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16. Abstract

The constraints on innovative grade crossing protective systems are delineated and guidelines for development indicated. Inventory data has been arranged to permit an estimate of the classes of systems needed, the allowable costs, and contribution of various types of crossings to accidents. Many crossings warrant very limited expense and account for very few ~~deaths.~~ A number of approaches are ~~possible~~ for the intermediate cost classes, based on use of conventional signals with low-cost activation systems. Use of similar elements, singly or in combination, ~~can also~~ improve effectiveness of more expensive systems. The very high cost locations may well benefit from interconnection of train and vehicle detectors and small computers.

Extensive analysis and laboratory investigation has been carried out relating to a microwave telemetry alternative to conventional track circuits and possible crossing-located radar and impedance train detection systems.

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PREFACE

This report results from research supported by the Federal Railroad Administration under two tasks: PPA RR02, "Grade Crossing Protective Devices", and RR03, "Grade Crossing Train Detection Systems". These programs are based on the same body of knowledge and complement one another making it particularly appropriate that a combined report be issued. Appreciation should be given to the many individuals in government, railroads, the signal industry, universities, trade associations, and elsewhere, who contributed so greatly to the overall effort. Individuals at TSC other than the authors who have contributed significantly to these programs include K. Hergenrother, F. R. Holmstrom, T. Newfell, and E. White.

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SECTION 1

INTRODUCTION

1.1 THEORY

Reducing the number of deaths and injuries from accidents at rail-highway intersections is a difficult and multi-faceted task. 1500 deaths and 3000 injuries occur annually at U. S. grade crossings. The severity of these accidents ranks second only to that of aircraft (as measured by ratio of dead to injured). These figures indicate that while grade crossing safety represents a small though significant part of the automobile safety problem, it is a major part of rail safety, accounting for a large percentage of rail-associated accidental deaths. The range of crossing characteristic differences provides a variety of problems which differ not only in degree, but in kind. In addition to the amount and type of traffic, both rail (passenger, freight) and highway (cars, trucks), the environment can be rural, suburban, or urban; there may be one track or many; the roadway may be broad, straight, wide, narrow, crooked or rough; motorists may have a view of the track for miles, or a few yards; road and/or tracks may have sharp curves in the vicinity of the crossing; and the immediate surroundings can include sidings, stations, switches, and diamonds (where tracks cross one another) as well as highway traffic signals and intersections. In approximately one-third on the cases trains are not involved; road hazards and disruptions of traffic such as the mandatory halting of school buses or oil trucks before all crossings are the cause. In a large number of cases, motor vehicles strike the train, sometimes hitting far back from the locomotive. Furthermore, many accidents arise at intersections protected by operating active signals.

There are many avenues which must be followed if significant improvement is to be obtained. Crossings must be designed and constructed to minimize road hazards and maximize visibility of approaching trains. Considerable attention is now being given to developing roadside signs which will better alert the motorist to the nature of the risk and describe actions to be taken. Many authorities feel that there is much room for improvement via driver education; they also call for stricter enforcement of obediance to present signals. While the FRA (along with FHWA and NHTSA) can and does provide research and guidance in these areas, basic legal responsibility for stricter enforcement rests with the states and municipalities. Another area of continuing research is effective signal design. Programs are also warranted in the improvement of visibility and possibly audibility of trains. Accurate and detailed inventory of present crossings is needed along with improved priorities for installation. The aspects of grade crossing protection to which TSC attention is directed in this study involves the more technological elements.

Of the approximately 220,000 grade crossings in the United States, only 20% are provided with active protection (signals such as flashing lights, gates, etc, which are controlled by the passage of trains). The remaining 180,000 crossings are protected by passive devices (signs such as the familiar "Stop, Look, and Listen" or "RR Crossing") which present the same aspect to the motorist regardless of the presence of rail traffic. Studies[1] indicate that significant reduction of accidents could be obtained through more widespread installation of active protection. The principal reason why this course has not been followed to a greater degree is the high expense of such protection. The least costly installation now possible, single track, flashing lights, is likely to cost $15,000 to $20,000, and typical gate installation involving a few minor complications can cost from $25,000 to $100,000. Except for private crossings, the costs are generally borne by the states, cities, and railroads (sometimes shared, sometimes entirely governmental), with limited assistance by the Federal government unless Federal highways are involved. Railroads often bear the entire expense of maintenance, which will be shown to be a major element of crossing protection costs. Thus, those groups on which the major part of the expenditure currently falls rank among the financially burdened institutions in our society. The result is a relatively limited rate of installation of active protective systems. Any means of achieving significant reduction in these costs will permit more rapid and widespread installation of protective signals, and permit more sophisticated warning devices where economically warranted and feasible.

In V-HRB, the subject of innovation in automatic signalling is treated as follows:

> There is a great need for the development of a less expensive method of activating signals, gates, and bells which warn of a train's approach. Existing devices, although effective in reducing accidents, are costly to install and maintain. A benefit-cost ratio greater

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[1] In the course of this report, frequent reference will be made to two previous studies on the subject of grade crossing safety prepared by Alan M. Voorhees & Associates, Inc., of McLean, Virginia. For simplicity the following abbreviations will be used:

<u>V-HRB</u>: (Ref. 1) "Factors Influencing Safety of Highway-Rail Grade Crossings," NCHRP Report #50, Highway Research Board, NAS, 1968

<u>V-FRA</u>: (Ref. 2) "A Program Definition Study for Rail-Highway Grade Crossing Improvement," FRA-RP-70-2, FRA, 1969

> than one for installing flashing lights or gates can be obtained at only a small number of crossings. Future research in this area should be aimed at some method of activation other than track circuitry. Track circuitry was invented in 1872. Since that time many refinements have been made. Recent improvements, however, have simply led to increased costs, and all have been dependent on track circuitry. The current state of electronics, radio, radar, etc., should allow individuals who are knowledgable in these areas to devise a method of <u>activation</u> which would be considerably less expensive than that currently being used...The state of present-day technology is not only such that it will allow such innovations, but also these innovations can be said to be overdue.[2]

It is to a broadened conception of this goal, the general application of the developments and capabilities of modern technology to grade crossing safety, that the TSC program has been directed. The examination of new concepts, and the constraints upon their application, represent major parts of this study. However, it is intended that this effort shall not only explore in depth the possibilities of new approaches, but shall also serve to stimulate the interest of the technical community generally, so that those with most immediate knowledge of relevant technologies will be encouraged to suggest their use. Such an aim carries with it the responsibility to act effectively to provide to such potential innovators the guidelines which will permit their involvement to be meaningful, and to aid in governmental policy determination by indicating both the potential and the limitations of technology. While these functions are necessarily carried out to a large degree in an informal manner, this report represents a formal embodiment of activities and conclusions to date.

