (225,000 vs. 27,000), so a considerable cost saving might be anticipated, if a large number of warning systems were to be installed. However, since the motorist-warning devices represent a major share of the cost of active grade crossing protection, it is unlikely that this approach would drastically alter the cost-benefit analyses⁷ which generally have indicated that only 20,000 to 30,000 crossings warrant major upgrading or new installation of train-activated devices. Thus, since all locomotives would still have to be equipped, the numbers become comparable (crossings vs. locomotives) and this "leverage" is lost. (However, a greatly expanded program of crossing installations, as could occur for a low-cost system, could restore some advantage of this type.)

A number of variations on the basic concept are possible, leading to systems differing widely in cost and performance. At the simplest level, one might have a continuously operating locomotive

transmitter which activates warnings at all properly equipped crossings within some approximate range. The next level of complexity would provide for transmission only when the train is approaching or occupying a crossing, with transmitter activation either manual or through some wayside device in advance of the crossing which could communicate with the locomotive to initiate operation. One could generate far more elaborate concepts, in which a locomotive might use an odometer with wayside recalibration points to monitor its location continuously, with transmissions coded for particular crossings activated from a route specification stored in a micro-processor memory; speed could readily be included.

At this stage of the development process these concepts generally compromise the fail-safe principle which has guided railroad signal practices for many decades. The normal condition for the crossing--no received signal--is no different for the case of approach of an unequipped or malfunctioning locomotive, than for the situation when no train is approaching. This difficulty could be addressed in part through operating rules, engineman intervention, and train indication techniques (discussed later). A particularly constraining requirement is that all motive power units which might traverse a locomotive-controlled crossing must be equipped with transmitters. In general, this would include most of the fleet of a railroad, and the problem is further complicated by the prevalence of run-through operations and locomotive leasing. Thus, this approach is, at best, only attractive if applied to many crossings, since very widespread installation of equipment in locomotives is required in any event.

A simple train-located transmitter could activate crossings indiscriminately and generate unnecessary or excessively lengthy warnings, thus causing loss of credibility with motorists, and the cost of such a device can be determined only from extensive development, particularly for operation on locomotives. On the other hand, dependence upon the train crew to deal with all cases or merely with exceptions, imposes an additional burden on them, and introduces a major potential point of controversy in the event of an accident. For this reason, manually operated systems may not be acceptable.

To compensate for the problems cited above, one can envision a system in which a locomotive approaching a crossing interrogates a passive wayside device, receives a coding for that particular crossing, and transmits the appropriate signal to activate that crossing only. One could also incorporate speed sensing and alter the warning as required. A specific sensor would be needed at the crossing to deactivate the warnings only when the train has passed. It would also be possible to require that a crossing-located transponder "answer" the locomotive when the signals were activated; failure to respond in a brief interval could sound an alarm to alert the engineer that the crossing was not actively projected. (See the following section on Train Indicators.) Expense is likely to escalate for these more elaborate concepts. It appears that the most reasonable and cost-effective concept would be a manual system, in which the engineman activates the transmitter (and must attempt to stop if no confirmation is received), combined with a very simple, low-cost warning at the crossing--perhaps a single strobe light. It would be important to such a concept that the motorist distinguish between this less reliable indication and the standard fail-safe signals, and be appropriately cautious. Such a system might be attainable at a substantially lower cost than present equipment. Its main relevance would be for those lower-traffic crossings for which the expense of conventional equipment cannot be justified, and it might offer a significant improvement in safety for them. However, in most cases, modification of the entire locomotive fleet would be required to obtain these benefits.

2.5 TRAIN INDICATOR

Under various specialized circumstances, both in Europe and the U.S., use has been made of train indicators--wayside signals for the locomotive engineer which prevent his entering a crossing until the motorist warning system is activated. This broad concept can be implemented in many ways, but often involves a fail-safe arrangement in which the wayside signal (train indicator) is normally red, changing to green only when the crossing signals are on. The typical application is for cases of infrequent, short, low-speed

trains which can easily stop if necessary. However, it has recently been suggested* that this concept could be expanded in a way that might permit significant reduction in the cost of warning equipment. At sufficiently low speeds, even a large freight train can stop within the normal grade crossing approach circuit distance. Thus, if the crossing does not activate, there is still sufficient time and distance in which to stop. For a relatively long, heavy train, this condition would be satisfied up to a train speed of approximately 20 MPH. For shorter trains, or a longer pre-arrival warning time at the crossing, this could be raised significantly. This concept is not mentioned with the implication that trains should be stopped at crossings. In addition to the havoc this could play with schedules and operating costs (there is approximately one public crossing per route mile in the U.S., with one in five actively protected), this approach would then lead to trains moving over crossings from a dead stop, which would greatly increase exposure time (and thus hazard) and highway congestion. However, with such a system in operation one might be able to consider a modest retreat from the extremely high reliability standards now imposed. Since the last increment of reliability is typically very expensive to achieve, this might offer an avenue to substantially reduced cost with no appreciable loss of safety and a very low probability that a train would, in fact, have to stop.

The viability of this concept depends upon the number of crossings to which it might apply and the accident potential associated with them. It further requires that significant cost reduction can be achieved with only a small diminution of system reliability. Nonetheless, this approach could be of special interest for the large number of crossings which are insufficiently hazardous to warrant conventional warning systems, but which do contribute a significant number of accidents.

*This approach was recommended in Contract DOT-TSC-870 with Storch Engineers, Chestnut Hill, MA.

2.6 MALFUNCTION INDICATORS

At present, any kind of failure of crossing protection to operate is normally expected to be reported by train crews. This would include broken gates, burned out flasher bulbs (observable through small windows in the sides of the flasher units), etc. Most suppliers offer light bulb assemblies which can be mounted to equipment cases which are dark if the system is operating on standby power. (These are so vulnerable to vandals and hunters that they are not popular with railroads.) A crossing which has become locked into an activated state (a frequent natural consequence of fail-safe design) will normally be reported to a railroad by local police. However, these systems for detecting malfunction can lead to substantial delays in repair, particularly for low traffic-density crossings. Operation on standby power, which often occurs through destruction of a fuse by an electrical surge, may only be detected on the next scheduled visit by a maintainer--possibly weeks later. Some malfunctions pose direct safety problems, and others--the "false alarm" types--reduce warning system credibility. Thus, it appears appropriate to consider ways of communicating relevant information to the railroads. A number of means might be considered. Small transmitters, attached to appropriate malfunction sensors, could pass messages from the crossing to receiver/recorders on each locomotive, indicating a crossing identification number and the type of problem. More directly, such information could be introduced into railroad signal or communication lines if present.

It is difficult to assess the practical value of such devices. This approach might reduce the standby power requirement, and could limit the duration of unnecessary activations. It could prevent the already-rare safety problems associated with malfunctioning crossings. However, none of these factors appears to have major impact upon the basic costs or safety of warning systems. Thus, these concepts might be highly relevant and cost effective for particular situations, such as crossings in remote locations.

2.7 MOTORIST WARNINGS

As indicated previously, the subject of new concepts for motorist warnings is one which can be treated effectively only on the basis of improved understanding of motorist behavior and accident causal factors. Automatic gates have been found to be highly effective, but conventional train-activated flashing lights alone apparently reduce accident probability by only 60 percent to 70 percent. Although one might speculate, it is not possible at the present time to determine whether some accidents continue to occur because these signals are not seen at all, seen but not believed, not understood, etc. A number of studies have recently been carried out or initiated addressing some of these topics, and significant advances appear possible within a relatively conventional framework. However, the potential benefits of any truly innovative concepts which might be developed have not yet been thoroughly evaluated.

3. SUMMARY

A number of possible technical innovations have been described. In general, technical feasibility, cost characteristics, and direct and indirect impact on grade crossing safety can only be estimated. Decisions as to the overall value and desirability of further investigation of these concepts depend upon a variety of factors which must be balanced according to specific policies and objectives. In order to facilitate this process, each of the innovations which have been treated here is presented in Table 1 described in terms of several aspects. One or more distinguishing characteristics are identified, accompanied by an estimate of technical feasibility. Potential safety and cost benefits are indicated, based upon the assumption of technical feasibility and widespread adoption. The research, development, and test effort expected to be necessary to bring a concept to fruition, assuming basic technical feasibility, is also shown. Non-technical factors which might limit acceptability are indicated; these include changes in the fail-safe requirement, train operations, expansion of railroad responsibilities, etc. Some concepts are seen to be of value primarily through making technically possible the public assumption of operational and maintenance responsibilities for crossing protection; others would inhibit this by requiring a wider range of railroad company involvement. This element is included in Table 1. The final category is the estimated overall impact on grade crossing safety, and again under the assumption of technical feasibility, fully successful development, and widespread implementation. It should be noted that the entries for "Innovating Warnings" are particularly uncertain, since this refers only to a broad class of possible devices and not any specific concept.

Research and Development Considerations

It is important to understand the implications and potential consequences of initiating a major research and development effort, even for the most promising concepts. In a purely technical sense, the task is generally a large one. Although the initial design

TABLE 1. CHARACTERISTICS OF INNOVATIVE CONCEPTS

	CONN. LINK	RADAR	TRACK RADAR	LOCO. MOUNTED	TRAIN INDICATOR	MAJ. - FUNCTION INDICATOR	INNOV. WARNINGS
BASIC CHARACTERISTIC	PERMITS PUBLIC RESPONSIBILITY	CWT*	CWT*	LOW-COST; NOT FAIL-SAFE; PARTIAL DEPLOYMENT NOT POSSIBLE	LIMITED APPLICABILITY	LIMITED IMPACT	POSSIBILITY OF LARGE IMPACT
TECHNICAL FEASIBILITY	YES	DOUBTFUL	NOT ESTABLISHED	YES	YES	YES	NOT ESTABLISHED
POTENTIAL DIRECT SAFETY BENEFITS	NO	SMALL	SMALL	NO	NO	SMALL	YES
POTENTIAL DIRECT COST BENEFITS	SMALL	DOUBTFUL	NOT ESTABLISHED	YES	YES	NO	NOT ESTABLISHED
REQUIRED RESEARCH EFFORT	LARGE	LARGE	LARGE	LARGE	MEDIUM	MEDIUM	LARGE
NON-TECHNICAL IMPEDIMENTS TO USAGE		SMALL	SMALL	MEDIUM-LARGE	MEDIUM-LARGE	SMALL	NOT ESTABLISHED
DEGREE OF INDEPENDENCE OF TRACK	HIGH	HIGH	VERY LOW	HIGH	N/A	N/A	NOT KNOWN
ESTIMATED OVERALL SAFETY IMPACT IF SUCCESSFUL	LOW	LOW	LOW	LOW-MEDIUM	LOW	LOW	MEDIUM-HIGH

*CWT= Constant-Warning-Time Train Detection

process can be limited in scope--the equipment is inherently simple in concept--the past experience of both Government and industry research has invariably included several lengthy and expensive cycles of design, field test, and redesign, generally accompanied by a steady rise in final system cost. Acceptability of new equipment by the industry has generally required attainment of a mean time between safe failures of at least three to five years, with non-safe failures virtually unknown; simply establishing that this has been achieved requires a substantial field test program. Such straightforward, evolutionary signal industry developments as motion-sensitive train detection and solid-state audio frequency overlay equipment have typically required as long as ten years to move from the drawing board to widespread use. Some innovations, such as solid-state flashers, have failed to achieve a level of performance sufficient to generate full market acceptance.

Other factors can also impede utilization of improved equipment. Each railroad has a fully-developed maintenance system--procedures, trained personnel, inventory, etc. Broadening the variety of equipment types in use might require changes to maintenance practices which could limit the actual benefits of any improvement. Another constraint is the likelihood that alternative hardware will either fail to be covered by existing industry standards, or will be in some conflict with them. These considerations apply quite generally to the entire technology of railroad signalling. They are felt nowhere more strongly than in the area addressed by the studies reported here--grade crossing motorist warning systems. Thus, while the search for greater effectiveness and reduced cost in such systems is a worthy and important goal, to which a number of possible avenues have been identified, achieving that objective will require large commitments of resources and time; research decisions must be made within this context.

On the other hand, the possibility of improving grade crossing safety through innovative technology is clearly present. Existing systems have been little affected by advances of recent

decades in electronic and electromechanical engineering. Systems of significantly lower cost could greatly increase the number of crossings at which train-activated warning devices could be justified, substantially improving their safety. More widespread usage of constant-warning-time systems would increase the motorist credibility, and therefore the safety, of all actively protected crossings. Thus, in spite of the challenging nature of the problem, research and development in this area is worthy of serious consideration.

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PART II
CONCEPT GENERATION
AND ANALYSIS

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1. INTRODUCTION

1.1 OBJECTIVE

This study was designed to synthesize and to analyze innovative techniques for railroad highway grade crossing (RHGC) warning systems. System elements which were emphasized include train detection, information transmission, control circuitry, and warning signals. Consideration was given to design and cost in relation to application, effectiveness, reliability, environment, regulation, and liability.

The recommendations made on the basis of the analyses in this study form a base for further Government development and evaluation.

1.2 SCOPE

This study was organized into a sequence of eight overlapping tasks.

TASK 1 — CONTRACTOR DEVELOPMENT PLAN

This task required the contractor to prepare a Management Development Plan. This plan included Scheduling, Staffing, Milestones, and Cost Projections.

TASK 2 — CONCEPT SYNTHESIS

The first technical task in the study was the synthesis of concepts which could be used in railroad-highway grade crossing warning systems. These concepts are discussed in the subsequent sections of this report and are divided into sensors, communications, signals, control and remote power.

TASK 3 — CONCEPT DESCRIPTION

This task was the complete description of the concepts synthesized in Task 2. These descriptions are included in subsequent sections of this report.

TASK 4 — HARDWARE ANALYSIS

Once the theory of operation of the candidate concepts has been described, the next task is to determine the hardware required to implement the candidate concept. Hardware descriptions are also included in subsequent chapters, along with their corresponding component descriptions.

TASK 5 — COST ANALYSIS

When a candidate concept has been fully described and the hardware required to implement it fully specified, the cost of the concept can be determined. Many system concepts were quite complex, causing them to be very expensive. Others fell short of meeting important technical requirements. Costs for those concepts were therefore, evaluated only approximately. Cost information for the recommended system is presented in Section 7.

TASK 6 — COMPARISON STUDY

This task was to compare candidate concepts and to perform a trade-off analysis among them. Factors considered in the comparison are described later in this section. For comparison purposes, concepts were grouped into sensors, communications, signals, and control circuits. The comparisons are described in the later parts of the corresponding sections of this report. These comparisons result in a recommended RHGC warning system.

TASK 7 — DEVELOPMENT AND TEST PLAN

A final consideration in this study was to determine how the recommended RHGC system can be developed and tested. The purpose of this task was to develop a plan

for development and testing of the recommended innovative system. This plan was divided into two phases and will take approximately four years. Aspects considered included collection of both technical and human factors data, safety, costs, and other problems.

TASK 8 — MODEL CONSTRUCTION

The final task in this study was the construction of a model illustrating the operations of the innovative RHGC warning system concept.

In addition to these tasks, the study program included five monthly reports, an interim presentation, a final presentation, and this final report.

1.3 PRESENT SYSTEM AND ITS PROBLEMS

Present or conventional RHGC warning systems have remained essentially unchanged in the last thirty years or more. Most rely on a track continuity system for detection of the trains presence. A train moving into an insulated block of tracks shorts one rail to the other, causing a relay to de-energize, which activates the signal. The signal is usually based on horizontally alternating red lights which are beamed down the roadway by special lenses to increase their brightness. Bells are generally included, and gates and/or additional red lights are sometimes used.

Conventional RHGC warning systems have several disadvantages. The use of track circuits for train detection necessitates proper bonding and insulation of rail sections. This requires constant maintenance and invites failure. A broken rail bond can make a train undetectable, although the fail-safe nature of the system causes the motorist warnings to activate. Ballast variations due to weather can cause a false warning. A train is detected when it is in a particular section of track, hence the motorist warning time varies with train speed. In the simpler realizations, no automatic provision is made for trains which stop or reverse their direction.

As a consequence, conventional signals do not always have credibility with motorists. A driver may stop or reduce speed in response to the red lights, but if a train is not immediately visible, he will proceed. If he can see the train he will often try to guess its speed and will proceed if he thinks he can cross the track ahead of the train. Motorists who have stopped for a train often proceed across the crossing after the passing of the last car, even though the red lights remain on. Generally the motorist is successful in these games. However, the consequences of a mistake may well be fatal.

In addition to the limited credibility, conventional signals are not highly conspicuous in many cases. A quick examination of a typical garish neon landscape along a typical busy road will show that the crossing signal is often the least conspicuous object there.

1.4 DESIRED FEATURES OF NEW SYSTEM

The first step in designing a new RHGC warning system is to decide what it should be expected to do. This list of features provides a means of evaluating and comparing various concepts. A list and brief description of each of these features follow.

1.4.1 Constant Warning Time

Constant warning time means that the motorist warning signal is activated a fixed amount of time before the arrival of the train at the crossing. Generally this warning time is between 20 and 30 seconds; it varies with vehicle speed and the number of tracks. Constant warning time allows the motorist to clear the crossing safely while eliminating needless waiting for slow trains or attempting to guess the train's speed. Constant warning time will be an important factor in establishing credibility.

1.4.2 Reliability

The crossing signal must also be dependable in order to be credible. When there is a train, a "stop for train" display must be activated, and when there is no train, the "stop for train" display must not be activated. If the display is incorrectly activated, credibility will be reduced.

1.4.3 Failsafe, Self-Check, and Malfunction Warning

Any system, no matter how well designed or how redundant will fail occasionally. Provision for this must be made in the design of the system. This is typically called "failsafe" and in a conventional RHGC system amounts to activating the "stop for train" warning if any sign of a malfunction is detected. In the innovative systems considered here, "failsafe" may have many more possibilities. There may be two levels of malfunction; one which completely disables the system and one which only eliminates redundancy. Self-check circuits may be used to monitor for proper operation. A separate "caution, signal malfunction" warning may be displayed to the motorist to alert him to the danger. This should also add to credibility. A warning may also be given to the engineer so that he can report the failure to aid in its rapid repair and to give him advanced warning to slow down for the crossing.

1.4.4 Ease of Maintenance

When a failure occurs, it is essential that it be repaired rapidly. To expedite this, the system should be designed so that it can be serviced easily and quickly. It is highly desirable that this work be done at the site, and that detailed circuit knowledge not be required for the servicing. Ease of maintenance will contribute to long term reduced costs of ownership, and rapid maintenance will contribute to credibility.

1.4.5 Weather and Vandal Resistance

The new RHGC system must resist degradation due to weather and vandals. This can be done by both proper packaging and hidden installations where possible. While catastrophic storms or dedicated vandals can damage any system, the system should not deviate from normal operations due to normal weather and vandal activity.

1.4.6 Flexibility

A very important feature of any new RHGC system is flexibility. Some systems may work very well and be very inexpensive when used in one particular crossing situation.

However, if they can not be adapted to cover most or all crossing situations, they will be unsuccessful in solving the RHGC problem.

1.4.7 Economy

A new RHGC system should, ideally, cost no more, or maybe even less, than present systems. The cost of installation and ownership is one factor which limits the number of active RHGC warning systems which can be installed. However, a new system which costs more than the present system is not necessarily undesirable if it provides sufficient advantages which are unavailable in present systems.

1.4.8 No Connection to Track

It is desirable that the new train detection method not be connected to the rails or installed in the roadbed. Connection to the rails and use of the rails for train detection necessitates insulation of the rails and maintenance of the rails beyond that required for other operations. Installation outside of the roadbed would allow maintenance of the facility to proceed without regard to the RHGC system.

1.5 SYSTEM CONCEPTS SUMMARY

Concepts for an innovative RHGC warning system are conveniently grouped into the areas of sensors, communications, control, signals, and remote power. The sensor subsystem includes the apparatus which detects the trains presence. The communications subsystem relays messages between physically separated subsystems. The control subsystem interprets sensor data, derives constant warning time, activates the signals accordingly, and performs self-check operations. The signal subsystem displays appropriate warnings to the motorist and engineer. The remote power subsystem may be used where necessary or convenient to power sensors or the whole system. While the subsystems are somewhat interrelated, it will be convenient to discuss them

separately. Figure 1-1 illustrates a hypothetical crossing where a new RHGC warning system might be installed.

1.5.1 Sensor Subsystem

Train sensors are conveniently divided into two groups, continuous and discrete. Continuous sensing techniques monitor the train's movement on a continuous basis, while discrete sensors detect the train at a finite number of specific locations.

1.5.2 Continuous Sensing Methods

An attractive candidate for continuous train detection was the track impedance method. This technique uses the track as a transmission line, shorted at one end by the train. Movement of the train causes the input impedance to vary, allowing measurement of both position and velocity. (Variations of the basic impedance include time domain reflectometry.) Such systems are in relatively widespread use. However, since they utilize the track as a conductor, their operation can be impaired by poor joints, poor insulation, and ballast variations, and they are not inexpensive.

Another continuous sensing method is horizontal doppler radar. A radar transceiver is mounted on the crossing signal and aimed down the track. Echos indicate train presence, and doppler shift indicates velocity. Unfortunately, horizontal doppler radar cannot see around curves and is therefore inflexible. Also, it cannot separate trains on adjacent tracks, and may therefore fail to detect an approaching train beside a receding train.

Acoustic sensing would detect a train by listening for the "signature" or set of sounds peculiar to a train. Acoustic sensors might be coupled to the rails, ground, or air. Unfortunately, all such techniques would require very elaborate signal processing, making them very expensive.

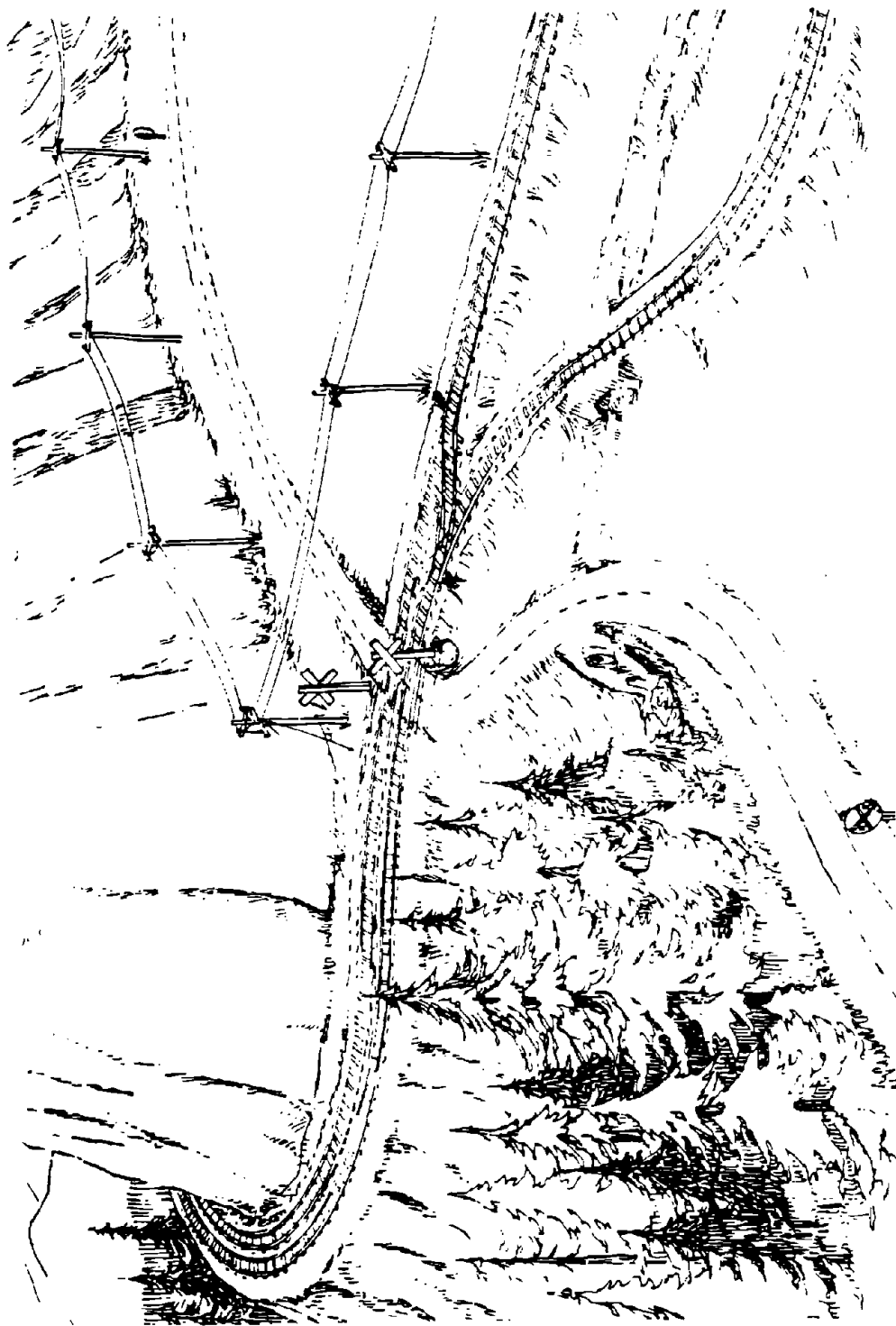


FIGURE 1-1. COMPOSITE PROBLEM RHGC

Train mounted transmitters or transponders could be used in conjunction with receivers or transceivers at the crossing. While such techniques might work, they would require the installation of transponders on all rolling stock, since the RHGC system must respond whether a locomotive or box car approaches first. Such an installation would be very expensive.

Some consideration was also given to video motion sensing techniques. Such techniques would be subject to light level problems, would require complex signal processing, and would be very expensive.

1.5.3 Discrete Sensing Methods

Present track circuit techniques can be thought of as a form of discrete sensing, since they detect the train as it crosses a particular point on the track and activate the signals accordingly. (However, detection is continuous after that point is passed.) Audio frequency overlay circuits also fall into this category. A possible variation of the audio frequency overlay circuit is the multifrequency track circuit. This concept would insulate the track at a number of points and use trap circuits to pass signals of different frequencies around the point. The train could then be detected at several places, and its velocity computed, allowing constant warning time. This technique is, however, subject to interference problems, and has all the previously discussed disadvantages of track dependent sensing.

Mechanical-electrical transducers or pressure sensitive devices are one form of discrete train detector. Three general types of mechanical sensors were considered. The first was a pressure switch which closes or opens only when a large force is applied. This type of sensor would be unreliable.

A second type of mechanical sensor is the strain gage, and a third type uses a piezoelectric ceramic material. The former produces a change in resistance in response to pressure, while the latter produces a voltage. Either of these devices would be reliable (by itself). Installation could be accomplished in a variety of ways. Devices would either sense weight on the rails or would sense bending of the rails due to the

train. Unfortunately, all mechanical devices suffer from a common problem: they all require exact installation/alignment of the roadbed. If the roadbed settles or washes after installation, the force applied to the sensor would change, causing incorrect operation.

Another group of sensors utilize magnetic field variations caused by the train. Four magnetic sensors were considered. These were the induction loop, the magnetometer, magnetoresistor, and the Hall effect device. Induction loops are a loop of wire in between the rails. A train overhead changes the loops inductance, and measurement of this change is used to detect the train. The magnetometer is also a loop, but is used differently. The movement of the train causes a changing magnetic field, which in turn generates a voltage in the loop. The train is detected by measuring this induced voltage.

Magnetoresistors produce a change in their resistance in response to a nonzero magnetic field. Hall effect devices produce a voltage in response to a magnetic field. Either device could be used in two ways. One way uses a permanent magnet connected between the rails as a source of magnetic field. The axles of the train increase the magnetic flux. This method requires attachment to the rails and develops problems when two such devices are used in close proximity. The preferred technique uses the natural magnetic fields which are concentrated by the presence of the train.

Other discrete sensing techniques include beam interruption and thermal sensing. Beam interruption techniques utilize the train to block a radar, sonar, or optical signal beamed across the track. They are attractive because they can sometimes be installed outside of railroad property, but only when there is a single track situation. In addition, they are subject to vandalism. Thermal sensing would operate in a manner similar to hot box detectors. However, setting the detection threshold low enough for ordinary bearings would allow a variety of interference from natural thermal sources.

1.5.4 Selection and Use of Sensor

Discrete sensors offer more flexibility than continuous sensors, and in addition, they can be used redundantly. Magnetic sensors are the most practical. They do not require a critical installation or adjustment, can be made inconspicuous by burying them in the roadbed or mounting them in a special tie that will not interfere with normal railroad operation in any way. The induction loop detector and Hall effect detector are the preferred magnetic detectors. Both were field tested on an actual railroad. The Hall device proved to be much more sensitive and is therefore recommended.

It will be expedient to utilize the discrete magnetic sensors in pairs. One crossing will have one pair straddling the roadway and two or three pairs on either side of the crossing. The two sensors in the pair are separated by several meters, while the various pairs are separated by hundreds of meters. Each pair measures not only train position, but train velocity as well. Acceleration can be derived from two velocity measurements. In this manner, constant warning time can be derived for a great variety of train movements, and the system can remain functional in spite of some sensor failures.

1.6 COMMUNICATIONS SUBSYSTEM

A system of discrete sensors requires a means of transferring information to the control circuitry. Control of remotely located warning signals will also require information transfer. These functions are handled by the communications subsystem. Communication techniques applicable to the RHGC warning system fall into three categories: dedicated wire, carrier (shared wire), and wireless. Each of these is applicable in different situations, and an RHGC system may use all three, as fits a particular situation.

A dedicated wire system based on buried cable is used in conventional RHGC systems. The only objection to universal use of buried cable in the new RHGC system is its high cost. However, its use is warranted for connecting units which are in close proximity.

A carrier communications system for the RHGC warning system would use existing power or signal lines to transfer information. The data modulates a low frequency carrier, which travels along the lines, and is received and decoded. No FCC license is required, since the signals are confined to the line. Since power and signal lines are present along most railroads with moderate to heavy traffic, the carrier system will generally be used for communications with units which are not in close proximity.

In some situations, sensors will be located where there are neither power lines or code lines adjacent to the tracks. In these cases it will be convenient to use a local power source and wireless communications. Wireless communications from ultralow frequency to light were considered for this application. Low frequencies required too much power or large antennas. Medium and high frequencies are subject to skip problems. Microwave and optical communications require critical antenna alignment. The very high frequency range was found to be ideally suited for this application in terms of power, bandwidth, antenna simplicity, and penetration of obstacles.

Three ways of obtaining failsafe operation of the communication system were considered. The first way requires all transmitters to operate constantly. This wastes both power and channel space. The second technique would interrogate each sensor in turn and ask for a status report. The third technique has every sensor report its status periodically. This technique both conserves power and channel, but uses a minimum amount of equipment, since sensors do not require receivers.

1.7 CONTROL SUBSYSTEM

Control functions could be accomplished by either analog or digital circuits which are either dedicated or programmable. Dedicated circuits are designed to work only in a specified crossing situation or situations. Programmable circuits are adaptable to a variety of situations by simple changes in switches, wiring, or components.

Flexibility requirements of the new RHGC warning system demand a programmable control system. The computation of constant warning time under a variety of train movement patterns is best accomplished by a microprocessor. Instructions are supplied from a programmable read-only memory (PROM). A control system is adapted to a particular crossing situation by insertions of an appropriately programmed PROM. Failsafe operation can be accomplished by the execution of self-check programs and the addition of special monitor circuitry.

1.8 SIGNAL SUBSYSTEM

Three separate signals were considered and are recommended for use in the new RHGC system. These are the motorist crossing warning, the motorist advance warning, and the engineer warning signal.

The motorist crossing warning signal should have three functions. First, it should alert the motorist that there is a crossing. Secondly, it should warn him to "stop for train". Thirdly, it should tell him "caution, signal malfunctions" when there is a malfunction. Several types of displays were considered, including flashing arrows, traffic lights, flashing crossbucks, lights in the crossbuck, a white strobe light on top of the conventional signal, and red strobe lights. The recommended signal type uses horizontal alternating red strobe lights as the "stop for train" display. This type of display was selected for its conspicuity, clarity, and low power consumption. The malfunction warning is conveyed by vertical alternating amber lamps. A high visibility crossbuck carries the crossing ahead message.

The motorist advance warning signal is an option which can be used in poor visibility situations. Several advance warning signal types were considered. It is recommended that the active advance warning sign be similar to the passive advance warning signs with alternating amber lights added. These lights are activated along with the "stop for train" lights at the crossing.

The engineer warning signal alerts the engineer to the condition of the crossing ahead. A constant amber "X" indicates proper activation of the RHGC warning system. A flashing "X" indicates a malfunction, allowing the engineer to report the malfunction and to sound his horn or whistle.

1.9 REMOTE POWER SUBSYSTEM

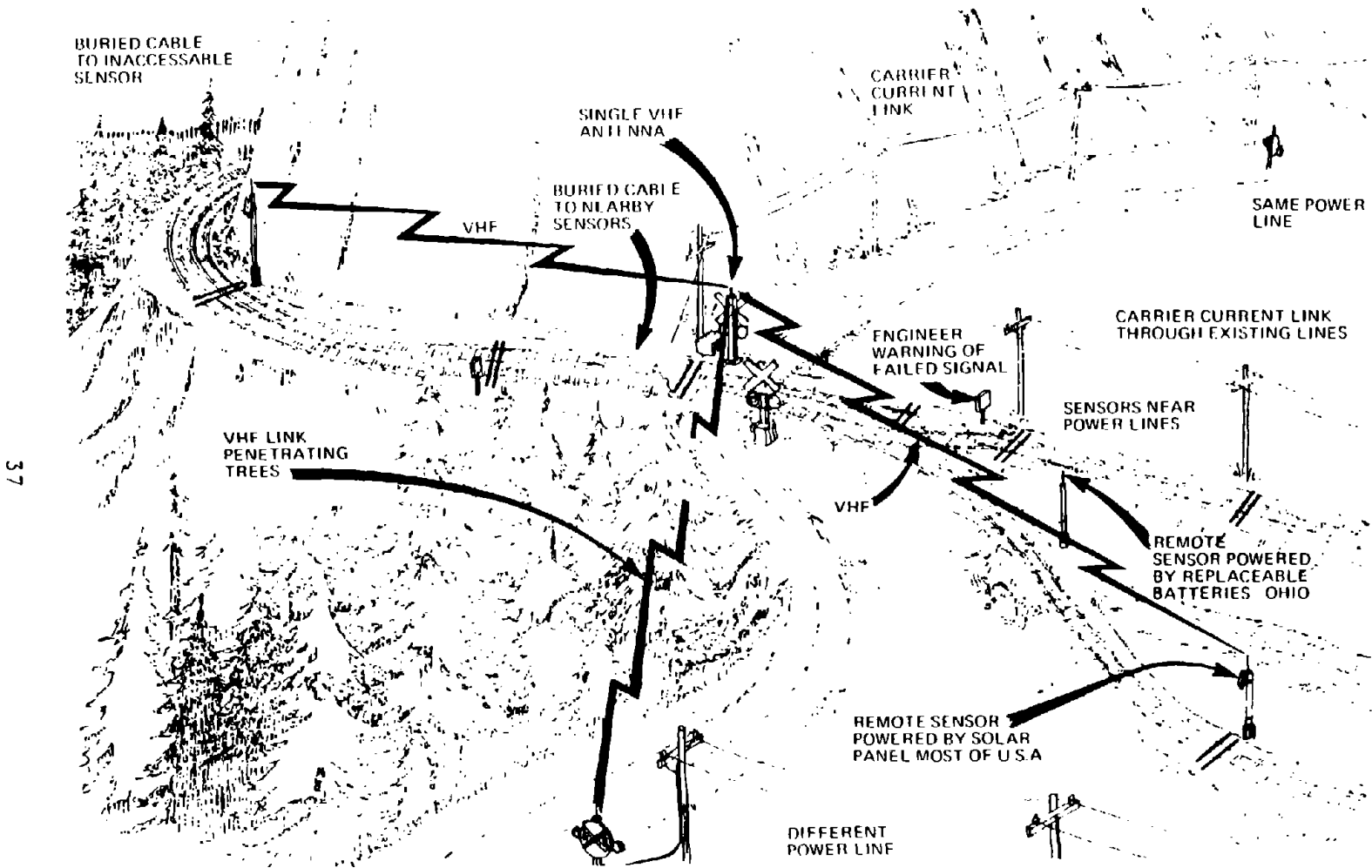
In some isolated installations, it will be desirable or even necessary to power equipment locally. Replaceable primary batteries, solar power, and wind power were considered as remote power sources. Batteries and solar power are adequate for powering the sensors. The use of solar panels used to charge batteries is preferred because of the greatly reduced maintenance cost. Windmill generators can produce enough power for the whole system. In this application, they would be used to maintain a charge in the standby batteries.

1.10 RECOMMENDED SYSTEM DESCRIPTION

The recommended RHGC warning system consists of four basic subsystems and an optional fifth subsystem. (See Figure 1-2.)

The sensor subsystem detects the train's presence and measures its velocity. Hall effect magnetic sensors are used in pairs. Two or three sensor pairs are installed on each side of the roadway, and one pair straddles the roadway.

The communications subsystem uses buried cable, carrier, or VHF communications to transfer information. Buried cable is used only for short distances. Carrier communications is used whenever existing power or signal lines run along the communications path, which should include most of the crossing situations. VHF is used for communications from locally powered sensors or to control advance warning signals operated from other power systems.



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FIGURE 1-2. SYSTEM USING DISCRETE SENSORS AND COMPOSITE COMMUNICATION LINKS

The control subsystem uses a microprocessor to compute constant warning time from sensor inputs. Instructions come from a programmable read-only memory, making the system very flexible. The microprocessor can also execute self-check programs to guarantee detection of improper operation. Special monitor circuitry also checks for improper operations.

The signal subsystem consists of three separate signals. The motorist crossing warning signal uses a high visibility crossbuck, alternating horizontal red strobe lights as a "stop for train" warning, and vertical alternating amber lights as a "caution, signal malfunction" display. The motorist active advance warning signal adds alternating amber lights to the passive advance warning signal and is used where warranted. The engineer warning signal indicates a properly activated RHGC warning system by a constant amber "X" and a malfunctioning system by a flashing amber "X". This allows for rapid reporting of malfunctions.

The optional fifth subsystem is used for remote power. Solar panels can be used to power sensors, while windmill generators can power the whole system. Both the solar and wind generators are used to maintain the charge of a battery.

2. SENSORS

2.1 PURPOSE

The first and probably the most important function of an automatic RHGC system is detection of the train. The sensing technique used by this innovative system must do more than simply detect the presence of the train in a particular block of track. It must provide adequate information to control the signals with instant warning time for a great variety of train movement patterns.

2.2 POSSIBLE SYSTEM CONCEPTS

This study considered a great variety of train sensing techniques. Some of these techniques are used in commercially available equipment while others are quite futuristic. Most, however, are new applications of existing technology.

Sensing techniques are divided into two general classes; continuous and discrete. A continuous sensing technique has the capability of detecting the trains movement on a continuous basis. A discrete sensing technique detects the train at one or more specific locations. Distance measuring radar and rail impedance are examples of continuous techniques, while beam interruption and pressure sensing are examples of discrete sensing techniques.

2.2.1 Continuous Sensing Techniques

Continuous train sensing techniques are highly attractive because the location and velocity of the train are available on a continuous basis. There are no "dead spots" where the train cannot be detected, and there is no way the train can confuse the control circuitry by irregular movement patterns.

Continuous sensing techniques include rail impedance, horizontal radar, acoustics, television, and train mounted transponders. Of these, the first two are practical and can be used in specific situations. Unfortunately, both have adaptability problems and cannot be easily applied to a wide variety of crossing situations.

2.2.1.1 Transmission Line Techniques

An interesting approach to continuous detection and monitoring of the train is to use the rails as the conductors in a transmission line. An alternating current signal is applied to the rails near the crossing and travels away from the crossing. The axles of the train create a short circuit at the location of the train, reflecting the wave back toward the crossing. Measurement of this reflected wave, typically through impedance measurement, provides information about the distance of the train from the crossing. This method appeared highly attractive during the early stages of the study because it allowed train detection on a continuous basis. However, it is subject to a variety of drawbacks, limiting its usefulness and increasing its complexity.

2.2.1.2 Basic Track Impedance Technique

An example of the application of transmission line techniques to train detection is the track impedance technique. A variety of systems based upon this principle are in widespread use.

Selection of the frequency at which impedance is to be measured is critical to proper operation of the track impedance technique. Consider the input impedance of an ideal transmission line, shorted at distance D and open at the point of measurement. As D is increased from zero to a quarter wavelength, the impedance is inductive and increases from zero to infinity.

As D is then further increased from a quarter wavelength to three-quarters of a wavelength, the impedance becomes first capacitive and infinitely high, then decreases

toward zero, and then becomes inductive and increases toward infinity. This behavior suggests that the frequency used should be low enough that the train is within a quarter wavelength (or less) when it is first detected. This eliminates any ambiguity in the train position. Detection range is limited by connecting an ac short circuit between the rails at the maximum desired detection distance.

Using a frequency low enough that the maximum detection range is less than a quarter wavelength has another advantage: If the maximum distance is less than approximately one-tenth wavelength, the impedance is approximately linearly proportional to the distance. This allows considerable simplifications in the associated computation circuitry. If the maximum detection distance is to be, for example, 1 kilometer, then the maximum frequency should be 30 kHz, which has a wavelength of 10 km.

Figure 2-1 illustrates the installation of a track impedance system. An ac shunt is connected between the rails at the maximum detection distance D . This not only makes trains undetectable beyond distance D (thus preventing confusion of the measuring equipment), but also limits the interference of one system with another. The rails must also be insulated at the crossing if directional information is desired. As the train moves into the detection range ($D' \leq D$), the short circuit due to the axles moves closer to the crossing, decreasing the impedance measured at the crossing. The train's position is proportional to the impedance, and its velocity is proportional to the rate of change in the impedance. Constant warning time can be derived from these two parameters.

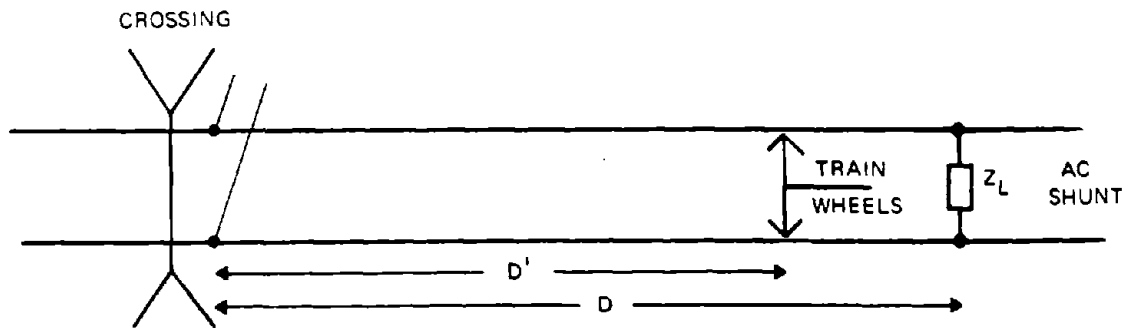


FIGURE 2-1. TRANSMISSION LINE MODEL OF TRACK APPROACH

A railroad track can be modeled as a lossy parallel wire transmission line. The series resistance, inductance, and shunt capacitance are due to the rails. The shunt resistance is the result of the track ballast. The equivalent circuit and typical values are shown in Figure 2-2.