To a large degree this report is both a review and summary of some of the many concepts, opinions, and conclusions expressed (in a spirit of cooperative friendliness) by many individuals professionally concerned with crossing protection. This includes representatives of government, universities, highway departments, railroads, and rail signal suppliers. That is not to say that any such person would agree in whole or in part with the contents of this document but simply to disclaim originality for most of the information and protection concepts delineated, particularly in the area of conventional techniques. It is, however, felt to be of value to provide here a single compilation of those factors, concepts, etc. which appear to embody a high degree of relevance, validity, and usefulness.

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[2] Ref. 1, p. 66.

SECTION 2

BASIC CONSTRAINTS INFLUENCING GRADE CROSSING PROTECTION

2.1 THE OVERALL ENVIRONMENT

The task of achieving improved grade crossing protection is strongly influenced by the remarkably diverse nature of the problem. Some aspects of this are readily apparent. Tracks and highway can intersect anywhere; in the very center of a small town, in a large city, in a suburb, or very commonly in even a completely rural setting. The allowed speed limits, both vehicular and rail, can vary from zero (stop sign) to 80 MPH or more. The motorist's view of the track may be clear or completely obscured. Traffic of both types can be very light or very heavy, uniformly distributed or peaked at certain hours, days, or even seasons. Possible weather variations, of course, include the full gamut found in the U. S. Both rail and road may follow curves, hills, etc.

However, beyond this relatively straightforward diversity, one finds a tangled web of standards, regulations, and economics. There are currently more than 70 Class 1 railroads, and a number of smaller, specialized operations. Each may have (and often does) its own set of procedures, rules, and practices for operations and maintenance. Intermixed with these are the rules of the various state regulatory bodies with which the railroads must deal; these can vary markedly among the several states in which a single railroad operates. For grade crossing protection matters, highway departments are often concerned as well, and one must not omit consideration of the role of local and county governments. The Federal government, through both FRA and FHWA (and, to some degree, NHTSA) is becoming increasingly involved.

Economic questions are equally muddled, with wide variation in guidelines as to who specifies and pays for installation, maintenance, and upgrading of protective systems. While one may use various approaches to determine the cost to society of grade crossing accidents, it is very difficult for the railroads themselves to sort out what safety is worth, or how to attain it. (The legal departments, for example, may be as concerned with actions which provide a stronger case to defend as with improved protection.)

Finally, there are the myriad work rules and union agreements which may complicate attempts to modify installation and maintenance of equipment and have clear impact on both the feasibility and cost of innovation.

Viewed simply as a straight engineering problem, the purely technical complexity of attempting to achieve extremely high safety standards under that very difficult environment, with minimal maintenance is not a subject to be taken lightly. The fact that solutions do exist at all, even if costly and in some ways imperfect, is largely the result of many years of experience and field testing, with continual incremental refinement, and many false steps. It is nearly a cliche to speak of the harshness of the railroad environment, but it is, in toto, so severe as to make exaggeration difficult. The fundamental requirement for absolutely failsafe operation of safety circuits is one which has never been met inexpensively or easily. It has been found all too often that the intriguing new approach has an even more intriguing inherent failure mode, or requires extra maintenance to the degree that both safety and economics are seriously compromised. While it is important that TSC not allow itself to be drawn into the basically conservative view of most railroads toward innovation in safety devices, railroad experience and wisdom must not be ignored or deprecated.

It should be noted that these conservative views are shared by the suppliers of rail safety equipment. Many of their staff came from non-railroad electrical engineering backgrounds, and started out with hopes of "revolutionizing the industry." In the course of a few years, they have come to recognize more clearly the very special and demanding requirements of railroad vital circuits.

2.2 CONSIDERATION OF LEGAL LIABILITY

There is virtually no class of accident in which fault and legal responsibility is easily determined, and grade crossing collisions are no exception. It is a rare accident that does not lead to litigation, and rarer still for the railroad to mount a successful defense. In addition to the apparent inclination of the average citizen to be more sympathetic to a victim or his heirs than to a large, impersonal corporation, it is extremely difficult to prove, particularly to a skeptical jury, not only that the protection was completely adequate by contemporary standards, but, further, that it operated correctly in the case at hand. There have been many lawsuits in which the testimony of numerous witnesses has been insufficient to convince a jury that the lights were indeed flashing or even that a gate was down.

One of the few assets a railroad attorney can hope for is some degree of legal protection by having followed (or exceeded) long established industry or government safety standards. This is by no means an overpowering aid, but it can be a significant help, and may well be a necessary, if not sufficient, condition for a successful defense.

It should be noted that this basic situation will continue to exist regardless of where the responsibility lies. A transfer of authority to state (or even Federal) highway agencies would not alter the basic consideration that some individual or institution must accept liability. Any attempt to circumvent this would almost certainly be neither legal nor acceptable to any electorate. Thus, the basic considerations leading to the present very rigorous standards for railroad vital circuits are very likely to prevail in any case. Grade crossing protection is typically such an integral part of a railroad's signal system, and so specialized a subject, that actual transfer of technical responsibility, including maintenance, to another body is difficult to imagine. A system in which railroads provide signal maintenance under contract to the responsible governmental agency is conceivable, but scarcely likely to simplify the liability situation.

2.3 COSTS OF GRADE CROSSING PROTECTION

2.3.1 Initial Costs

Any attempt to realize safety improvements through cost reduction and resultant more widespread installation of protection requires a careful examination of the major sources of expense in present systems. The primary cost factor is labor of installation; this represents about 40% of the total for both simple and more complex systems. Another substantial expense is associated with the necessary engineering design and layout. For a very simple case, this will be at least one or two man-weeks, and in general contributes approximately 10% of the total cost. About 5% is invested in the actual signal devices and hardware. The remaining 45% is absorbed by the necessary insulated joints, track circuit transmitters and receivers, etc. This breakdown is summarized in Tables 1 and 2, based on analysis of actual and planned costs for installations in New England. The typical dollar figures are for four absolutely minimal installations, two of which have been visited. Signal devices are two poles, each with crossbucks and double-direction flashers. Analysis of costs for four automatic gate crossings, ranging in total price from $22,000 to $86,000, indicates that the relative percentages of Table 1 are valid as a general rule. While this conclusion is not necessarily applicable to all possible systems, a useful rough estimate of the total cost of any protective system is that installation labor will approximately equal material costs.