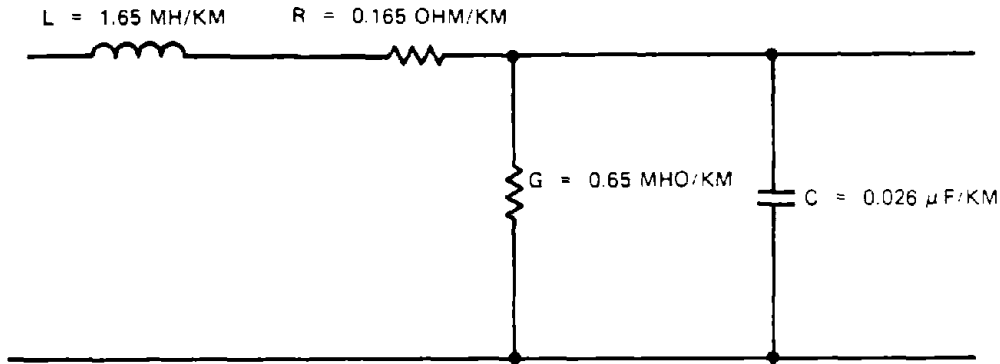


FIGURE 2-2. TRACK EQUIVALENT CIRCUIT

Using transmission line theory, the characteristic impedance is:

$$Z_o = R_o + jX_o = \sqrt{\frac{R - j\omega L}{G + j\omega C}}$$

For typical operating frequencies (above 100 Hz), the series resistance and shunt capacitance may be neglected, resulting in:

$$Z_o \approx \sqrt{\frac{j\omega L}{G}}$$

The general equation for input impedance of a transmission line is given by:

$$Z_{in} = Z_o \frac{Z_L \cosh \gamma d + jZ_o \sinh \gamma d}{Z_o \cosh \gamma d + jZ_L \sinh \gamma d}$$

where $\gamma = \alpha + j\beta = \sqrt{(R + j\omega L)(G + j\omega C)}$

Re-arranging the expression for γ and using the binomial expansion yields a close approximation.

$$\gamma = \alpha + j\beta = \frac{R}{2\sqrt{L/C}} + \frac{G\sqrt{L/C}}{2} + j\omega\sqrt{LC}$$

The rails are driven by a constant current source resulting in a voltage ($E = jZ_{in}$) being developed across the track (see Figure 2-3). The voltage is filtered and detected, producing a dc voltage (E_D) which is proportional to the distance from the crossing to the

train. Differentiating the distance voltage produces a voltage ($E_v = \frac{dE_d}{dt}$) which is proportional to the velocity of the train. The polarity of the velocity voltage determines the train's direction. A negative voltage indicates a decrease in impedance and an approaching train; a positive voltage indicates a train is leaving the crossing. From the velocity and distance voltages a microprocessor computes the arrival time of the train at the crossing. Since the computation of arrival time is a continuous process, when the arrival time reaches a predetermined value, the warning signals are activated. This results in a constant warning time grade crossing warning system which is independent of velocity.

A major challenge with this system is that the input impedance does not remain constant for a given distance but is dependent upon ballast resistance. The track ballast is subject to extreme environmental conditions which causes changes in ballast resistance. The result is a different input impedance and a corresponding computed distance for a given distance depending upon the environmental effect on the ballast. It is evident from Figure 2-4 that input variations are severe enough to require ballast compensation for accurate train detection. Compensation for ballast variations adds to the complexity and reduces the accuracy of the basic system. In some cases, low ballast impedance can even make the train invisible beyond a short distance, and the system must detect such situations so that warnings can be activated.

Another problem lies in the area of reliability. The basic system is not inherently failsafe. Failsafe properties are achieved by periodic self-check tests. When an error in operation is detected, the appropriate malfunction warning signals are activated. The addition of self-check circuitry further adds to the complexity of the system.

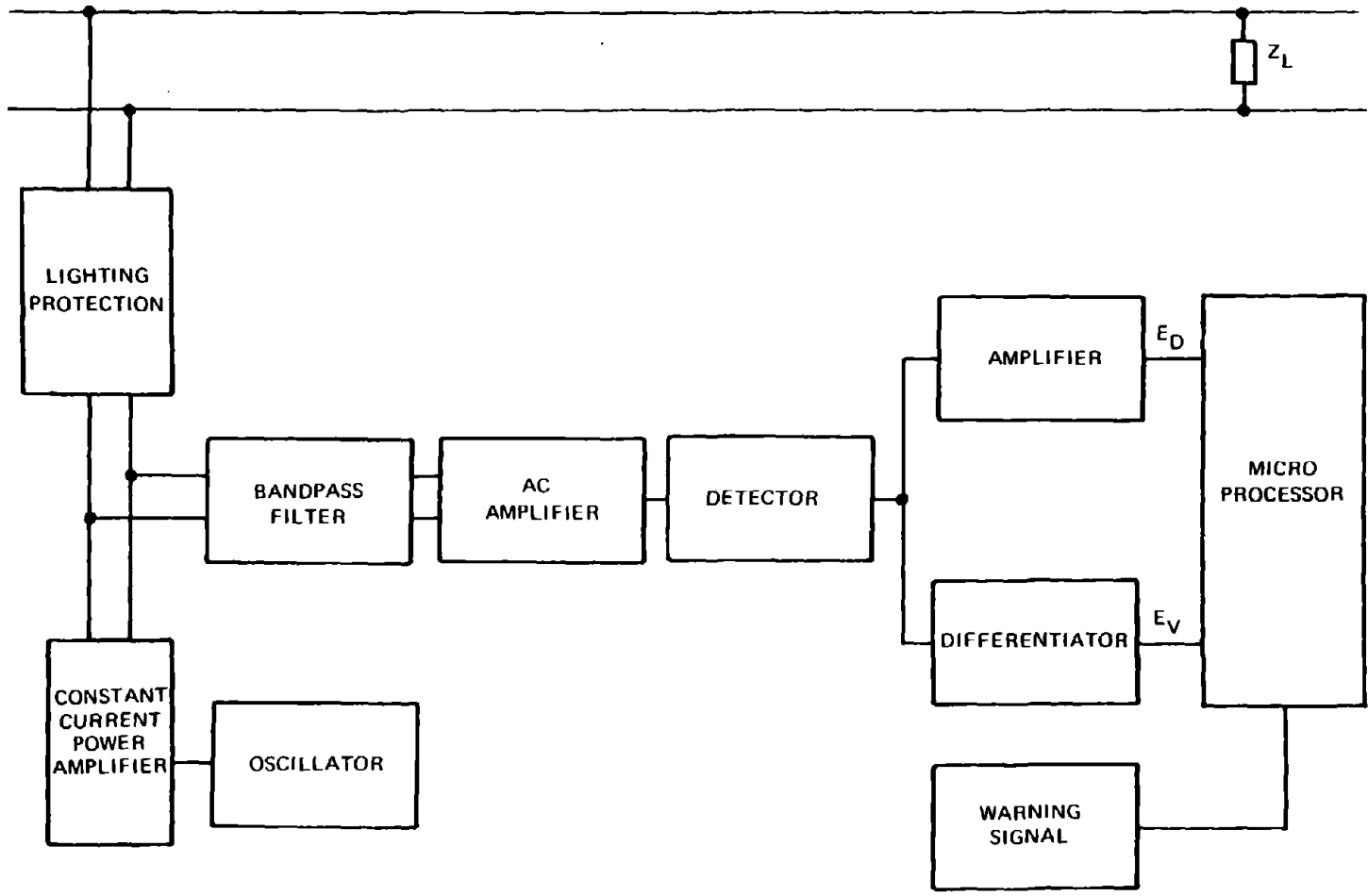


FIGURE 2-3. SIMPLIFIED RAIL IMPEDANCE TRAIN DETECTION SYSTEM

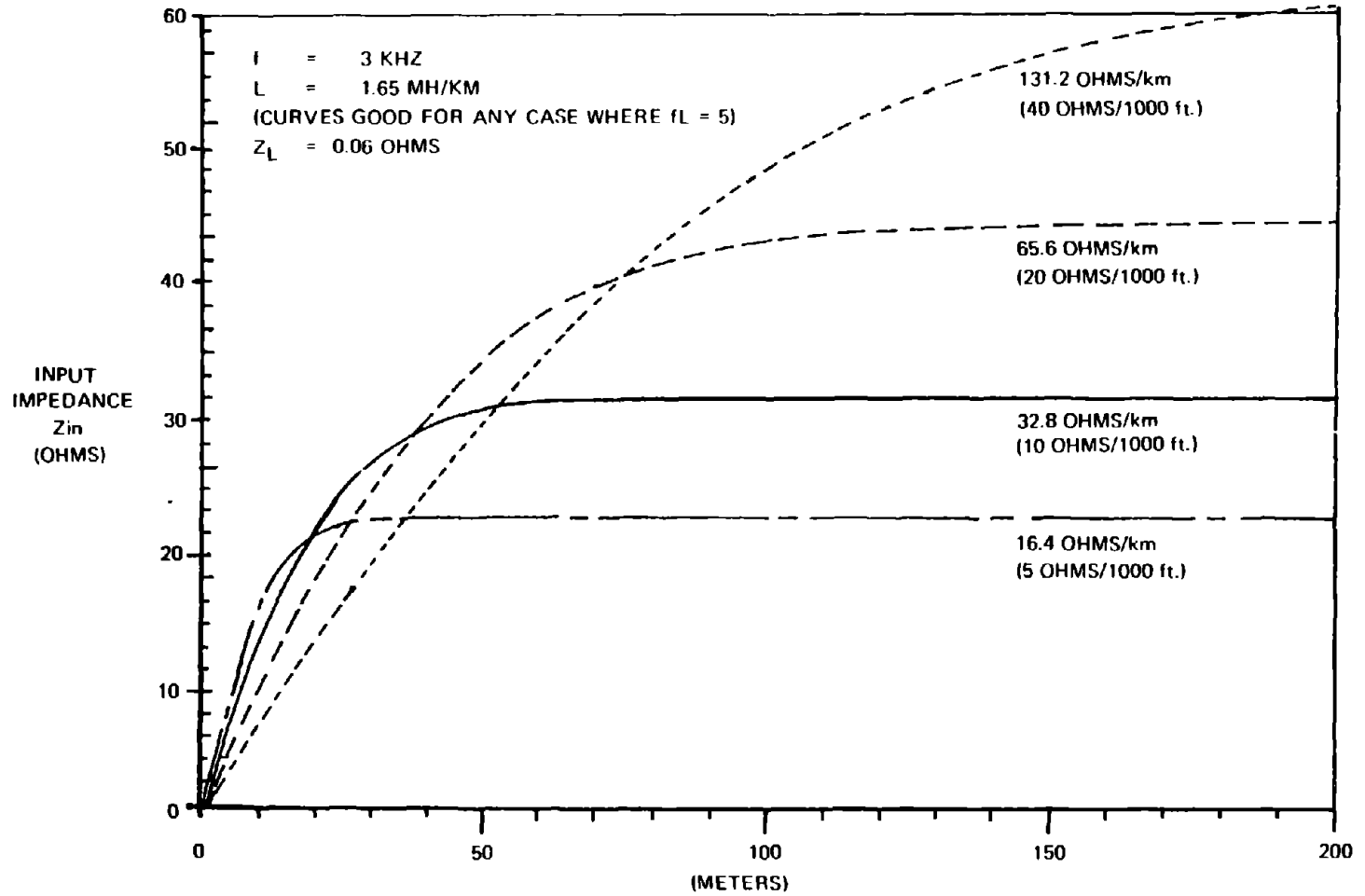


FIGURE 2-4. INPUT IMPEDANCE VS DISTANCE TO TRAIN FOR VARIOUS BALLAST RESISTANCES

To summarize the advantages of the track impedance method compared to other grade crossing warning systems are as follows:

The impedance method provides continuous update of arrival time. If the train stops or backs out of the protected area, the warning signals are deactivated.

Track impedance systems are compatible with other dc and audio warning systems. The only requirement is that shunts and insulated bypass elements are frequency selective.

Discrete sensors are not required. Therefore, communications links and sensor power sources are not needed.

However, the rail impedance method has some disadvantages, including:

The impedance method is very sensitive to ballast conditions. Environmental effects can cause large variations in the ballast resistance, and the system can be inoperative (in a safe failure mode) under some ballast conditions.

This system requires all sidings, switches, and crossings (other tracks) to be insulated from the measured track. Special circuitry is required to adapt this system to tracks with switches.

In addition, the presence of conducting material between or near the rails (even if not directly connected) will cause changes in the characteristic impedance. This will be true of switches, crossings, and metal bridge structures and reinforcements. This change in characteristic impedance will result in a reflected wave and hence a change in impedance at the measuring point. The impedance rate of change with train distance will then have different rates for trains on either side of the conductor, confusing the measurement equipment.

Reliable operation depends on low impedance connections from measurement equipment to the rails, from one rail section to another, and from rails to wheels.

Operation can be degraded by rust, dirt, oil, or anything else on the rails.

2.2.1.3 Other Transmission Line Techniques

Track impedance is not the only concept for train detection which uses the track as a transmission line. Alternate concepts would employ time domain reflectometry (TDR) to locate the train. A pulse or burst of carrier is injected into the track near the crossing and travels down the track. Upon encountering a short caused by the train axle, the pulse or carrier burst is reflected back towards the crossing. The time of arrival of the return pulse is proportional to the distance of the train.

The duration of the pulse or carrier burst in such a TDR system is limited by minimum detection distance desired. Suppose, for example, a train at a distance of 50 meters is to be distinguishable from one at a distance of 100 meters. The minimum length path from crossing to train and back is 100 meters. The pulse or burst duration must then not exceed $\approx 1/3$ microsecond or the transmission will mask reception. If a carrier burst is used, at least one whole cycle must be transmitted, necessitating a minimum carrier frequency of 3 MHz. One immediately obvious drawback of the use of either the short pulses or the high frequency carrier is radiation. The track is a long and imperfect transmission line at these frequencies, and radiated signals can be expected to interfere with communications services.

These techniques will suffer from unwanted reflections from track discontinuities, poor joints, switches, and any other deviations from a perfect transmission line. Figure 2-5 illustrates these problems. In (A), an ideal echo is received from a train. In (B), a slightly bad rail bond causes a small reflection. In (C), a bad rail bond causes a large reflection and reduces the echo due to the train. In (D), some signal travels to the adjacent track through a switch, producing echos from both switches and another train.

If these false echos were the only ones, the system could be made to work by using a microprocessor to catalog all echos and ignore those which did not move. However, in Figure 2-5(E), the reader may observe multiple echos which are due to reflections of reflections. Some of these will move as the train moves, making detection of the correct echo very difficult.

In summary, time domain reflectometry techniques (TDR), whether using pulse or carrier bursts are:

- Subject to all disadvantages of track impedance techniques, described previously.

- Will cause radio frequency interference.

- Will require complex processing to separate the true train echo from others, due to track irregularities.

2.2.1.4 Horizontal Doppler Radar

A horizontal Doppler radar can be used for train detection by aiming it down the track. A typical installation uses two radar units. These are mounted on the crossing signals, and they require no connection with the track or roadbed.

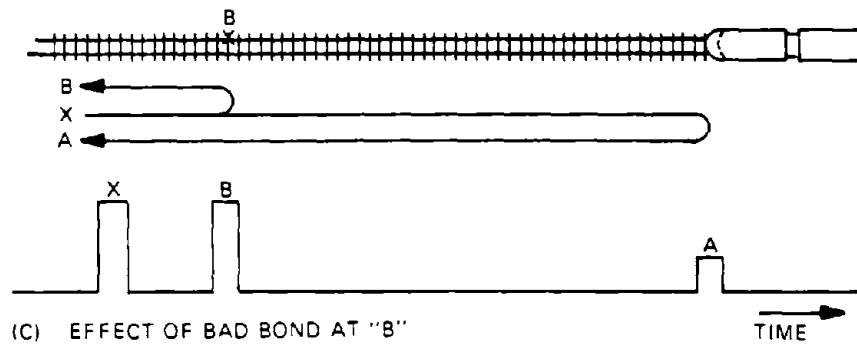
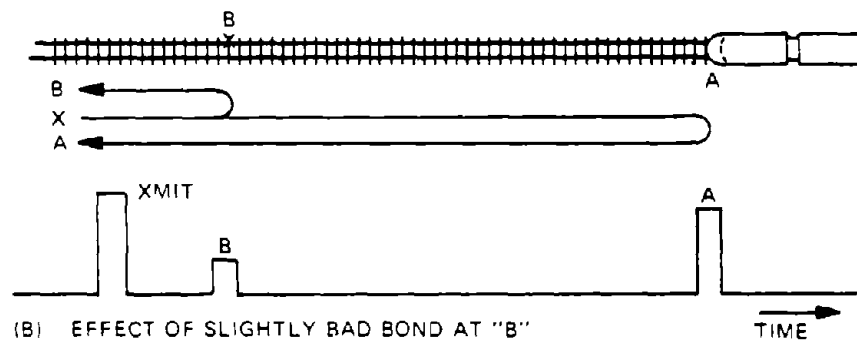
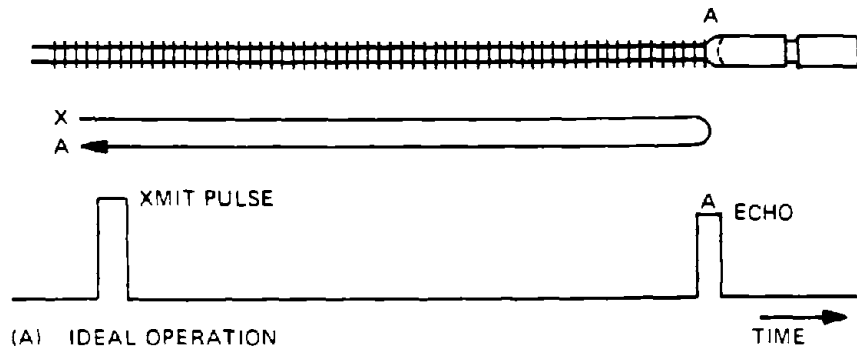


FIGURE 2-5. TIME DOMAIN REFLECTOMETRY (Sheet 1 of 2)

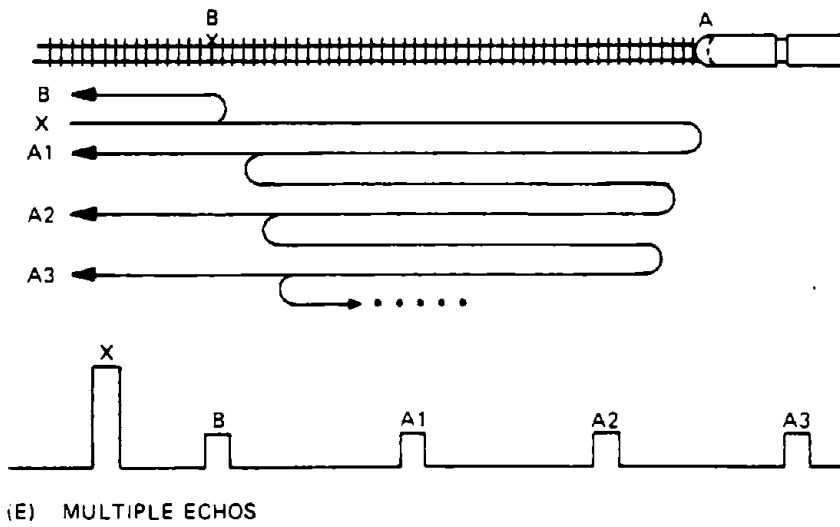
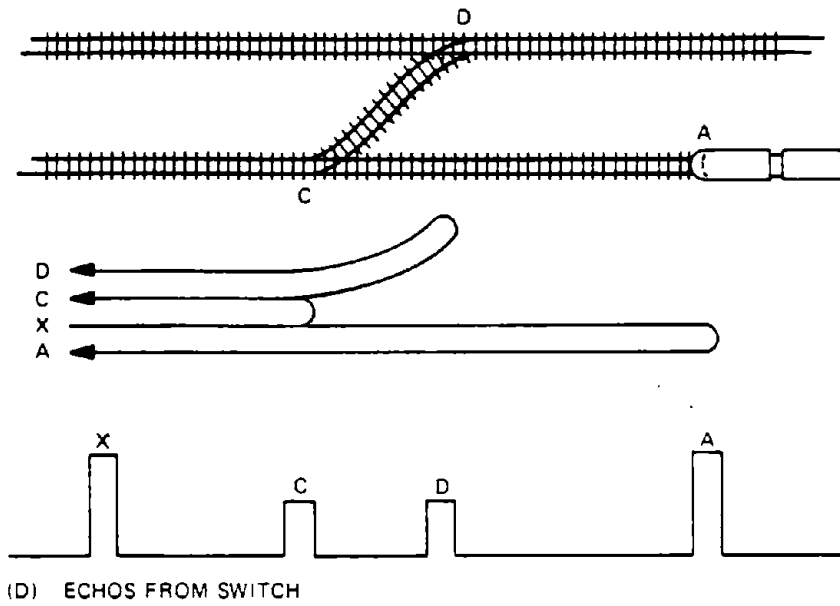


FIGURE 2-5. TIME DOMAIN REFLECTOMETRY (Sheet 2 of 2)

The basic principle of Doppler radar is that the frequency of the signals reflected from a moving object differs from the frequency of the transmitted signal. An approaching train produces an increase in frequency, while a receding train produces a decrease in frequency. This change in frequency is directly proportional to the train's velocity, allowing easy computation of train movement.

One problem in the radar system is determining exactly what the distance to the train is. (This is essential to providing constant warning time.) To measure distance requires measuring the time required for a signal to travel from the transmitter to the train and back to the receiver. This is a much more complex process than simply measuring a beat note frequency difference in Doppler radar.

More serious problems arise in applying the radar sensor to curved and multitrack situations. A train on a curved track may be invisible until it is close to the crossing. In multitrack situations, the sensor will be unable to distinguish trains adjacent to each other. This makes it possible for a slow or stationary train to mask the echo from a rapidly approaching train on the other track. While the radar sensor is certainly a good motion sensing device in certain situations, its applicability to grade crossings is definitely very limited.

2.2.1.5 Acoustic Sensors (Sonar)

Acoustical train sensing could detect trains by the characteristic sound "signatures" produced. A microphone or equivalent would be installed on a permanent post, buried in the roadbed, or attached to a rail. The signals produced and transmitted through the air, ground, or rail will be processed through a minicomputer to identify the train and calculate its position and velocity. Extraneous noises, such as from automobiles, road crews, airplanes, or poor track junctures could be distinguished from the train signature by using appropriate electronics.

Acoustic sensors have been used in phonograph pickups, fetal heart monitors, hydroplanes, vibration sensors, and strain sensing devices¹. A method of transmitting an

¹ Charles Edmiston, "Piezoelectric Ceramic Transducers," Electronic Design (No. 18, September, 1974), pp. 78 - 82.

acoustical pattern through the rails has been tested by the British. Notches cut into the rail caused the train wheel to transmit a sound pattern. By determining the time interval to receipt of the pattern at the crossing, the velocity could be calculated.

Placing sensors away from the rails is one of the objectives of a new system. However, acoustical pattern recognition in this case involves sophisticated technology and would therefore be expensive. They will require constant updating due to changing rail and ballast conditions and background noise, making this sensor not worthy of further consideration.

2.2.1.6 Train Mounted Transceiver

A train mounted device could be incorporated in the train presence detection system. Transmitters on the front and back cars of the train would generate a low power directional signal. A number of discrete receivers must be placed along the track. A control system will monitor the output of the receivers and compute train presence, velocity, and turn on the grade crossing displays when necessary.

Another technique would be to equip a train with one or more transponders. The train mounted transponder would retransmit the signal of the track mounted transmitter as the train passes by, thus communicating to the control circuitry that it is approaching the crossing. Several transponder arrangements may be used to transmit train presence at two or more locations. Velocity can therefore be computed by a trackside mounted microprocessor, or could be part of the transmitted signal if connected to the train speedometer.

Many incapacitating problems with these train mounted transmitter-transponder systems exist. It will be expensive to install and maintain a train mounted transmitter or transponder. There will be serious engineering problems when working with multiple track grade crossings. One system will interfere with the other even if different frequencies were assigned to indicate a particular track. It will be difficult to determine the location of the transmitted signal and therefore a constant warning time will have a large margin of error.

2.2.1.7 Video Motion Sensing

The visual image of a train may be discriminated from other objects passing by the field of view of a television camera. A video image of the passing train on a camera monitor can be processed and confirmed as a train. Velocity, computed from one camera or perhaps two, must be calculated and a constant motorist warning time must be provided.

This system is unsuitable because it will be very expensive and a sophisticated technology is required to process the video images to indicate train presence.

2.2.2 Discrete Sensing Techniques

Discrete circuit sensing techniques include those methods of train detection which detect train presence at one or more specific locations. Also considered to be discrete sensors are track circuit techniques which detect the train's presence in a fixed block of track, but cannot further specify its location. Some discrete sensing techniques are pressure, magnetics, beam interruption, and track continuity.

2.2.2.1 Track Circuit Techniques

Any sensing technique which uses the wheels of the train to complete a circuit involving the rails may be called a track circuit. All of these techniques require special insulation and bonding of the rails in the section of track in which train presence is to be detected.

2.2.2.2 Track Circuit

The track circuit approach to train detection has been used widely for nearly a century. The technique is simple. One section of track is insulated from the rest. The rails within this section are bonded together to provide electrical continuity. A voltage (usually dc) is applied to a relay coil and the rails. When a train enters the block of track, its wheels and axles form a short circuit, bypassing the relay. The relay de-

energizes, activating the signal. This system is failsafe in that the relay is normally energized, and removal of relay power activates the signals. In normal use, signals are generally activated whenever a train is present, although the possibility of failure from a poor rail bond does exist. Signals are not infrequently activated by ballast variations due to weather, however, and no means of constant warning time is provided.

2.2.2.3 Audio Overlay

A variation of the dc track circuit utilizes audio frequency signals. These signals are introduced in the track some distance from the crossing. When no train is present, the tones are received at the crossing. As the train enters the insulated block, it shorts the track, causing the tone to disappear, and thus activating the signal. However, as with the dc track circuit, constant warning time is not possible, since detection is on a block basis.

2.2.2.4 Multifrequency Audio

An interesting possible variation of track continuity techniques is the multifrequency track circuit. Basically, this technique detects train presence as it passes several specific points.

Several frequencies are introduced into the track at the crossing. One rail is bonded continuously, while the other is insulated at several points. A trap circuit is installed around each insulated joint. This circuit blocks passage of one and only one tone. Thus, all frequencies are present in the block nearest the crossing, and only one frequency is present in the block furthest from the crossing. As a train approaches, the frequencies disappear in a set order. The time between their disappearances allows the controlling equipment to compute constant warning time.

One feature of this system is that it does not require a communications subsystem. However, it has all of the disadvantages of having to maintain rail bonds and insulated joints which are present in existing track circuits, multiplied by the number of blocks

desired. In addition, non-linearities due to poor connections may generate harmonics and cross products, requiring careful system design and making it difficult to operate more than one such system in the same general area. Thus, while the multifrequency track circuit is an interesting concept, it is not generally desirable for the innovative RHGC warning system.

2.2.2.5 Mechanical-Electrical Transducers

These types of train detectors utilize the weight of the train to provide an indication of its presence. Such techniques include the mechanically limited pressure switch, the strain gage bridge, and the piezoelectric transducer.

Mechanically Limited Pressure Switch. The tremendous weight of a train can be detected very simply by using a mechanical switch. Such a switch would be mounted underneath a rail. The weight of the train would depress the rail, activating the switch. The switch would be mechanically limited to react only to very large forces, such as generated by a train.

This device has all the disadvantages of requiring a direct connection to the rails and critical packing of the roadbed. Erosion of the ballast in time will cause malfunctioning. In addition, a mechanical device of this type is certain to have reliability problems. Ice and dirt may become packed around the switch, causing further problems. Such switches are thus not recommended for the innovative RHGC system.

Strain Gage. The strain gage is a mechanical sensing device used to monitor the presence of mechanical stress or strain. This device makes it possible to monitor mechanical loads and torques, such as are present in the rails of a railroad track. As the train's great weight is transferred to the rails, the rails are visibly deflected. The mechanical strain that results from this deflection can be transformed into a corresponding electrical voltage. Monitoring this voltage identifies the train's presence.

When the strain gage device is subjected to a mechanical strain, its physical length is increased. This increased length causes an increased characteristic electrical resistance of the device. Therefore, a variable applied pressure results in a variable resistance, and when applied in an electronic circuit, a corresponding voltage drop will be observed.

This concept can be used to trigger a presence-indicating system when a certain voltage level is reached. When the pressure applied to a rail at a given location results in a voltage level corresponding to the level produced when a train is present, the triggering circuit will be turned "on" and train presence will be indicated.

When designing the actual physical arrangement of the strain gage in the train detector application, the characteristic train weight must be transferred from the rail to a mechanical strain on the strain sensing device. This transfer, or coupling, can be accomplished in two ways. The strain gage element can be bonded directly to the flexing rail, or the device can be indirectly coupled via a mechanical link from the rail to the bending bar to which the strain gage is bonded.

To obtain optimum operation, the strain gage device must be properly bonded to the tensile surface. Precautions must be taken in preparing the bonding surface for the application of the epoxy resin bonding substance and proper conditions must be made to allow proper curing of the resin. These necessary precautions make mounting the strain gage to the rail rather difficult and perhaps unstandardized. In the mechanical link case, or the indirect connection, the strain gage device can be mounted in the factory under ideal conditions. This allows a standardized sensor device to be produced (see Figure 2-6).

The basic property of the strain gage is that a change in the device length, ΔL , will cause a change in the electrical resistance, ΔR . (Figure 2-7.)

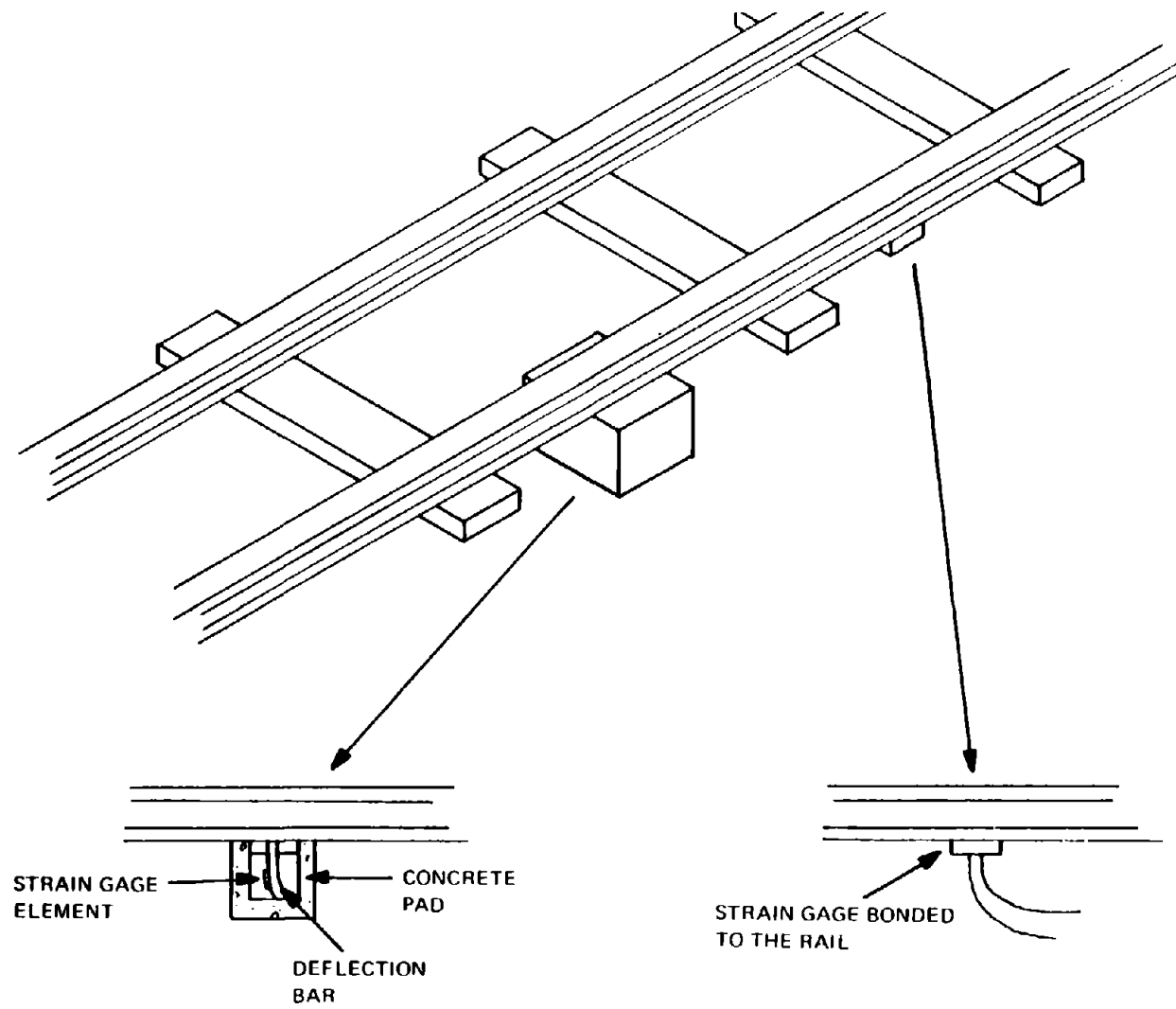


FIGURE 2-6. STRAIN GAGE SENSOR MOUNTING ARRANGEMENTS

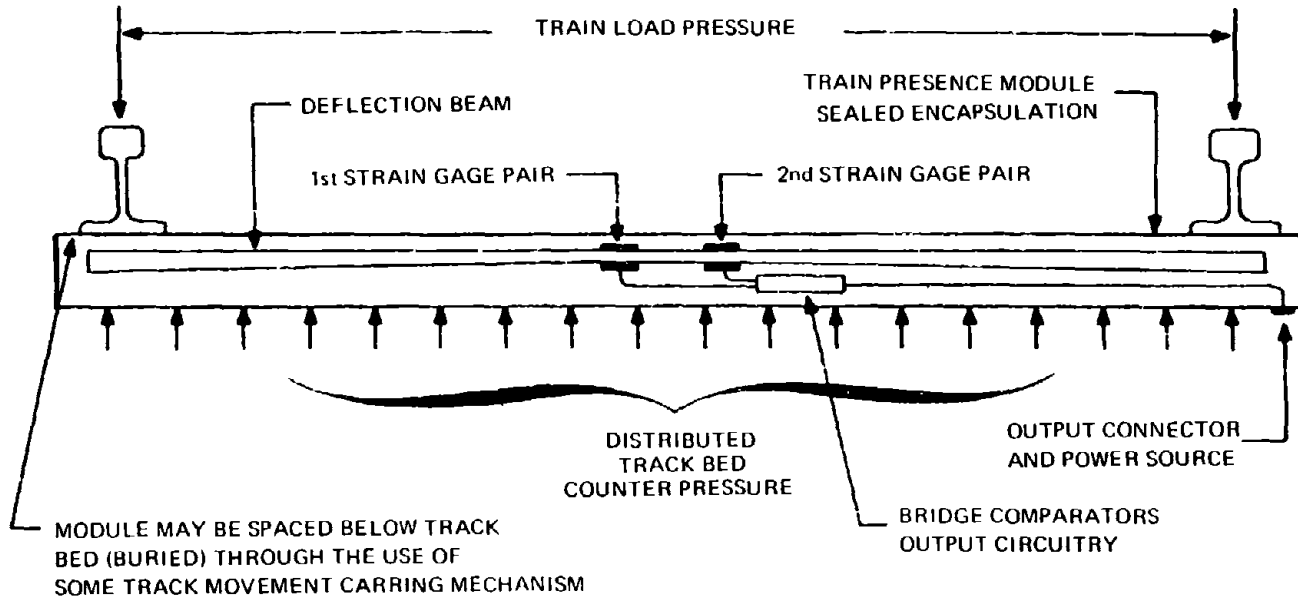


FIGURE 2-7. TYPICAL PRESSURE SENSING MODULE

The ratio of the change in resistance, for each unit of resistance, to the change in length per unit length of the sensing element is called the "gage factor".

$$\text{Gage factor} = K \frac{\Delta R/R}{\Delta L/L}$$

where: ΔR = change in resistance
R = unit resistance of the device
 ΔL = change in length of the device
L = unit length of the device

The gage factor is an intrinsic quantity of every individual strain gage device. The value is known as the "sensitivity factor" of the strain gage.

The strain gage is composed of wire or foil strain-sensitive metallic material or of semiconductor material. The wire sensing-element provides more accurate measurements than the foil element and is generally more expensive. The semiconductor gage has been more recently developed and provides the desirable characteristics of the metallic gages².

The strain gage is usually placed in a wheatstone bridge configuration, so that no strain will yield no voltage and maximum strain will yield maximum voltage. The voltage level characteristic of the train presence will trigger the train-presence signaling circuitry. This feature produces the "fool proof" feature of the detector, for virtually the only way this triggering voltage can be produced will be when the train is present.

Typically the value of resistance of the strain gage element is 150, 350, or 500 ohms, but other values may be obtained if required. The strain sensing device is commonly temperature compensated so that stray values of electrical resistance due to thermal changes will be canceled.

² SR-4 Strain Gage Handbook - An Introduction to Bonded Resistance Strain Gages (Volume 1, BLH Electronics, Inc., Waltham, Massachusetts, September, 1971).

Piezoceramic Electric Transducer. Piezoelectric crystals are able to generate voltages when subjected to mechanical pressure. They are used in phonograph pickups, accelerometers, butane lighters, and as pilot lights in gas heaters^{3,4,5}. The tremendous weight of the railroad train may be used to actuate a piezoceramic electric sensor.

The sensor may be placed in a mechanical arrangement so that it will be possible to transfer the changing force of the moving train on the rail to a changing mechanical pressure on the sensor. The sensor may be directly bonded to the rail at its ends so that a deflecting or essentially stretching rail will cause a voltage to be generated from the device. However, this method will limit the versatility of the entire train presence detection system. The sensor responds only to a changing mechanical pressure (Figure 2-8). A non-moving train above the sensor will not be detected. An alternative is to allow a pressure to be applied to the device when a fixed level of pressure is applied to the rail by the train. (See Figure 2-9.) This arrangement requires a sensor module to be either firmly embedded in the track ballast or firmly installed on the track.

The disadvantage with using the piezoceramic electric device as a train sensor is that the device responds to a differential pressure input. When the pressure is applied gradually there is no significant voltage produced. If a train is stopped, directly above, the sensor will demonstrate no knowledge of the train's presence. The voltage resulting from the initial train presence will be discharged across the terminals of the sensor. Since the device

³ Charles Edmiston, "Piezoelectric Ceramic Transducers," Electronic Design (No. 18, September, 1974), pp. 78-82.

⁴ Glennite Piezoceramics Catalog, (Gulton Industries, Inc., Metuchen, N. J.).

⁵ Carmen P. Germano, "Flints That Don't Wear Out," Electronic Design (No. 13, June 21, 1974), pp. 88 - 89.

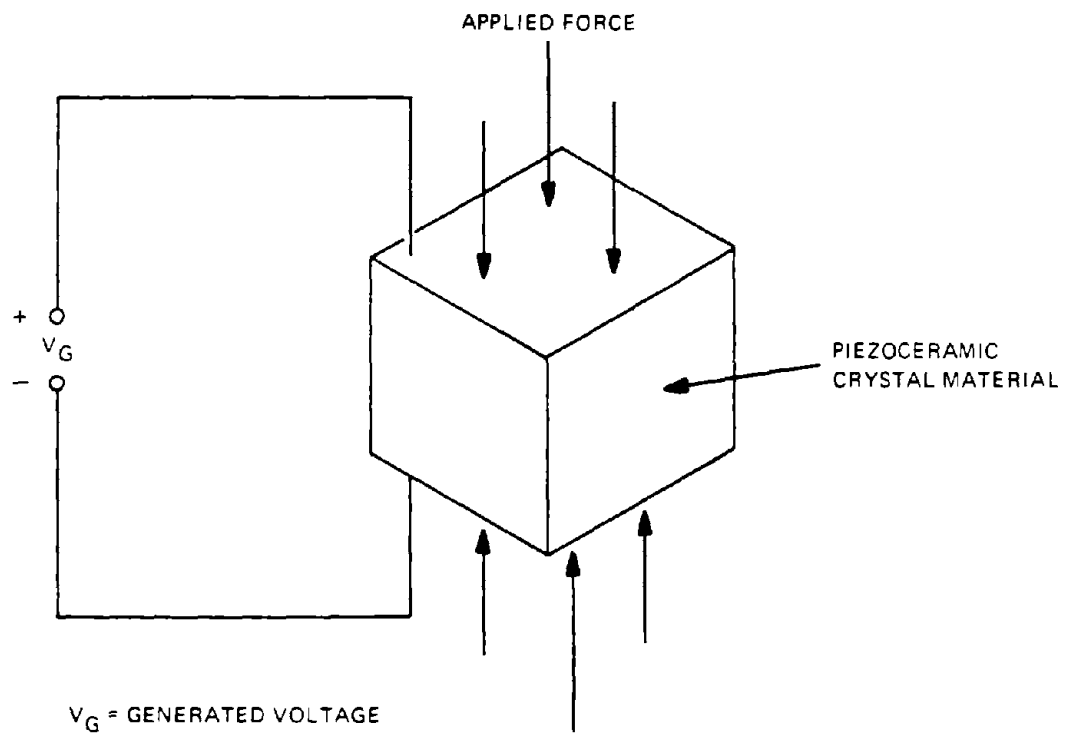


FIGURE 2-8. PIEZOELECTRIC TRANSDUCER

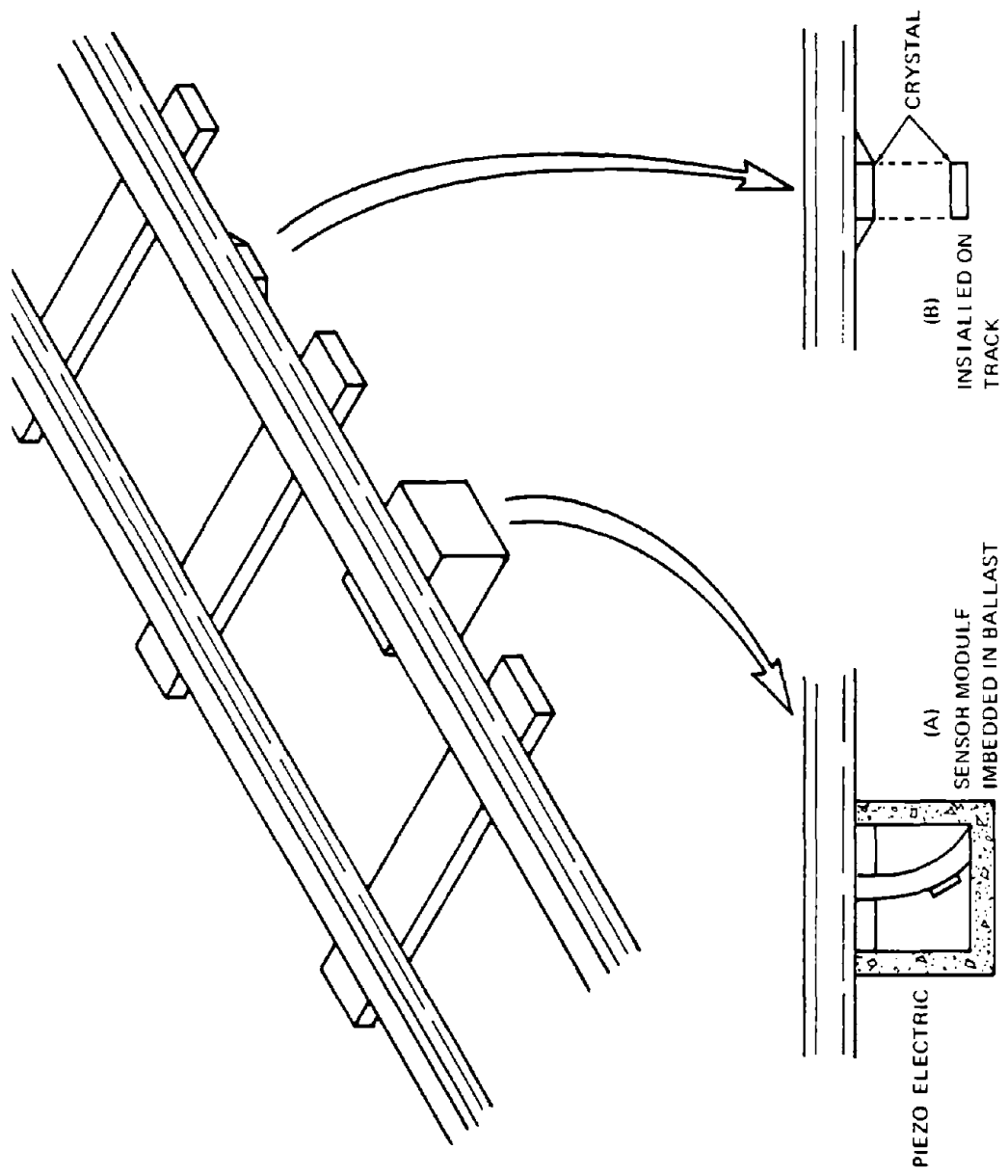


FIGURE 2-9. PIEZOCERAMIC MOUNTING ARRANGEMENTS

behaves as a charged capacitor, it will reach a peak and the charge will then dissipate through the load resistor or electronic triggering network .

An advantage of the piezoceramic crystal is that it produces an output voltage signal with no required bias current. When the device is operating, the voltage has the capability of transmitting a signal a finite distance through the wire without a need for external amplification.

The piezoceramic electric device discussed conforms to the following equation for the generated open circuit voltage:

$$V = gtT$$

where; V = open circuit voltage
g = piezoelectric coefficient (in./lbs)
t = thickness of the ceramic device (in.)
T = applied average stress (lb/in.²)

The equation becomes a bit more complex when using the acoustic sensing property of the device.

The characteristic capacitance of the device is given by the equation:

$$C = K \frac{A}{t}$$

where; C = capacitance
A = area (exposed surface)
t = thickness of the device

The energy developed by the crystal is given by:

$$\text{Energy} = 1/2 CV^2$$

After a brief investigation of the piezoceramic pressure transducers available, the most promising for the direct transformation of mechanical to electrical energy is the lead zirconate titanate crystal. The material has a high temperature stability range and a relatively high dielectric constant, as well as being rugged and durable.

2.2.3 Magnetic Sensors

Trains are made from large masses of iron, and hence have distinctly magnetic properties. Several types of magnetic train sensors are possible, including induction loops, Hall-effect devices, magnetoresistors, and magnetometers.

2.2.3.1 Induction Loop

The electromagnetic loop detector is currently used in vehicular traffic control.⁶ The detector senses the presence of a motor vehicle and converts this to an electrical signal. It is proposed that the electromagnetic loop can also detect railroad train presence.

Inductance L (or self inductance) is the ratio of the flux linkages to the currents which they link:

$$L = \frac{N\phi}{I}$$

where; I = The current flowing in the coil
N = the number of turns of the loop
ϕ = the total flux

In the vehicle detector the value of ϕ, the flux, will vary.

⁶M, K, Mills, "Magnetic Gradient Vehicle Detector", (paper presented at IEEE Conference on Vehicular Technology, Cleveland, Ohio, Dec. 1973)

Basically, the loop is energized with a high frequency current; the presence of a train or any other conductive object within the loop's electromagnetic field will cause a reduction of the self-inductance of the loop. This change in the loop self-inductance is due to eddy currents induced into the conducting material of the train. It is difficult to calculate the predicted change in self-inductance because of the complex geometry of the underside of the train and other unknown quantities.

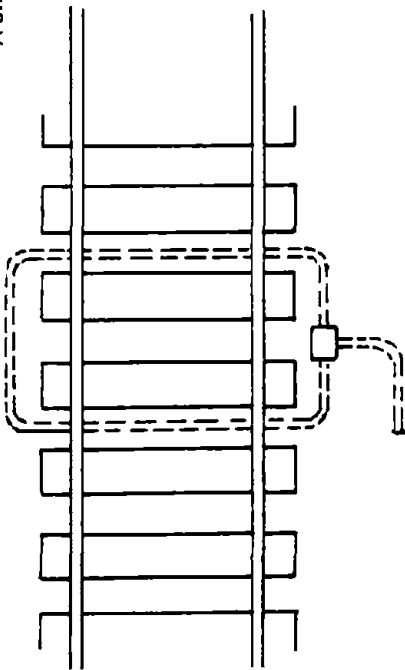
There are several designs that use the principle of changing inductance. One such method is the self-tuning detector, where the loop is part of a parallel tuned tank circuit, and where a feedback loop is used to adjust the oscillator frequency to keep the detector automatically tuned to the same amplitude point on the resonance curve. The train can then be detected by monitoring the output of the feedback loop.

A bridge-balance detector is a loop as one leg of a balanced-bridge circuit. The change in the voltage on the sensing loop will cause an imbalance in the bridge circuit and hence indicate the presence of a conducting object; the train.

The phase shift detector utilizes the relative phase shift of the tank circuit as the vehicle passes over the electromagnetic field of the loop. As a vehicle changes the self-inductance of the loop, there is a change in the relative phase of the signal output. This phase change is the difference between the crystal oscillator phase (referenced as zero) and change in phase of the loop tank circuit-phase. The phase change will indicate vehicle presence.

The induction loop will be mounted in the track ballast between the rails. The loop may be planted in a rectangular form between two ties or may be secured above the ties and identified so that it will not be interfered with (Figure 2-10). The supporting electronics will be placed beneath the loop in the ballast or may be safely located with the power supply and communications transmitter, off to the side of the track.

A SINGLE LOOP SENSOR



LOOP IS ALL UNDERGROUND

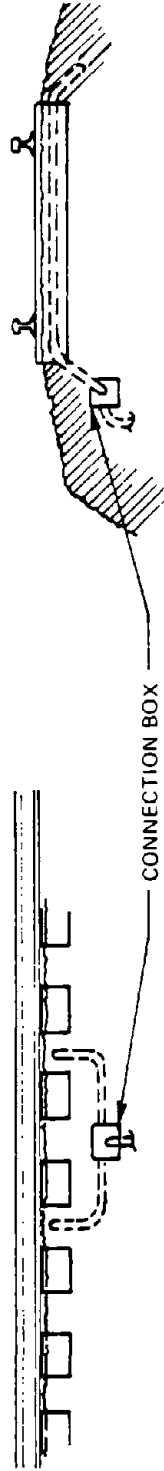


FIGURE 2-10. ELECTROMAGNETIC LOOP DETECTOR

2.2.3.2 Magnetometers

The term "magnetometer" has been widely used to describe all types of magnetic flux sensing devices, especially those which sense variations of current induced in a coil or set of coils, or inductive loops. These devices produce a voltage signal by integrating the flux change in the loop caused by the phenomena being measured, like the change in the earth field when a train is present. An inherent problem with this method is its dependence on train velocity for signal strength.

Commercial magnetometers developed for highway vehicle detection have been used as a train presence detector. The system has most of the desirable train sensor features. The device is capable of being sealed, ruggedized, and buried in a compact module below the track bed surface, thus offering high protection against severe weather, environment, and vandalism. It is also insensitive to standing water, ice, snow, or other non-magnetic or non-moving objects in the vicinity. Feasibility models of the magnetometer sensor technique have demonstrated several potentially serious problem areas, such as high power consumption per sensor. Initial production, installation, and maintenance costs for potential practical systems appear relatively high but not unreasonable.

2.2.3.3 Magnetoresistor Sensor

The magnetoresistor is a semiconductor component characterized by a resistance which increases in an increasing magnetic field. Electric signals can be derived from the change in magnetic flux density caused either by moving the magnetoresistor into a constant magnetic field, or by varying the magnetic field strength around a fixed magnetoresistor⁷. In this way the magnetic flux surrounding a passing railroad train can be used as a means of detecting its presence.

⁷ Ulrich Eberhardt and Walter Oehler, "Use of Magnetoresistors in Measuring Non-Electric Quantities" (reprinted from Siemens Aktiengesellschaft Electronic Components Bulletin IV, No. 1, Order No. 2-6300-218-101, 1969).

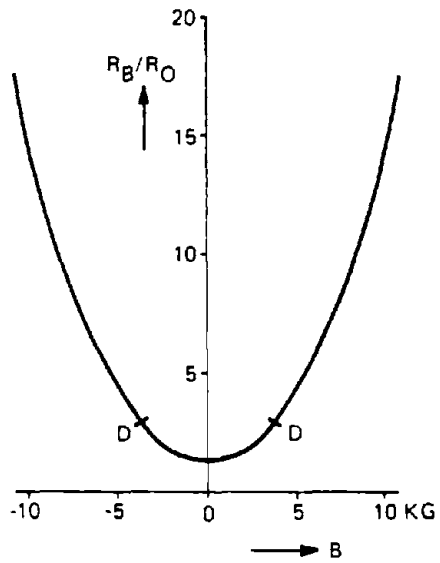
The magnetoresistor, like the Hall sensor arrangement, can be mounted between two magnetic flux concentrators. A permanent magnet must be included in this circuit to bias the magnetoresistor to a satisfactory operating point (see Figure 2-11). The strength of the magnetic field surrounding the train is approximately 20 Gauss. The dynamic range of R_B will therefore be rather small. Therefore the magnetoresistor must be included in an appropriate electronic circuit to utilize this changing resistance characteristic. The amplified output voltage from a balanced bridge circuit in which the magnetoresistor, is included, will then be included in a triggering circuit. When a signal representing the train appears, the train-presence communication circuitry is triggered and a train will be detected (Figure 2-12)⁸.

An alternate method is worth considering. The magnetoresistor can be used to accurately measure displacement of the rails by a passing train. A constant magnetic field circuit will be fixed beneath the rail. The magnetoresistor will be connected to a rod that is bonded to the underside of the rail. As the train passes overhead the rails will be deflected, causing the magnetoresistor to be displaced within the stationary magnetic field (Figure 2-13). The value of the resistance from the device will also vary and will be included in an electronic triggering network. Several problems are inherent with this technique; the fixed magnetic field may not remain at the desired distance from the magnetoresistor (changing track ballast is one cause for such a shift), and attachment to the rails is always undesirable.

2.2.3.4 Hall-Effect Sensors

In either a conductor or semiconductor, a magnetic field generates a voltage, called the Hall voltage, which is proportional to the magnitude of the cross-product of the field and current ($H \times I$). With a constant current, the Hall voltage is directly proportional to the magnetic field, making the devices popular for measuring magnetic fields.

⁸ Klaus Bahr, "The Magnetoresistor: A Very Simple Solid-State Transducer," Electronic Design News (January 15, 1972), pp. 36 - 39.



RESISTANCE VS MAGNETIC FLUX DENSITY CHARACTERISTIC
CURVE OF A MAGNETORESISTOR

B = MAGNETIC FLUX DENSITY

R_O = RESISTANCE OF THE MAGNETORESISTOR
WITH ZERO MAGNETIC FIELD

R_B = RESISTANCE OF THE MAGNETORESISTOR
INSIDE THE MAGNETIC FIELD

D = A DESIRED OPERATING POINT

FIGURE 2-11. MAGNETORESISTOR CHARACTERISTIC CURVE

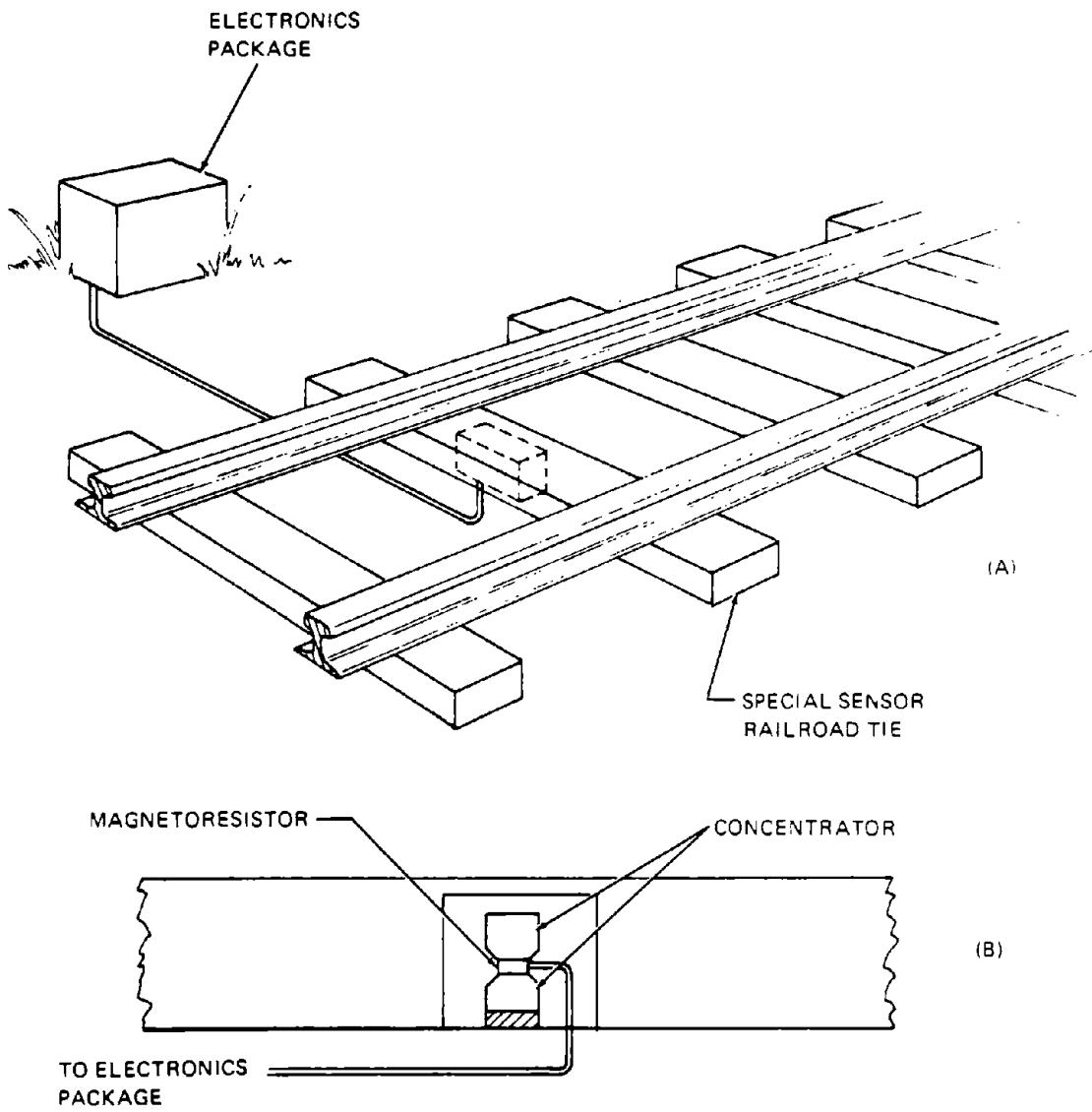


FIGURE 2-12. MAGNETORESISTOR WITHIN SPECIAL TIE

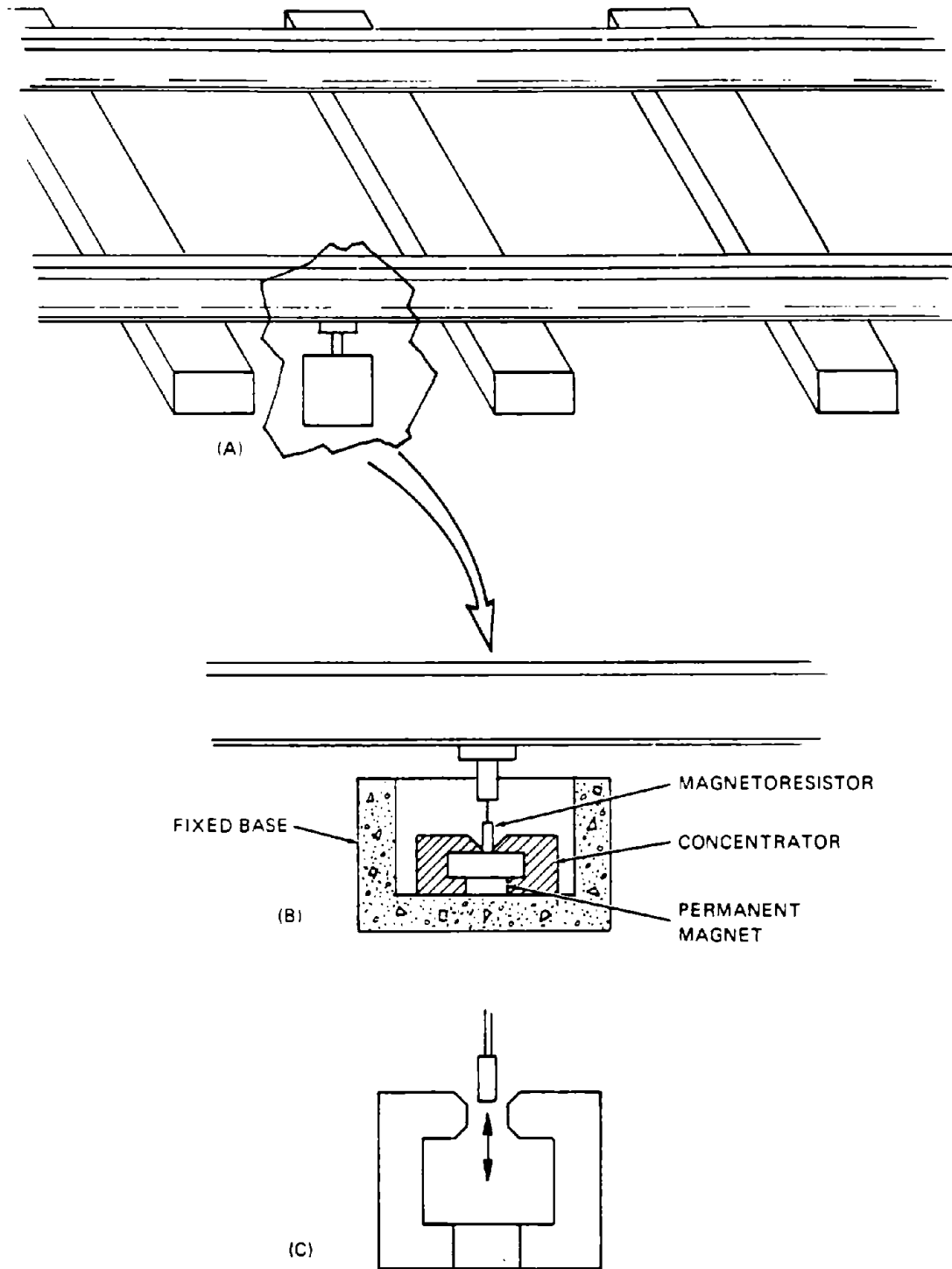


FIGURE 2-13. MAGNETORESISTOR UNDERNEATH RAIL

In a block of conductor or semiconductor carrying conventional current as shown in Figure 2-14, with the absence of internal forces, current flow is undistorted. Assuming the material is homogeneous, this current flow is of uniform density.

When a magnetic field is applied, electron flow follows a curved path. This curving of the current path causes a build-up of negative charges on the right side of the material.

Balance is restored when electrons pile up on one side of the material and holes, or positive charges, gather on the other. This charge build-up continues until the voltage across the material exactly balances the force exerted by the magnetic field. Then the electron flow is exactly as it was in the undisturbed material, except that a Hall voltage is present at right angles to the initial current^{9,10}.

The originally proposed Hall device train detector was arranged as shown in Figure 2-15. A train passing over the magnetic circuit set up by the concentrators, permanent magnet, and Hall device, will change the flux density through the Hall device. When the train is directly overhead, the magnetic flux density will be at a maximum and therefore the Hall voltage will also be at a maximum.

A Hall device mounted between magnetic flux concentrators has since replaced the previously proposed Hall device train detector. This new configuration senses the distortion of the earth's magnetic field by the magnetic mass of a passing train. The concentrators channel the flux distortion through the Hall device which then activates the logic, turning on the signals. Main advantages of the new sensor system are that it

⁹Barron Kemp, Hall Effect Instrumentation (Indianapolis: Howard W. Smas, Inc., 1963).

¹⁰H. Weiss, "Galvanometric Devices" (reprinted from Siemens Aktiengesellschaft Electronic Components Bulletin, Order No. 2-6300-234-100, West Germany).

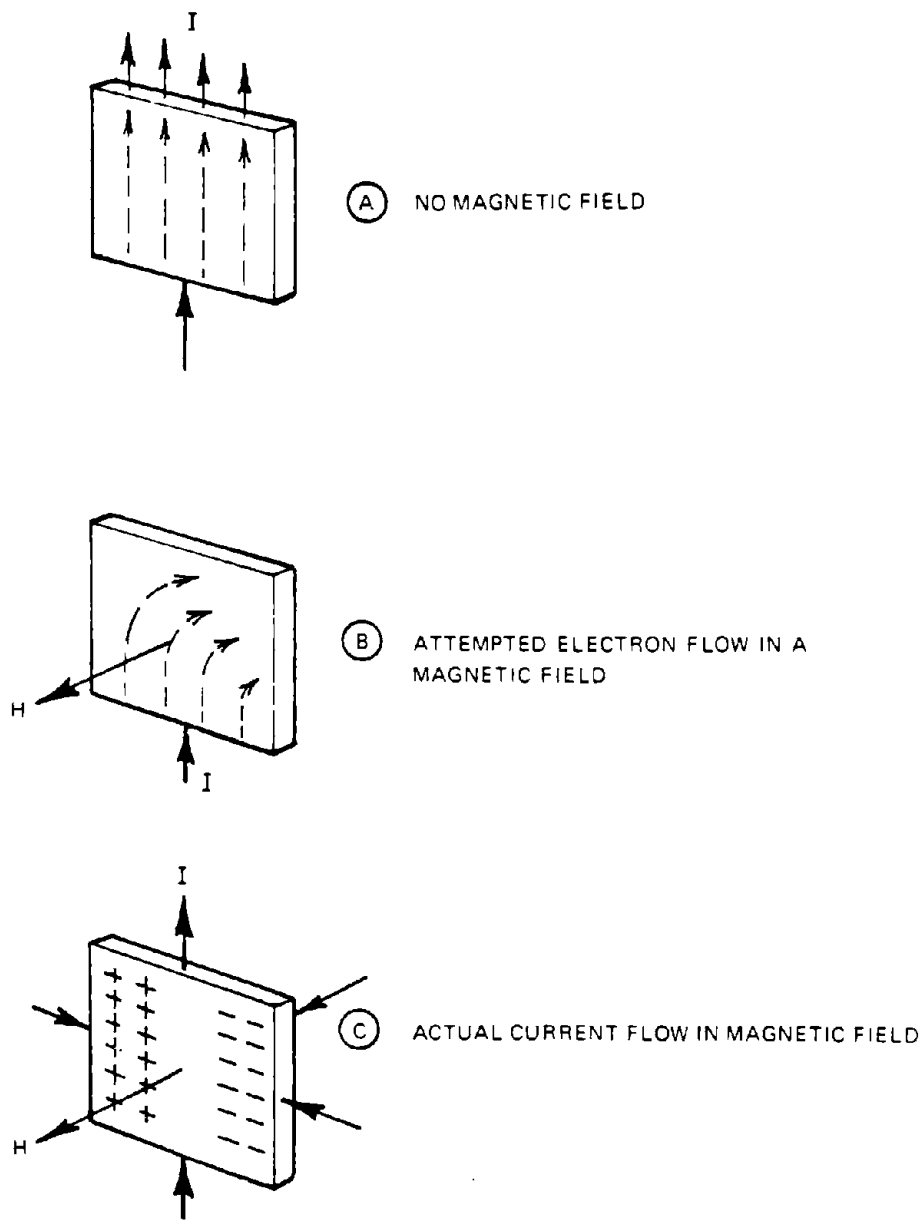


FIGURE 2-14. HALL EFFECT

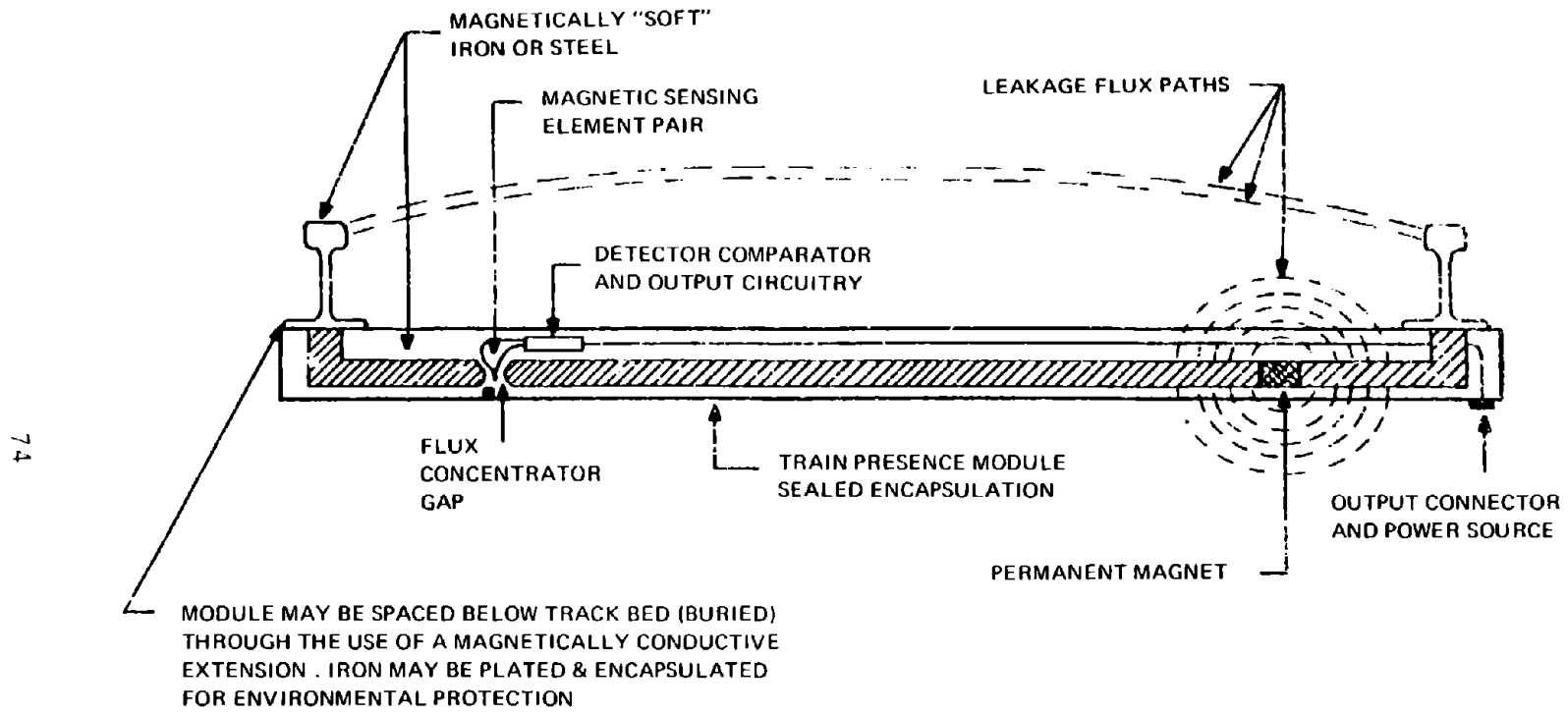


FIGURE 2-15. ORIGINAL HALL-EFFECT DETECTION

needs no attachment to the rails and its alignment during installation does not require that it be pointed directly upward toward the train. If the sensor arrangement becomes offset from the perpendicular either before or after installation, the train detector system will still operate and indicate train presence. Several methods of installation are possible.

A special railroad tie can be constructed of reinforced fiberglass with the flux sensing package premounted inside. (See Figure 2-16.) The supporting electronics package will also be placed in this tie and appropriate electronics cards will be plugged in. (With varying power supplies and communications links it is necessary to encode and transmit the presence signal in different ways.) This tie will be designed to withstand shock and vibration from rail traffic and allow easy replacement of internal packages.

Another method of installing the modularized sensor package is to have a hole drilled in the underside of a regular tie (see Figure 2-17). The Hall device-concentrator package will slide into the hole and the electronics package may be mounted on an adjacent cavity in the tie. The packaged units will be equipped with insulating material and environmental shielding. This sensor tie would be distinguished from other ties by special marking compatible with the railroad standards. The advantage of this mounting method is that by using a regular tie, the sensor is protected from exposure to the weather and vandals. The connecting wires from the sensor and the communicator link will be shielded in electrical conduit and buried beneath the surface.

The Hall probe module does not have to be mounted in a railroad tie but can be buried in the ballast between the ties (see Figure 2-18). Some sort of non-magnetic plate is required to identify the sensor and protect the package when maintenance crews hand work the road bed.

The Hall probe used in the train detector consists of a Hall element, flux concentrators (made of stress relieved 1020 cold rolled steel), and necessary supporting electronics. The Hall device is a monolithic integrated circuit consisting of a linear Hall cell and a

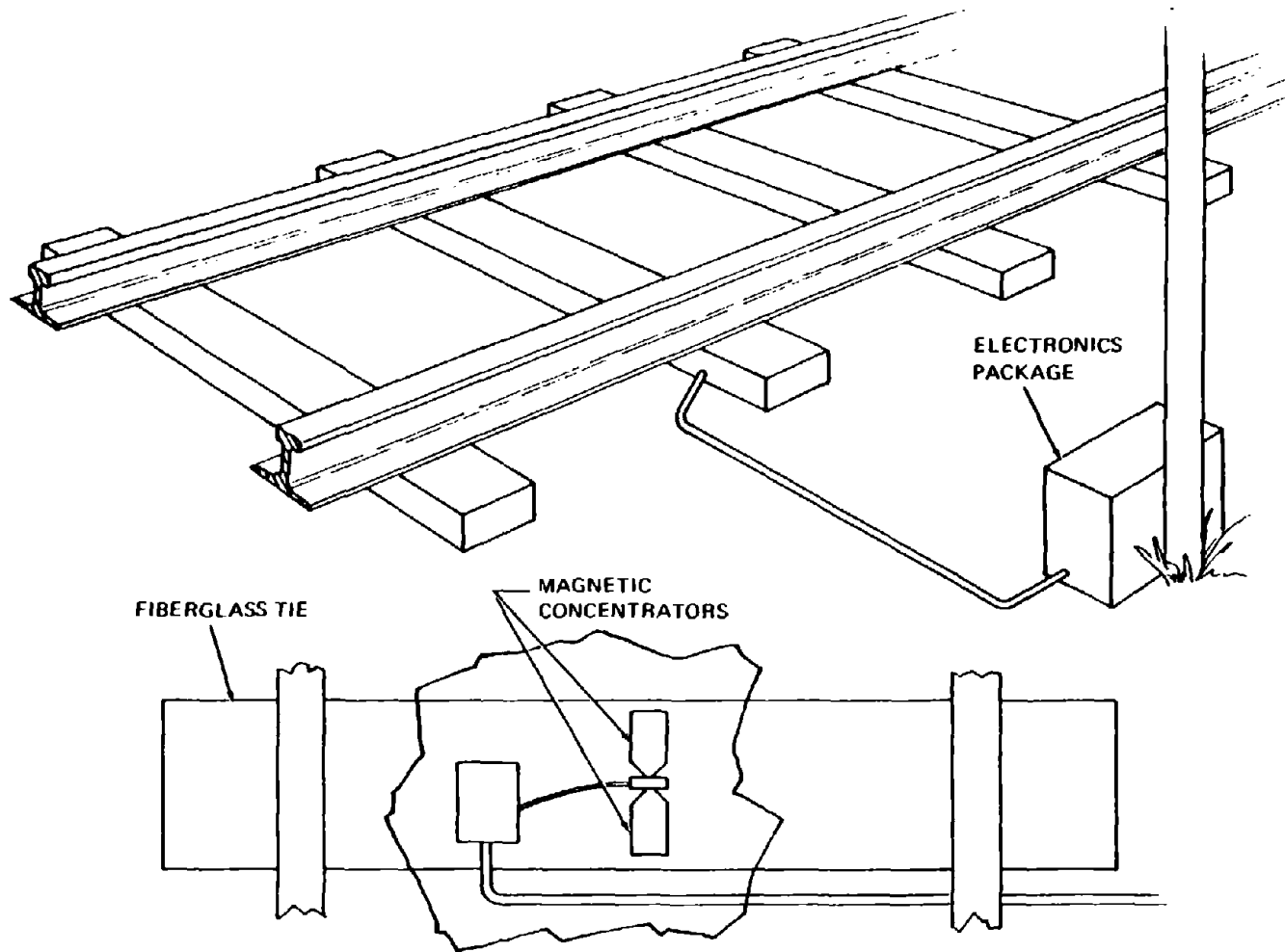


FIGURE 2-16. SENSOR PACKAGE WITHIN SPECIAL FIBERGLASS TIE

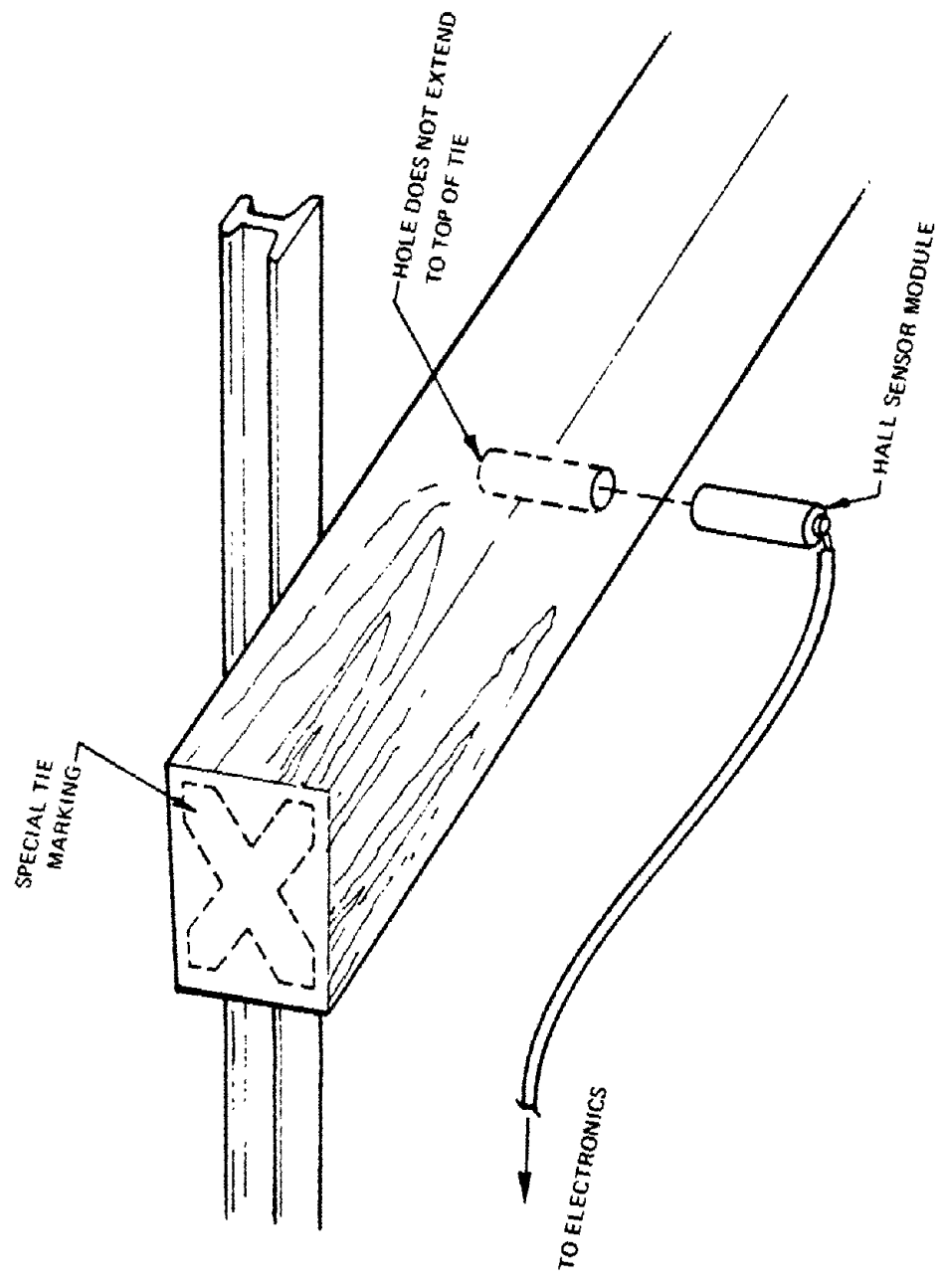


FIGURE 2-17. HALL DEVICE INSTALLED

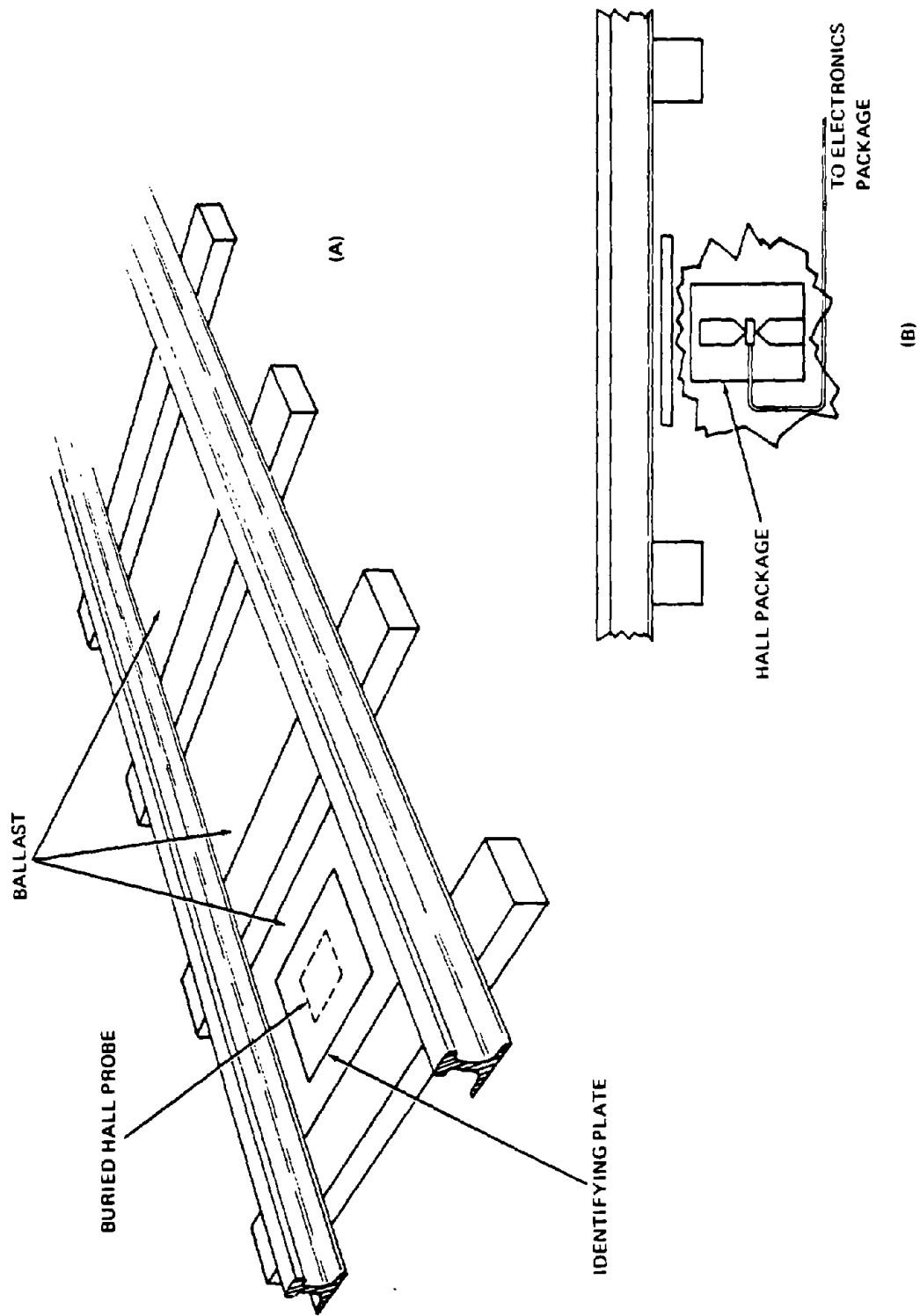


FIGURE 2-18. HALL PROBE IN BALLAST

differential amplifier. Commercial Hall effect circuits with board mounted regulators will soon be available with temperature stability. They are expected to be approximately 100 times better than that of discrete Hall effect components. Since the amplifier and generator are on the same substrate, the problems of noise with long leads that would exist with a discrete amplifier are greatly reduced.

Recently introduced Hall effect switches are directly compatible with both diode-transistor and transistor-transistor logic, allowing the use of new monolithic technology which sharply reduces manufacturing cost¹¹.

2.2.4 Beam Interruption

The familiar photoelectric cell and light beam, as used for door openers, can be used to detect an oncoming train. Both the light source and photoelectric eye would have to be mounted above track level to permit only the train to intercept the beam. (Variations include interruption of radar and sound beams.) Physical damage from weather, vandalism, etc, would be a major problem, as it would be difficult to mount the detector hardware so as to fully protect it and permit reliable operation.

2.2.5 Thermal Detectors

The thermal radiation from the railroad cars can be detected using the same principle as the current hot box detectors. Instead of detecting overheated journal boxes the sensor would be set to detect lower levels of heat intensity. Problems may arise with weather conditions, sunlight, and other outside disturbances. If this technique is to be considered as a railroad car detector, electro-optical infrared technology must be advanced in this area.

¹¹M. K. Mills, "Magnetic Gradient Vehicle Detector" (paper presented at IEEE Conference on Vehicular Technology, Cleveland, Ohio, December, 1973).

2.3 SELECTION OF THE PREFERRED SENSOR

Each sensing technique discussed in this report has some advantages and disadvantages. Some are ideally suited for certain specific applications, while others are quite flexible. Some are hardly suitable for use in any applications. No sensor was without at least minor disadvantages.

Table 2-1 presents the characteristics of the various sensors discussed here.

It is to be understood that this table is based in many cases upon the judgment of the authors, rather than testing or analysis. "Failsafe-ness", for example, is a crucial attribute, but no system can be adjudged failsafe without reduction to practice and extensive testing.