The major cost element, labor, is difficult to attack directly. Aside from work rules and union agreements, which do not at present appear to be a problem, the present systems have a lengthy past, and this element has been subjected to considerable scrutiny. The railroads and signalmen are not deliberately doing things the hard way. Significant reduction of installation costs must be sought through exploitation of alternative concepts which offer hope of greater simplicity. This applies also to engineering design, a significant factor.

Table 1. Typical Costs for Basic Flashing Light Installation

Item	Typical Cost	Percent of Total
Materials (Lights, poles, foundations)	$5600 ($700)	40% (5%)
Labor and Field Engineering	$5600	40%
Design	$1400	10%
Misc.*	$1400	10%

*Crew housing, truck and auto milage, etc.

Table 2. - Typical Costs for Materials

Flashing lights, poles, etc. (2)	$ 500
Relays	600
Relay case	450
Batteries	250
Pole foundations (precast) (2)	120
Cable	200
Rectifiers	100
Audio frequency transmitters	1800
Audio frequency receivers	1600
Insulated joints	500

As the above items represent at least half of the total cost, it is clear that no dramatic reductions in this total can be expected through development of inexpensive hardware alone. At the same time, any truly low-cost system will ultimately be limited by the expense of the basic warning devices, and these are worthy of consideration.

Prices now charged by the small group of railroad signal suppliers do not necessarily establish the minimum possible. The advantages in having well established markets in which they can offer complete systems (a considerable advantage over a company selling only track circuits or lights or gates), combined with a relatively small total market (approximately 1000 new protective systems are installed per year) has led to what appears to the outsider to be a relatively comfortable, unaggressive marketing situation. Price competition may not be as strong a factor as could be desired, and entry of new companies to the marketplace is difficult. In addition, the relatively common situation in which the railroads purchase the equipment and are then wholly or partially reimbursed by state, local, and/or Federal government can reduce the inclination of the buyer to bargain aggressively.

Therefore, a study has been completed comparing costs for similar equipment in other areas; specifically, highway traffic signals, and signs (both highway and advertising). The results were not particularly encouraging. Table 3 indicates some typical values. It seems noteworthy that these components are comparable in cost, and total installation costs are even higher than for railroad applications.

Table 3. Range of Costs for Comparable Non-Railroad Hardware and Installation

Item	Material Cost	Labor Cost
15' pole, including foundation	$75 - 100	$150 - 250
Simple flashing lamp* (single unit)	75	100 - 150
Sign 4' x 2' (mounted)	50	25 - 110

*Grade crossing installations typically have four flashers per pole. They are tightly focussed for high intensity with low power consumption, so that proper alignment adds significantly to installation cost.

There are, of course, a number of significant differences. Reliability requirements are generally not quite as severe in highway applications as for rail, and highway signals, in addition to being very broadbeam, are designed for high intensity and do not require standby batteries. The optical systems for rail signals are fairly sophisticated, involving lenses of very specific and narrow beam patterns. The signals use bulbs of only 11 to 18 watts; "highway crossing red" is a very deep shade, with only 9% light transmission. The AAR and some equipment manufacturers are currently looking into this subject and significant improvement is probably possible. TSC will keep apprised of progress in this area and will consider an active role if warranted. However, it is doubtful that such efforts can lead to more than a marginal increase in effectiveness of decrease in cost. Nor, considering the relatively low cost of flashing lights, does it seem relevant to seek improvement in this area until the cost of labor, design, control circuits has been very dramatically reduced (by at least an order of magnitude).

As a final point, it is useful to examine a truly low-cost (passive) device to gain insight into the minimum expense attainable for active devices. V-FRA indicates that crossbucks have a service life of seven years (as opposed to 30 years for active systems), require no maintenance, and cost $150. This represents an annual cost of approximately $25. As will be seen in a subsequent section of this report, that figure is approximately the annual expenditure necessary for a $250 active device with a 30-year lifetime requiring maintenance equal to 5% of the initial cost. In other words, a simple crossbuck, almost the simplest possible warning device, may be thought of as having an initial cost (on a properly normalized basis) of $250. This example indicates the challenge of trying to develop warning devices for the vast number of crossings for which only minimal expense can be cost-effective.

2.3.2 Maintenance Costs

To focus all attention on installation cost is to be led astray with respect to economic reality. A number of studies, particularly by the AAR, have indicated that the expense of maintenance is typically about 5% of initial cost. If one considers the original equipment to have a lifetime of 30 years (a standard figure), with interest rates of 4%, the amortized cost of the installation is also 5% per year, so that maintenance is shown to represent approximately half of the real cost of present grade crossing protective systems. Reasonable variations in lifetime, interest rates, and maintenance do little to change this basic result, which is a fair approximation for many systems other than automatic signals. (The fact that installation and maintenance may be paid for by different sources is, of course, irrelevant so far as overall cost-benefit considerations are concerned.)

The need to be concerned with maintenance needs has roots which go beyond economics. Qualified maintenance people may be in short supply on a particular railroad, and their time can be worth more than the simple hourly rate. A crossing which requires excessive attention may be responsible for omission of other tasks of equal or greater overall importance, but not as immediately demanding.

In addition, an excessive need for repairs and adjustments implies that protection will be lacking a significant part of the time. Even with full failsafe characteristics, warnings at such a crossing will soon lose credibility, and the effectiveness of the signals will be severely compromised, a loss not only with respect to safety, but also in the basic cost-benefit calculations.

This is another reason for the intense concern of railroad signal people with reliability. In fact, an occasional complaint of signal engineers is that certain types of equipment are now being made in "improved lower" cost form, and as an apparently inherent consequence have significantly increased failure rates.

2.3.3 Conclusion

Thus, two points should be made: (1) Reduction in initial cost, even to a very substantial degree, can bring only a limited improvement in the true overall expense, and (2) development of systems which require substantially less maintenance is an equally valid alternative route to cost reduction. (It is to be hoped that new concepts will permit improvement with respect to both aspects simultaneously.) A conclusion also worth noting is that the total materials cost in an installation represents only 1/4 of the real total cost, and the signal hardware itself represents only 3% of the real total.