Examination of the table suggests that the most satisfactory devices are the Hall effect, magnetoresistor, and induction loop sensors. Close contenders were beam interruption, magnetometer, and the strain gage. The undesired features of the magnetic sensors are seen to be relatively minor. Since they are sensitive to magnetic materials, they require power supply and installation on railroad property.

2.3.1 Experimental Verification

The Hall sensor and the electromagnetic loop were tested in an actual railroad environment. The Hall sensor was buried beneath the surface and the loop was spread across several ties nearby. The purpose of this experiment was to prove these two preferred methods do produce significant and discernable train presence signals.

The electromagnetic loop was constructed of four turns of No. 16 copper wire. This inductor was placed in a parallel resonant tank circuit and turned to reach its resonant frequency at 400 kHz. (Figure 2-19). The signal from the tank circuit was passed through a diode and amplified and then sent to a strip recorder (Figure 2-20).

TABLE 2-1. SENSOR SYSTEM COMPARISON

Sensor type	Functional capability													
	Constant warning time	Failsafe	Subject to failure from normal weather	Rail insulation required	Rail switch interference	Connection to rail	Affected by ballast change	Foreign metal interference	Mounting critical	Multitrack operation	Curved track operation	Remote power supply required	Processing complexity	No. of functional capabilities different from ideal sensor
Ideal sensor	Y	Y	N	N	N	N	N	N	N	Y	Y	N	L, M	0
Track circuit	N	Y	Y	Y	Y	Y	N	Y	N	Y	Y	N	L	6
Audio overlay	N	Y	Y	Y	Y	Y	N	Y	N	Y	Y	Y	L	7
Multifrequency	N	Y	Y	Y	Y	Y	N	Y	N	Y	Y	Y	L	7
Rail impedance	Y	Y	Y	Y	Y	Y	Y	Y	N	Y	Y	N	L	6
Horizontal radar	Y	Y	N	N	N	N	N	N	Y	N	N	N	H	4
Acoustic sensor-rail	Y	N	N	N ^a	Y	Y	Y	Y	Y	Y	Y	N	H	7
Acoustic sensor-ground	Y	N	N	N	N	N	N	N	Y	N	Y	N	H	4
Acoustic sensor-air	Y	N	N	N	N	N	N	N	Y	N	N	N	H	5
Strain gage bonded to rail	Y	Y	N	N	N	Y	N	N	Y	Y	Y	Y	M	3
Strain gage mechanical link	Y	Y	Y	N	N	Y	N	N	Y	Y	Y	Y	M	4
Piezoceramic bonded to rail	Y	N	N	N	N	Y	N	N	Y	Y	Y	N	M	3

a - Good mechanical bond required

b - Magnetic material only

TABLE 2-1. SENSOR SYSTEM COMPARISON (Continued)

Sensor type	Functional capability													
	Constant warning time	Fallsafe	Subject to failure from normal weather	Rail insulation required	Rail switch interference	Connection to rail	Affected by ballast change	Foreign metal interference	Mounting critical	Multitrack operation	Curved track operation	Remote power supply required	Processing complexity	No. of functional capabilities different from ideal sensor
Piezoceramic mechanical link	Y	N	Y	N	N	Y	N	N	Y	Y	Y	N	M	4
Pressure limited switch	Y	Y	Y	N	N	Y	N	N	Y	Y	Y	Y	M	4
Hall probe-fiberglass tie	Y	Y	N	N	N	N	N	Y ^b	N	Y	Y	Y	M	2
Hall probe-regular tie	Y	Y	N	N	N	N	N	Y ^b	N	Y	Y	Y	M	2
Hall probe in ballast	Y	Y	N	N	N	N	N	Y ^b	N	Y	Y	Y	M	2
Magnetoresistor in special tie	Y	Y	N	N	N	N	N	Y ^b	N	Y	Y	Y	M	2
Magnetoresistor in regular tie	Y	Y	N	N	N	N	N	Y ^b	N	Y	Y	Y	M	2
Magnetoresistor in ballast	Y	Y	N	N	N	N	N	Y ^b	N	Y	Y	Y	M	2
Electromagnetic loop in ballast	Y	Y	N	N	N	N	N	Y	N	Y	Y	Y	M	2
Magnetometer	Y	N	N	N	N	N	N	N	N	Y	Y	Y	M	2
Video motion	Y	Y	N	N	N	N	N	N	Y	N	N	N	VH	4
Train mounted transponder	Y	N	N	N	N	N	N	N	Y	N	Y	Y	M	4

a - Good mechanical bond required

b - Magnetic material only

TABLE 2-1. SENSOR SYSTEM COMPARISON (Continued)

Functional capability

L = low
M = medium
H = high
VH = very high
Y = yes
N = no

Constant warning time	
Failsafe	
Subject to failure from normal weather	
Rail insulation required	
Rail switch interference	
Connection to rail	
Affected by ballast change	
Foreign metal interference	
Mounting critical	
Multitrack operation	
Curved track operation	
Remote power supply required	
Processing complexity	
No. of functional capabilities different from ideal sensor	

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Sensor type													
Beam Interruption	Y	Y	Y	N	N	N	N	Y	Y	Y	Y	M	3
Thermal detector	Y	N	Y	N	N	N	Y	Y	Y	Y	Y	H	6

a - Good mechanical bond required
b - Magnetic material only

The Hall sensor was buried in the ballast between the ties. (Figure 2-21.) The Hall probe (concentrator-Hall sensor-concentrator arrangement) was aimed directly at the underside of the passing train. The Hall device was powered by a remote dc power supply. The Hall voltage signal was fed into an electronics package where the signal was further amplified and processed. The final output signal was then sent into the stripchart recorder.

A switching engine, a train of an engine and two passenger cars, and a service train of four small power cars passed over both the loop and the Hall sensor.

The results of this experiment indicates that it is entirely possible and practical to detect the presence of a railroad train and railroad maintenance equipment with either sensor. The electromagnetic loop did prove to be affected by the motors and generators of the engine; signal spikes were produced (Figure 2-22). The Hall device was able to monitor the magnetic field of the metallic train with greater accuracy than the loop. It may even be economically possible to electronically count the axles of the train, using the Hall probe.

2.3.2 Final Selection

The experimental testing showed that the Hall effect device is preferable to the induction loop, for train sensing. While both techniques detected the train, cars, and service vehicle, the induction loop was far more sensitive to electrical interference from the electric motors. In addition, the Hall device produces a much sharper output, allowing for possible identification of axles.

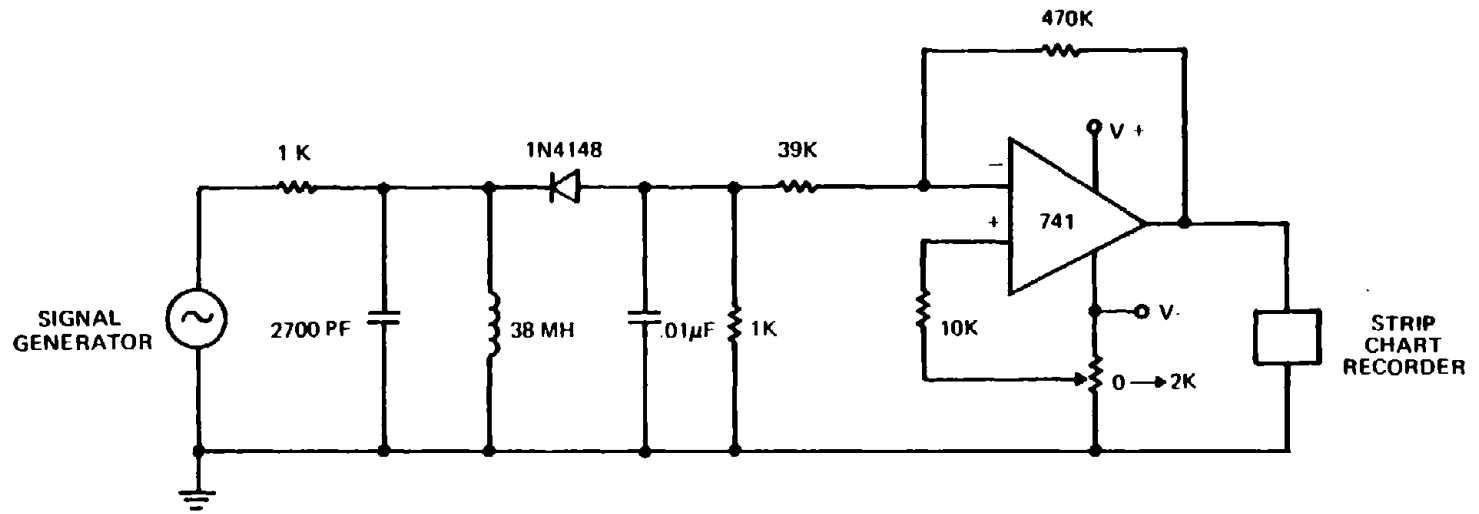


FIGURE 2-19. ELECTROMAGNETIC LOOP TRAIN DETECTOR CIRCUIT

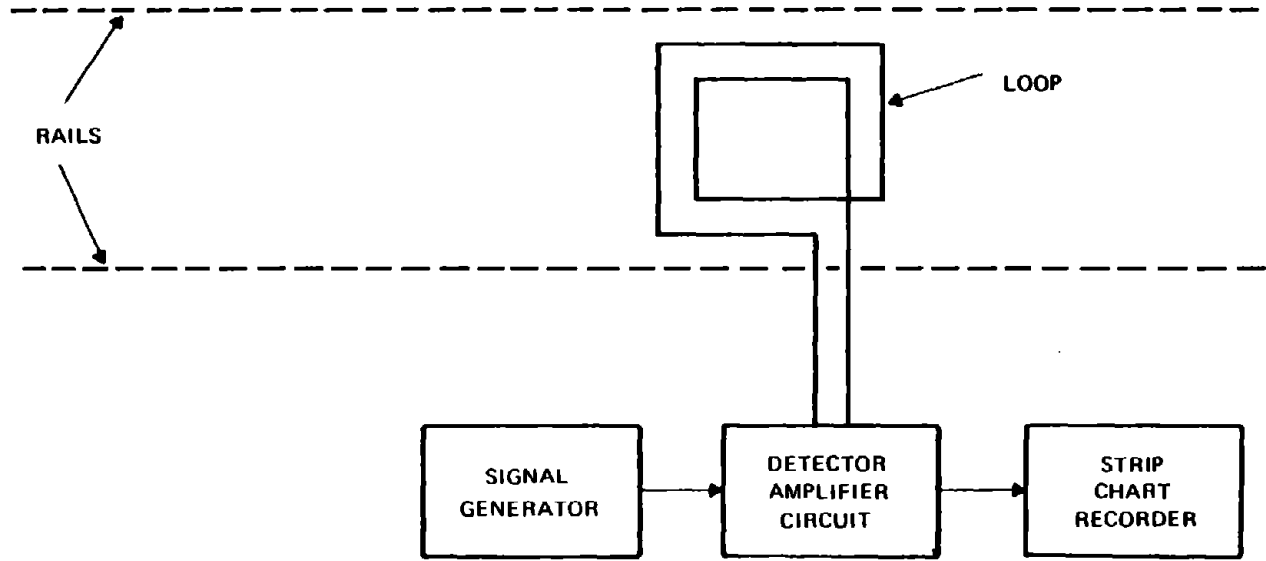


FIGURE 2-20. ELECTROMAGNETIC LOOP TRAIN DETECTOR SYSTEM

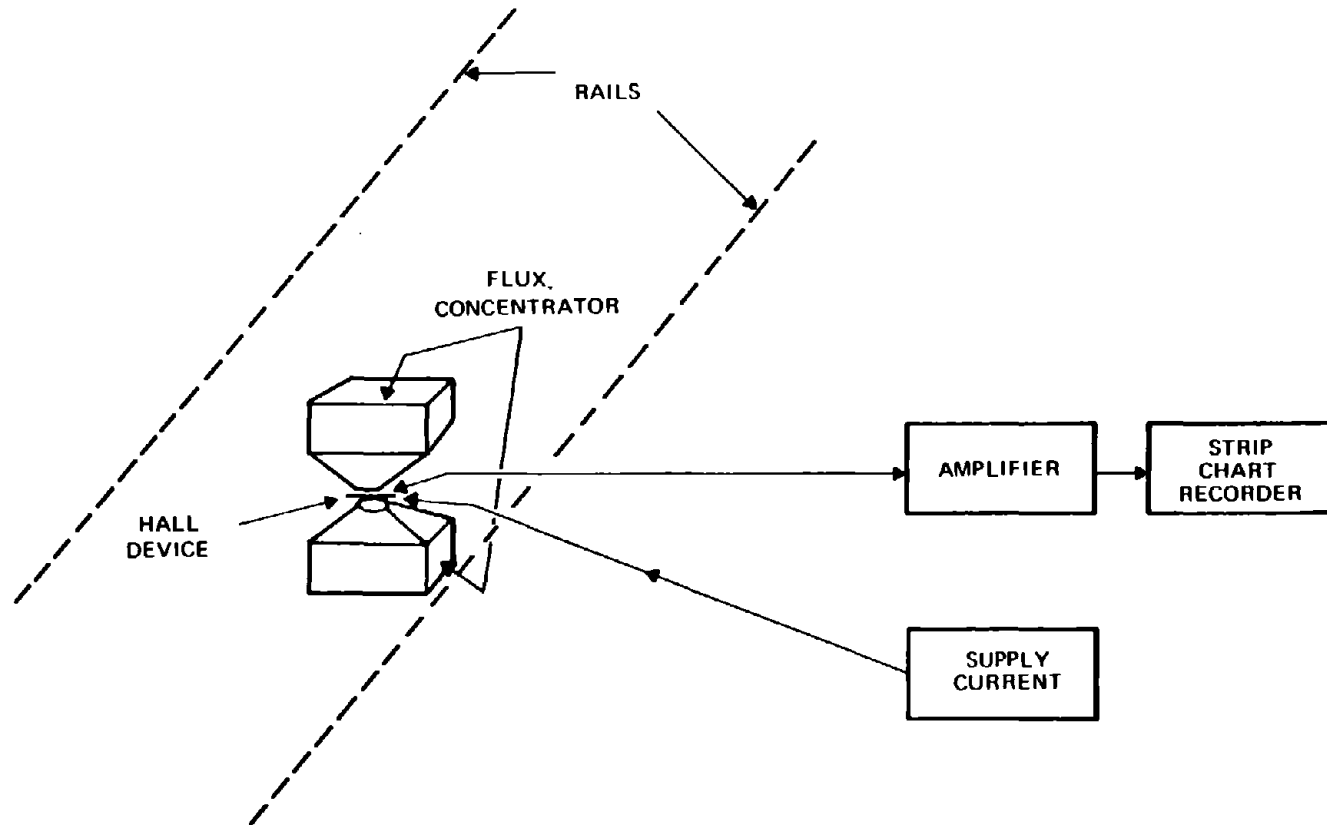


FIGURE 2-21. HALL SENSOR BURIED IN BALLAST

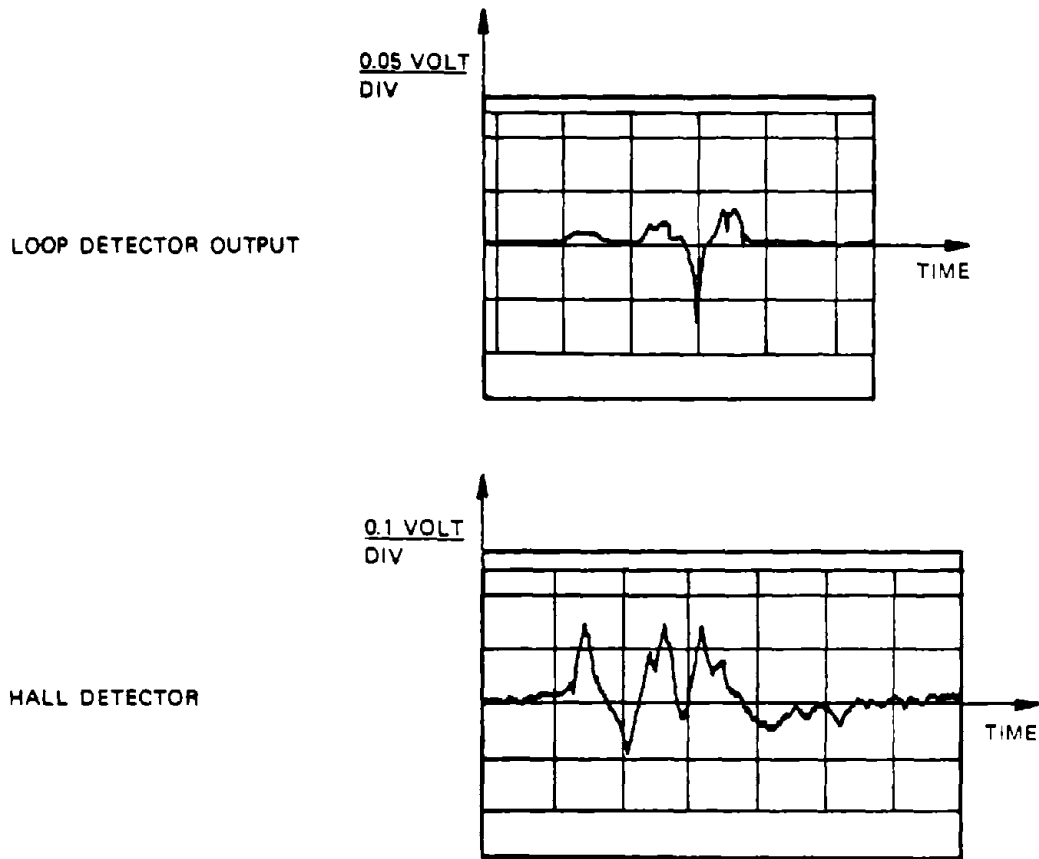


FIGURE 2-22. OUTPUT FROM LOOP AND HALL DETECTORS

3. COMMUNICATIONS SUBSYSTEM

3.1 REQUIREMENTS

An innovative RHGC system requires several subsystems and components, including the sensors, control and emergency power supply, the motorist crossing warning signals, the motorist advance warning signals, and the engineer warning signals. Since many of these components are physically separated from one another, a means of transferring information is required. This process can be called the communications subsystem.

The choice of communications system depends on what properties it should have and where it is to be installed. The crossing warning system communications involve only a very small amount of data such as sensor/signal identification number, train direction, train velocity, etc, and hence requires only a very small channel capacity. In addition to those requirements for the system, general requirements and desired features of a communications system include:

- Failsafe operation

- Dependability of message delivery

- Accuracy of message delivery

Most existing communications of railroad-highway crossing warning equipment is done through buried cables. While the buried cable system is generally reliable, it is very expensive to install and to service. This expense, which can be as high as \$20 per foot, provides the motivation to consider other systems.

Communications systems applicable to the railroad-highway grade crossing warning fall into three general groups: cable, carrier, and radio. (Acoustic techniques are

undesirable from both cost and reliability viewpoints.) Table 3-1 illustrates the techniques applicable to each system and the place where they can be applied. Figure 1-2 illustrates a hypothetical situation in which all three types of communication links are used.

3.2 EVALUATION

The primary objection to buried cable systems is their cost. At rates of \$10 to \$20 per foot, the costs of burying cable to the sensors and/or signals can be a significant fraction of the cost of the whole system. However, the buried cable system requires a minimal amount of encoding/decoding equipment. For links over very short distances, the use of carrier or wireless systems is absurd, and buried cable will be cost effective.

Carrier communications systems employ modulated carriers to transport information from one device to another. The carriers travel on wires or cables, as opposed to being radiated. These wires or cables may take many forms, including power lines or special signal lines. The use of carriers of several different frequencies allows many different signals to utilize the same set of lines. Most railroads with moderate to heavy train traffic will have parallel railroad lines. These lines include both power for wayside signals and a code line which is used to control the wayside signaling system. In this case the sensors should be powered from these power lines, and can use either the railroad wayside power lines or the "code line" for communications. The carrier signal will not interfere with the wayside signals. The code signals are of a very low frequency. It will be necessary to choose frequencies which do not interfere with any carrier signals already in use on this line. If the power line is used, there will be no interference problem, since carrier signals are not now present. Some consideration was also given to the use of the rails as a transmission line for a carrier system, but this was found to be unreliable.

In the event that a sensor is located in a remote area and therefore powered from batteries, solar panels, or some other local power source, wireless communications

TABLE 3-1. COMMUNICATIONS SYSTEMS

<u>System</u>	<u>Techniques</u>	<u>Where is it usable?</u>	<u>Where is it desirable?</u>	<u>Cost is a function of</u>
Cable	Buried poles	Anywhere	Equipment separated by a short distance	Distance and terrain
	Power line (RR)			
Carrier	Power line (Power Co.)	Existing lines present	Most urban and rural locations with moderate to heavy rail-	Essentially constant
	Code signal line	(usually the case)	road traffic	
	Any other existing line			
	Rails			
Wireless	ULF - Ground currents			Mostly constant but may vary with terrain, obstacles, and distance
	LF -		Signal in remote area powered by batteries -	
	MF - HF	Anywhere	No line power available	
	VHF/UHF			
	Microwave			
	Optical			

becomes of interest, since it will be far less costly than any system which requires burying or stringing cable. Many different parts of the spectrum were considered, but the most practical frequency range for this application is VHF, from both cost and technical viewpoints. The VHF system uses simple transmitters and receivers, a simple omnidirectional whip antenna, and will penetrate most obstacles.

A practical system will probably incorporate either both buried cable and carrier links or buried carrier and VHF links. It is possible that all three links might be employed in the same crossing system as shown in Figure 1-2. The buried cable is used only for those sensors and signals which are in close proximity to each other; other sensors and signals utilize either a carrier link or a VHF link, as fits the situation. Modularity and format commonality assures that all systems will be compatible; links are included in a system by inserting the appropriate module in the circuitry. This approach provides a system which is adaptable to a variety of situations and is cost effective in each.

Any system requiring communications links must provide for reliability and for fail-safe operation of those links, since the whole system will be only as dependable as its communications. To conserve power during battery operation and to conserve channel space, communications equipment will be operated only when required. Upon being activated or deactivated by a train, a sensor will report its direction and velocity. When a train is present or is not present, each sensor will report its status at regular intervals of about five minutes. If the control circuitry fails to receive a report from each sensor in the preset interval, it regards the sensor or link as having failed and displays a warning accordingly.

3.3 WIRE LINKS

When sensors and/or signals are in close proximity, it will be cost effective to connect them with buried cable. Buried cable is preferable to overhead cable because it will be nearly immune to weather and vandalism and will also be invisible.

Many possibilities exist for signaling formats on cable. It would be possible to provide a separate conductor or pair of conductors for each different message to each different piece of equipment. However, such use of multiconductor cable and multiple cable systems will greatly complicate the installation and maintenance problems. To simplify the installation and maintenance, a single pair of wires and a common buss can be used. All sensors and signals using the cable link communicate on the same pair of wires. Different pieces of equipment are identified by unique codes. Cables are simply connected from one piece of equipment to another, eliminating any need to splice cables or to provide connector assemblies.

The coding and information could be transmitted by simple "baseband" or dc codes. However, this technique lends itself to interference between signals from two pieces of equipment. If two pieces of equipment should be transmitting at the same time, there is no way to detect it. Therefore, a dual tone or audio frequency shift keying (AFSK) system is suggested. In this system, information is transmitted by transmission of one of two tones, depending on whether it is a logic "1" or a logic "0". Should two sensors be transmitting at the same time, it is likely that both tones will appear simultaneously and the condition will be detected. Also, barring interference caused by two simultaneous transmissions, messages can be decoded even if one of the tone oscillators fails.

This signaling scheme is compatible with that used in the carrier and VHF links. Another advantage to this system is the dc power may be supplied to the sensors through the same cable. This common buss technique is currently used in computers to reduce interface problems. The cable connecting the various devices acts as a transmission line, and is terminated on each end (Figure 3-1) to prevent echoes from confusing the equipment. Each transmitter is equipped with a simple monitoring circuit which inhibits it from transmitting when another signal is on the line.

Power requirements for the buried cable links should be negligible. Receivers will be designed to have a high input impedance and will therefore not load the line. The

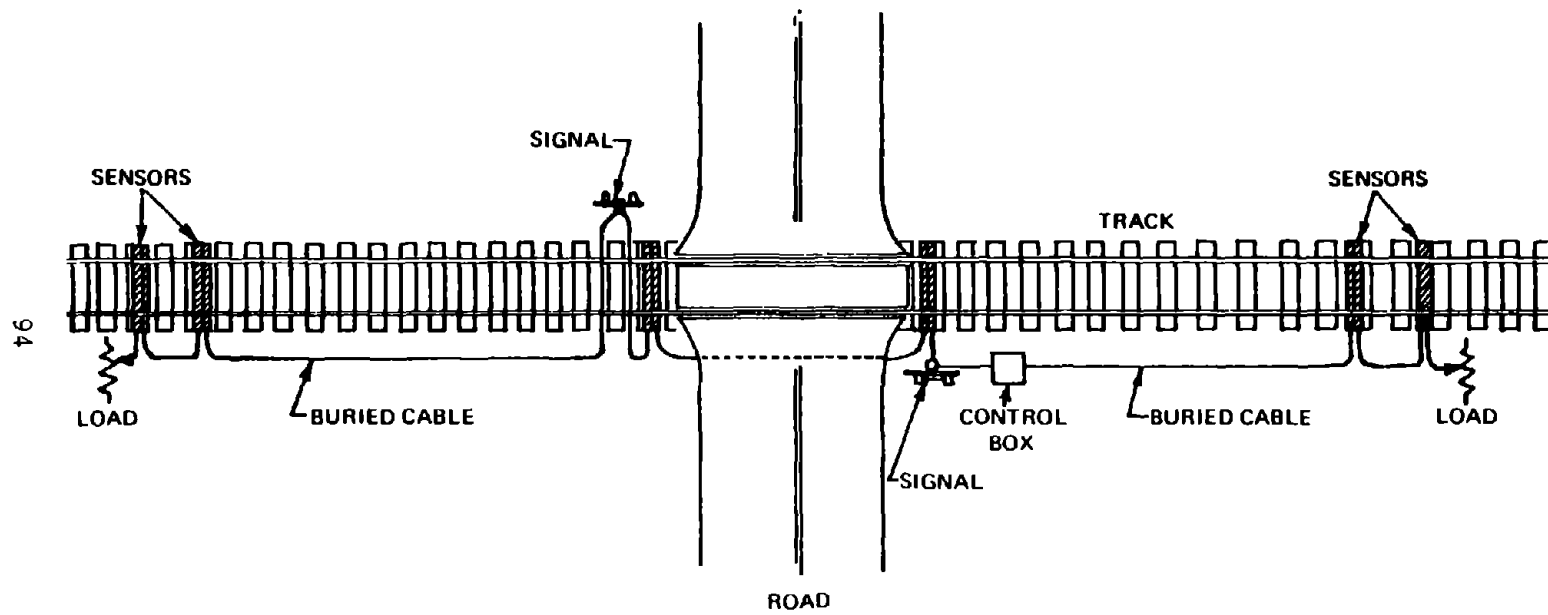


FIGURE 3-1. CONNECTION OF EQUIPMENT AND BURIED CABLE

load seen by a transmitter will be the two nominal 600 ohm loads at the ends of the cable. These will appear in parallel and will therefore be equivalent to one 300 ohm load. A sinewave voltage of 10 volts peak will easily overcome all thermal and equivalent noise. The power required is then;

$$P = \frac{V^2}{2R} = \frac{10^2}{2(300)} = 167 \text{ mW}$$

This power level will be negligible compared to the lights and other circuitry which are powered from the same source. Remember, also, the sensor transmitters will operate with a very small duty cycle (less than 0.1 percent).

Figure 3-2 shows typical cable communications link equipment in block diagram form. Dc power for the sensors is supplied to the cable through an audio frequency choke, which provides a very high impedance to the tones used for signaling. The receiver input is a high input impedance operational amplifier. The input impedance is sufficiently high that its effects on the line are negligible. After the amplifiers have reduced the signal impedance to a satisfactory level, the two signaling tones are separated by filters tuned to their particular frequencies. The outputs of each of these filters is then detected and compared to a fixed reference to determine whether it is present or not. If a tone is detected, the synchronization circuits begin to integrate and sample the received detected signals to produce the data output, which is forwarded to the appropriate circuits.

The circuitry in the transmitter module which inhibits transmission while another transmission is in progress is quite similar to that of the receiver. The transmitter is activated by a message signal from the sensor. This signal consists of perhaps a dozen bits which specifies the condition of the sensor or train velocity and direction. Upon activation, the output amplifier is connected to the signal line and oscillators 1 and 2 are keyed into the amplifier according to the data, which includes both the sensor identification and the sensor message. For compatibility, the transmitted format of these signals will be identical to that used by the carrier and VHF systems. The transmission circuitry and the oscillators are powered only when it is actually needed to transmit information.

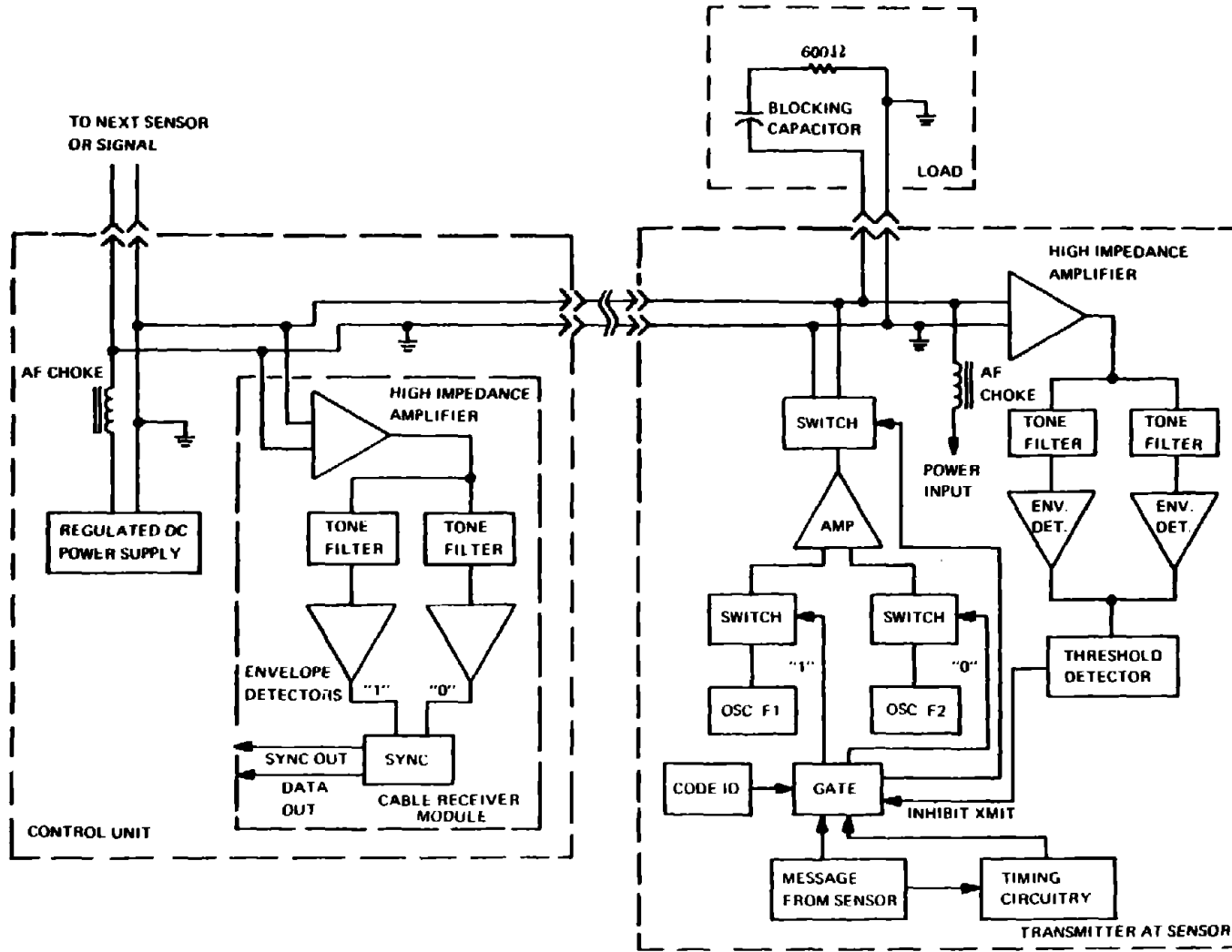


FIGURE 3-2. CABLE COMMUNICATIONS LINK BLOCK DIAGRAM

A load must be attached to the cable at each end to prevent echoes. This load includes a blocking capacitor to prevent the dc power from reaching the load. The 600 ohm resistor is thus only a load for the signals, and otherwise consumes no power. This load might be packaged in a small box which could be attached to the appropriate connectors of the last sensors on the line.

3.4 CARRIER SYSTEM

The carrier system utilized by the railroad-highway grade crossing warning system will have many features common to presently used carrier systems, but will also have some unique features of its own. One feature of the proposed carrier system is that it will not require an FCC license or channel assignment. Agreements must be reached among the parties using carriers on the same line so that the frequencies chosen do not interfere with one another. Also, "type" approval must be obtained from the FCC. This amounts to a certification that any radiation from the equipment is at or below set standards.

Three lines which are applicable to the RHGC system carrier communications are the railroad code line, the railroad power lines, and commercial power lines. Commercial power lines adjacent to the railroad may have a variety of voltages and may run for a variety of distances. Such lines might typically be three-phase lines with 7200 volts between each line and the neutral. In addition, they may contain carriers used by the power company. The use of carriers which did not cause interference to existing power company carriers would probably present no problem. However, installation of trap circuits would not be so easy, so there would be no direct range limitation other than power transformers. None the less, they may be the only link to a remote advance warning sign. At least some presently available equipment has the provision of using a carrier signal on a commercial 110 Vdc line to activate an advanced warning sign¹.

¹Methods to Improve Effectiveness of Railroad Highway Grade Crossing Protection, " Exhibit D-1, Advanced Reports (Communications and Signal Section, AAR Committee D - Highway Grade Crossing Protection, 1971), pp. 142-147.

Railroad power lines are typically single phase 60 Hz at 440 to 550 volts. These lines are presently used only to power wayside signaling equipment, and the use of carriers on these lines is presently minimal or non-existent. Load impedance should be nearly constant. The sensors should draw negligible power from these lines, and with proper fusing can be prevented from being any threat to proper operation of the wayside signals. The lower ac voltage level will also reduce the requirements of the coupling capacitor. Trap circuits could be installed by the railroad as desired. The railroad owned power lines are therefore preferable to the commercial lines.

The railroad wayside code line is probably the best choice for carrier communications where it is available. Such a line should be present on tracks with moderate to heavy rail traffic. The use of this line by the RHGC system is essentially the same as its use by present railroad carrier systems. It will be necessary to assign frequencies which do not interfere with existing carriers on the line, either directly at the carrier frequency or through the generation of harmonics. Communication range can be limited, if desired, by using frequency selective trap circuits. Also, choosing a high frequency carrier (thus increasing its attenuation rate) or lower power can limit the range of the signals.

The use of the rails themselves as a transmission line for carrier signals was considered. However, this technique has numerous disadvantages. Unless special precautions are taken to maintain electrical rail bonds, it would be easy to develop a partially open line. Train wheels and axles will produce multiple short circuits. Both of these effects will tend to produce very large losses in signal transmission. In addition, the use of electrical equipment, especially electrically powered locomotives, will generate very high noise levels. This technique has the disadvantage of having to make numerous direct connections to the rails.

An example carrier system for the RHGC system is shown in Figure 3-3. The receiver has a high input impedance and does not load the line. The output coupling network of the transmitter is tuned to the transmitter frequency and presents a high impedance to carriers of other frequencies. The transmitter for this system might be packaged

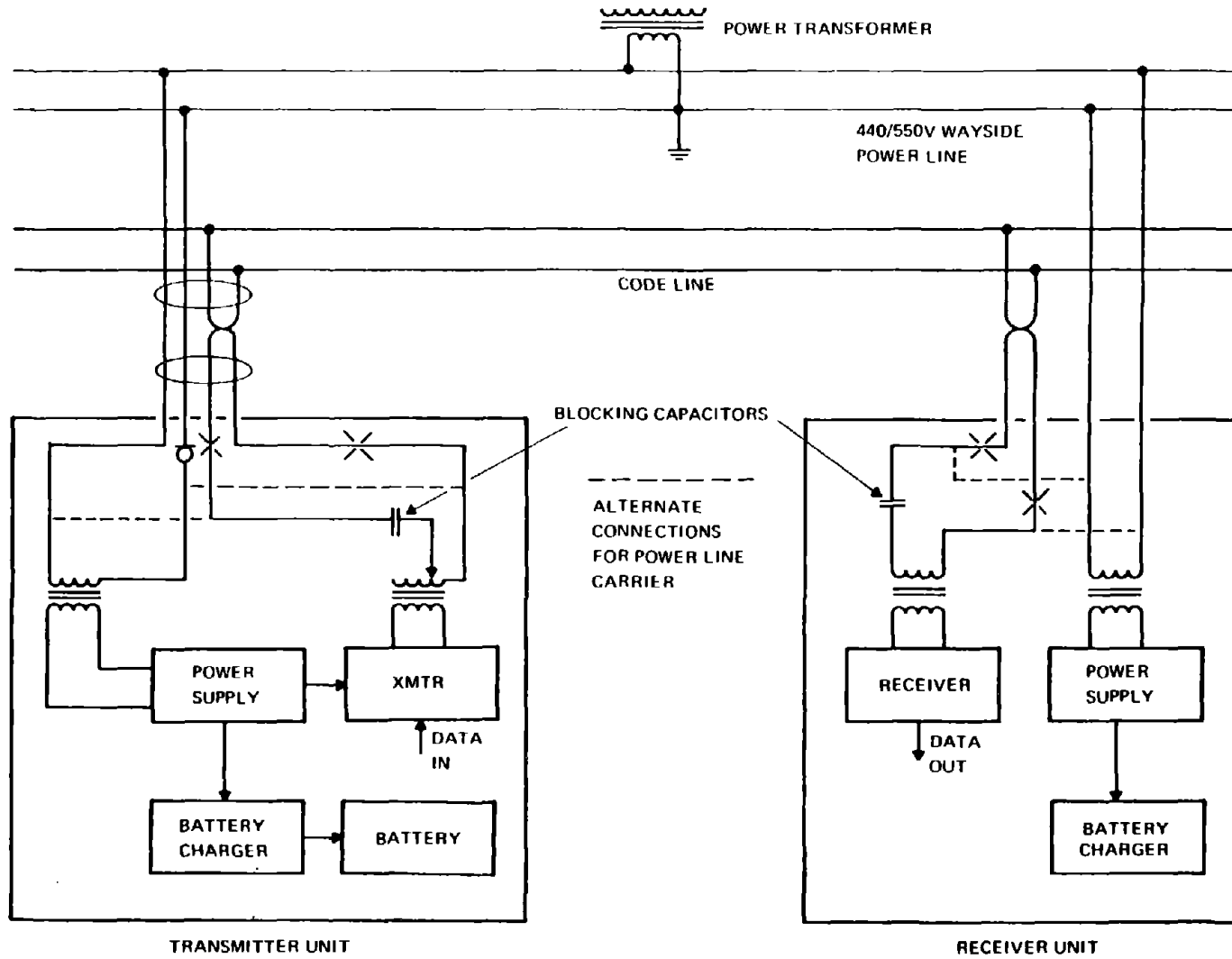


FIGURE 3-3. CARRIER COMMUNICATIONS SYSTEM

along with the sensor circuitry and buried near the track. Power is obtained from the line, and under normal conditions, operates the sensor and transmitter directly. It also charges a battery for operation in the event that line power disappears. Although this system shows the code X line being used for signaling, the railroad power line could also be used by changing one connection in the transmitter and one in the receiver. The only change necessary to utilize commercial power lines is the replacement of the coupling capacitor with one of appropriate ratings.

The carrier frequency used by the railroad-highway grade crossing carrier system should be in the range of 30 to 200 kHz. It would also be possible to use frequencies in the range of 200 to 300 kHz, but higher frequencies are more subject to radiation problems than lower frequencies. The power requirements for reliable communications depends on the noise present on the lines, and this is difficult to evaluate in general². However, power company carrier systems generally use power outputs of 10 watts to communicate over distances of 50 kilometers. Since attenuation is proportional to distance, a power output of 1 watt should suffice for communications over distances of up to 5 kilometers as required by the crossing warning system.

The reliability of this system will be that of the power lines connecting the sensors and signals. The use of standby battery power will allow the equipment to continue operating in the absence of line power. Only a break in the line between the transmitter and receiver will disrupt the link. In the event that the code line is used, the

²J. D. Moynihan and R. C. Cheek, "A Study of Carrier Frequency Noise on Power Lines - Part 1," AIEE Transactions on Power Apparatus and Systems (Vol. 70, Part II, 1951), pp. 1127-1134.

J. D. Moynihan and R. C. Cheek, "A Study of Carrier Frequency Noise on Power Lines - Part 2," AIEE Transactions on Power Apparatus and Systems (Vol. 70, Part II, 1951), pp. 1325-1334.

J. D. Moynihan and B. J. Sparlin, "A Study of Carrier Frequency Noise on Power Lines - Part 3," AIEE Transactions on Power Apparatus and Systems, (Vol. 72, June, 1953), pp 573-581.

whole wayside system will be disrupted as well as the crossing system, so rapid repair can be expected.

The carrier system is designed to be compatible with the cable and VHF systems. In this respect, it utilizes the same coded identification of the system and the sensor, in the same format. All transmitters and receivers operating on the same line in the same system will use the same carrier frequency. This is analogous to the common buss concept used in the cable system. Information is conveyed by means of frequency shift keying, and transmitters are only operated when they have a message to transmit.

The basic equipment for the carrier system is the transmitter module and the receiver module. All equipment is designed to operate over the entire 30 to 200 kHz band with only minor adjustment and parts substitution. The inputs of both the transmitter and the receiver are fused to prevent any possibility of their shorting the wayside power line. The standard blocking capacitor will have sufficient ratings for use on 600 Vac lines; if the equipment is to be used on lines of a higher voltage, a capacitor of appropriate rating is substituted. This capacitor also provides a high impedance to the 60 Hz power, so that only a small amount of 60 Hz current can flow through it. The transformer provides a low impedance shunt to ground. The combination of the high impedance of the capacitor and the low impedance of the transformer prevent application of large 60 Hz voltages to the equipment.

A simplified receiver block diagram is shown in Figure 3-4. The first receiver element after the transformer is a bandpass filter which separates the desired signal from those of other frequencies. An amplifier which follows the filter increases the signal amplitude. The signal is then mixed downward to produce a lower frequency signal. The lower frequency will be common to all receivers so that only one crystal is required and so that the filters for the mark and space frequencies, can be common to all receivers. After separating mark and space frequencies the presence of a signal is detected and becomes a logic level output. Presence of both a mark and space frequency at the same time will indicate the presence of two signals at the same time.