2.4 WARRANTED PROTECTION EXPENDITURES FOR VARIOUS CLASSES OF CROSSING

As has already been suggested several times, cost is a most important constraint. However, to know the investment required for a given rail-highway intersection is to have only half of the information required for a reasoned decision as to the desirability of protecting that crossing. Determination of the other half, the benefits to be gained, is a difficult and somewhat uncertain task. An important topic in grade crossing studies for many years has been the determination of hazard indices for various classes of crossings and protection. This report will not delve into that area. However, in development of new systems, it is highly desirable to have a thorough understanding of the overall situation in order to estimate the possible associated improvement. Further, it is most important to know at the outset what can be accomplished (with respect to both safety and marketing) with a system in a given price range. While the existing inventory and accident data base will not support calculations of high accuracy, useful information can be gained from very approximate values.

V-FRA performs the very useful task of estimating the number of crossings in each of 36 different classes of rail and highway traffic. In addition, the results are further broken down into rural and urban crossings, for five different types of protection. (Their tables are derived by extrapolation from inventories of over 14,000 crossings in five states.) In the previous report, (V-HRB), an equation is developed for the annual number of accidents (N_a) to be expected at any crossing for specified rail and highway daily traffic (T_r and T_h, respectively). Slightly simplified, this can be written as: $N_a = 4 \times 10^{-6} \times T_r \times T_h$.[3]

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[3] Ref. 1, Figure 24, p. 61.

This assumes the hazard rating of crossbucks, but is basically as good an estimate as can currently be made for passive devices in general. Admittedly, such a procedure can give only a very crude estimate. V-HRB itself, for example, lists eight parameters which may be relevant to the hazard rating of a particular crossing, and many more could be added. However, this simple formulation is adequate to provide a useful means of determining those classes of crossings for which protection costing various amounts may be appropriate.

Combining the inventory data and accident prediction equation, and taking the average cost of an accident as \$20,000 (approximately the value used in V-FRA) Table 4 has been developed, covering passively protected existing crossings. The data is presented in the following form in each box:

a. Number of crossings in category
b. Number of years between accidents
c. Annual fatalities (total) for category
(There is approximately one fatality for every five accidents, so calculation of years between fatalities or annual accident rate is a trivial operation.)
d. Annual accident cost per crossing

As indicated previously, maintenance costs are typically about 5% of initial cost for a wide variety of active protection systems, and reasonable estimates of service life and interest rates suggest that it is reasonable to charge the initial investment at 5% per year, also. Thus, for a favorable cost-benefit ratio,

$$\begin{aligned}\text{Annual Accident Cost} &\geq \text{maintenance + amortization}\\ &\gtrsim 5\%\text{ of initial cost} + 5\%\text{ of initial cost}\\ &\gtrsim 10\%\text{ of initial cost,}\end{aligned}$$

or Initial Cost $<$ 10 x Annual Accident Cost.

In other words, the cost of a protective system must be less than 10 times the predicted annual cost of accidents at the crossing in question (on a statistical basis) if protection is to be warranted under a cost-benefit criterion. This result should be generally valid as an approximate guideline, related only to service life, maintenance costs, and interest rates. This relationship can be combined with the data of Table 4 to obtain the breakdown indicated in Table 5, which is the goal of this section. The number of crossings for which protective systems with costs in various categories would be warranted is shown, along with the dollar cost and number of deaths associated with accidents at crossings in each cost classification.

Table 4. Categorization of Grade Crossings by Rail and Highway Traffic (Excludes crossings with automatic protection.)

	Range of Average Daily Highway Traffic					
Range of Average Daily Rail Traffic	0 - 500 (137)	500 - 1000 (699)	1000 - 5000 (2006)	5000 - 10,000 (6906)	10,000 - 20,000 (13,477)	Over 20,000 (25,289
0 - 2 (1)	65,100 1800 yr. 7 $11	8750 357 yr. 5 $56	16,620 124 yr. 27 $160	4090 36 yr. 23 $550	2250 18.5 yr. 24 $1080	250 9.9 yr. 5 $2020
3 - 5 (4)	20,200 456 yr. 9 $44	1960 89 yr. 4 $220	3320 31 yr. 21 $640	840 9 yr. 19 $2210	370 4.6 yr. 16 $4310	80 2.5 yr. 7 $8090
6 - 10 (7)	19,400 261 yr. 15 $77	2420 51 yr. 10 $390	5060 17.8 yr. 57 $1120	520 5.2 yr. 20 $3870	450 2.7 yr. 34 $7550	210 1.4 yr. 30 $14,160
11 - 20 (16)	13,960 114 yr. 24 $175	2180 22.4 yr. 20 $890	3230 7.8 yr. 83 $2570	860 2.3 yr. 76 $8840	700 1.2 yr. 121 $17,250	230 .6 yr. 74 $32,370
21 - 40 (28)	3500 65 yr. 11 $310	720 12.8 yr 11 $1570	920 4.5 yr. 41 $4490	180 1.3 yr. 28 $15,470	130 .7 yr. 39 $30,190	0 .4 yr 0 $56.650
Over 40 (132)	1600 13.8 yr. 23 $1447	280 2.7 yr. 21 $7380	440 .9 yr 93 $21,200	220 .3 yr. 160 $72,900	50 .2 yr. 71 $142,300	0 .1 yr. 0 $267,00

Mean value of traffic for each category shown in parentheses.

Table 5. Categorization of Grade Crossings with Passive Protection, in Terms of Warranted Protection Expense.

Class	Warranted Expense	Estimated Number of Crossings	Predicted Total Deaths	Approximate Total Cost of Accidents
1	Under $300	65,100	7	$ .7 Million
2	$300 - $1000	48,350	29	$ 2.9 M
3	$1000 - $3000	32,540	55	$ 5.5 M
4	$3000 - $10,000	15,510	84	$ 8.4 M
5	$10,000 - $30,000	13,950	222	$22.2 M
6	$30,000 - $100,000	3,480	215	$21.5 M
7	$100,000 - $300,000	1,530	272	$27.2 M
8	$300,000 - $1,000,000	630	345	$34.5 M

The degree of protection afforded in each case has been assumed to be perfect; that is, expenditure of the indicated sum will reduce the cost of accidents to zero. In reality, one can apparently expect no better than about 90 to 95% accident reduction at best, and possibly considerably less for the very low cost systems. Thus, one could obtain better accuracy in the tables by multiplying the warranted initial costs by the protection effectiveness to obtain the amount really justified. However, the whole model and the data on which it is based is sufficiently crude that such a correction would have little meaning. These numbers should really be trusted to no better than a factor of two in any event.