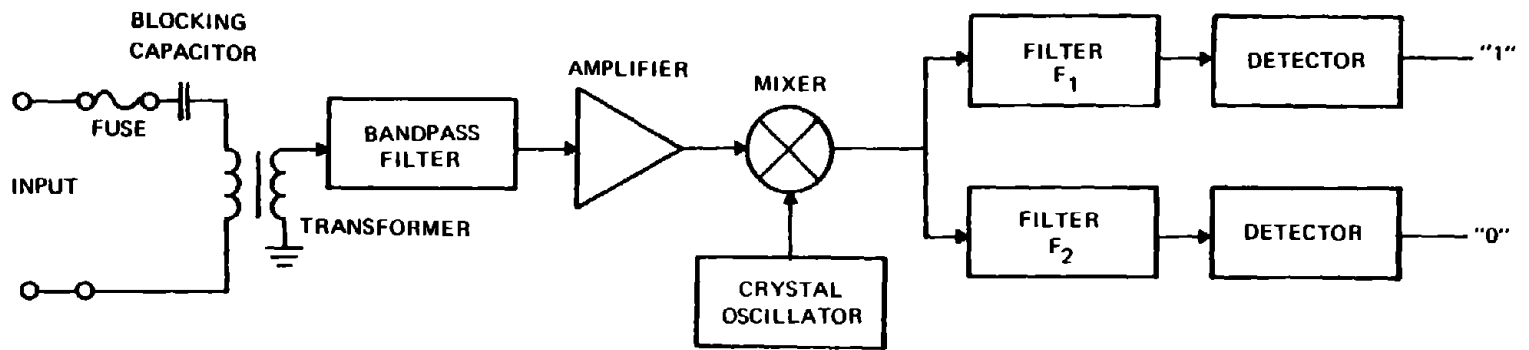


FIGURE 3-4. SIMPLIFIED RECEIVER BLOCK DIAGRAM

A simplified transmitter block diagram is shown in Figure 3-5. The mark and space frequencies are generated by two independent crystal oscillators. One of these frequencies is gated to the driver amplifier, according to whether the data is a "1" or a "0". The 1 watt power amplifier is a class D RF amplifier³. A class D amplifier is used because of its high efficiency (better than 90 percent) and immunity to variations in temperature, drive, etc. The square wave voltage produced by the Class D amplifier is returned to a sinusoidal shape by the output tuning network. The variable tap transformer allows the amplifier to produce 1 watt for a variety of load impedances.

3.5 WIRELESS SYSTEMS

While buried cable and carrier systems should take care of the communications needs of most railroad crossing warning systems, there will still be cases where a wireless communications link will be cost effective. One such case is where there is no ac power, and no code line. In this case, the sensors will operate from batteries (possibly charged by solar panels or windmills), and it will be less expensive to install a simple wireless link than to string or bury wires. A second application of wireless links is to control the advance warning signals, which may be more conveniently powered from nearby commercial power lines. These cases are illustrated in Figure 1-2.

3.5.1 Frequency Selection

The first step in designing a wireless system is to decide what frequency range will be used. While communications can be accomplished over the distances of interest to a railroad crossing warning system with any frequency from ULF to light, the VHF range has several advantages which will be discussed subsequently. First, the salient features of various frequency ranges will be discussed.

³Frederick H. Raab, "High Efficiency RF Power Amplifiers," Ham Radio (Vol. 7, No. 10, October, 1974), pp. 8-29.

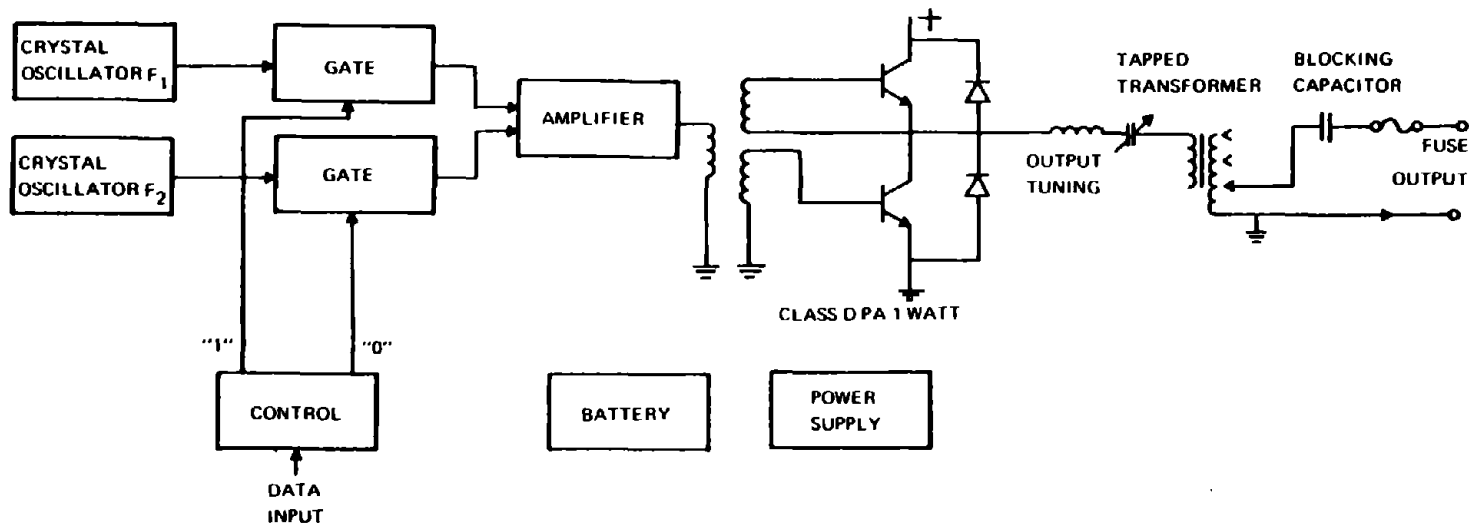


FIGURE 3-5. SIMPLIFIED TRANSMITTER BLOCK DIAGRAM

The lowest usable frequency range for this application is the very low frequency (VLF) range of about 1 to 10 kHz. Such systems would use buried loop antennas or buried grounded dipole antennas to produce the low frequency fields. These fields would decay rapidly with distance, preventing one system from interfering with another. Some experiments aimed at location of trapped miners^{4, 5} have utilized this frequency range. In these experiments, the signals were detectable at distances of 1 to 4 kilometers. However, the transmitter power was in the range of 10 to 20 watts and the receiver bandwidth was in the range of 2 to 5 Hz. The high transmitter power requirement is not compatible with battery operation, and the narrow bandwidth would require excessive time to transmit identification and data information. VLF systems are therefore not recommended for this application.

Low frequency radio signals (50 to 200 kHz here) could be used for signaling. Power requirements would be only about a watt or so, and the bandwidth would be adequate to support the desired information rate. While long distance communications stations require large transmitting antennas for use with these frequencies, the railroad crossing warning system requires signaling only over a few kilometers, so antennas between one and five meters high would be sufficient. However, some practical problems arise in using this frequency range. The antenna appears to be a very small capacitance to the matching network, and consequently even one watt will generate voltages of several hundred volts. In addition, any water, snow, or leaves resting on the antenna base will significantly alter the effective capacitance, requiring an automatic tuning circuit. This would add greatly to the complexity of the otherwise simple transmitter. A LF system is therefore not recommended.

⁴R. G. Olsen and A. J. Farstad (Westinghouse Electric), "Electromagnetic Direction Finding Experiments for Location of Trapped Miners," IEEE Transactions on Geoscience Electronics (Vol. GE-11, No. 4, October, 1973), pp. 178-185.

⁵Jim McDermott, "ULF Direction Finder for Miners Passes Tests at 1500-ft. Depth," Electronic Design (Vol. 22, No. 20, Sept. 27, 1974), pp. 32-33.

Medium frequency (MF) and high frequency (HF) systems (300 kHz to 30 MHz) could easily span the required distance. Power requirements would be low. Since the antenna would not be such a small part of a wavelength at these frequencies, tuning would not be as great a problem as it would be at low frequencies. However, these frequency ranges are subject to "skip" propagation. It would not be unusual for a signal control system to receive signals from halfway across the continent which were much stronger than those of its own sensors. While some of the confusion could be eliminated by selective coding, it would be very difficult to prevent interference from all possible sources. In addition, it will be difficult to get a channel assignment in this band. The use of MF or HF communications is therefore not recommended.

Microwave systems (Figure 3-6), operating in the range of 1 GHz and above, have been proposed as both an alternative to the track circuit and as a communications link for discrete sensors^{6,7}. Power requirements are not great, and the beams can be made highly directional to avoid interference with other systems. However, there are several drawbacks to the use of microwave communications systems in this application. First, microwave signals are ideally suited to handling large amounts of information in large bandwidths. The relatively small amount of data transmitted by the railroad sensors and controls makes very inefficient use of the channel assignment. This may make it difficult to obtain such assignments. Microwave transmitters are both less efficient and more expensive than lower frequency transmitters. While directional antennas can be used to focus the beams on the desired receivers, it is also necessary to have one directional antenna for each direction from which signals are to be

⁶John B. Hopkins and Morrin E. Hazel, Technological Innovation in Grade Crossing Protective Systems (Technical Report No. DOT-TSC-FRA-71-3, Cambridge, Massachusetts, June, 1971).

⁷Hopkins, et. al., A Communication-Link Approach to Activation of Grade-Crossing Motorist Warning Systems, Technical Report FRA-OR&D-75-80, July, 1975.

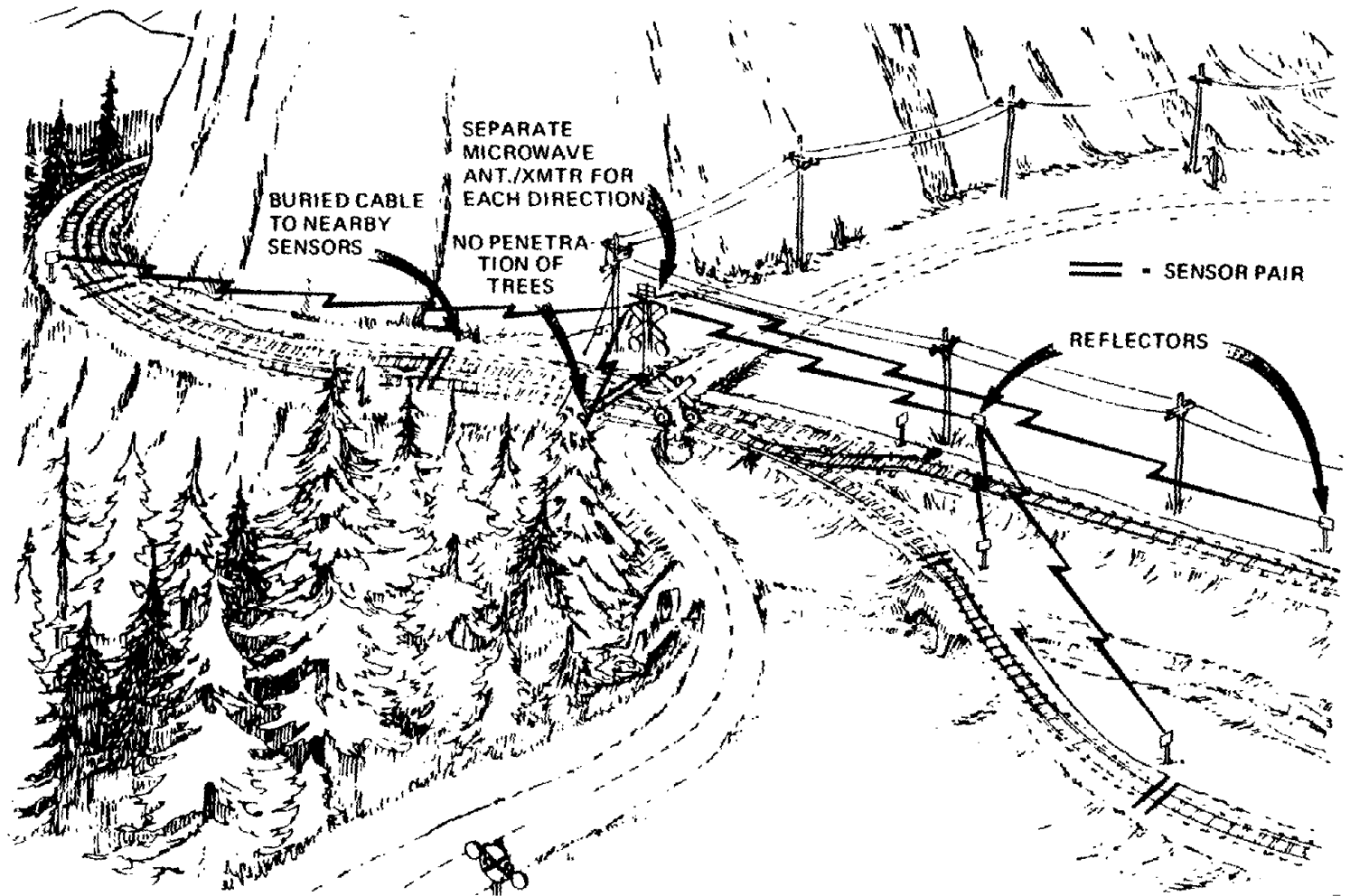


FIGURE 3-c

received or to which they are to be transmitted. Antennas must be properly pointed or no signal will be received. In addition, microwave signals will not penetrate hills, buildings, and forest without increased transmitter power. For these reasons, the use of microwave communications is not recommended for this application.

Optical systems include lasers, infrared, and a variety of other devices. Such systems would not only be very expensive, but suffer from numerous problems. Directional alignment of transmitter and receiver will be very critical. A complex coding technique will be necessary to separate the desired signal from a variety of noise due to the sun, sky, headlights, etc. Optical communications are therefore a poor choice for the railroad crossing system.

This leaves the very high frequency (VHF) range, which is 30 to 400 MHz for present purposes. Power requirements for the transmitter will be 200 mW or less. The channel assignments are well suited to this application, providing neither too much nor too little bandwidth. Transmitter and receiver circuits are simple and inexpensive. A simple whip antenna approximately one meter high provides omnidirectional coverage. Signals at these frequencies will penetrate most obstacles. While there will occasionally be some skip interference, it will not be extreme, and can be ignored by selective coding. Usage of the 30 to 50 MHz region has been declining, so it would not be too difficult to obtain an assignment there. Thus a VHF system is recommended as the wireless link for the railroad crossing warning system.

3.5.2 The VHF System

A VHF communications system applicable to the railroad highway crossing protection system is shown in Figure 3-7. The basic elements of such a system are the antenna, transmitter, and receiver. It will be convenient to package these components so that they can be mounted together. This will prevent signal losses in the connecting lines in both the transmitter and the receiver.

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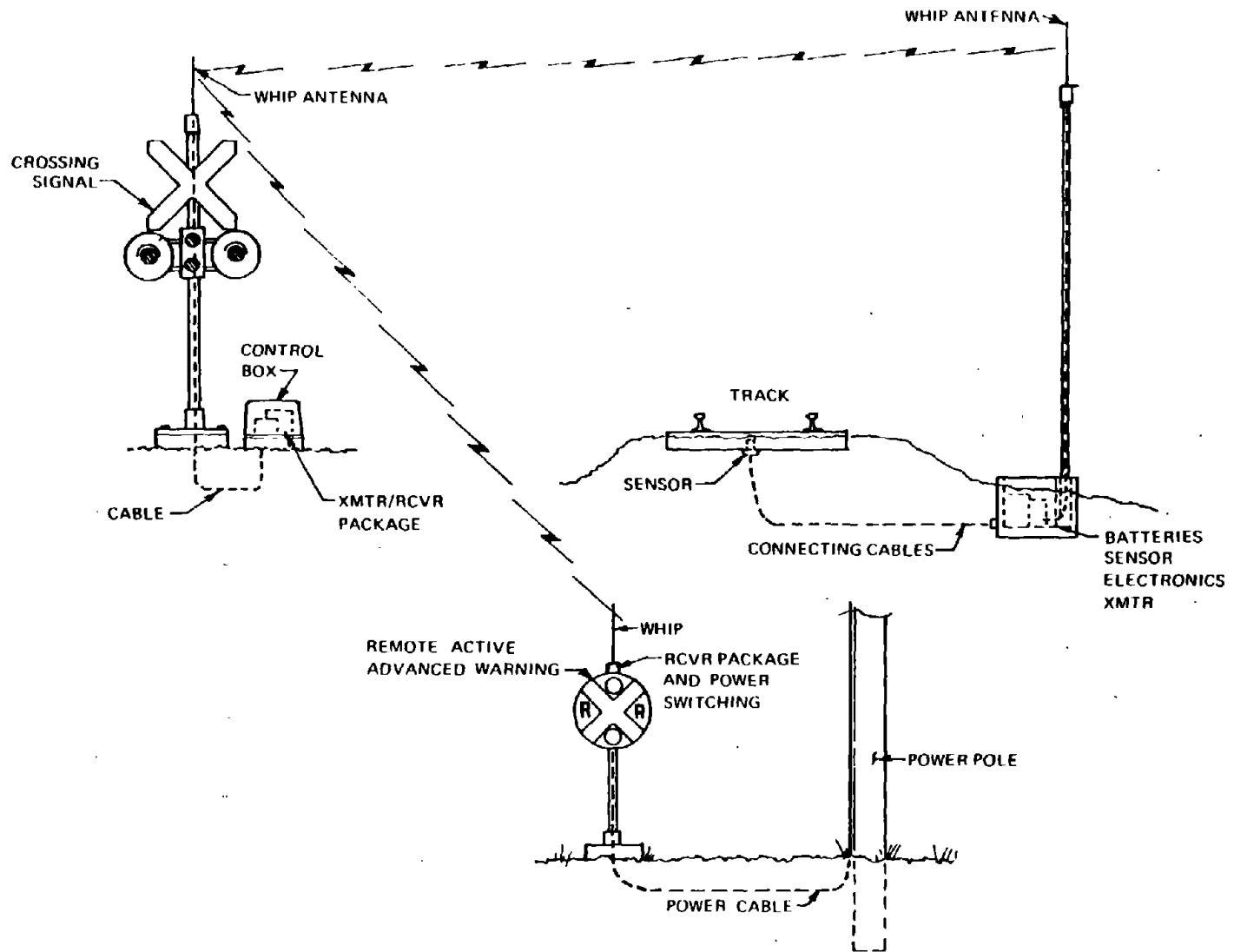


FIGURE 3-7. VHF COMMUNICATIONS SYSTEM

Each group of sensors will require a transmitter/antenna unit. This unit should be mounted on a pole near the sensor location so that its signals will not be blocked by nearby objects or by the train. The battery power supply and connecting cables are buried for their protection from the environment and from vandals. Since this pole has to support little more than its own weight, it can be of fairly light construction. The whole pole-transmitter-antenna assembly might be enclosed in a fiberglass cover to make it uninteresting to vandals. The pole also provides a convenient mounting place for solar panels or windmill generators. Disturbance to the environment and to aesthetics should be negligible.

The crossing signal provides a convenient mounting place for the VHF antenna. This module is simply attached to the top of the signal near the control circuit box. The receiver package can be mounted on top of a remote advance warning sign which is powered from commercial power lines nearby. Otherwise, the transmitter and/or receiver will be installed with the control or sensor electronics.

The configurations shown here are only examples. The particular choice of modules will depend on the particular situation.

The VHF transmitter and receiver modules are shown in block diagram form in Figure 3-8. This diagram actually shows both transmitter and receiver in the same module, in which case a switching relay is required. The transmitter and receiver circuits can be packaged as plug-in cards and installed as needed.

The most practical modulation technique for frequencies in this range is audio frequency shift keying (A FSK). In this technique, one of two audio tones is generated according to whether the data is a "1" or "0". These tones modulate the frequency of an oscillator in the same manner that a voice signal would modulate it. This technique allows for a great tolerance in the stability of the carrier frequency, since offsets in carrier frequency do not cause changes in the demodulated audio tones. For purposes of commonality, the tones will be the same in all units. With reasonably fast data transmission, there will be little advantage in using different tone pairs in different signals.

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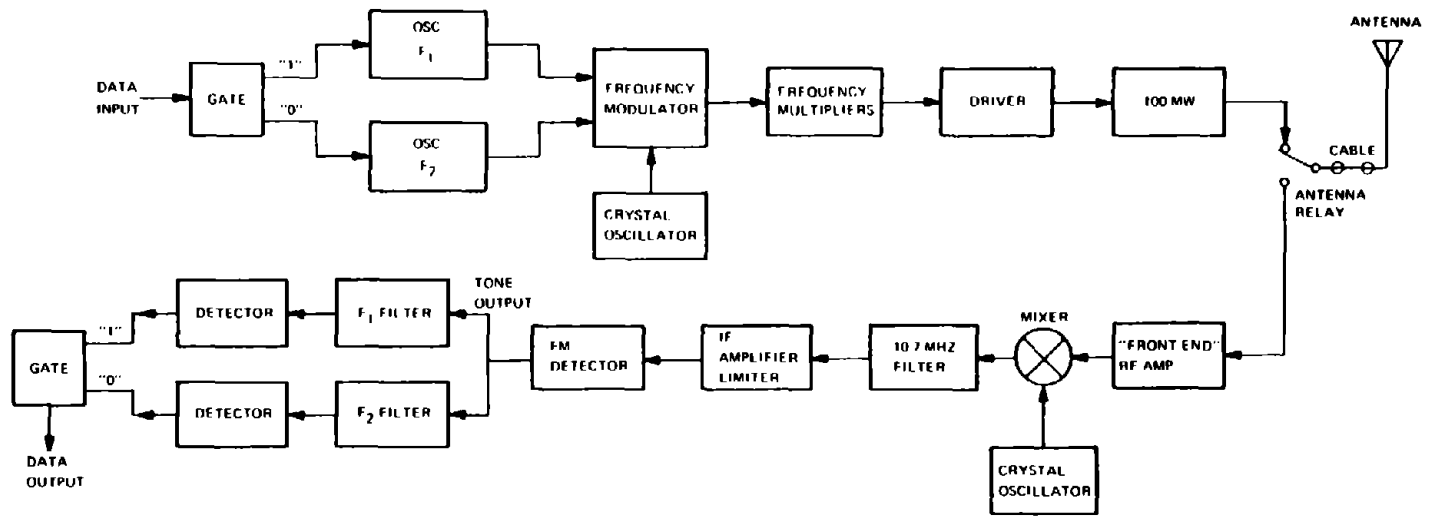


FIGURE 3-8. VHF TRANSMITTER-RECEIVER BLOCK DIAGRAM

The transmitter then consists of two tone oscillators, gated to a crystal controlled modulator, frequency multipliers, a driver, and power amplifier. The receiver is a superheterodyne type, with most of the components essentially the same as are used in commercially available portable FM radios. The receiver signal is amplified and then converted to an intermediate frequency of 10.7 MHz. It is then further amplified and limited to remove amplitude changes, after which it is detected. The output of this detector is either noise or one of two audio frequency tones, according to what was transmitted. The presence of a tone indicates a "1" or "0" (or no transmission).

There will occasionally be propagation anomalies which allow one system to receive signals from another system in a different geographical area but using the same channel assignment. Skip will occur occasionally in the lower VHF frequencies, and weather related phenomena can produce tropospheric ducts at the middle and higher VHF frequencies. Generally, however, these long distance signals will be considerably weaker than those of the nearby transmitters. To prevent any possible confusion, selective coding will identify each signal uniquely. The components of a given system will respond only to signals with the proper identification; all others will be ignored.

Determination of the power requirements of the transmitter requires a link analysis. This includes such factors as distance, frequency, antenna gain, and receiver sensitivity. A sample calculation for a 50 MHz link follows:

Required receiver output S/N	=	20 dB
Receiver bandwidth	=	3 kHz
Antenna gain (whip)	=	2 dB
Maximum range	=	5 km
Noise temperature	=	600°K

Noise power is then

$$N = KTB = 2.48 \times 10^{-14} \text{ mW} = -136 \text{ dBm}$$

Combining these, the required signal at the receiving antenna must be

$$P_{RMIN} = 20 \text{ dB} - 2 \text{ dB} - 136 \text{ dB} = -114 \text{ dB}$$

Path loss in free space is given by

$$L_P = \left(\frac{4\pi d}{\lambda} \right)^2$$

where d is distance and λ is wavelength. For a carrier frequency of 50 MHz, $\lambda = 6$ meters. At a distance of 5 km,

$$L_P = \left(\frac{4\pi \times 5000}{6} \right)^2 = 1.096 \times 10^8 = 80 \text{ dB}$$

Assuming that the transmitter antenna gain is the same as the receiver antenna gain, the required transmitter output is then

$$P_T = -114 \text{ dBm} - 2 \text{ dB} - 80 \text{ dB} = -36 \text{ dBm}$$

which is less than a microwatt.

While this is a calculation based on ideal conditions, it does show that power requirements are small. In a real situation, the path loss will be increased by foliage, hills, buildings, multipath reflections, and many other factors, and there will be interference from other communications equipment and other sources such as automobile ignition. A transmitter with an output of 100 mW would, however, have a 56 dB safety margin, which should be more than adequate to take care of these problems.

3.6 COMMON CODING AND FAILSAFE TECHNIQUES

To make an effective three link communications system, it will be necessary to define common format, coding, and failsafe techniques. This definition will simplify the design and servicing of the equipment and improve reliability.

3.6.1 Coding and Format

Previous discussion has shown the need to identify each system uniquely, as well as to identify a particular sensor or command and to relay information. We will now examine exactly what is required to accomplish this.

There are approximately 250,000 grade crossings in the United States. An 18-bit binary sequence will identify $2^{18} = 262,144$ different crossings uniquely, and would therefore suffice for any present needs. It is difficult to say how many crossing identifications will be required. Certainly not all crossings will be protected by active devices, nor will all of the active crossing warning systems use this system, nor will all of these employ VHF links, nor will all of those using VHF links use the same channel. However, it will be possible for Canada, Mexico, and other countries to employ the same types of systems. The device of a 20-bit identification sequence provides for $2^{20} = 1,048,576$ unique identification codes, which should provide for any foreseeable situation.

The next information which must be transmitted is an identification of which sensor or device within a given system is reporting or is commanded to operate. Commands include such things as "advanced warning turn on" or "engineer warning go to steady on". An eight-bit sequence will specify $2^8 = 256$ different commands and sensors, and should be adequate for any system. These codes might be conveniently grouped by link so that the first two bits identified the link. This would allow the activation of only the proper link, keeping the others clear.

Finally, there is sensor status and velocity/direction information. Status includes "operating satisfactorily", "minor fault", "major fault", "train present", "train absent", "train just appearing", and "train just leaving". Four bits will specify 16 status messages. One additional bit will specify direction. The number of bits required to convey velocity information depends on both the range and the accuracy required. Specification of velocity to 0.1 km/hr increments will result in a 1 percent

or better accuracy at velocities of 10 km/hr or more: Since trains in the future might be expected to travel at velocities of up to 300 km/hr, 3000 different velocity values must be indicated. This requires 12 bits, since $2^{12} = 4096$.

To transmit system identification, sensor/command identification, and data then requires a total of 45 bits. Allowing 5 bits for error correction/detection results in a 50-bit sequence. A reasonable bit rate is 1 kb/s, so total transmission time for any one sequence is 50 milliseconds.

It will be desirable from a cost effectiveness viewpoint to provide error detection circuitry but not error correcting circuitry. Error detection can be accomplished by simply generating parity check bits which are transmitted in the five final bits of the 50-bit sequence. One bit could check each 9 data bits. Parity can be computed by a simple counter circuit which toggles for "1" but not for "0". The same type of circuit in the receiver generates parity bits according to the received data. If these parity bits agree with those received, the message is assumed to be correct. If not, it is assumed incorrect and discarded.

3.6.2 Failsafe Operation

It is important not only to insure the reliability of the system through proper design of equipment, but also to provide for failure if it should happen. If a sensor of communications system fails to operate properly, the control circuitry must know this so that it can display the malfunction signals to both the motorist and the engineer.

Present track circuits provide failsafe operation by keeping the switching relay energized except when shorted by the wheels and axles of the train. Should the power disappear or the cables break, the relay de-energizes and activates the signal.

A similar technique could be used in the new railroad crossing warning system by requiring all sensors to transmit at all times. The absence of a signal would then

indicate a failure, and a malfunction warning would be given. However, this technique not only clutters the communications channels but also causes unnecessary power consumption by the transmitters, degrading their standby power capability.

For these reasons, it is desirable to operate the sensor communications on an intermittent basis. A sensor reports immediately when it is activated or deactivated by a train. Failsafe operation is insured by causing the sensor to report its status at set intervals whether or not a train is present. The absence of a satisfactory report causes a malfunction warning to be displayed.

It would be possible for the control circuitry to interrogate each sensor and order it to report, thus preventing two sensors from reporting simultaneously. While this technique has the desirable property of controlling the reports, it will require receivers to be installed at all sensors. This not only adds to the expense of installation, but adds another component which may fail.

The automatic sensor status reporting is satisfactory for this application because sensor messages are of relatively short duration, compared to the reporting intervals. A 50-bit sensor message will take about 50 msec to transmit, while the sensor must report its status perhaps once a minute. Occasionally, two or more sensors will report at the same time. This condition will generally be detectable either through the presence of both mark and space signals at the same time or through bad parity checks, or both. The reporting interval assigned to each sensor in the system should be slightly different to insure that two subsequent reports do not overlap. Messages such as "train just arrived" or "activate advance warning" can be repeated two or three times to insure reception.

3.7 CONCLUSIONS

A RHGC system will require a communications subsystem to transfer information between sensors and the control circuits, and between the control circuits and the sig-

nals. Flexibility requires provision to use any of three communications links, as needed. These links are:

Buried cables, used when the distance is short.

Carrier, used when existing power or signal lines are available nearby.

VHF, used when sensors are remotely powered or no lines are present near the desired path.

Failsafe operation is insured by having all sensors report their status on a periodic basis.

4. SIGNALS

4.1 PURPOSE

The ultimate purpose of the sensor subsystem and the communication subsystem is the activation and control of a warning signal. This system concept calls for three basic types of displays (signals), which are:

Motorist Crossing Warning Signal	STOP for Train
	CAUTION - Signal Inoperative
Motorist Advance Warning Signal:	CAUTION - Crossing Ahead
Engineer Warning Signal:	ALERT - Crossing Ahead
	CAUTION - Signal Failure

This system will provide for credibility and rapid maintenance, as well as safety. It may be used with gates or without, just as present systems are used with and without gates. The functions of each element in the display subsystem and some general characteristics will now be discussed.

4.2 MOTORIST CROSSING WARNING SIGNAL

The motorist crossing warning signal has several purposes. First, it must alert the motorist to the presence of a railroad crossing even when no trains are present. This allows the motorist to slow his vehicle to avoid the bumps associated with the crossing. Secondly, when a train is present or expected, the signal should attract the motorists attention and cause him to stop. Thirdly, when the signal is not operating properly, it should cause the motorist to be especially careful in approaching and crossing the

tracks, since he must decide whether or not they are clear. It is desirable that the later two functions cause different warnings to be displayed, since the desired motorist behaviour is entirely different.

4.2.1 General Requirements

The meaning of any sign or display must be clear and concise. If it confuses the motorist, consumes his time and attention, or is ambiguous it will not be effective and may tend to increase the possibility of an accident.

A railroad crossing signal should be recognized as such. Even when there is no train, a railroad crossing has special problems which the motorist must be aware of, such as bumps caused by the rails and the spaces near them. In addition, a train and an automobile are not the same in either appearance or movement patterns, so the motorist must be looking for a train.

The signal must be visible and conspicuous. It must also be capable of battery operation for approximately two days in the event of failure of the primary (line) power. The signal must also be failsafe and reliable, as must be all of the subsystems. Failsafe and reliability aspects are discussed in Section 5.

The signal must also be credible to the motorist. Reliable circuit design, separate "stop for train" and "signal inoperative" displays, and constant warning time will ensure this.

4.2.1.1 Crossbuck

The crossbuck design should be retained and/or incorporated into the design of any new warning signal. Motorists in the USA and other countries readily identify the crossbuck design with a railroad crossing. Retention of the crossbuck will make use of existing motorist associations.

Several types of crossbuck designs are possible (Figure 4-1). Conventional designs (A) and (B) used in the United States use black lettering on a white crossbuck. Recent and current studies on passive crossings^{1,2} have suggested some new high visibility designs. One such type (E) uses a red and white crossbuck for contrast against a variety of backgrounds, and is similar to European designs. Another suggestion is the use of a bright yellow-green (D) or highway yellow (C) crossbuck. The latter has also been tried in Canada³. The bright yellow-green design may not be very desirable because it may blend with some types of foliage. Preference for another type should not be made until the current studies are completed.

The active crossing warning system should utilize the new crossbuck design adopted for passive crossing warning. It is recommended that this new type of crossbuck be installed only on active warning signals which are equipped with both a malfunction warning display different from the "stop for train" display and with constant warning time control circuits. The new crossbuck will then denote a credible crossing warning system and will thus be valuable in introducing motorists to the new signals.

4.2.1.2 Lights

The illumination of various lamps is one means by which the signal will convey information to the motorist. Different information is conveyed by and different conspicuity

¹Slade F. Hulbert and R.C. Vanstrum, "Passive Devices at Railroad Highway Grade Crossings," Proceedings of 1972 National Railroad - Highway Grade Crossing Safety (Columbus, Ohio, August 29, 1972), pp. 26-29.

²Howard H. Bissell, "New Passive Devices" (paper for 1974 National Railroad-Highway Grade Crossing Safety Conference, Colorado Springs, Colorado, August 20, 1974).

³"Railway Crossing Sign Symbol Type," Exhibit D-3, Advanced Reports (Communications and Signal Section, AAR Committee D - Highway Grade Crossing Protection, 1971), pp. 154-155.

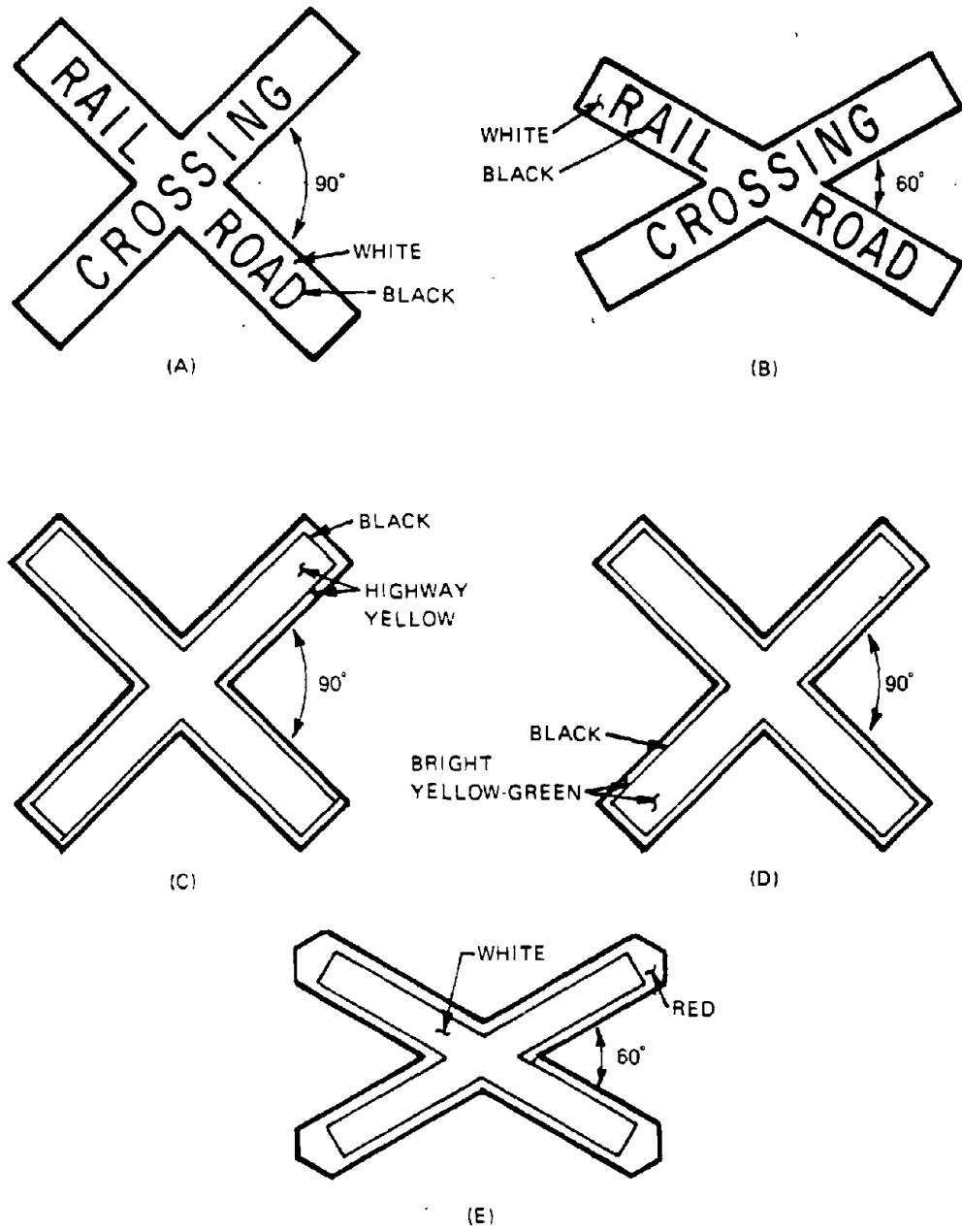


FIGURE 4-1. CROSSBUCK DESIGNS

is obtained from different color lights. The same is true of whether or not the lamp is dark, illuminated, or flashing, and of any pattern generated by a set of lamps.

The colors red, amber, and green have the clear and well accepted meanings of "stop", "caution/slow", and "ok/go" and can therefore be used to convey such information without confusion. Orange is not clearly distinguishable from red or yellow. Blue and White lights can be used to attract attention, but have no clear meaning. The use of blue might also result in a mistaken association with an emergency vehicle. Thus only the colors red, amber, and green should be used where color is to convey meaning. White might be used to attract attention or to give certain specific information. Blue and orange should be avoided. In fact, color should in general be used only as a secondary means of conveying information, since color-blind people will also use the signal.

A flashing light is much more conspicuous than a constantly illuminated light; it provides a continuous comparison of dark-to-light which stands out in a variety of background lighting conditions. A moving light is also more conspicuous than a fixed light. However, physical movement of the light, such as in a wig-wag signal, require inherently unreliable mechanical arrangements. An illusion of movement can be obtained by alternately flashing two (or more) lights. This arrangement is very effective in attracting the motorists attention, and has the additional advantage of redundancy. If one light fails, the other still conveys the warning. Two or more lights in an alternating or moving pattern is therefore recommended.

Words can also be used to convey specific information. For example, a flashing "STOP" could be used as the "stop for train" warning. However, words are not as readily recognizable as symbols, and recognition depends at least somewhat on a basic familiarity with the language used. Current tendencies favor the use of internationally recognized symbols for highway signs, and the same should be true for railroad crossing signs. The primary message should be conveyed symbolically or positionally. Words could be used ("stop" on each light of a present crossing, for example), but

should not be the primary method of information conveyence. The addition of words will probably be of little value except in identifying a new type of signal.

4.2.1.3 Strobe Lights

A strobe light uses a gas discharge tube to produce a brief high intensity light pulse. Generally xenon gas is used, and the resultant flash is white. However, filters or other gasses can be used to produce colored light. Such lights are commonly used in flash attachments for cameras. They generally use less power than flashing or rotating incandescent lights, and are more reliable as well.

Because of its high intensity, a strobe light is highly conspicuous. Currently, strobe lights are being used in place of or in addition to blinking or rotating incandescent lights in marking towers, aircraft, and emergency vehicles. While white is usually used in these applications, colored strobe lights have also been used. Experiments have also been done in using strobe lights to increase locomotive conspicuity⁴. In these experiments, two strobe lights were mounted on the cab of a locomotive and flashed alternately. A rate of 2 to 3 flashes per second appeared most effective. A brightness of 400 to 600 candela was highly conspicuous at night. A brightness of 4000 to 6000 candela might be desirable for daytime use, but over 1000 candela may annoy people, and 600 candela is still highly visible. Automatic day/night brightness compensation could be accomplished by controlling pulse duration with a photocell.

A strobe light or lights might be used in the crossing signal to increase conspicuity or equivalently, to attract motorists' attention. However, its application is somewhat different in that after the motorist notices the strobe light, he must watch the train, rather than the signal. While a strobe will certainly be conspicuous, it may tend to

⁴John B. Hopkins, and A. T. Newfell, Guidelines for Enhancement of Visual Conspicuity of Trains at Grade Crossings (Report FRA-OR&D-75-71, Transportation Systems Center, Cambridge, MA, March, 1974).

distract the motorist as he nears the crossing and obscure his watching of the train. This suggests that the strobe light housing allow full brightness to be visible from directly in front, but lesser brightness to be visible from the sides. This will allow a motorist parked near the crossing to concentrate on the train while remaining aware of the operation of the lamp. Figure 4-2 illustrates a simple tapered-slit reflector which should accomplish this without wasting (absorbing) light energy.

It is important to note that the strobe light is effective only because it is more conspicuous than other lighting presently used. Present alternately flashing red lights were no doubt similarly effective when they were first introduced. If, for example, strobe lights become widely used attention getters for advertising displays, their effectiveness for railroad crossing warning and emergency vehicle conspicuity will be greatly reduced. It is therefore recommended that legislation be enacted limiting the use of strobe lights visible from roadways to warning signs and public safety vehicles. This will be the only real solution to the conspicuity problem.

4.2.1.4 Gates

The use of crossing gates has been shown to be highly effective in reducing the number of railroad-highway grade crossing accidents at a given crossing. They should be used whenever money for them is available. However, since gates do add significantly to the cost of a system, it will not be possible to use them at all crossings.

The efforts of this study are therefore directed at the rest of the signals (i.e., the crossbuck and light assembly) with the understanding that gates are an option which can be added and should be added when economically feasible.

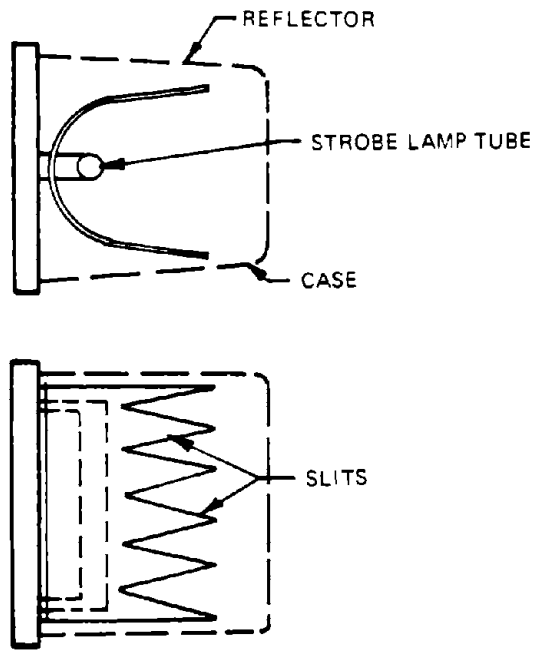
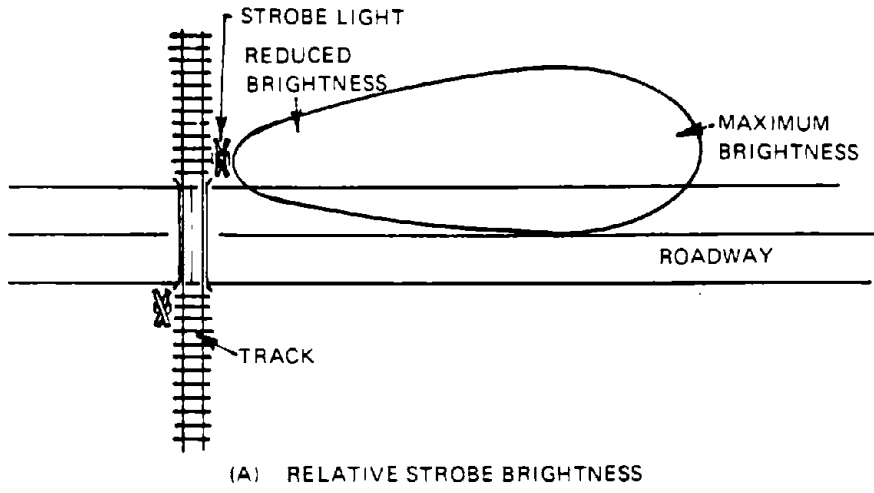


FIGURE 4-2. STROBE LIGHT MOUNTING

4.2.1.5 Displays

Previous discussion has shown the need for two distinct displays: "stop for train" and "caution, signal inoperative". Several other displays have been suggested, in particular multitrack information, directional information, and "all clear".