Another sensitive parameter is the cost per accident; the figure used here, $20,000, seems reasonable, but is subject to modification as better data is obtained. Again, such a correction is easily incorporated by simply scaling all dollar values by the appropriate factor. A similar correction may be necessary in a sophisticated treatment to allow for variations in average accident severity for different types of protection. (There is evidence that hazard indices might better be written as three numbers, indicating property damage, bodily injury, and fatalities. This approach could be extended to separate values for night/day, clear/obstructed visibility, etc. However, it is not clear that the data base will ever permit such extensive refinement.)

Three types of costs are not included in these tables. First, the expense associated with motorist delay has been ignored, as this occurs principally at high traffic crossings, where grade separations must be considered, and which in general are currently protected with active devices. More careful investigation of this factor will be warranted in future examination of sophisticated systems for such applications.

A second factor not considered here is the cost of collisions which do not involve trains. The cost of such accidents is typically far lower than for train-involved cases, and the frequency is not substantially greater, so the impact of this category on the figures developed above is not major. Also, to the degree this figure may be significant, it is assumed that there will not be wide variation among different protection types. This is an assumption which must be kept in mind in considering different approaches, as it will not always be valid, and the non-train case could take on more relative significance as basic effectiveness is improved so that there are fewer train-vehicle collisions.

A third cost is that borne by the railroads for expense other than maintenance. Attempts (usually futile) to brake a train to avoid an accident, or the necessary stop following a collision, represent significant expense. (There has been at least one case in which an entire train of produce spoiled due to such a delay.) Derailments can be caused by crossing collisions, particularly when trucks are involved. In some areas trains are required to stop prior to crossing, and rail speed limits may be restricted in the vicinity of crossings. Thus, in addition to the direct legal expense of accidents, there are a number of fringe benefits for railroads in the installation of automatic protection or grade separations.

2.5 LIMITATIONS TO STRICT APPLICATION OF THE COST-BENEFIT CRITERION

Cost-benefit (or cost-effectiveness) concepts are invoked frequently in this study. Indeed, such an approach is a virtual necessity if one is to establish criteria for crossing protection in a wide range of possible total environments. However, it is worth reiterating several factors alluded to elsewhere in this report which reduce such a standard to the status of a useful guide, or basis for estimation, rather than a magic formula for determining optimum protection for a particular crossing or even class of crossings.

(1) As indicated earlier, grade crossings can differ widely in virtually every parameter used to characterize them, and there may well be change from year to year, as well. Thus, the task of carrying out a fully adequate inventory is extremely difficult, and while such results will be of very considerable value, any single piece of data must be regarded with some scepticism as to whether it tells the whole story, or is sufficiently timely.

(2) A similar warning must be applied to accident data. Traditionally automobile accidents have received very cursory investigation; the reporting system has been even more confused in grade crossing accidents. These problems are now being corrected, but any such data-acquisition program has inherent limitations, if for no other reason than the expense involved in a truly thorough investigation.

(3) Even assuming that data adequate in determination of (for example) meaningful hazard indices is obtained so that one can estimate reduction of accidents, there are both costs and benefits which may either inadvertantly or through impossibility be ignored. Costs of motorist delay, for example, depend not only on the scheduling of rail and highway traffic, but also on the composition of that traffic, whether business or pleasure, car or truck, short, fast passenger trains or slow freights, etc. The probability of accidents not involving trains may be affected by a number of factors difficult to take into account. One can even imagine situations where an alternative road with a grade separation becomes overloaded to the point of considerable hazard because of signal problems on the unseparated road. All of this is in addition, of course, to the basic difficulties of determining a meaningful value for the cost of accidents and deaths.

2.6 ACCEPTABILITY OF MINIMAL PROTECTIVE SYSTEMS

Protective systems which combine very low cost and slightly reduced reliability may represent an important advance in reduction of accidents and show a high cost-benefit improvement. The difficulties in testing such systems will be indicated in a later section. However, the problem of acheiving acceptance of any such method by railroads, regulatory bodies, and the public will almost certainly be an even more severe obstacle. There are many areas of modern life in which cost-effectiveness is considered a valid criterion, but this view seldom prevails when the matter at hand combines human life and death, and high public and political visibility. Relieving railroads of liability may or may not be possible; in any event, some organization will have to bear the expense of accidents, and will therefore have to be convinced that a new protective system will reduce overall accident costs. However, in making judgements as to cost-effectiveness, a complicating factor is that total costs to the society are not necessarily borne by a single party. Reference V-FRA, for example, suggests a cost per accident of approximately $20,000 ($100,000 per fatality), but it appears that this average is rather greater than current settlements. Thus, a system with a favorable cost benefit ratio in the large may not represent a cost-effective technique for the railroads of any other responsible party.

In addition, there are a number of other costs which also are not assessed against the bodies charged with protection installation and maintenance. These include delay costs for both motorists and trains and accidents due to the presence of crossings but in which the train is either not present or not involved. (Such accidents are approximately as common as train-vehicle collisions, though generally much less severe.)

While state and Federal regulatory bodies may ultimately have considerable influence in this area, the general tenor of the times is in the direction of increasing vigilance and evermore stringent standards. It would be a heroic task indeed to attempt to institute a system which railroads oppose on grounds of safety, and which, in a given location, may have known failure modes with a mean time between failures less than for conventional systems. The argument that more crossings can be protected for the available funds, and that total injury and loss of life will be reduced, will very probably be unconvincing to those in the vicinity of a proposed sub-standard crossing.

This is not to say that improvement through innovation is impossible, or even unlikely. However, these considerations do impose constraints on the nature of successful innovation, and suggest that lower cost systems achieved at the expense of reliability or effectiveness may be of less benefit than hoped.

SECTION 3

GUIDELINES FOR EXAMINATION OF NEW CONCEPTS

3.1 INTRODUCTION

Improvement of grade crossing protection through technological innovation is a worthy and promising endeavor. However, in addition to the many and varied inherent constraints delineated in the previous chapter, it is necessary to define carefully the general function of such signals to suggest desirable system characteristics, and to examine certain overall concepts in order to eliminate those which have basic and fatal weaknesses. Such an effort can be only a guideline for future action; very few totally valid generalizations can be made concerning grade crossings. Since installed cost and human response are crucial to the success or failure of any system, firm predictions are impossible. On the otherhand, the very difficult task of improving grade crossing protection has long been the subject of innumerable suggestions, inventions, etc., many of which do not effectively come to terms with the true nature of the problem. It is hoped that this chapter will aid in stimulating innovative thought while at the same time directing it along fruitful paths.

3.2 GENERAL GUIDELINES

3.2.1 Functional Requirements

The basic requirements made upon grade crossing warnings are essentially the same as for any other signs or signals, whether active or passive, located at the crossing or in advance of it. Three aspects are fundamental: conspicuity, clarity, and credibility:

Conspicuity: If a warning is to have any effect, it must first be perceived, often against diverse and cluttered backgrounds. To the degree such a signal is made more conspicuous, the motorist is more likely to notice it. Note that the "signal" or "warning" may even be the sight or sound of the train, and enhancement of train visibility or audibility can be considered as the same type of improvement as use of brighter flashing lights, reflectorized signs, or removal of a distracting background.

Clarity: Perception of a warning is of little use if its meaning is incorrectly interpreted. As pointed out in V- HRB[4], it is most important that the motorist be given the information he needs in as precise form as possible, and that information

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[4] Ref. 1, Table 24, p. 35

only. In this undertaking (as in all other aspects of grade crossing protection) one must be particularly careful to take into account the population which will be exposed to the warnings, so that virtually everyone will understand. It is in this functional requirement that one sees the need for uniformity of signals (to communicate to motorists from other regions and to minimize comprehension time) and for symbolic, rather than verbal warnings, to overcome language differences, marginal literacy, poor eyesight, etc.

Credibility: Several basic constraints can be subsumed under this general heading. If the motorist perceives and understands the warning, but does not believe it, the signal has lost all value. Examples are common in ordinary traffic signalling - speed limits, stop lights, parking prohibitions all come to be ignored if enforcement and obvious danger are both lacking. While more rigorous attention by police has helped significantly in some areas, particularly urban, the best enforcement is the motorist's conviction that an activated signal implies the imminent passage of a train. To the degree that this belief fails to exist, the signals are compromised, sometimes to the point of near-total ineffectiveness. Thus, the basic source of credibility is signal accuracy. If the warning fails to operate when required, even with an indication of failure, or, far more common, is frequently activated with no trains present, the motorist will quickly learn to ignore it. A signal which under some circumstances provides 2 to 3 minutes warning (rather than the standard 20 to 30 seconds) is nearly as useless as one which is always activated, for motorists will come to mistrust it completely. Yet, obtaining high accuracy can be both difficult and expensive. A large variety of train movements are possible (high speed, low speed, reversals, station stops, switching to another track, etc.) and a train detection system must be sophisticated enough to be able to make such discriminations and process sensed information in such a way as to obtain a nearly uniform warning time for all cases. Yet, this is a very worthwhile goal, in view of impact of signal accuracy on overall effectiveness.

3.2.2 Non-Train Involved Accidents

An important consideration which relates to all three of the above factors is system design which will minimize the occurance of accidents in which a train is either present but not involved, or not present at all. While such accidents are generally far less severe that vehicle-train collisions, they are approximately twice as numerous, and warrant serious attention. Some accidents in these classes result simply from poor highway characteristics in the vicinity of a crossing, but many are associated with evasive maneuvers to avoid a train, or collision with vehicles which have stopped because of train presence, anticipated train arrival, caution, or legal requirement. The last case relates particularly to the use of STOP signs and mandatory stop laws for certain vehicles such as buses and trucks. These are areas of controversy, not only because of the associated vehicle-vehicle collisions, but also because of the increased exposure time in crossing the tracks and the greater likelihood of the engine stalling.

3.2.4 Relationship to General Highway Signaling Practices

As a small, yet important, point, some comments are in order on the relationship of grade crossing protective signals to general highway signing and signaling. The ubiquity of the automobile in American life has required that considerable effort be put into warning, controlling, and informing motorists. Traffic engineers have developed a systematic way of approaching these tasks, and have established certain guidelines and conventions. In some cases these arise from sound human factor studies; in others codification has occured simply because the rules and customs, however arbitrary, become far more effective when applied universally.

Many of these considerations are indicated in V-HRB[5], particularly with respect to passive protection, and will not be belabored here. Other aspects apply to active signaling. For example, considerably greater effective intensity could be obtained from standard flashing lights if they were of somewhat different color, and this is currently a subject of inquiry. However, a basic constraint is that the lights still be identified by virtually the entire motoring public (color-blind excluded) as red, the only signal which universally means stop. (Similarly, red should never be used unless a full stop is intended.)

Finally, it is extremely important that basic information, such as the fact that the intersection is with a railroad track, be presented in a uniform manner, so that the motorist will have as clear an understanding as possible of the hazard he faces. Thus, the use of a crossbuck shape, or horizontally-aligned flashing lights, now common throughout the country, could be abandoned only at considerable peril and with very well-established evidence.

3.2.5 Reliability

The requirement for extremely high reliability is frequently alluded to in this report, and need not be belabored. As in other areas of rail safety, accidents are both dramatic and severe, and the basic requirement on railroad signal systems has always been high reliability and failsafe operation. The environment is difficult - great temperature extremes, high vibration, infrequent maintenance, attempted vandalism, very high and very low humidity,

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[5] Op. cit.

exposure to lightning, etc. Yet, present systems, developed over many years, achieve an impressive record; innovative systems must be measured by the same standards.

However, it is appropriate to point out that very high overall system reliability can be obtained by parallel operation of two or more elements, each with only a moderately low failure rate, as well as by use of a single very high-reliability unit, such as is commonly used. This avenue, rarely followed in railroad signaling, is commonplace in other applications, and deserves careful scrutiny.

3.2.6 Cost

As for reliability considerations, the importance of minimal-cost protection is indicated frequently in this report, and does not require extensive restatement here. As seen earlier, a very large number of crossings do not warrant, on a cost-benefit basis, expenditure of more than a fraction of the current cost of protection. Further, even for crossings which justify substantial investment, reduction of the cost of any elements will permit either a more effective installation at the location in question, or protection at a greater number of crossings. Also, it is worth reiterating that grade crossing protection expense has three major components: hardware, installation labor, and maintenance. A significant reduction of any one of these elements represents a meaningful improvement.