Directional information could help the motorist find the train, and a multitrack display would discourage the motorist from proceeding after the end of one train when another was approaching. However, both types of information are of a nature which helps the motorist cope with present unreliable or non-credible signal systems. If the signal is known to be reliable and provides constant warning time, the motorist will learn to trust it. Multitrack and directional information is then unnecessary. In fact, it will be undesirable in that it detracts from the primary "stop for train" message and consumes additional power.

An "all clear" signal could be given to the motorist by the illumination of a green or flashing green light. Such a display would presumably be advantageous in multitrack situations since the motorist would learn to wait until the "all clear" appears before proceeding. However, in reality, the "all clear" will be of doubtful value because the motorist will proceed when the red lights are extinguished (in the absence of an "all clear" display). Also, the "all clear" display consumes extra power. Its failure (illumination when it is in fact not "all clear") implies certain railroad liability for any resulting accidents. An "all clear" display is therefore deemed undesirable, as are multitrack and directional information.

4.2.2 Stop for Train Display

The primary display in the crossing signal is that which conveys the "stop for train" message. This message is presently conveyed by alternating red lights, arranged horizontally. Some other possibilities include alternating red strobe lights, the addition of a white strobe to the present lights, a traffic light, a flashing arrow, a flashing crossbuck, and four alternating red lights mounted in the crossbuck. These will

be discussed subsequently. Other configurations are no doubt possible, as are combinations of the above. Mechanically moving arrangements, such as wig-wags, are not considered for reasons of reliability. The same affect can be obtained by sequences of lights.

4.2.2.1 Arrow

A flashing arrow (Figure 4-3) is a highly conspicuous warning display. In this display, all lamps are initially dark. They are then illuminated in sequence until all are illuminated, giving the appearance of movement or pointing. Amber arrows of this type are presently used by road work crews to indicate "go around".

This type of display could be adapted to a "stop for train" display by using red lamps and mounting the display below the crossbuck. While there might be some confusion, it is conspicuous and motorist acceptance is probable. Train direction could be given by the direction of the flashing sequence.

There are, however, two distinct disadvantages to this type of display. First, it will consume as much as ten times the power consumed presently by two alternating lights. This is a decided disadvantage for standby power operation. Secondly, the movement of the arrow is confusing, and probably more harm than help. Some motorists will look for the train in the direction to which the arrow points. Others will regard arrow movement as train movement and look in the opposite direction. Those looking in the wrong direction will see no train and may proceed over the track in front of an approaching train. The arrow display is therefore not recommended.

4.2.2.2 Traffic Light

A traffic light type signal (Figure 4-4) would prove effective at stopping vehicle traffic since the motorists would not like to risk getting a ticket. Since a railroad-highway crossing is basically a traffic problem, the use of traffic signals has been suggested. Meanings of "stop for train", "caution, malfunction", and "all clear" are obvious and clear.

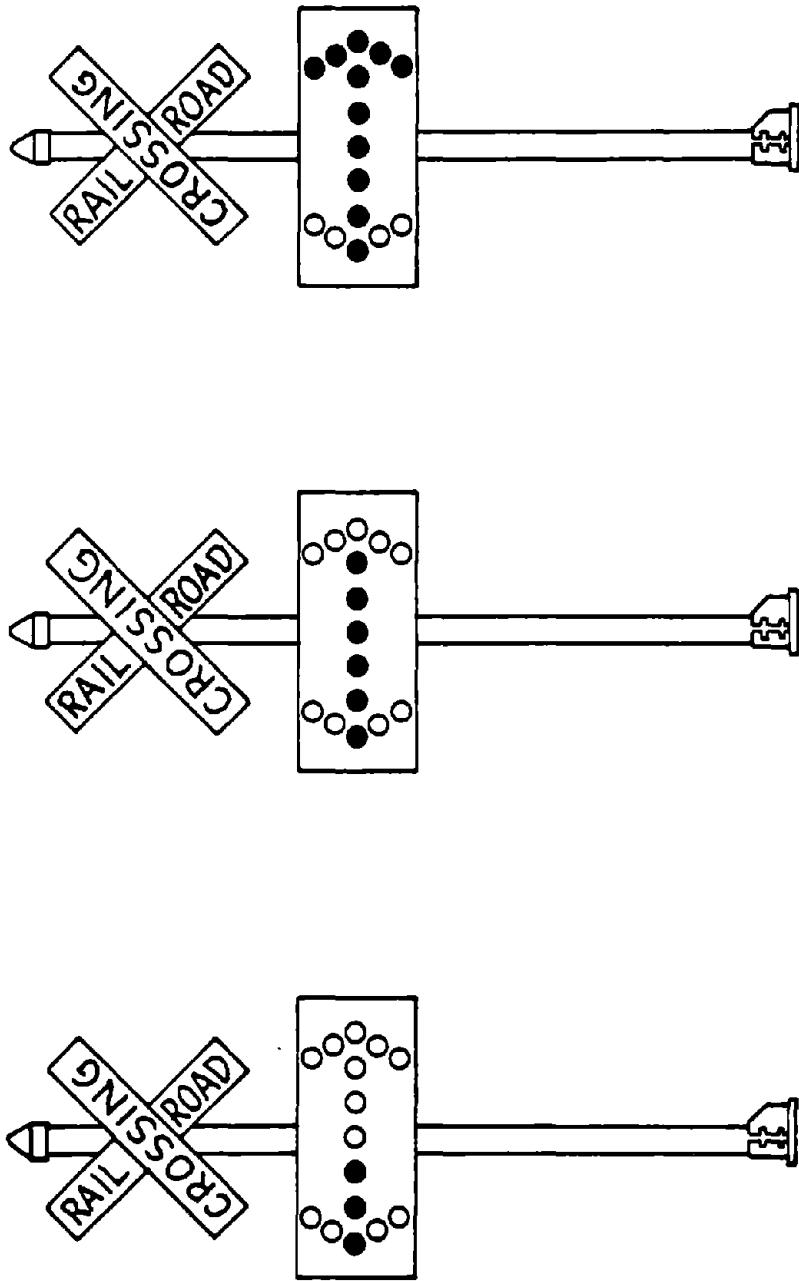


FIGURE 4-3. SIGNAL BASED ON ARROW

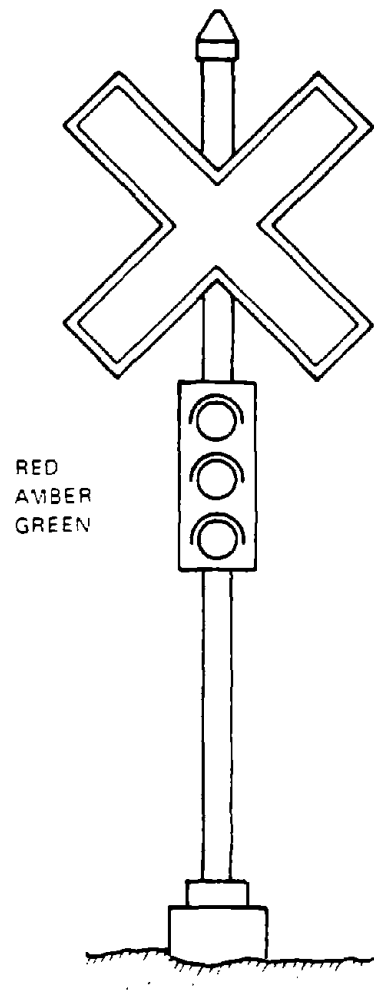


FIGURE 4-4. SIGNAL BASED ON TRAFFIC LIGHT

Consideration of the use of a traffic light type crossing signal immediately reveals several problems. A crossbuck should be used to warn of problems associated specifically with a railroad crossing. The signal thus resembles a railroad signal rather than a traffic light, and its effectiveness as such will be reduced. The "all clear" green light is neither necessary or desirable, but its elimination further reduces any similarity to a traffic light. This leaves a single red and a single amber light, so there is no redundancy in the event of lamp failure. The single red lamp illuminated constantly will not be highly conspicuous. However, causing it to flash may convey the message "stop, then proceed" as does a single flashing red traffic light. For these reasons, the use of a traffic light type signal is not recommended.

4.2.2.3 Flashing Crossbuck

An interesting "stop for train" display would flash the entire crossbuck (Figure 4-5). Such a display could be made conspicuous, and the motorist could probably learn to recognize it as a "stop for train" signal. Such a display might house neon or fluorescent lights behind translucent material.

While such a display is possible, it will require several hundred watts of power to make it conspicuous in the daytime. Simple sun shields will not be possible. This type of display is therefore not recommended.

4.2.2.4 Lights in Crossbuck

Another interesting concept is the installation of four or five red lights in the crossbuck itself (Figure 4-6). With four lights, the pattern would alternate diagonally (A and E on, then B and D on). With five lights, the center (C) would alternate with the extremities (A, B, D, and E). Such light patterns would be conspicuous, and would provide redundancy. Meaning would be obvious.

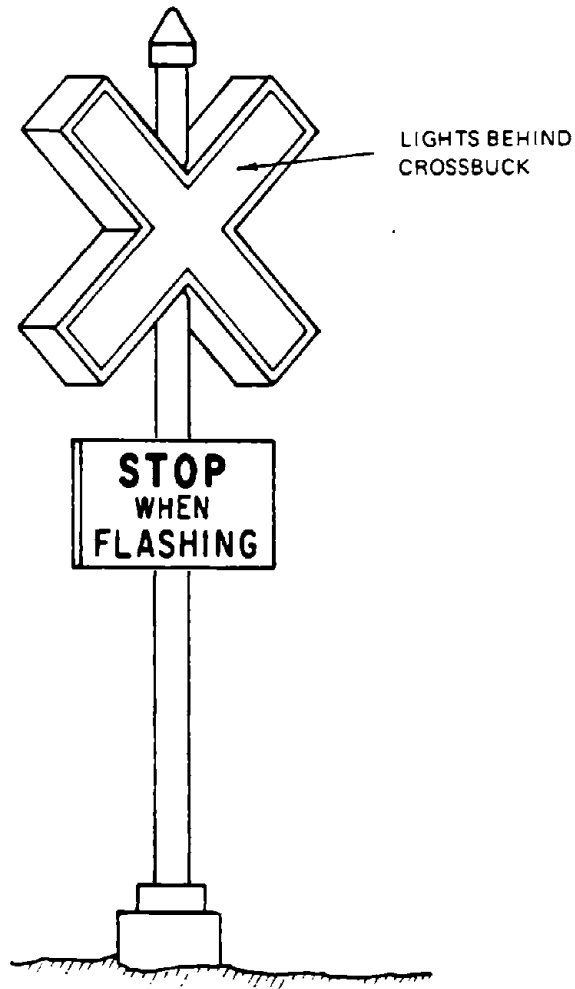


FIGURE 4-5. SIGNAL BASED ON FLASHING CROSSBUCK

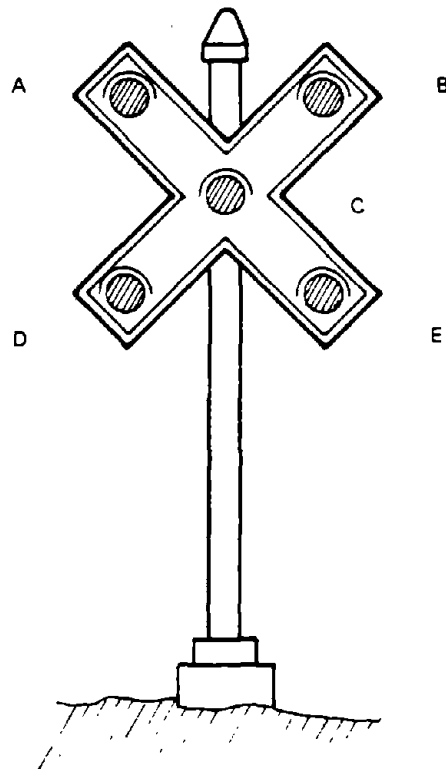


FIGURE 4-6. SIGNAL BASED ON CROSSBUCK LIGHTS

There are some slight disadvantages to this display, although they are not as great as the disadvantages of the displays previously discussed. The simultaneous illumination of two or four lights will naturally increase power consumption. It may be necessary to use higher powered lamps to achieve the same conspicuity, since there will not be the large black disc presently used for contrast.

4.2.2.5 White Strobe

A white strobe light might be mounted on top of the signal (Figure 4-7) and activated along with the alternating red lights for added conspicuity. With this signal, the conventional red lights convey the "stop for train" message, while the strobe provides the conspicuity.

While this signal would certainly be conspicuous, the white strobe will tend to dominate the motorists attention, and thus tend to divert it from the red lights. The white strobe implies no message in itself. In addition, the power to operate the strobe light is added to that already required to operate the alternating red lights. This approach is therefore not recommended.

4.2.2.6 Alternating Red Strobes

A pair of alternating red strobe lights can be used to provide the "stop for train" message. These strobe lights would occupy the same position as do the present red incandescent lights (Figure 4-8). The red strobe lights will provide both the required conspicuity and the clear message "stop for train". The use of two lights provides for redundancy. Horizontally alternating red lights are in general use only with railroad crossings.

The red light can be obtained from either the use of a proper strobe light (which emits red light) or a red (absorption) filter. Power requirements should be no more than present incandescent lights, and may be considerably less. An actual comparison of

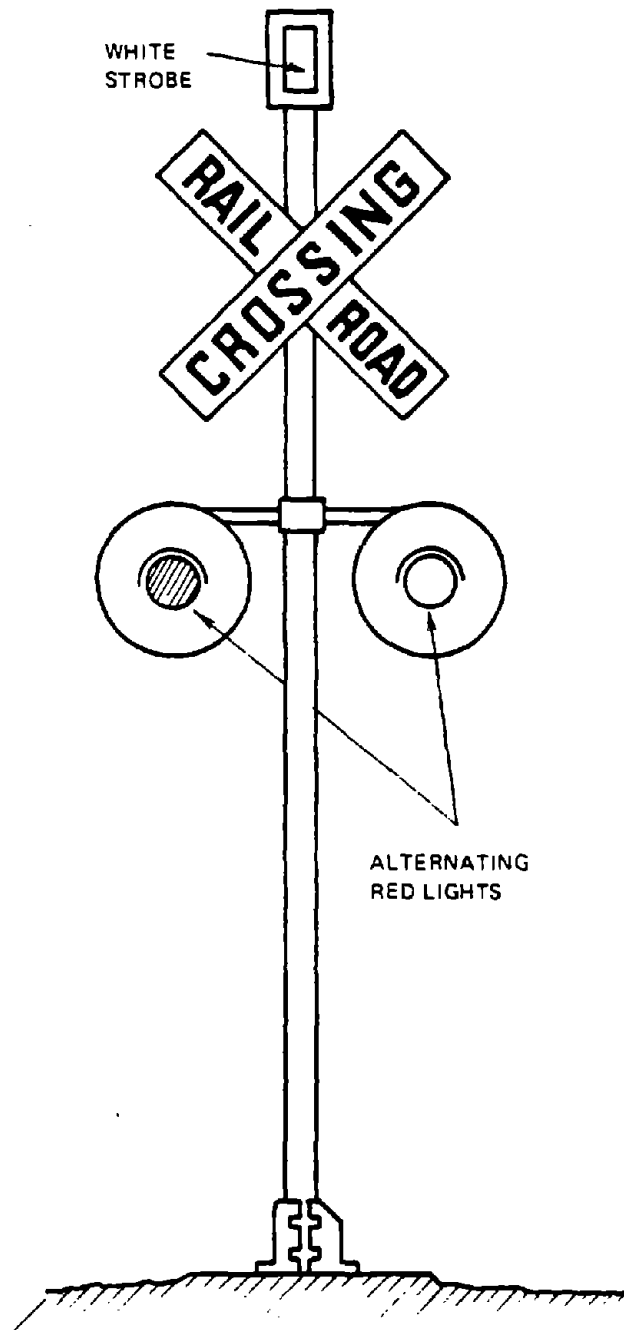


FIGURE 4-7. SIGNAL WITH STROBE LIGHT

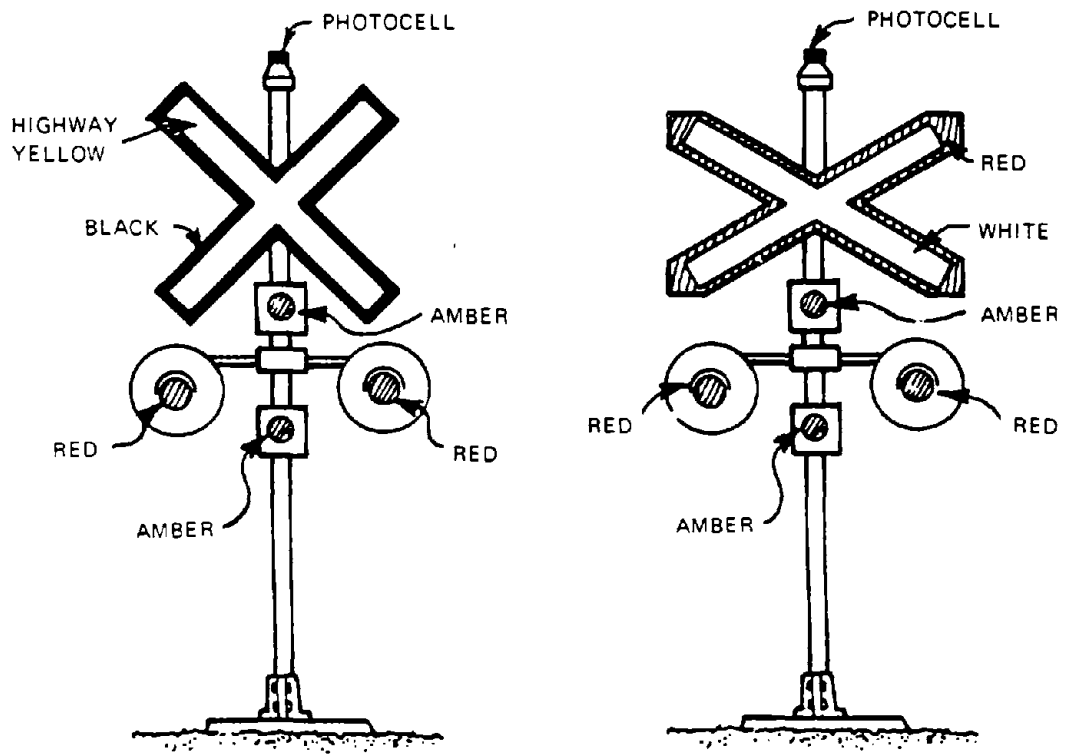


FIGURE 4-8. RECOMMENDED SIGNAL BASED ON STROBE LIGHTS

strobe lights to incandescent lights in this application requires a human factors survey, which was beyond the scope of this study.

Effective strobe intensity can be varied by variation of the flash duration. This can be controlled by a photocell, which allows automatic compensation for ambient lighting changes. Duration can also be shortened during standby operation to conserve battery energy.

A display based on alternating flashing red strobe lights with automatic intensity compensation is therefore recommended. A simple human factors experiment will be required to determine the desired intensity. Current work at TSC may provide this data. Table 4-1 summarizes the relative merits of each of the display techniques discussed here. Final verification of effectiveness awaits final testing in Phase III (see Section 8). Figure 4-8 shows this configuration in use with two new crossbuck designs.

4.2.3 Failure Warning

The remaining problem is how to convey to the motorist the message "caution, signal inoperative". This must be clearly distinct from the "stop for train" message. This rules out any use of the red lights; such as flashing them simultaneously. The "caution" message suggests the use of amber, and both redundancy and conspicuity require that two lights be used.

Horizontal mounting of the two amber lights might be convenient, since it would allow their installation in the same assembly as the red lights. However, this will be easily confused with the horizontal "stop for train" message, particularly by color-blind drivers. Vertical mounting is therefore required. While it might be convenient, since it would allow the use of a single assembly, it does not provide the conspicuity of separate lights. A spacing of a meter (as shown in Figure 4-8) or more between lights is recommended.

TABLE 4-1. STOP FOR TRAIN SIGNAL COMPARISON MATRIX

<u>Type of display</u>	<u>Conspicuity</u>	<u>Motorist recognition of message</u>	<u>Approximate normalized power consumption</u>	<u>Redundancy</u>	<u>Reliability</u>
Alternating red lights	Poor	Good	1.0	Yes	Good
Alternating red lights with white strobe	Good	Fair	1.1 - 1.5	Partial	Good
Alternating red strobes	Good	Good	0.2 - 1.0	Yes	Good
Red arrow	Good	Poor	3.0 - 5.0	Yes	Fair
Traffic light	Fair	Fair	1.0	No	Good
Flashing crossbuck	Poor	Fair	4.0 - 10.0	Possible	Poor
Red lights in crossbuck	Fair-Good	Good	2.0	Yes	Good

Amber strobe lights are recommended for added conspicuity. However, it is especially important that the "caution, signal inoperative" display not interfere with the motorists ability to watch for trains. This can be done by proper shielding of the strobe light. An interesting variation of the malfunction warning would use one red and one amber light. This combination could be used at severe or poor visibility crossings to convey "stop, check for trains, then proceed".

An important question arises in the use of "caution, signal malfunctioning" displays: Is it better to activate the amber light display only when a malfunction has been detected, or is it better to let it run continuously and to deactivate it when a malfunction occurs? The later seems to have some advantages, in that motorists approach a dark traffic light with caution. It also has an advantage in that in the event of failure of both primary and standby power, the message "caution, signal inoperative" is implied. Similarly, failure of both the system and the primary power will not put the continuous power drain of the malfunction warning on the batteries.

However, present motorist reaction to a dark railroad crossing signal is a brief check for trains followed by proceeding across the tracks. A motorist encountering a signal with dark lights will probably pay no attention to them, especially when many older signal types, which are always dark, will be in operation. The activation of the amber lights will attract attention, especially since it is unusual. Simultaneous failure of both power sources or of both the system and the primary power are very unlikely events.

One should note that the alternating amber lights are presently used occasionally in Ohio to denote a bad crossing where no real active protection has been installed. No conflict exists between the proposed malfunction display and the existing "semiactive signal", since both convey essentially the same "caution, watch for train" message.

4.3 MOTORIST ADVANCE WARNING SIGNAL

When visibility of the crossing is poor or the accident rate is particularly high, it will be desirable to use an active advance warning sign. This sign will activate only when a train is approaching the crossing, and will alert the motorist to a "stop for train" condition ahead. It can also be activated to alert him to a malfunction signal ahead. Some informal testing⁶ has shown advance warning signs to be effective, and one such unit is presently manufactured.

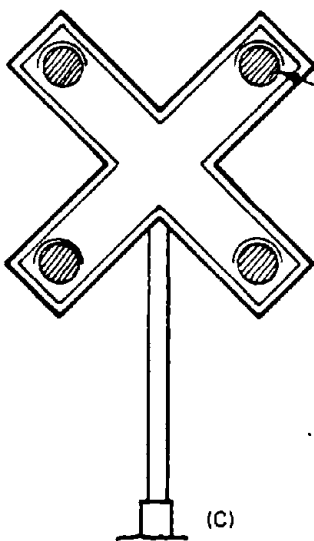
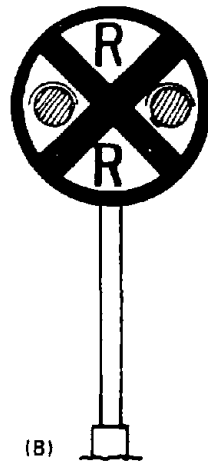
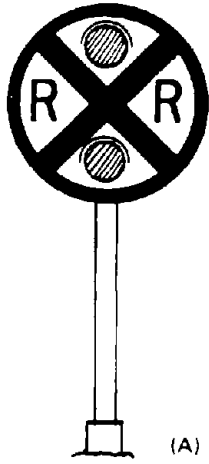
There are many possible configurations for an active advance warning sign, some of which are shown in Figure 4-9. Figure 4-9(A) shows flashing lights installed in a conventional passive advance warning sign. Figure 4-9(B) is a variation of this in which the position of the lights and "R's" are reversed to provide a horizontal light pattern. Figure 4-9(C) shows four lights mounted in a highway yellow control cross-buck; the lights would alternate in pairs with diagonal lights illuminated simultaneously. Another possibility is flashing the arrows alternately in the "look for trains" type of advance warning sign, Figure 4-9(D). No doubt many other types of active advance warning signs are also possible.

Current and recent work^{7,8} may select a new type of advance warning sign, or may verify use of the present sign. To utilize existing motorist associations, the same

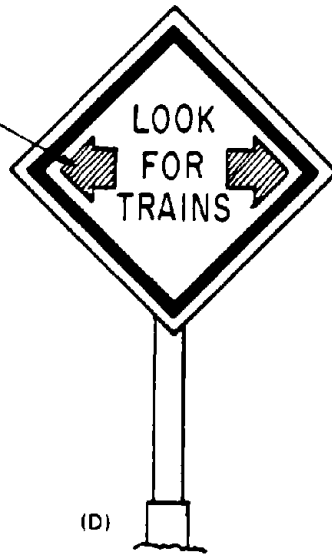
⁶"Methods to Improve Effectiveness of Railroad Highway Grade Crossing Protection," Exhibit D-1, Advanced Reports (Communications and Signal Section, AAR Committee D - Highway Grade Crossing Protection, 1971), pp. 142-147.

⁷Slade F. Hulbert and R.C. Vanstrum, "Passive Devices at Railroad Highway Grade Crossings," Proceedings of 1972 National Railroad - Highway Grade Crossing Safety (Columbus, Ohio, August 29, 1972), pp. 26-29.

⁸Howard H. Bissell, "New Passive Devices" (paper for 1974 National Railroad-Highway Grade Crossing Safety Conference, Colorado Springs, Colorado, August 20, 1974).



ILLUMINATED



ALL SIGNS HIGHWAY
YELLOW AND BLACK

FIGURE 4-9. POSSIBLE ACTIVE ADVANCE WARNING SIGNS

basic sign design should be used for both active and passive advance warnings. Controlled lights can be added to any type sign to enhance its conspicuity and to attract motorist attention.

Any advance warning signal should use two alternating lights. This configuration not only provides redundancy, but adds conspicuity. Amber should be used, since the intended message is "caution, stop for train ahead". Red would indicate "stop", and other colors would be ambiguous. Strobe lights could be used for added conspicuity.

The advance warning sign will normally be powered from nearby lines. A battery for use during power failures could be provided. However, the consequences of an advance warning failure are not as severe as those of a crossing signal failure, so in general, standby power should be unnecessary. If deemed necessary in a particular application, the power requirements could be reduced by flashing only one light and reducing its duty cycle or brilliance.

Failsafe operation of the control link can be provided by using three control messages. To activate or deactivate the advance warning sign, the control system transmits either a "turn-on" or "turn-off" command. When the sign is to remain inactive, the control system transmits a "stay off" command at periodic intervals. Failure to receive such a command within the preset time interval activates the sign. Additional failsafe operation can be provided by monitoring the light outputs with phototransistors. An "all ok" message is returned to the control system when the lights illuminate. Failure to receive this message activates the engineer warning, which will result in a maintenance crew being dispatched.

4.4 ENGINEER WARNING SIGNAL

4.4.1 Objectives

The third signal used in the new crossing warning system will warn the engineer in the locomotive of a crossing ahead with improperly operating equipment. At present, the

engineer has no advance warning of this situation, and is usually unable to tell the difference between a properly operating system and a system with a failure, since both display red lights.

There are three possible uses for the engineer warning signal:

The engineer is able to report a crossing signal failure so that a maintenance crew can be dispatched immediately.

The engineer can sound his horn or whistle vigorously to attract motorist attention.

The engineer may take such other actions as specified by future railroad operating rules. These might include attempting to slow the train, but this is of doubtful practicality.

4.4.2 Characteristics

The engineer warning signal should be located at or near the present whistle or bell post. This may typically be 500 feet from the crossing. The actual distance will depend on train speeds on that section of track.

The best form for this signal is an amber "X", as shown in Figure 4-10. This form was selected because of its similarity to the flashing white and green "X" signals presently used in time-out circuits.

Under normal conditions, the approaching train would see a constantly illuminated amber "X", which would verify proper operation and activation of the crossing. If the crossing warning equipment has detected a failure, the flashing amber "X" gives the engineer a positive indication of this condition. In the event of a power loss, burned out lamp, or other disruptive condition, the "X" may be dark. This will also be interpreted by the engineer as indicating a failure, thus providing failsafe operation.

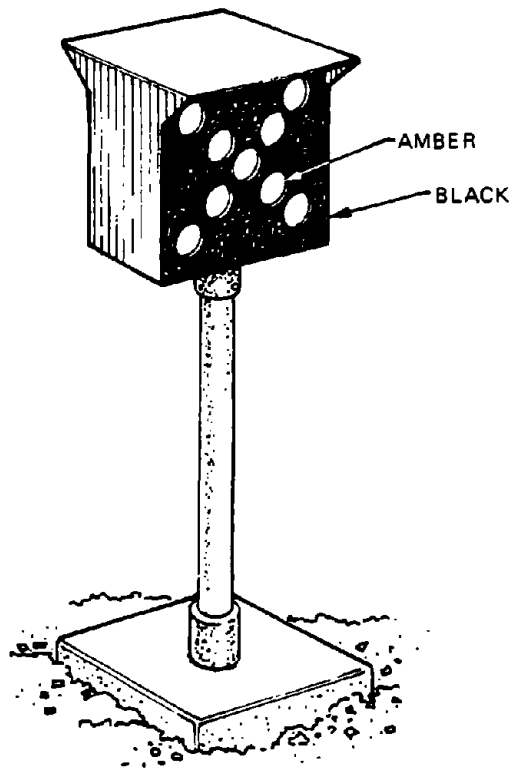


FIGURE 4-10. ENGINEER WARNING SIGNAL

Both the nature and the use of this signal are somewhat arbitrary, and can be tailored to such forms as desired by the railroads or the AAR. However, something similar to the engineer warning just described is needed to insure a reliable crossing system, and can be added quite easily to the rest of the components.

4.5 CONCLUSIONS

The innovative crossing warning system will incorporate three basic signals (displays). These are:

Motorist Crossing Warning Signal. This signal uses a high visibility cross-buck, horizontally alternating red strobe lights to signal "stop for train", vertically alternating amber lights to convey "caution, signal inoperative", and can optionally be equipped with a crossing gate.

Motorist Active Advance Warning Signal. This signal is an option to be used where warranted by poor visibility or other conditions. It will be similar to a passive advance warning sign, but will include alternating amber lights which are activated along with the red lights at the crossing.

Engineer Warning Signal. This signal alerts the engineer of a failed crossing warning system ahead. It displays a constant amber "X" for normal operations and a flashing "X" for failure. Consequently the engineer can report the failure and sound his horn vigorously.

It is also recommended that:

The new high visibility crossbuck design be used only with constant warning time signal systems, so that a motorist will identify it as a signal that he can trust.

The use of strobe lights near roadways be limited (by legislation) to emergency vehicles, crossing signals, and other such uses.

5. CONTROL SUBSYSTEM

5.1 PURPOSE

The control subsystem, Figure 5-1, will represent the "intelligence" in the new railroad-highway grade crossing warning system. The control subsystem must compute constant warning time from the sensor inputs for a great variety of train movement patterns and activate or deactivate the stop-for-train, failure, advance warning, and engineer warning displays accordingly. It may also control gates and bells, and may have to include circuitry to interface with automobile traffic signals or a variety of other equipment.

The control subsystem is also responsible for insuring failsafe operation of the whole system. It will be responsible for checking sensor status and display status reports and displaying a malfunction warning, if appropriate.

The circuitry in the control subsystem can be broken into four functional groups. These are:

The timing circuits

The display power circuits

The failsafe circuits

Power control and regulation circuits

5.2 COMPUTATION AND TIMING CIRCUITS

There are a variety of ways to perform the computations and timing necessary to control the displays with constant warning time. These include relays, digital circuits,

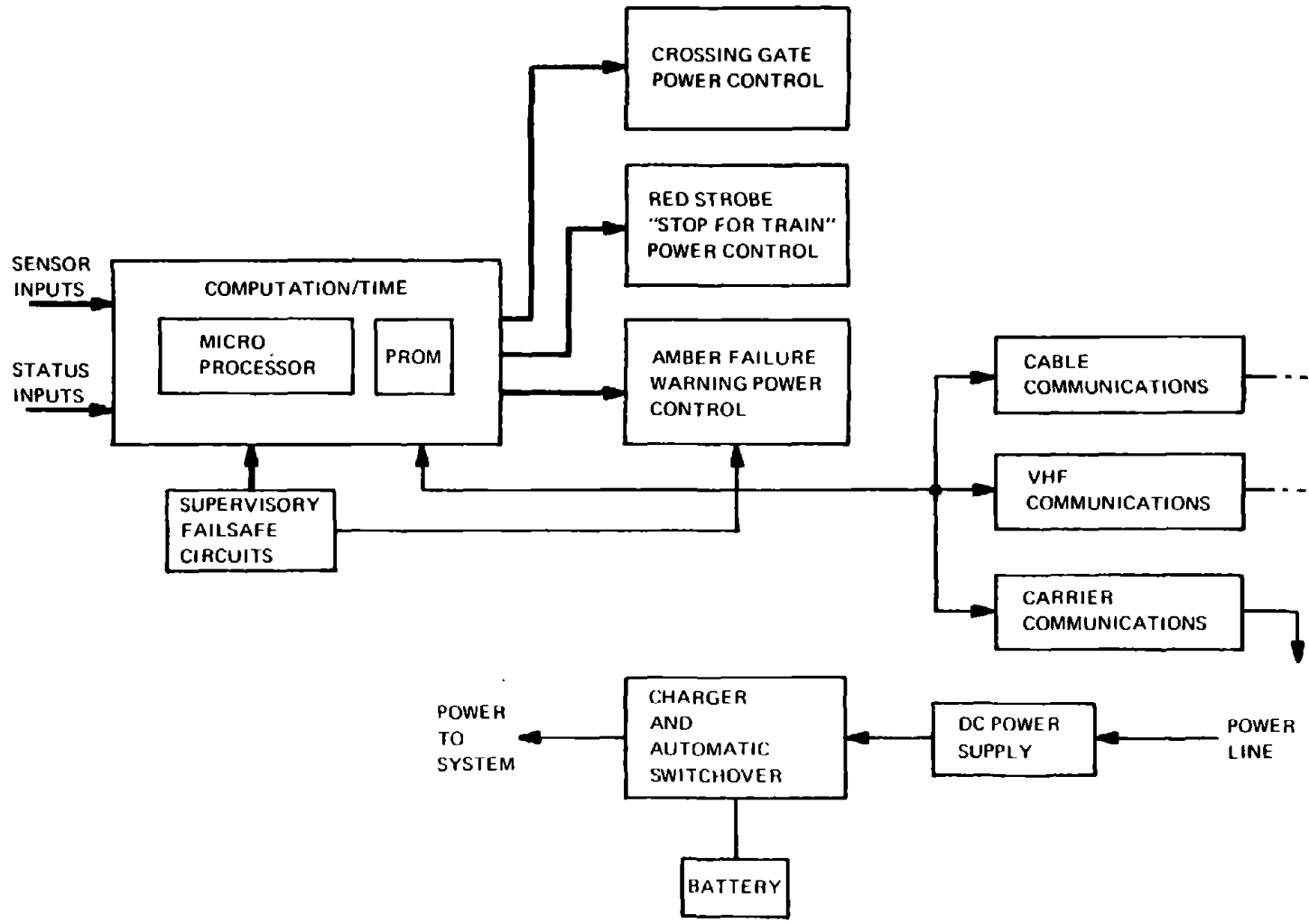


FIGURE 5-1. CONTROL SUBSYSTEM BLOCK DIAGRAM

analog circuits, and microprocessor based circuits. Since this new system will be required to monitor train movement in a great variety of possible patterns and track situations, the circuitry will actually be more concerned with making logical type decisions than with numerical calculations or timing. While these decisions can be implemented in discrete circuits (relays or logic), to do so would require an enormous amount of circuitry. In addition, it would be awkward or impossible to adapt this circuitry to more than a few situations without redesign effort. This can be one of the major cost factors in present systems which must be adapted to a special situation.

For these reasons, it is highly desirable to use a microprocessor as the central controlling element. This microprocessor would not differ greatly from the units which are widely used in portable calculators. In this control system, it functions as a small computer, acting on received data in a manner prescribed by a preset program. The program is supplied from a programmable read-only memory (PROM). The PROM is a circuit which furnishes preprogrammed data (in this case, instructions for the microprocessor) upon command. These data are entered in the circuit permanently at the factory prior to installation of the circuit package in the equipment.

This technique allows a great deal of flexibility in how the signal can operate, allowing it to be adapted to a large variety of situations. A program for a particular signal is written to fit its particular situation. Factors would include such things as velocities of train and automobile traffic, the number of tracks, and the location of any switches. A number of prearranged programs would be prepared for standard situations such as single track, double track, or double track with one switch. When a situation did not fit a standard model, a special program would be prepared. This program would become part of a library of programs which could be used if similar situations appeared again. After selecting or preparing the program, the manufacturer would have it entered into the PROM.

In the event that a track situation changes (for example, the addition of a sidetrack), a new PROM is ordered and installed. This will be a much less complicated process in most cases than would be redesigning and modifying the actual circuitry.

5.3 COMPUTATIONS

The computations and the decision processes which the computing and timing circuits must make are based on the locations of the sensors. This study program investigated exactly what information should be produced by the network of discrete sensors and how it should be used. Two key questions were: Should sensors be installed singly or in pairs? How many sensors or sensor pairs are required?

The sensor pair system is preferred over the single sensor system. A sensor pair not only notes the arrival time of the train, but measures its velocity as well. In a system using single sensors, the train must cross two sensors before velocity can be computed. The use of several sensor pairs allows the system to determine acceleration from the difference in the velocity at the two pairs. This system also provides redundancy, in that the failure of one of a sensor pair does not disable the system. Both sensors in a pair can also use the same communications equipment.

In all situations, one sensor pair will straddle the roadway, thus being the equivalent of the present-day "island circuit" used with track circuit detectors. Two or three other pairs of sensors will be used on each side of the crossing on each track. In cases where train movement is generally predictable, both as to velocity and acceleration, two sensor pairs will suffice. When trains with greatly differing velocities or with large accelerations or decelerations use the same track, it will be desirable to install three sensor pairs.

The following discussion will illustrate many of the aspects of designing the "software" or program by which the control subsystem can monitor train movement and time the signal displays accordingly. Discussion of both single sensor systems and dual sensor systems is included. The program is limited to single track systems, and should be regarded as an example of the complexity, rather than an actual program to be used.

By using sensors placed as shown in Figure 5-2, train velocity can be sensed. Then, by knowing the velocity, the time of arrival can be determined and a constant warning

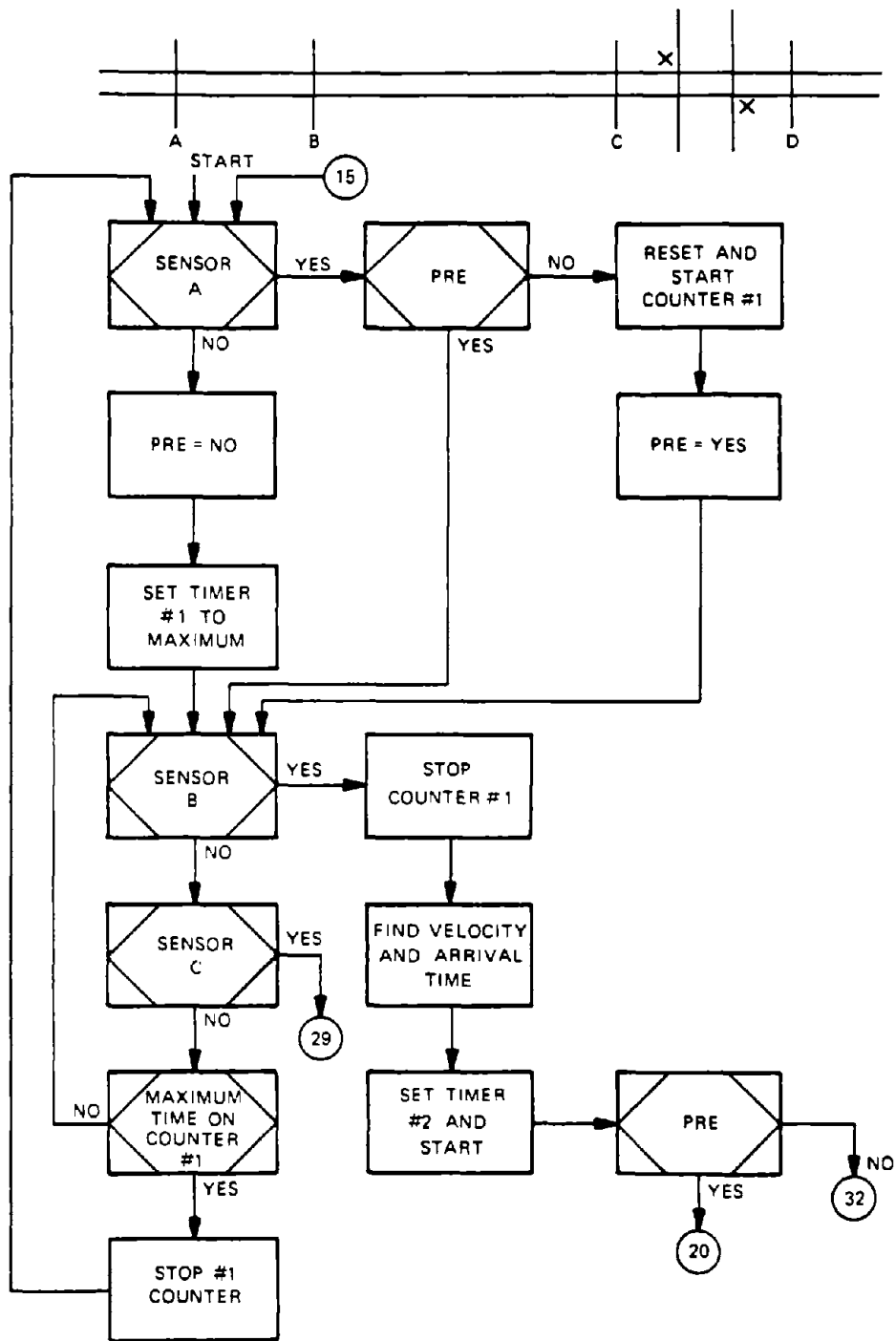


FIGURE 5-2. SINGLE SENSORS VELOCITY SENSE

time can be provided by the crossing signals. For each velocity, there is a different amount of delay time before activating the crossing signals.

This constant warning makes the signals more meaningful. Even if the train is moving at its slowest speed, the signal will not be activated until the train is 25 seconds away from the crossing. The constant time of about 25 seconds is sufficient to warn motorists at an average crossing. The actual time value could be set differently for a crossing that may require more warning.

Figure 5-3 shows the method to be used for including many inputs to control one set of signals. A signal must be activated when the train approaches from the left or right. Also, multiple tracks will require duplication of sensors and processors.

The figure shows that any number of inputs may be used to control the signals. Activate 'A' is the condition determined by the left to right processor. 'B' is the input from the right to left processor. When any one of the 'Activates' is a 'yes' value, the signal will be turned on. When all of these inputs are a 'no' value, the signal will go off again. One processor is used for each direction and for any track of multiple tracks.

Figures 5-2, 5-4, and 5-5 show the steps needed to determine the velocity of a train and to time the signals. The diagram also allows for a train to stop or change direction. The sensors cannot sense the changes in velocity, but the signal can deactivate if the train never reaches the crossing within some reasonable time.

To detect an acceleration, dual sensors must be used. Figures 5-6, 5-7, 5-8, and 5-5 show the steps necessary to sense a train that has changing velocity. This system satisfies all the conditions that a train might provide.

The velocity sensing system, Figure 5-2, is made up of parts to satisfy five of the seven conditions. These parts are integrated into the single system shown.

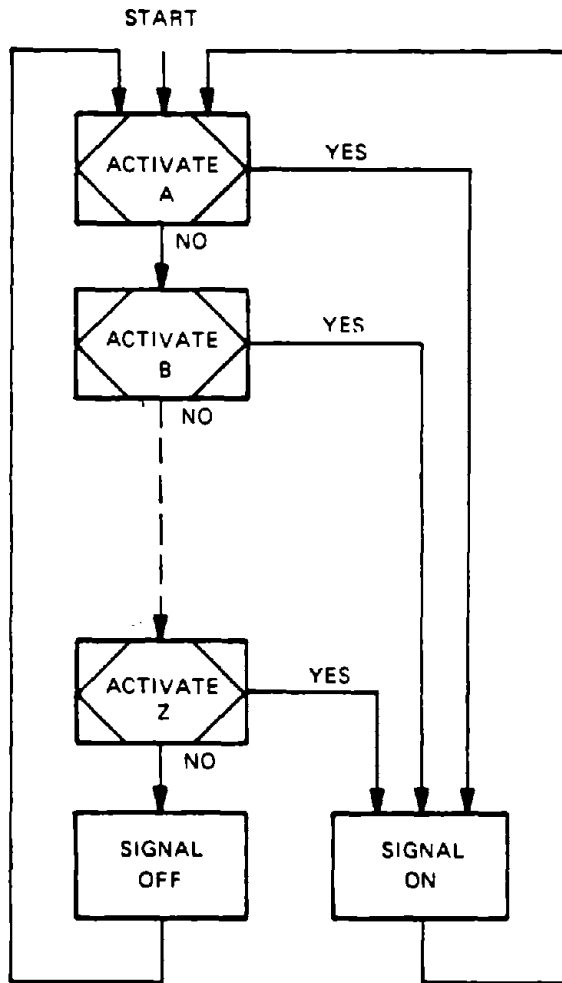


FIGURE 5-3. MULTIPLE DIRECTION AND RAIL CONTROL

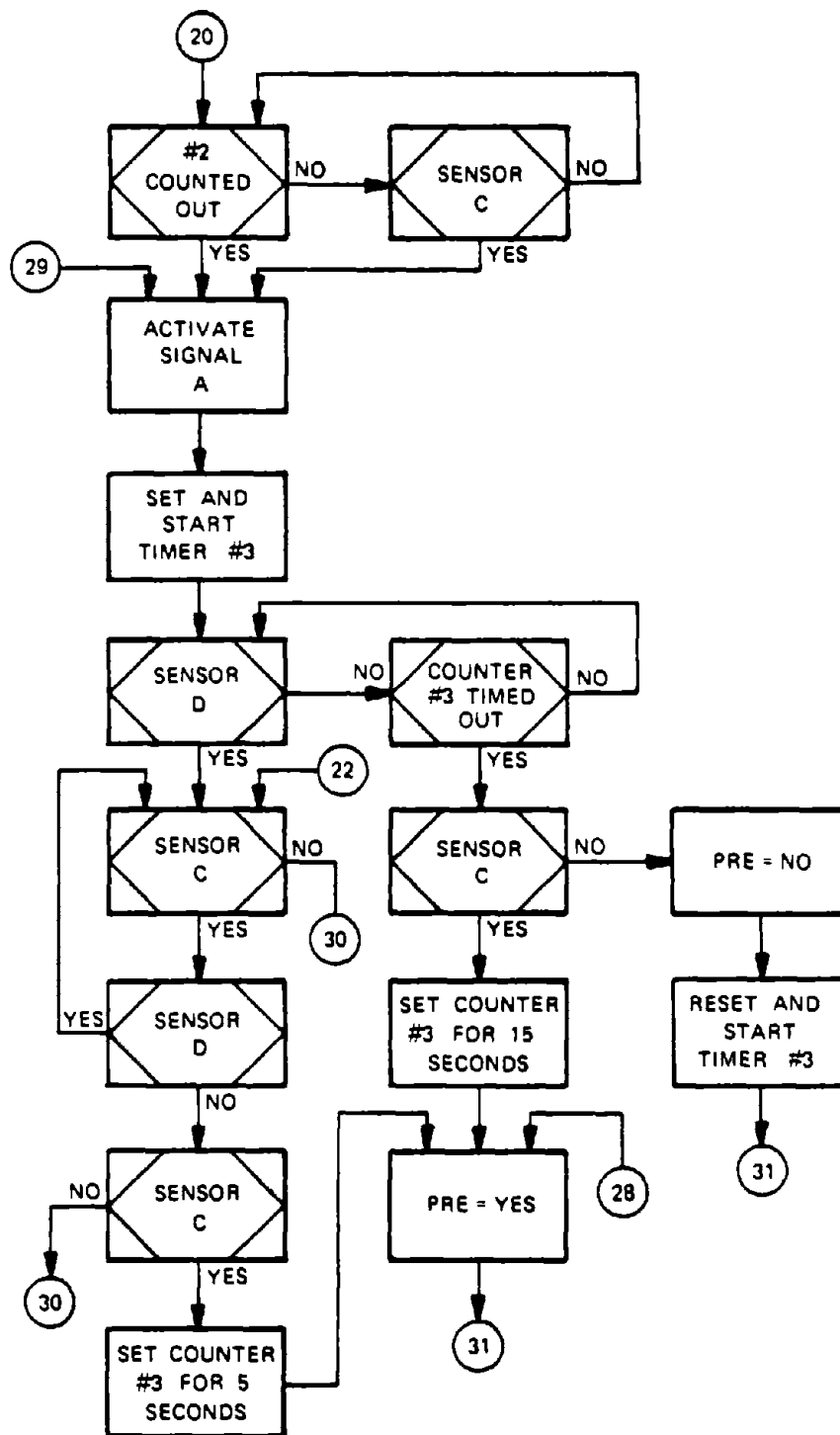


FIGURE 5-4. SENSORS OPERATION LOOP

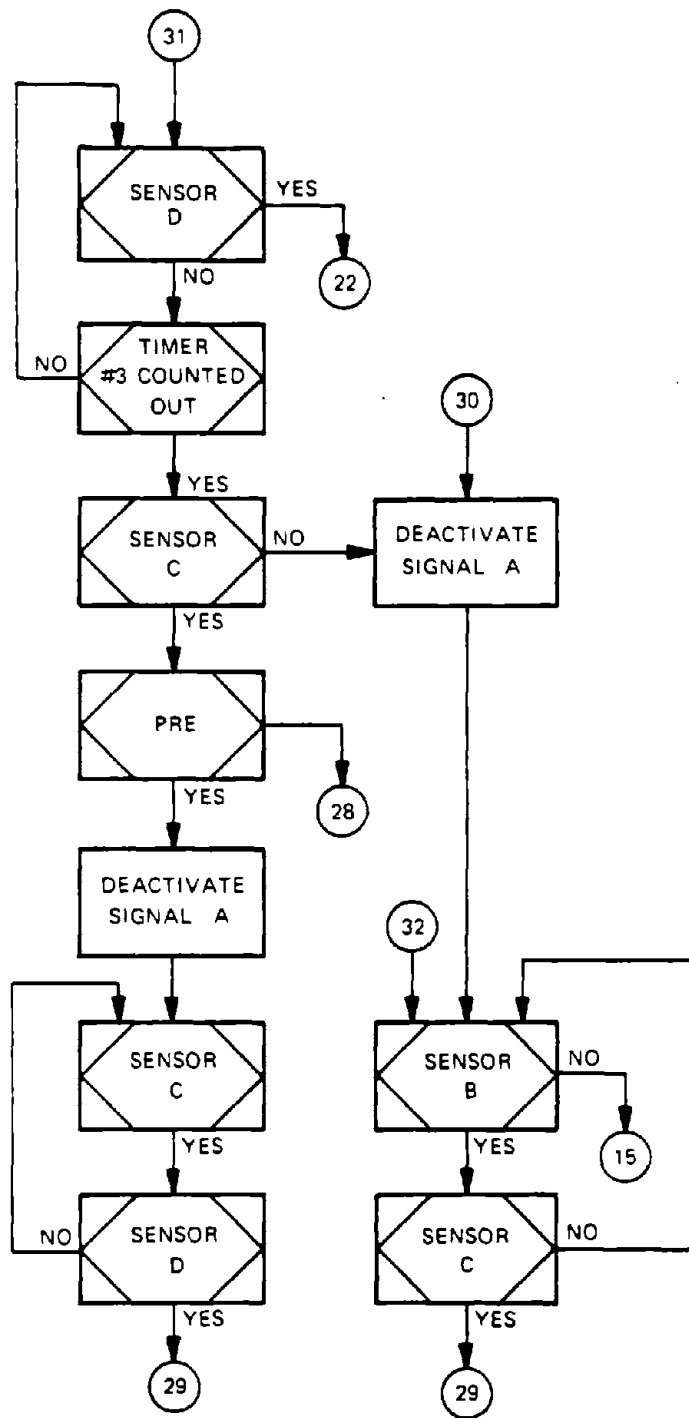


FIGURE 5-5. SENSORS OPERATION LOOP

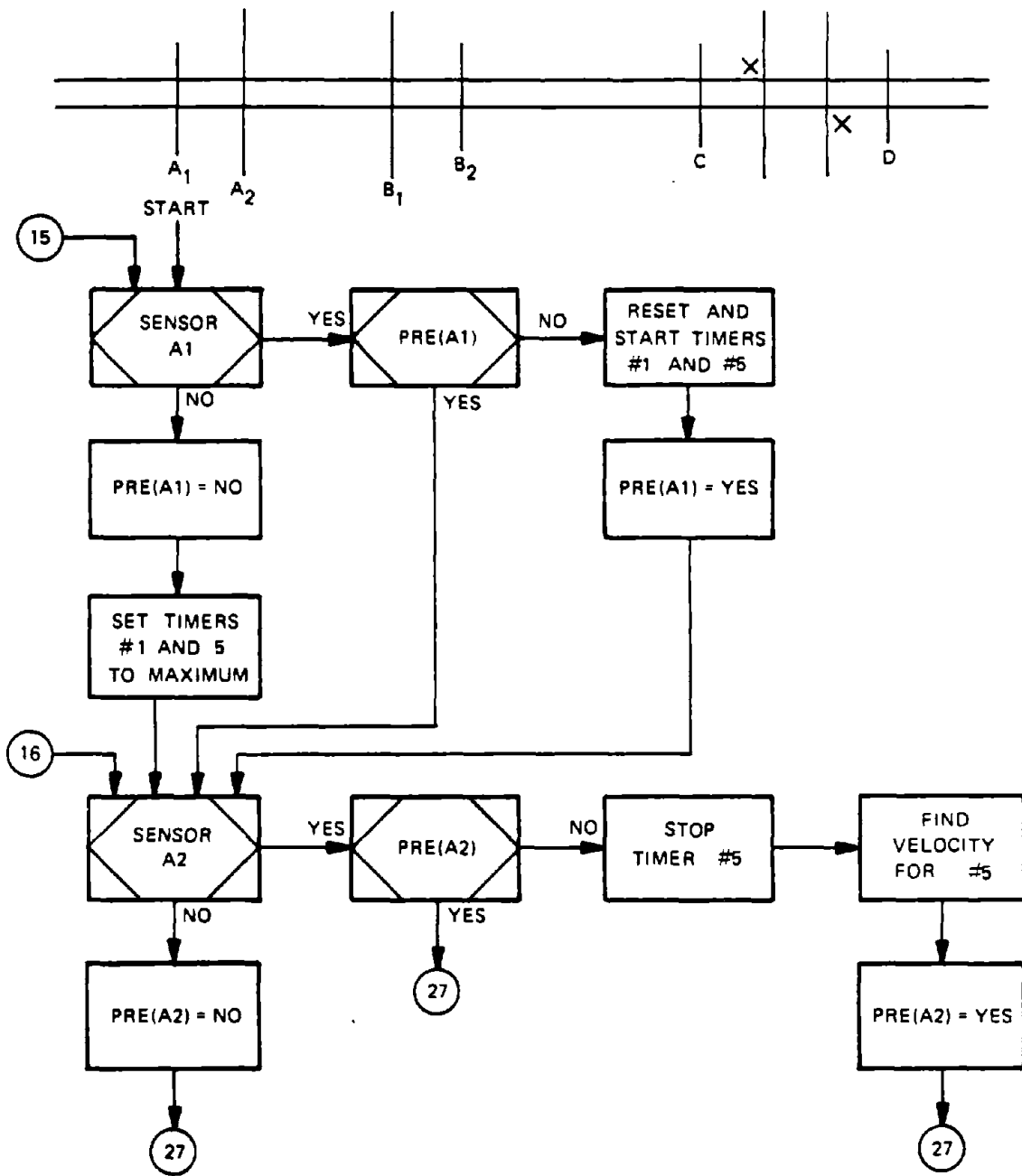


FIGURE 5-6. SENSORS OPERATION LOOP

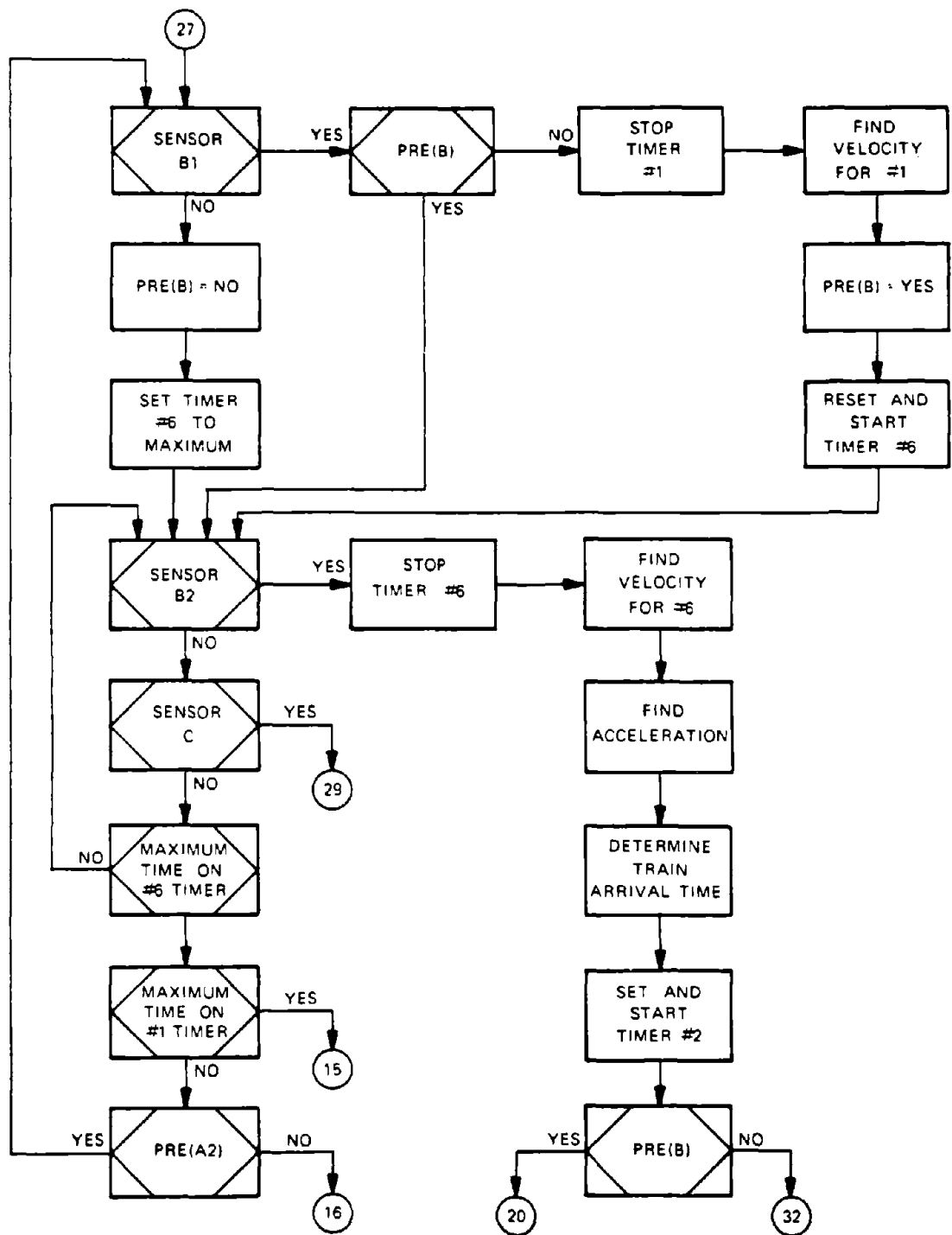


FIGURE 5-7. SENSORS OPERATION LOOP

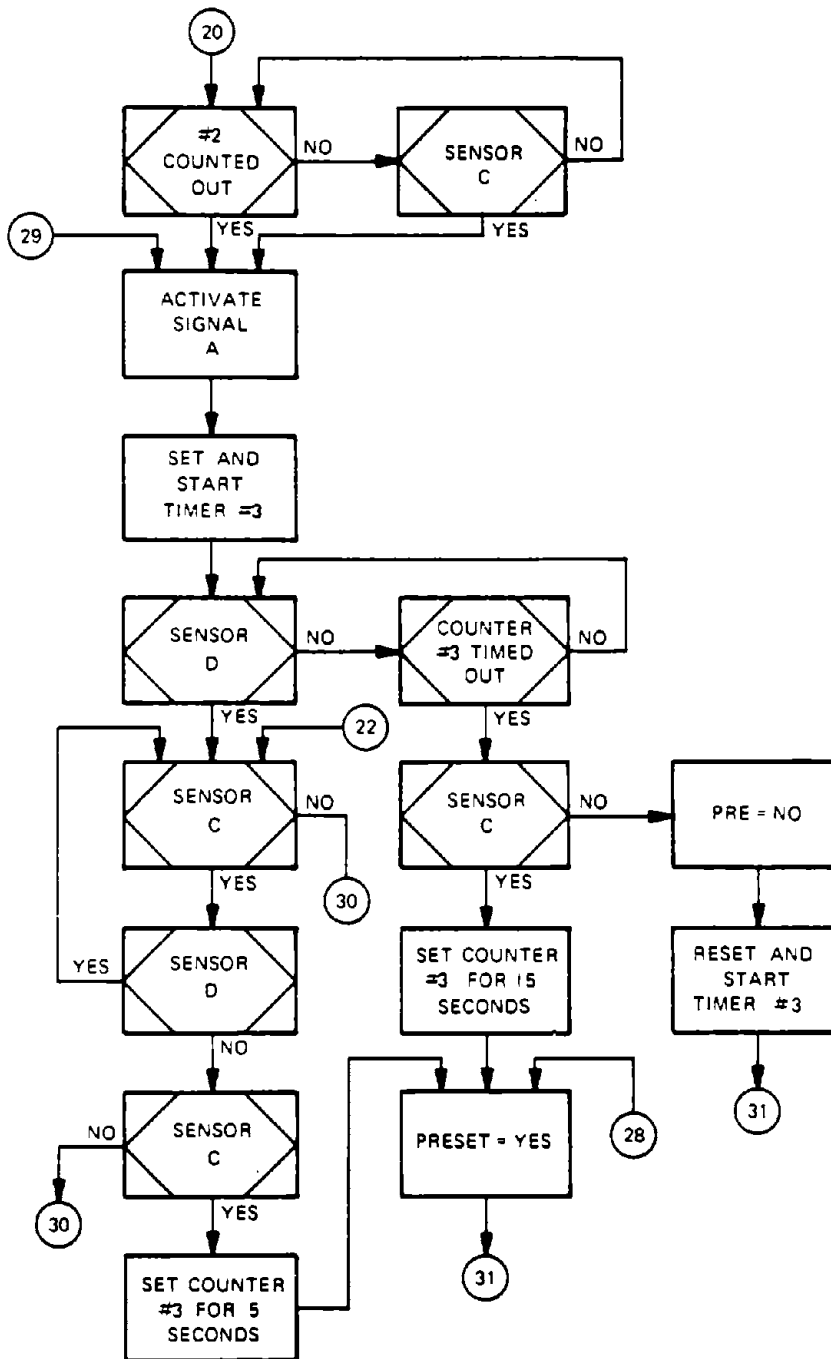


FIGURE 5-5. SENSORS OPERATION LOOP

To start, the system control follows the arrows and branches at decision blocks. With no train on the track, the control tests sensors A, B, and C in the loop and maintains this loop until one of the sensors is activated. In this loop, the first counter is set to maximum count to prevent errors on a restarted system. PRE is a latch that is set to indicate the previous condition of sensor A. Every time through the loop this condition indicator is updated.

For the first condition, the train will be at a constant velocity in left to right direction. Sensor A would then be the first to indicate train presence. Control then branches at this point to reset timer one and start it counting.

The control now begins a new loop, sampling sensor B and C and the time in counter one. If the counter reaches a maximum before the train reaches sensor B, the control will include sensor A in the loop. When the train reaches sensor B, the number one counter is stopped and velocity and time of arrival are determined. Counter two begins to count the time before activating the signal. After the signal has been activated, timer three, Figure 5-4, is set to the value of constant warning time. If the train does not reach sensor D before counter three times out, it is reset and times a second time. The signal is deactivated if the train does not cross within the next count, Figure 5-5. Then another loop senses the train if it approaches the crossing or backs away.

If the train reaches sensor D, Figure 5-2, before the counters time out, a loop is used which uses counter three. When the train leaves the sensor D area, the signal is deactivated.

In the acceleration sensing flow chart, Figure 5-6, a loop is initially formed to include A1, A2, B1, B2, and C. When the train is sensed at A1, timers one and five are reset and started. PRE (A1) stores previous values of A1 and is set to be "yes". These counters will count until sensor A2 senses the train, then the velocity is determined over the distance A1 to A2.

The loop continues to check A1, A2, B1, B2, and C until sensor B1, Figure 5-7, indicates train presence.

At this point, timer no. 1 is stopped and a velocity is determined over the distance A1 to B1. Now timer no. 6 is reset and started. A small loop is used to monitor sensors B2 and C. When B2 senses train presence, timer no. 6 is stopped and both velocity and acceleration are determined. The arrival time at the crossing is calculated and timer no. 2 is set and started. When timer no. 2 has counted out, Figure 5-8, the signal is activated and the train should be some constant time away from the crossing.

The rest of the reset circuit is identical with the velocity sensing circuits, Figure 5-5.

The conditions that are to be met by the processor are listed below:

The normal condition; with the train moving from A to B to C to D, Figure 5-2, with constant velocity.

Moving from A to B to C to D with decreasing speed.

Moving from A to B to C to D with increasing speed.

Moving from A to B to C and stopping at D after clearing the crossing.

Moving from A to B and stopping at C.

Moving past A and stopping at B.

Stopping at A.

Other conditions which affect the processor include:

Reversing after stopping at any of the sensors.

A short train that stops past the sensors and not on them.

The single sensor processing does not have enough information to sense an increasing or decreasing speed, but all other conditions can be satisfied to produce accurate signals under normal conditions and under the conditions of a stopped train.

The dual sensor processor is supplied with enough information to sense a constant acceleration, as well as velocity. It satisfies all the conditions listed. The processing requirements amount to only a few extra steps, or a few more logic gates and counters than the single sensor system. It also requires two more sensors. However, the increased accuracy of the warning time in the dual sensor system makes it more desirable.

The average acceleration and deceleration is 1.2 km/h/s. For an increasing speed, the velocity could increase by 30 km/h over a 25 second warning interval. Actually, this would shorten the warning time if the acceleration were not accounted for.

At an initial speed of 10 km/h, the warning would be shortened to 10 seconds and at an initial speed of 100 km/h, it would give only 22 seconds of warning.

An example of velocity sensing would be as follows:

The velocity of the train would be constant at 100 km/h. The distance from A to B, Figure 5-2, would be 200 meters, and distance from B to the crossing would be 1 km.

The time taken from sensor A to B is measured as 7.2 seconds. The time of arrival is computed to be in 36 seconds. Twenty-five seconds is subtracted from this amount and counter no. 2 counts for the remaining 11 seconds.

The signal is then activated which gives a warning for 25 seconds before the train arrives.

For the dual sensor system acceleration can be accounted for. As an example: A train at an initial velocity of 25 km/h and an acceleration of 0.15 km/h/s would move from sensor A1, Figure 5-6, to sensor A2 in 1.43 seconds if they are 10 meters apart. The train moves from A1 to B1 in 26.7 seconds if they are 200 meters apart. The velocity at B1 is 29.0 km/h. For the distance of 10 meters from B1 to B2, the time between sensors is 1.24 seconds.

The processor computes velocity at A to be 6.99 m/s and at B to be 8.06 m/s and the change in velocity to be 1.07 m/s/26.7 seconds or 0.04 m/s/s. By using the distance of 1000 meters from B1 to the crossing, the processor finds the final velocity and averages to determine that the average velocity is 10.54 m/s and that 1000 meters will be covered in 94.9 seconds.

The processor will wait for 69.9 seconds and activate the signal. This leaves about 25 seconds warning time.

5.4 DISPLAY CONTROL CIRCUITS

Display control circuits are those circuits which apply power to the lights (or gates, bells, etc.) when instructed to do so by the computation and timing circuits. The microprocessor and its associated circuitry will be implemented from CMOS for low power consumption. The outputs of such circuits are inherently too low in power to operate lights or gates directly, so an intermediate circuit must be used.

These circuits will be standard design power switching circuits. All displays will be powered from the 24 volt supply; the same power control circuit is used whether the system is operating on ac line power or standby battery power.

The circuit used depends on the display to be operated. Incandescent lamps can be operated by dc power transistors with suitable driving amplifiers. Gates and bells will have their own special requirements. Strobe lights will require a special voltage step up circuit, identical to that used in camera flash attachments. Power control

circuits for different types of lights or displays can be built on similar printed circuit cards and installed as needed in the control box.

5.5 FAILSAFE OPERATION

Failsafe operation includes not only monitoring the sensor status reports, communications link status, and lamp status, but also checking of the timing and control circuits themselves.

Monitoring of sensor status reports is accomplished by simple timing. If a preset interval has elapsed, and all sensors have not checked in with satisfactory status reports, the malfunction warning is activated.

When lamps are activated, their illumination is measured by phototransistors in the lamp housing. The absence of a satisfactory report by the illumination measuring circuitry also initiates a malfunction status. However, if only a single lamp fails to light, only the engineer warning is displayed.

These functions are accomplished by the microprocessor and PROM program with appropriate interface circuits. Since computations and logical decisions will be completed in a few milliseconds, the processor has much idle time which can be put to use in self-check and failsafe functions. When there is no train present, the microprocessor can be instructed to execute a mock program. The simulated sensor inputs are supplied by some special circuits, which also check for a correct answer. Displays are inhibited during self-test. The appearance of a train also aborts the self-test sequence. Failure to produce the correct timing and control outputs during the self-test program causes a malfunction warning to be displayed. Such a program could be executed much faster than in real time, and could be executed at regular intervals of ten minutes or so, whenever a train was not present. Any circuit failure would thus be detected immediately.

5.6 POWER SUPPLY CIRCUITS

The power supply circuits for the control subsystem and the displays will be common. These circuits provide for automatic charging of the batteries when line power is available, and for automatic switchover to battery operation when line power disappears.

These circuits will be of standard design and do not therefore warrant discussion here. Whenever voltage regulation is required, switching regulators will be used so that battery power is not wasted during standby operation.

5.7 PACKAGING

The control circuits must be packaged so that they are protected from the environment and from vandals but are still easy to service.

Protection from the environment and from vandals is accomplished by using a case of rugged construction and by mounting it unobtrusively. All connecting cables will connect to the bottom of the control box so that they are both invisible and inaccessible without first removing the box (Figure 5-9). The control box itself might also be fabricated so that it could be mounted recessed in the concrete base of the signal. It could be removed for servicing by undoing the mounting bolts, but would otherwise be unnoticeable.

Each different element of the control subsystem will be built on its own printed circuit card. These cards are then plugged into card sockets of standard form inside the control box. Only circuit cards for those functions required for a particular system need to be included in a given box. For example, the VHF interface card would be installed only if the VHF communications link were used. Proper design of the connections to these circuit cards will insure compatibility.

A malfunction can be located by simple trial-and-error replacement of the cards from a set of good cards. The service person need have no special electronics training to

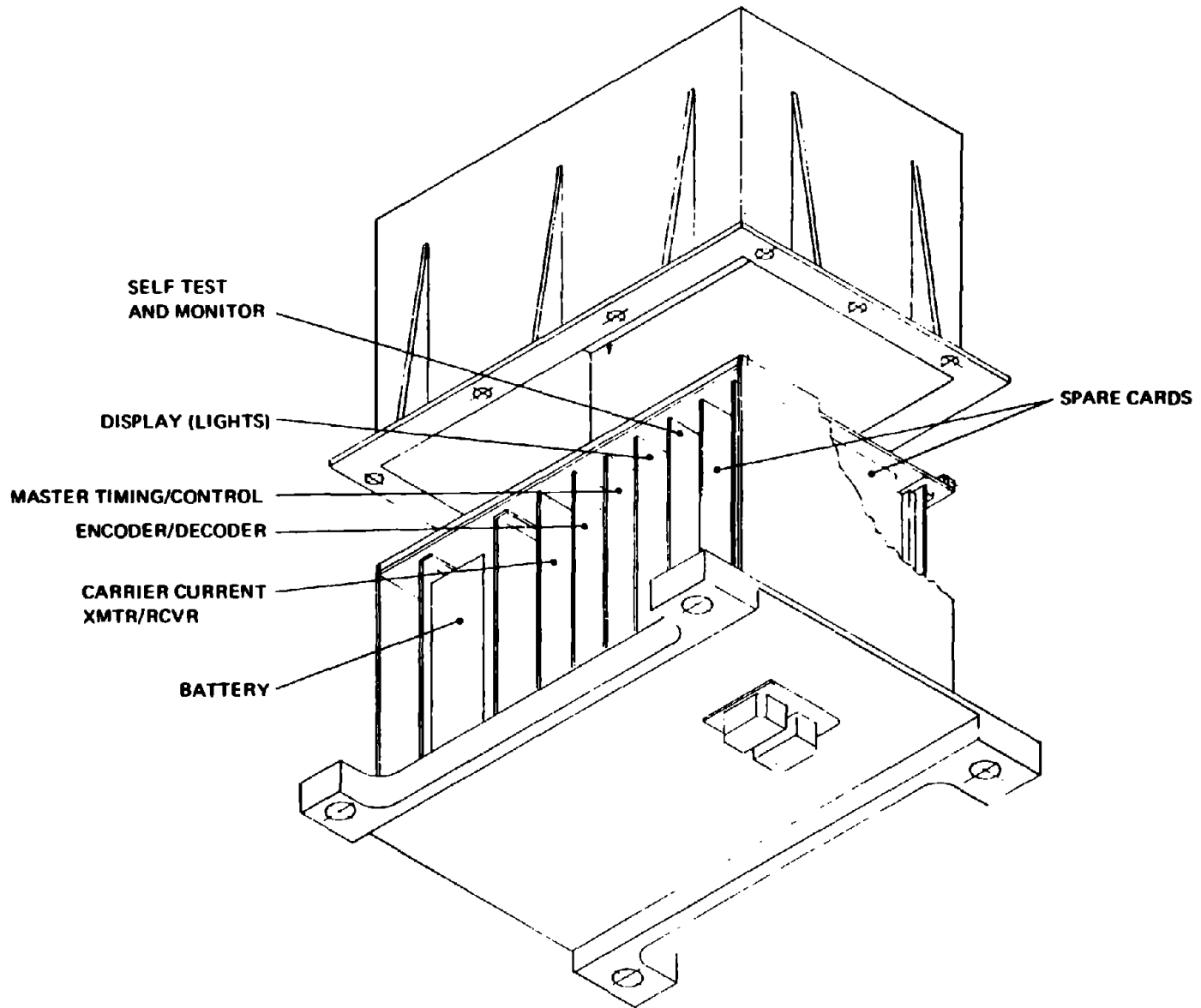


FIGURE 5-9. CONTROL CIRCUIT PACKAGE

do this. The time required to service the signal will be primarily that of removing the control box from its mounting and then removing its cover. The defective circuit card can then be returned to a shop or to the manufacturer for repair. It might also be discarded, depending on its cost.

6. REMOTE POWER

6.1 GENERAL

In geographical areas where no ac power is available, a suitable power source must be provided for the grade crossing signal. Power for the sensor and active signal can be provided separately. At present the active signal, (lights, bells, etc.) are sometimes operated by battery, so the power system is already available and need not be discussed further. The problem then reduces to powering the sensors with their amplifiers, associated logic, and transmitters.

It is assumed in this discussion that the sensor in question is a pair of commercially available Hall devices that together require 250 to 300 milliwatts for operation and 1 watt each for a heating element in cold regions. The amplifier, logic and transmitter through the use of LSI and CMOS require negligible power compared to the 2.3 watts for the Hall devices and heaters in a worst-case situation; that being, keeping the sensor at 50°F with an outside temperature of -20°F. Under normal temperature variations in the continental U.S. this worst-case situation would only occur in a few northern states only several nights a winter.

6.2 BATTERY POWER

Two types of batteries¹ are on the market today that could be used in this application. Primary batteries are non-rechargeable and must be replaced periodically. They are

¹Eveready Battery Applications Engineering Data, Union Carbide Corp.

available with various ampere-hour ratings and price tags. Secondary batteries are rechargeable and therefore, more economical than primary batteries. They can also be virtually maintenance free if the charge on the battery is maintained in some manner. This can be done by the use of a solar cell voltage source. Arrays of cells have been built to provide 1 watt of power from a 6 cm by 18 cm panel.² A computer program has been developed to calculate the optimum size of the solar array and a matching battery for any given location and power need. This program uses the insulation data published by the National Weather Service. The angle of arrays can be specified for greatest efficiency. The battery size can also be given to produce a realizable system.³

6.3 WIND POWER

Wind power can also be used to power either the sensors or the whole system. A medium size wind generator can produce 200 watts under typical wind conditions.⁴ Thus a small generator mounted on a pole could provide power for a sensor while a medium sized generator could power a whole system, lights and all. Note that wind power, like solar power, is used to charge batteries which then provide power during low wind conditions. Only recently has interest been renewed in wind power generators, so many new developments in this area can be expected.

The worst-case situation requires 2.3 watts of peak power under abnormal weather conditions. To calculate power requirements for battery selection, a set of assump-

²Daniel T. Bernatowicz, "The NASA-Lewis Terrestrial Photovoltaic Program," Tenth IEEE Photovoltaic Specialists Conference (November, 1973).

³F. T. C. Bartels and D. W. Moffett, "Design Analyses and Specification of Photovoltaic Solar Terrestrial Power Systems," Tenth IEEE Photovoltaic Specialists Conference (November, 1973).

⁴Edward Noll, "Winding Up the Wind," Ham Radio, Vol. 8, No. 1, pp. 50-53 (January, 1975).

tions needs to be made for what might be termed an average sensor location. The sensors will be on continuously so that 300 mW is continuous; the heater need not be on in the summer or parts of the spring and fall, while the winter will probably require heater power almost continuously. Since no data is available to the writer at this time on actual temperatures of the average grade crossing site, the assumption of worst-case power consumption for 12 hrs/day for winter and 2 hrs/day for one-half of spring and one-half of fall will be used. Under these assumptions a 442 ampere-hour battery would be required for 1 year of service. Rechargeable lead-acid batteries with a 100 ampere-hour rating would be used. They have a large capacity, work at temperature extremes, have long shelf life, and can be overcharged or discharged completely without seriously affecting the capacity when recharged.

Using six lead-acid batteries per sensor site would require their being recharged every 6 months, assuming a 50 percent efficiency rate for the batteries. If they need to be recharged more often, (for instance, due to a long cold period) the yellow malfunction light would go on to indicate a day or two remained before the sensors would become inoperative. This would allow for new or recharged batteries to be installed. In areas where prompt replacement is difficult, the solar panels could be employed to delay the replacement time for the batteries. With the proper size solar panel, the need for battery replacement would diminish to almost zero, leaving that sensor site independent of outside maintenance for several years.

6.4 CONCLUSIONS

It should be technically and economically feasible and preferable to:

Power remotely located sensors and their associated circuits from rechargeable batteries charged from solar panels.

Power crossing signal displays and control circuits using a wind generator to recharge the standby batteries.

7. COST ANALYSIS

7.1 PROPOSED CROSSING SYSTEM COST FACTOR

7.1.1 System Options

The basic rail crossing system detects the train presence and speed at intervals adjacent to the crossing, communicates this information to the crossing control, and activates appropriate warning devices. Figure 7-1 shows the basic system layout. Approaching a crossing the train is sensed at decreasing distances to accurately provide a constant warning time. Electronic equipment at each sense point detects the train presence and speed, then communicates this information to the crossing control. Timing of these signals at the crossing control is then used to calculate a constant warning time. Crossbucks with lights warn the motorists in each direction. Additionally, active display at the whistle pole warns the engineer when a crossing malfunction occurs. This basic system is symmetrical about the crossing, providing detection of approaching trains and warning signals for both directions.

Additionally, the basic system has three options. Each is required for specific crossing situations that may be normally encountered. These options are outlined as follows:

1. Communications Options

Intercommunication between the signals, sensors, and other equipment may be by:

Buried cables

Carrier current signals

VHF signals

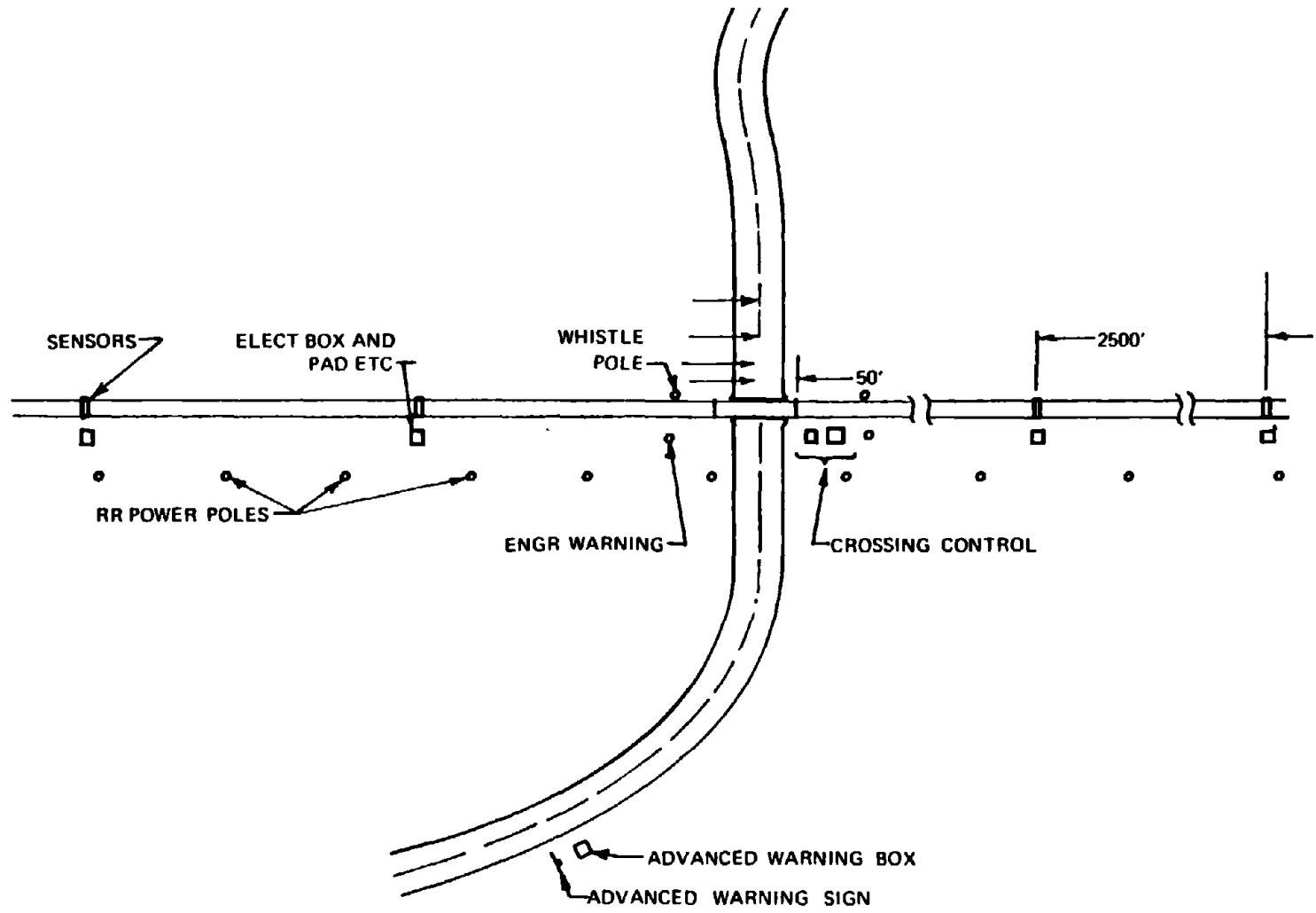


FIGURE 7-1. BASIC RAIL CROSSING SYSTEM

2. Multitrack Options

Where more than one track is at the crossing, additional sensors and logic circuits are required.

3. Advance Warning Option

In specific situations, providing advance warning to the motorists may be desirable.

Communications of the train sense signals may take one of three forms; buried cable, carrier current, or VHF transmissions. The buried cable is used for short runs between the sensors and the electronics packages, and to the engineer warning, etc. The longer runs, such as the 5000 feet each way from the crossing, would prove uneconomical for cable. Usually, a railway power line parallels the tracks. This line could also be used for communications via a carrier current system. Where available, the power line could provide both power and communications for the sensors. Where not available, a low power VHF system could provide the communications. The carrier current system is marginally less expensive and preferred, but where no power lines are available the VHF system, working on batteries may be required.