The frequent references to the importance of low cost should not, however, obscure the fact that the basic criterion must be overall cost-effectiveness. A system which requires a 20% greater expenditure but yeilds a 50% improvement may be a substantial step forward. Recall also that such "improvement" may be not only in terms of reduction of train-vehicle collisions, but also reduced motorist delay and fewer non-train involved accidents.

3.2.7 Failsafe Design Requirement

For many decades, it has been a basic requirement of all circuits, components, and systems for railroad signaling that they be "designed on the closed-circuit principle".[6] That is, all electrical systems involving safety("vital circuits") are being designed so that, to the maximum degree possible, any failure anywhere in the systems will lead to display of the most restrictive signal, generally STOP. As applied to grade crossing protection, this requires activation of the warnings (gates, flashing lights, etc.) under

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[6] This phrase is used in both, Rules, Standards and Instructions for Railroad Signal Systems, FRA, Bureau of Railroad Safety, Nov. 1969, p. 12, and Part 34, p. 2 of the Signal Manual of the Association of American Railroads.

circumstances of any type of failure. This is part of the attraction of the most basic track circuit illustrated in Figure 3.1. For proper action, the train wheels and axles short-circuit the relay, and activate the warning any time that region of track (block) is occupied. In addition, such activation will occur for power failure, broken rail, accidental or malicious short-circuiting of rails, or a broken connection or wire at any point. This closed-loop feature is a typical characteristic of failsafe design. (Relays and gates, for example, generally drop by gravity when power is lost.)

The reason for establishment of such a requirement is not difficult to deduce. If a motorist (or train) is stopped unnecessarily, accidents can occur only through carelessness, insufficient operation skill, etc. But if a vehicle or train is not warned at a time when such a warning is required, i.e., presence of a train at a particular location, a very serious accident is almost guaranteed. Further, railroads are seldom sued for large sums over unwarranted delays, whereas the cost of a vehicle-train accident resulting from failure of a protective system can be high indeed.

On the other hand, if a designer's only goal is reduction of the number and severity of grade crossing accidents, slavish adherence to such a design principle can be counterproductive in several ways. First, the additional complexity and design sophistication necessary to achieve truly failsafe operation of a total system contributes significantly to the substantial cost of such installations, limiting the number of crossings which can be protected, particularly at a very low failure rate.
However, of greater significance is the rigid constraint which this has imposed on the system designer, forbidden (under penalty of complete failure in the marketplace) even to consider non-failsafe systems, regardless of potential high reliability and low cost. It is particularly unfortunate in this era of sophisticated, high-reliability space and defense systems that innovation should be stifled on the basis of allowed technology, rather than confronted simply by ultimate functional requirements.

Further, presentation of the most restrictive signal aspect is not necessarily a safe failure mode insofar as grade crossings are concerned. At first exposure to an unnecessarily activated signal, a motorist will only wait a limited amount of time, and then will cross. After several such experiences, he will learn that the signals can be safely ignored and they have become both ineffective and valueless.

On the other hand, it may well be that the "no train" signal aspect - no activation - is not necessarily interpreted in as permissive a manner by the average motorist as by a railroad signal engineer. The typical vehicle operator, knowing very little of failsafe design, probably having observed both grade crossing signals which had failed (safely) and completely inoperative normal traffic signals, is unlikely to interpret a quiescent flashing light installation as a guarantee of safe passage. While this

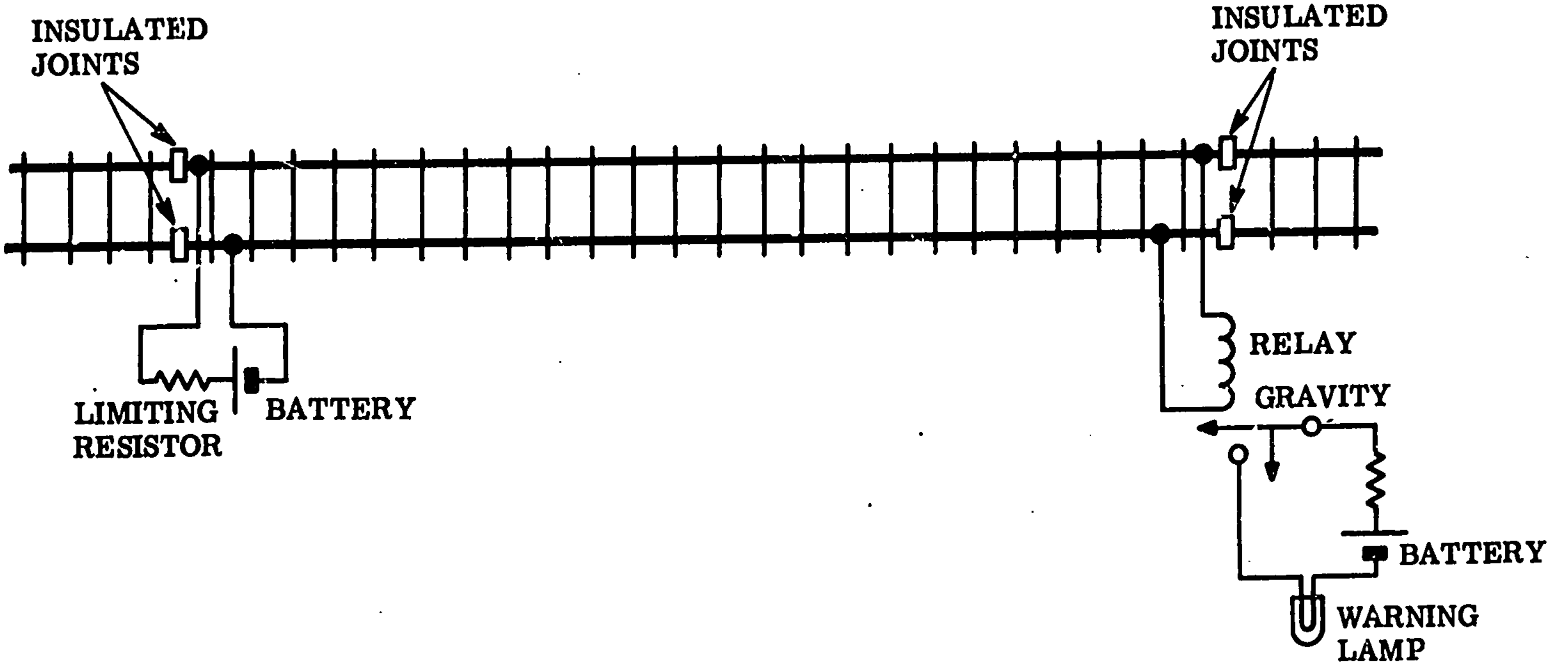


Figure 3.1 Basic DC Track Circuit

topic is particularly appropriate to human factors studies as yet not performed, it appears reasonable to assume that he will treat such signals as equivalent to a standard crossbuck, and may not, in fact distinguish between inoperative active protection and passive signing.