Where more than one track is at the crossing, additional sensors and logic circuits are required. These equipments will interface with the basic equipment boxes, communications, and signals. The resultant system will sense a train, or trains, on any track approaching the crossing and display the warning.

In specific situations, such as possibly caused by deep cuts or tunnels, the warning signal may not be visible to an approaching motorist. An advance warning may be desirable to provide adequate motorist warning time. The advance warning would display essentially the same information on approaching trains as at the crossbuck.

7.1.2 System Cost

Pricing of the rail crossing system requires a defined equipment base line and a quantity estimate for production. The following section develops a budgetary estimate based on a quantity of 100 units. Such an estimate will provide a viable comparison for the present grade crossing equipments. For lesser quantities, such as 10 units or 1, the cost per unit will increase. The increase is due to the learning curve in installation and in tooling costs required for production. As a guide line, a percentage of the unit cost is added to offset the low production levels. These percentages for the grade crossing equipments is estimated as follows:

100 units or over	basic unit cost
10 units	basic unit cost + 15%
1 unit	basic unit cost + 55%

The following analysis of the costs provide budgetary estimates for the proposed rail crossing system. The cost for a present system is also estimated for comparison. A dollar breakdown and comparison is as follows: (1975 dollars)

Basic Systems

Present crossing system	\$21,252
Proposed crossing system (Carrier TX)	\$30,940
Proposed crossing system (VHF TX)	\$31,120

Two-track Option

Present crossing system	\$43,080
Proposed crossing system (Carrier TX)	\$39,440
Proposed crossing system (VHF TX)	\$39,620

Advance Warning

Present crossing systems	N/A
Proposed crossing system	\$7,000

Maintenance Costs

Present crossing system	5% per year
Proposed crossing system (Carrier TX)	5% per year
Proposed crossing system (VHF TX)	10% per year

7.1.3 Sensors

The study recommends a sequential detection system. A series of sensors placed along the track would monitor the trains approach. The sensor methods proposed are loop detector and Hall device. Both methods are similar in that they detect the passing of a large iron body (such as a train). The two devices are also similar in their installation as shown in Figures 2-10 and 2-17. Pricing estimates of the two units are equivalent.

7.1.4 Remote Station

Each remote station consists of two sensors spaced about 10 feet apart and the equipment to communicate back to the local station at the crossing. Six of these remote stations are used, as shown in Figure 7-1, to detect approaching trains. Options include two types of communication and multiple tracks. Figures 7-2 and 7-3 show the basic remote station layout.

Figure 7-4 shows the basic remote station internal layout. Where local railroad power lines are available, the carrier current system is used. Otherwise, a VHF-system subunit and antenna provide the communications. Also, without power the remote unit will require extra batteries. Additional tracks will require increased electronics but will utilize the same communications system. The cost outline, below, gives the budgetary cost for the remote stations required at each crossing.

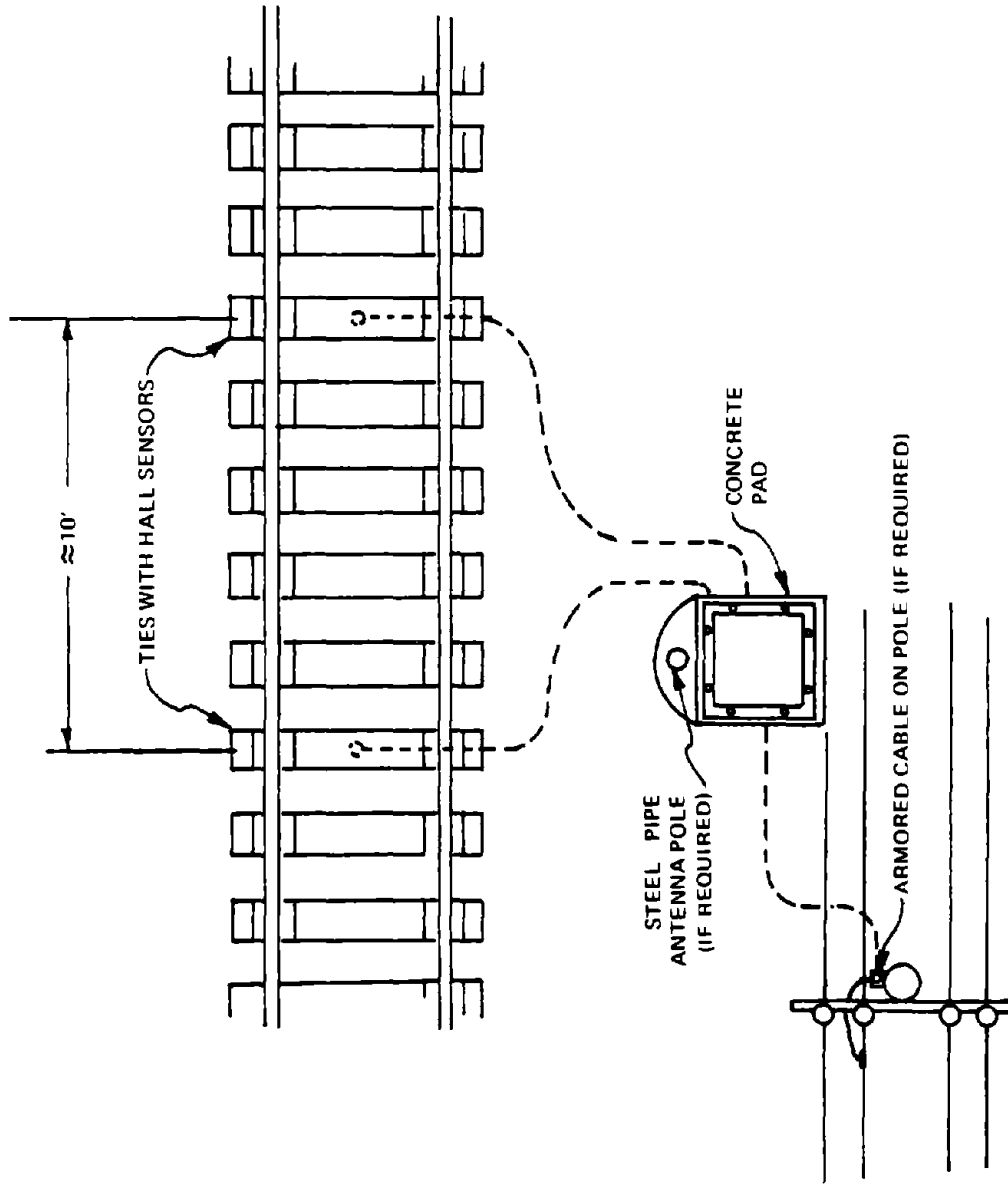


FIGURE 7-2. REMOTE STATION

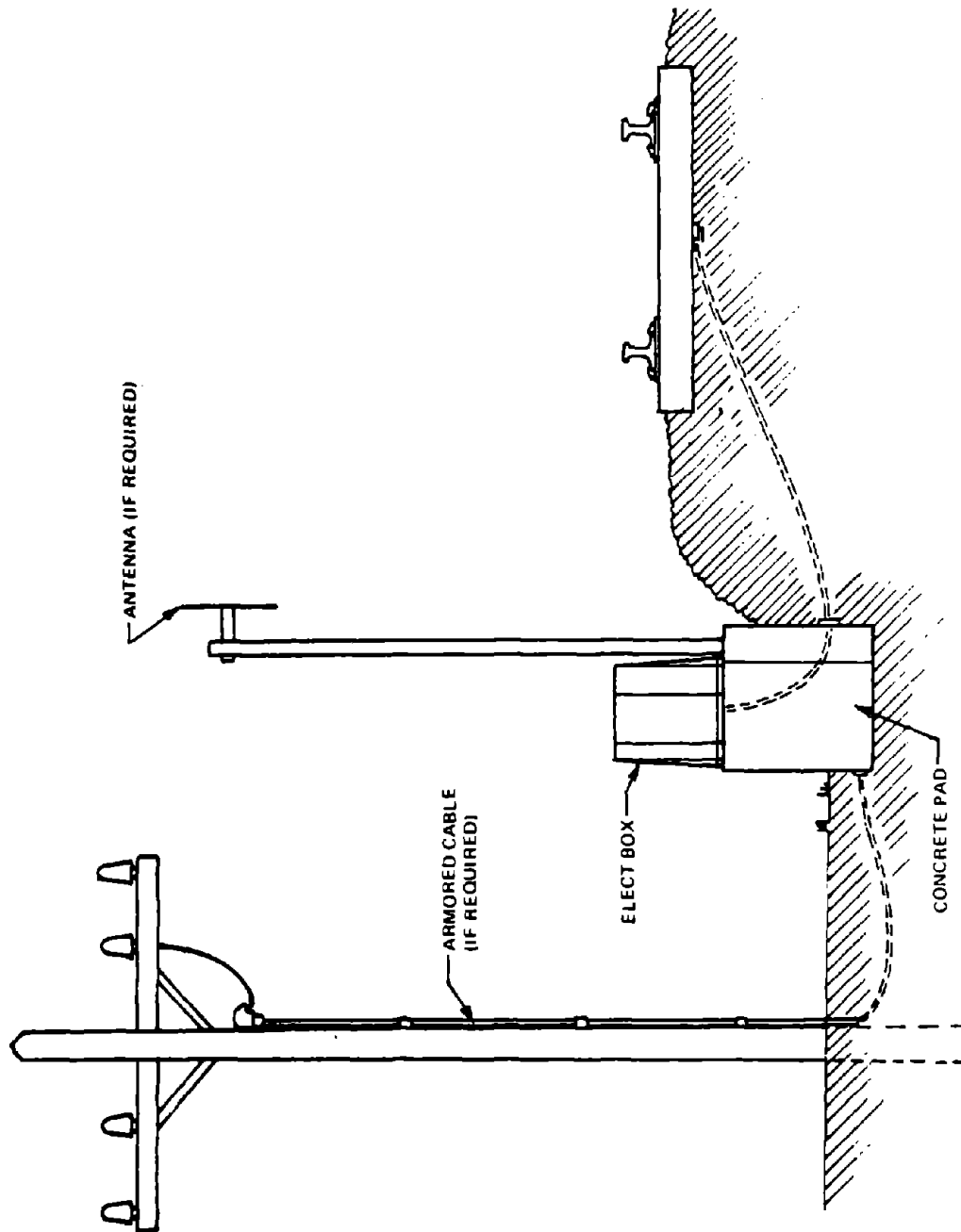


FIGURE 7-3. REMOTE STATION - SIDE-VIEW

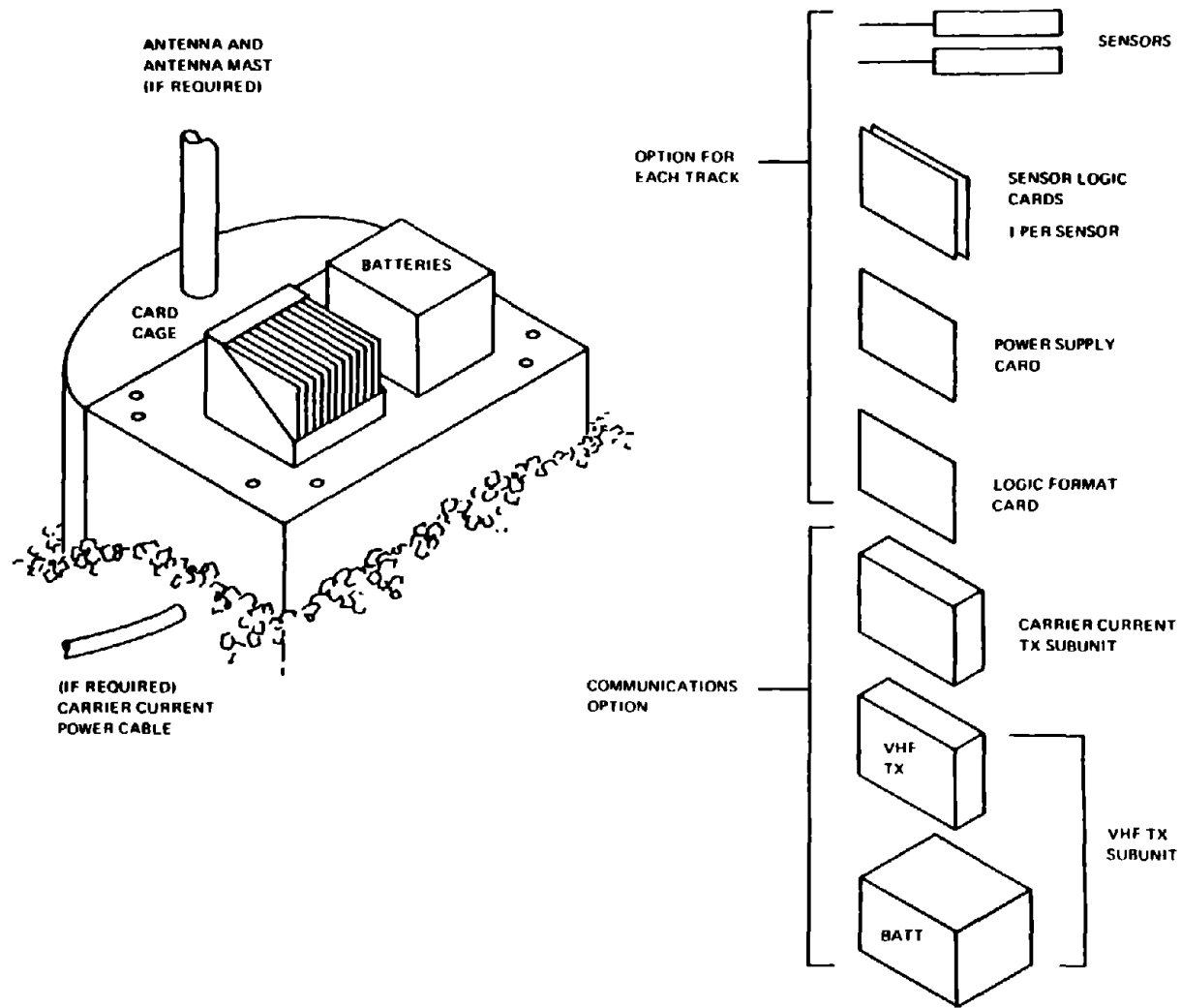


FIGURE 7-4. REMOTE STATION ELECTRONICS

Costs related to remote sensing system:

<u>Basic Unit</u>	<u>Carrier TX</u>	<u>VHF TX</u>	<u>2-track</u>	<u>Total</u>	<u>4-units</u>
\$1920	\$970			\$2890	\$11,560
1920		\$840		2760	11,040
1920	970		\$1170	4060	16,240
1920		840	1170	3930	15,720

Remote sensing system cost breakdown:

Basic Unit

Sensors	\$800
Electronics	600
Power supply	100
Enclosure	<u>420</u>
	\$1920

Carrier TX Option

Battery	\$70
Carrier TX	200
Cabling	<u>700</u>
	\$970

VHF TX Option

Battery	\$140
VHF TX	350
Antenna and mounting	<u>350</u>
	\$840

2-track Option

Battery	\$70
Electronics	300
Sensors	<u>800</u>
	\$1170

7.1.5 Local Station

The local station receives train position information from the remote stations and provides warning displays. As shown in Figure 7-5, the local station has display units in addition to the electronics. Active crossbucks warn the motorists and engineers warning displays indicate failure in the crossing system. Optionally, advance warning signals will be made available for the motorists. Other options include the communications system and multiple tracks as previously outlined. Power, though, will always be available at equipped crossings.

The electronics equipment at the local station, as shown in Figure 7-6, receives the data from the remote stations via either VHF or carrier current communications. The data is decoded and combined with local sensors. Logic circuitry then makes the appropriate decision and provides light control. Figures 7-7 and 7-8 show, respectively, the crossbuck and the engineers warning. The crossbucks light for an approaching train or both they and the engineers warnings light for equipment failure.

The battery box as shown in Figure 7-9 provides reserve power in case of a power line failure. Because of the heavy power drain of the warning lights, operation at an unpowered site was not considered. The batteries provided will operate the system for more than one day.

Only one local station system, with options, is required for each crossing. The budgetary costs are as follows:

Costs related to local station:

<u>Basic Unit</u>	<u>Carrier TX</u>	<u>VHF TX</u>	<u>2-track</u>	<u>Advance Warning</u>	<u>Total</u>
\$19,180	\$200				\$19,380
19,180		\$900			20,080
19,180	200		\$3820		23,200
19,180		900	3820		23,900

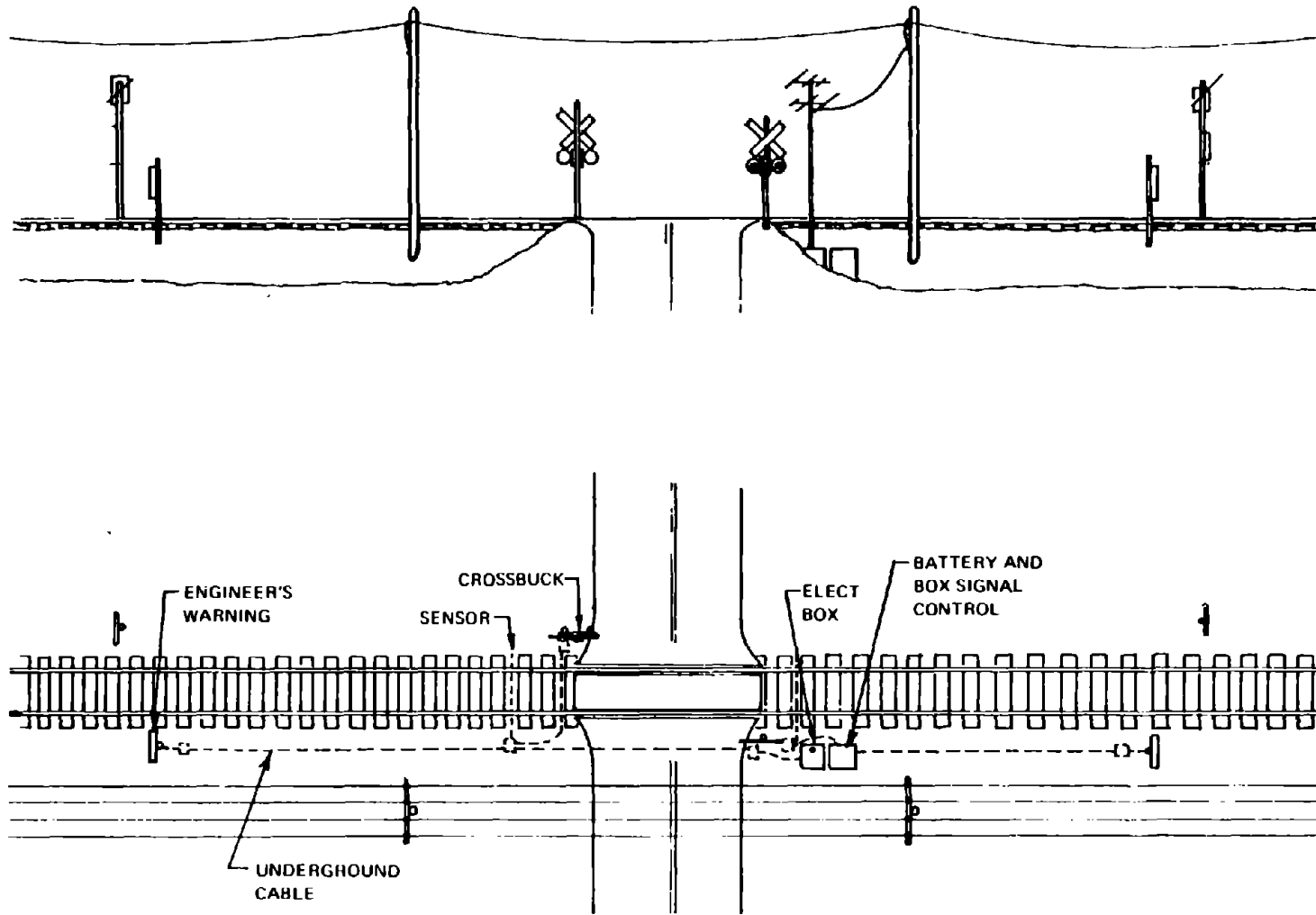


FIGURE 7-5. LOCAL STATION

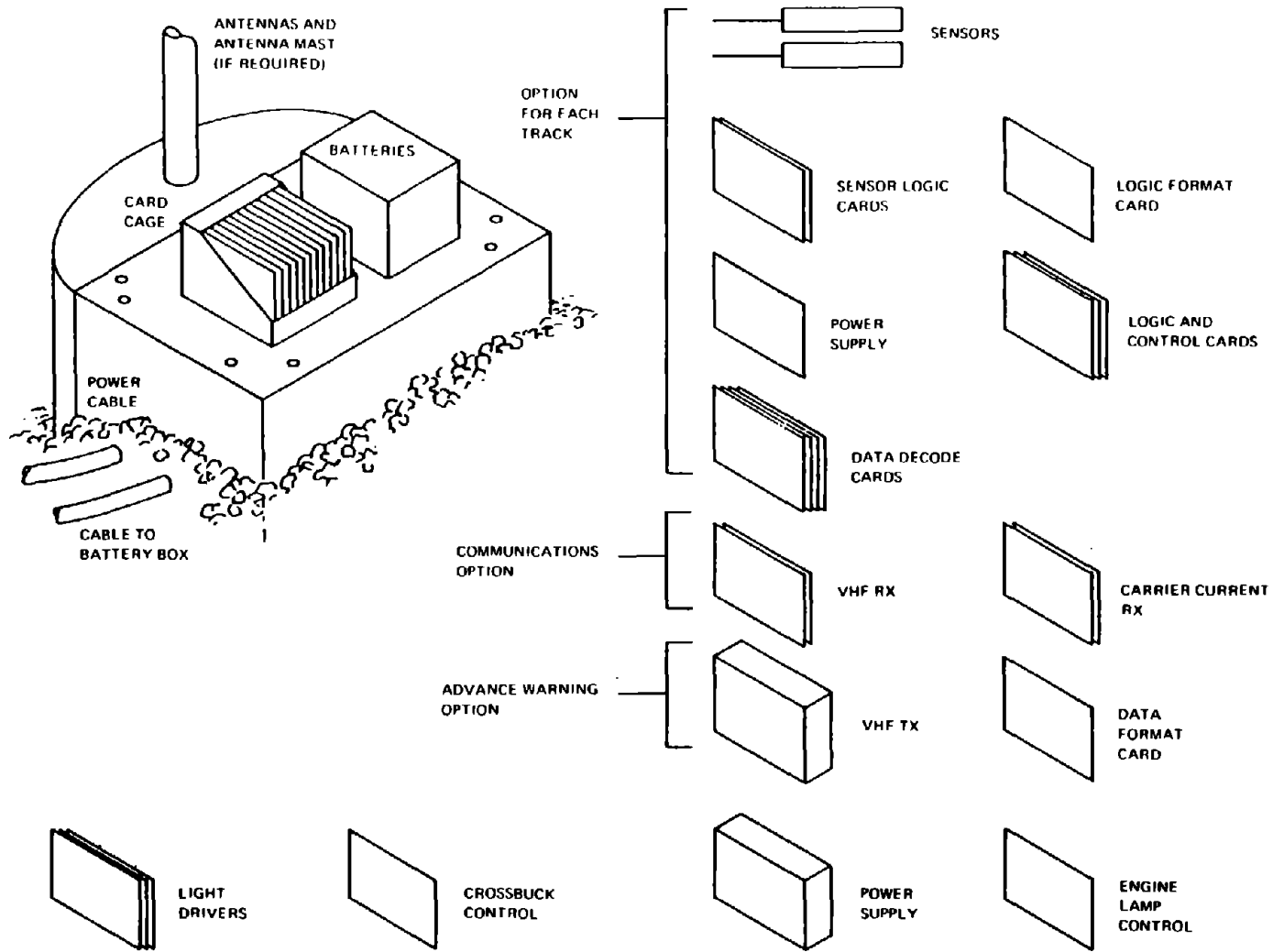


FIGURE 7-6. LOCAL STATION ELECTRONICS

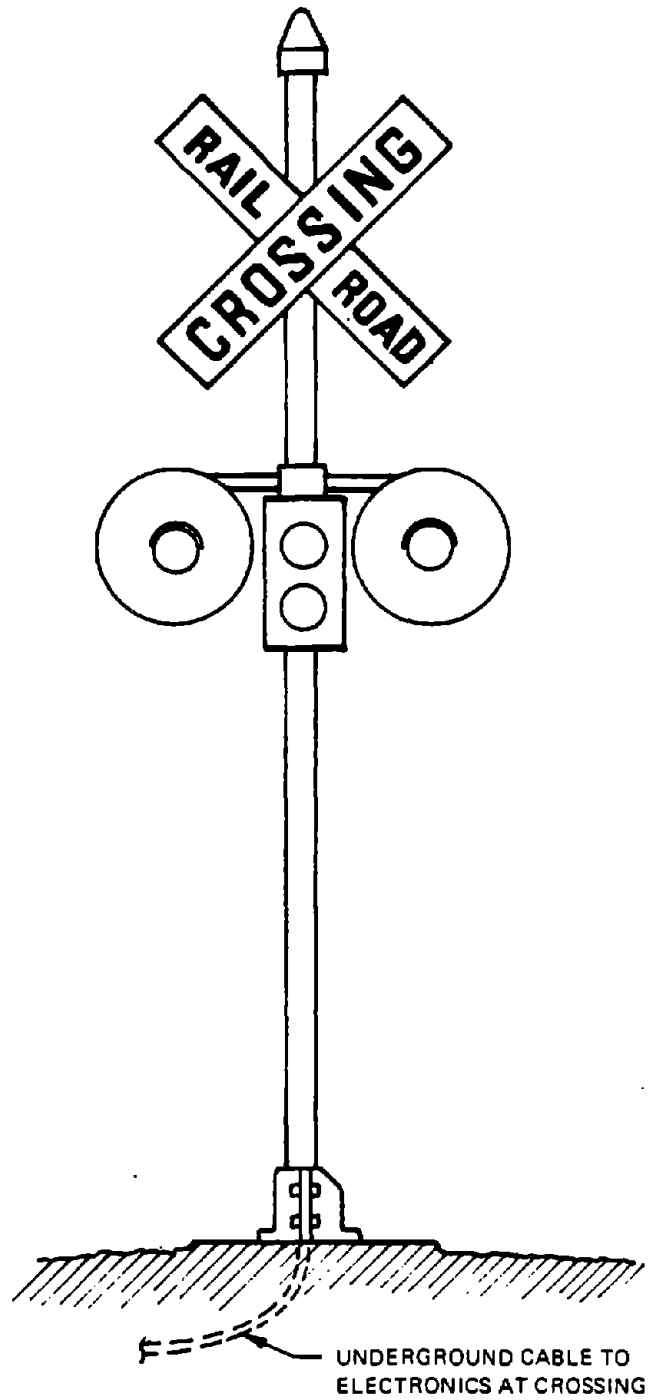


FIGURE 7-7. CROSSBUCK

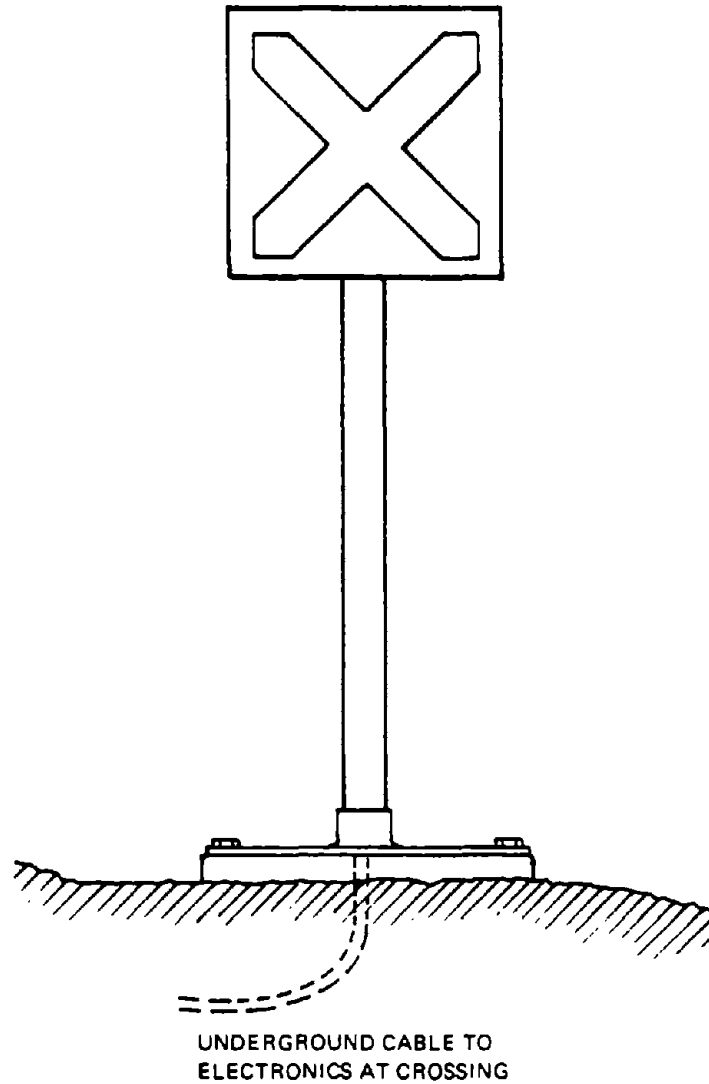


FIGURE 7-8. ENGINEERS WARNING

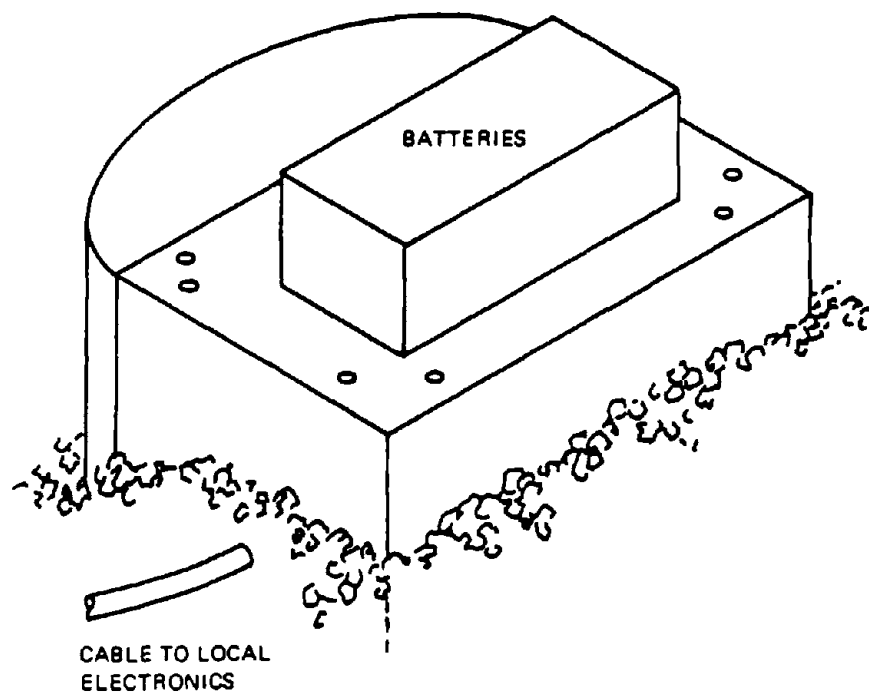


FIGURE 7-9. LOCAL STATION BATTERY BOX

<u>Basic Unit</u>	<u>Carrier TX</u>	<u>VHF TX</u>	<u>2-track</u>	<u>Advance Warning</u>	<u>Total</u>
\$19,180	\$200			\$850	\$20,230
19,180		\$900		850	20,930
19,180	200		\$3820	850	24,050
19,180		900	3820	850	24,750

Local station cost breakdown:

Basic Unit

Sensors	\$800
Enclosure assembly	840
Electronics	2700
Power supply	250
Crossbucks	700
Lamps	2000
Engineers warning	1200
Batteries	420
Interwiring	<u>10,270</u>
	\$19,180

Carrier TX Option

\$200

VHF TX Option

VHF receiver	\$350
Antenna and mounting	<u>550</u>
	\$900

2-track Option

Sensors	\$800
Logic	1300
Cabling	<u>1720</u>
	\$3820

Advance Warning Option

\$850

7.1.6 Advance Warning

The advance warning system provides a warning display to approaching motorists who otherwise may not see the crossbuck with adequate time. The advance warning display is located up to one-half mile from the crossing and is controlled by a VHF link. As shown in Figure 7-10, the display contains a VHF receiving system, light control, and batteries to operate the systems. The budgetary costs for the advance warning display is as follows:

Advance warning

2-units	total
\$3500 each	\$7000

Advance warning cost breakdown:

Enclosure assembly	\$840
Electronics	1100
UHF TX and RX	1050
Antenna and mounting	1250
Power supply	500
Batteries	560
Advance warning display	<u>1700</u>
	\$7000

This cost includes the additions required for the local signal system and two advance warning units. The division is as follows:

Local system	\$850
2-warning units	<u>6150</u>
	\$7000

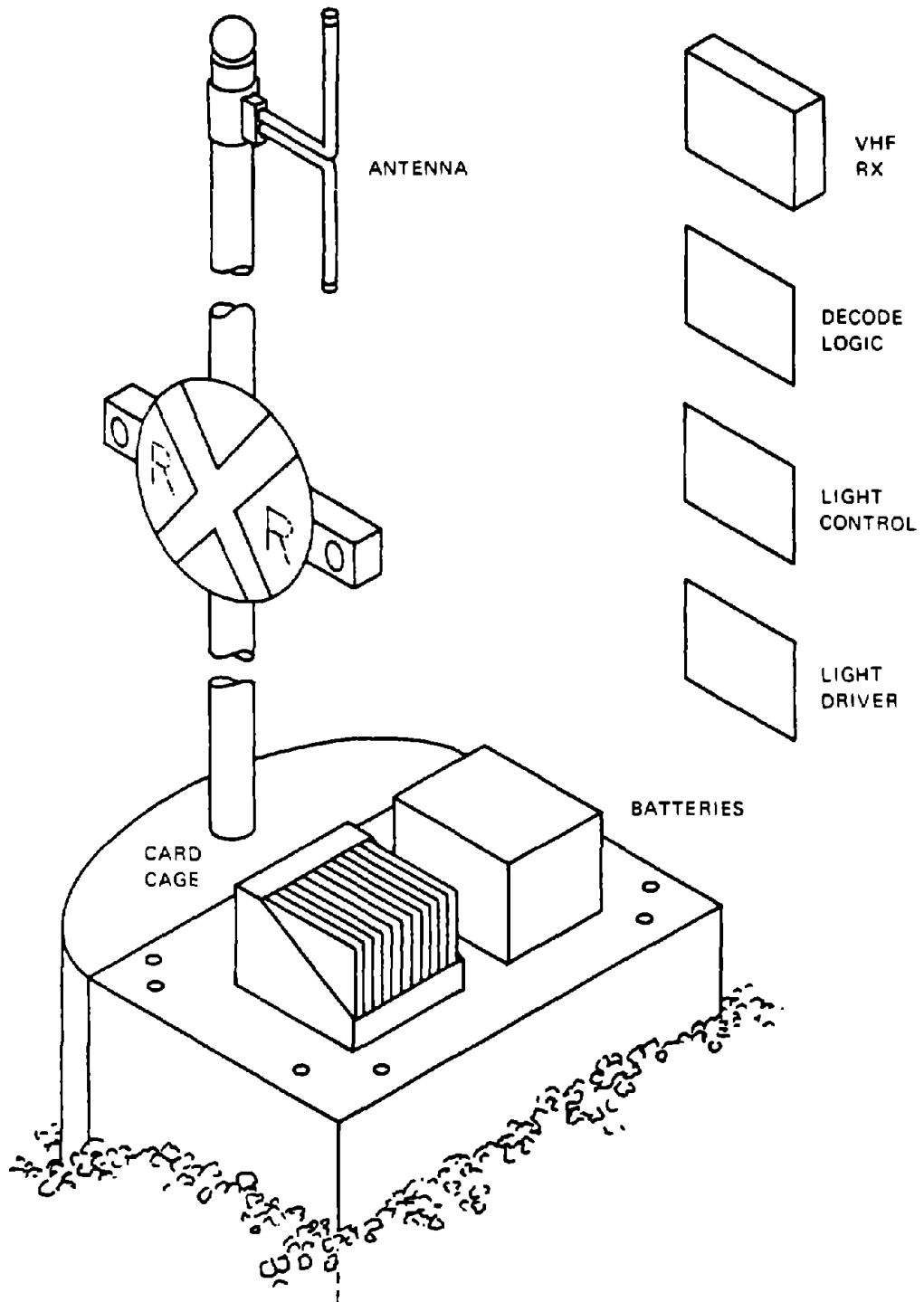


FIGURE 7-10. ADVANCE WARNING SYSTEM

7.1.7 Maintenance Factor

The total cost of ownership includes both the initial costs, as outlined, and the maintenance costs. Following the precedents set by the present crossing equipment¹, the design goals should include low maintenance and a 30 year minimum life. Normal system maintenance should not exceed 5 percent of the initial cost. Battery powered systems, though, have the added cost of routine battery replacement. For the system proposed, the replacement cost will add another 5 percent of the initial cost per year.

7.2 PRESENT SYSTEM COST

The present rail crossing system provides only basic signaling of a train approach. The sensing technique consists of rail-to-rail continuity measurements that sense when the trains are a fixed distance from the crossing. The basic features of constant warning time and engineers warnings as well as options of advance warnings are not available. A budgetary cost estimate for a basic, one-track rail crossing system is as follows:

<u>Basic rail crossing*</u>	
Material	\$8211
Labor and field engineering	8211
Design	2415
Miscellaneous	<u>2415</u>
	\$21,252

Note: The *reference document lists basic rail crossing costs as of 1971. These costs were increased 50 percent as an allowance for the four years between 1971 and 1975.

¹ John B. Hopkins and Morrin E. Hazel, Technological Innovation in Grade Crossing Protective Systems (Technical Report No. DOT-TSC-FRA-71-3, Cambridge, Massachusetts, June, 1971).

Maintenance for the present system will follow the guide line of 5 percent of the initial cost per year for a 30 year life.

7.3 COST CONCLUSIONS

The proposed system for a basic rail crossing will cost 46 percent more than the cost of the present designs. However, as the complexity of the crossing increases, the cost differential changes to an 8 percent decrease for a two 2-track configuration. The proposed system also provides many advantages in sophisticated warning control which are not possible with present systems. These include the engineer warning, malfunction warning, and constant warning time for virtually all ballast conditions and train movement patterns. Note that if \$5000 for a motion detector is added to the present system costs, the basic cost for the new system will be only 18 percent greater for single-track systems. For double-track systems requiring two motion sensors, the cost of the new system will be equivalent or slightly less than that of the present system.

8. CONCLUSIONS AND RECOMMENDATIONS

8.1 SUBSYSTEMS

The innovative railroad-highway grade crossing warning system will consist of four basic subsystems. These are:

Sensors

Communications

Displays (Signals)

Controls

8.2 RECOMMENDED SYSTEM

The recommended system will have the following general characteristics:

Constant warning time for almost any train movement pattern.

An indication to the engineer of a malfunction which will not be confused with a Stop-for-Train warning.

No electrical connections to the rails will be required.

The sensors are installed in the roadbed or special ties with a minimum of difficulty and will require minimum special attention by roadwork crews.

Fail-safe operation.

Ease of maintenance through modular construction.

Low power consumption.

Adaptable to a great variety of crossing situations.

Immunity to weather and most vandalism.

Ease of maintenance.

Unfortunately, it was not possible to meet the goal of installation outside of railroad property with any system which was cost effective and reasonably adaptable to different situations. It was also impossible to make the new system less expensive than present systems. However, the new system does meet all of the other objectives, most of which are impossible with present systems.

Train detection is best accomplished by using pairs of discrete magnetic sensors. A given crossing situation will use five or seven sensors pairs per track. One of these sensor pairs straddles the road, replacing the present island circuit. The others are spaced on either side of the crossing and make possible both velocity and acceleration prediction for a variety of train movement patterns.

The sensors themselves use Hall-effect devices to detect the changing magnetic field of the train. No magnetic source is required, as the large amount of metal in the train produces changes in the magnetic field which can be easily detected. This device is installed in the roadbed, halfway between the rails. Orientation is not critical, so it could be installed simply by burying it in the ballast. (An interesting packaging technique would mount the sensor in a special tie.) A sensor of this type has been tested and shown to be effective in detecting trains, rolling stock, and service cars.

A discrete sensor system will require a communications system to relay its information to the control circuits. No single means of communications is a universal "best choice" so a three-link communications subsystem is recommended. These three links are buried cable, carrier, and VHF. Buried cable is used only to connect equipment which is in such close physical proximity so that it is cost-effective. Carrier links use the existing railroad power or code line or commercial power lines to transport low frequency (30-200 kHz) carriers between equipment. Such power or code

lines should be available along most railroads with medium to heavy rail traffic, so a carrier link will generally connect all but the closest sensors to the control circuits. However, carrier systems cannot be applied easily if there are no convenient lines. This may be the case in remote areas (where sensors are battery powered) or between the control system at the crossing and the advance warning signs. In this case, a wireless system is convenient, and VHF (300-500 MHz) is recommended. The use of any of or all three links allows the system to be adapted to a great variety of situations. Figure 1-2 illustrates a system of discrete sensors and composite communications links applied to the hypothetical crossing system of Figure 1-1.

The innovative crossing warning system includes three displays or signals. These are the motorist crossing warning, motorist advance warning, and engineers warning. The motorist crossing warning is similar to the presently used signal. However, it will utilize a new style crossbuck, which will only be used with signals with the new control circuits. The red incandescent lights may be replaced with alternately flashing red strobe lights for added conspicuity. In addition to these lights, the signal will have two amber lights, arranged vertically and mounted between the two red lights. The amber lights will be activated in the event the system fails. The active advance warning sign is an option which can be used where warranted by poor visibility. This sign will be similar to present or future passive advance warning signs. It will, however, have two alternately flashing amber lights which will be activated to signal train presence at the crossing ahead. The engineer warning signal alerts the engineer to a crossing warning system with a failure, allowing him to report it and to sound his horn more than usual to warn motorists. This signal will be an amber X, which flashes for failure and is steady when the system is activated and working properly.

The control and timing circuitry is based on a microprocessor and a programmable read-only memory (PROM). This system is not unlike that presently used in portable calculators. The microprocessor monitors train movement, computes its velocity and acceleration, and activates the displays according to sensor data and instructions

from the PROM. Systems are adapted to various crossing situations by inserting an appropriate instruction set (program) into the PROM at the factory.

The power requirements for the sensors and their associated communications systems are small, allowing battery power to be used if line power is not available. Rechargeable batteries might also be used, with recharging power provided by solar or wind generators.

The costs of this new system will be greater than those of the present systems for typical installations. The increased flexibility of the new system will, however, greatly reduce this difference for awkward situations which require much special control circuitry. In addition, the new system provides many more benefits than are possible with conventional systems.

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APPENDIX
REPORT OF INVENTIONS

In this report a number of new concepts or applications are explored. Although these are based primarily on existing technologies, certain of the applications are novel. These include use of the Hall-effect sensor for train detection; (p. 68), a novel application of a carrier communication system to grade crossings; (p. 97); and an application of ROM-based solid state control technology to grade crossing subsystems (p. 145).

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