Thus, it appears that failsafe design does not, in fact, lead to a truly safe failure mode; nor is it, for that matter, completely attainable. Total power failure, accidental or intentional disabling of a signal, obscuration by man or nature, all represent unsafe system failures. Further, failure in a dangerous mode may not represent the penultimate disaster that it often seems to railroad men. (It should be noted that their thinking is likely to be oriented particularly toward block signal systems and prevention of train-train collisions. Here, due to the far more constricted nature of the traffic, the very lengthly stopping distances, the well trained and small number of people involved, the use of active permissive signals, etc., one can more nearly bring about failsafe design, and penalties for failure are far greater than for grade crossings. Note also that for reasonably low rail traffic density and adequate sight distances, statistics indicate that even with no protection at all the probability of a given vehicle suffering a collision is extremely small.)

Careful consideration of the above factors indicates that there may well be a role for grade crossing protection systems which are not completely designed on the closed circuit principle. Clearly, very high reliability will still be a necessity. Also, the viability of such approaches will depend in large degree on full utilization of improved passive protection, both in advance of and at the crossing, and on the train, in the form of enhancement of conspicuity by means of paint, reflective material, and broad coverage, high-intensity lighting. Non-failsafe systems might typically be considered for low traffic density crossings for which more expensive protection is not warranted (a large percentage of existing crossings). Good sightlines would generally be required. Experience under such conditions would then indicate suitability to more hazardous locations.

With such systems, it would be most important for the railroad or other authorities to be informed of failure as rapidly as possible. Thus, it might be desirable (particularly in the case of flashing lights alone) to have an indication of activation which would be more conspicuous to the train crew.

In summary, this discussion is not intended to encourage development of non-failsafe systems per se. The objective is merely to present the concept that overall system effectiveness and reliability sufficiently high to meet the rigorous standards of grade crossing protection may be obtainable through techniques which are not completely failsafe, and that such systems can be the basis of significant advances in safety. Whether these possibilities are realized remains to be seen, but they should not be ruled out a priori.

3.2.8 Permissive Signals and Failure Indicators

A question which impinges directly on the issue of failsafe operation is that of the desirability of having a visable indication either that a system is or is not working. When a motorist sees a traffic light which is completely dark, he generally realizes that this indicates a failure and caution is required. A grade crossing, however, is normally in that state. It is desirable that any such permissive signal be very low in power consumption, to avoid unduly large emergency batteries. On the other hand, one must also note that such a signal may eliminate the need for batteries, particularly in regions for which power failures are infrequent and of short duration. While the kind of questions raised here are more related to policy than technical innovation, they are included because of the possible impact on overall constraints, and because the desirability of such concepts is affected by the manner in which they might be realized.

Another aspect of this topic is the possible use of special signals to indicate a system failure, either a mode where some element has become inoperative or untrustworthy, or perhaps when a train has been indicated but does not arrive after a fixed interval. Note that two signals (which may be physically the same) are involved: one to inform the motorist that special care is required, and one to alert passing train crews so that maintenance people can be dispatched quickly. The realization of such signals, if used at all, would of course be strongly influenced by the character and quantity of rail and highway traffic.

As a final point, whether or not failure indications are presented to the motorist, it may often be possible to interconnect the crossing signals with the overall railroad signal system so that failures are immediately relayed to a central point. The steady spread of CTC systems is especially relevant to this point.

3.2.9 Problems Associated With Test and Evaluation of New Concepts

Meaningful evaluation of the effectiveness of currently existing systems is only marginally possible. To examine, for example, the relative merits (or more important, cost-benefit ratios) of flashing lights versus automatic gates requires pushing present data somewhat beyond its limits. Many of the factors mentioned earlier come into play here. The great variety of crossings, the many parameters needed for an accurate description, and the variation of highway and rail traffic over the years make comparison very difficult.

One may hope that completion of a thorough, uniform inventory, and the development of improved accident data (both acquisition and processing) will aid greatly. However, for new systems this often can be of no help. Two types of information are needed. The first relates to the technical operation of the innovative techniques. Determination of mean time between failures and its observed failure modes under actual operating conditions is a necessity, yet can take many years to acquire when one seeks reliability of the level need for rail vital systems, and available investment is limited. This type of testing can generally be carried out with railroad cooperation, with the new method in parallel with the conventional, and activating only recorders, etc., while the existing control circuits drive the warning signals. If the new system in some way conflicts with the operation of the original, very severe problems will result; no railroad is likely to risk an accident with an admittedly experimental protective system, and no other body (such as a government) can be expected to accept full liability, particularly in this difficult area. (A common aspect of lawsuits is the alleged failure of the signals.)

This difficulty is met directly when new signal devices, rather than activation techniques, are considered. In this second case, one must consider not only the technical operation, but how motorists will respond to a different means of indicating iminent passage of a train. The victim of an accident under these circumstances may have a legitimate complaint that he did not understand the meaning of the warning. One can imagine the legal complexities which would result. Thus, beyond the question of reliability, any system which presents a significantly changed aspect to the motorist poses a real challange in the evaluation of its effectiveness, not only in devising and interpreting tests, but also in implementing them in actual service.

This problem will be especially severe with any method which admittedly sacrifices reliability or effectiveness (to however small a degree) in order to obtain dramatically reduced cost. The improvement on a cost-benefit basis may be substantial, but testing of any such concept (or achieving public acceptance) will not be easy.

The most promising means of circumventing some of these difficulties, where appropriate, is through initial use in advance warning systems. There, the liability questions are at present much less intimidating, and yet one can devise experiments and observations to obtain a good indication of effectiveness as well as reliability. However, even this approach may not be feasible if the proposed system interacts (of might conceivable interact) in a potentially harmful way with an existing protective system.

Another possibility is that a railroad might accept unproven protection at a currently unprotected location. Any well-tested system would be far more likely to decrease than increase the railroad's risk of an accident, and so could be acceptable. Of course, any such installation would expose the governmental agency involved to risk of public and political displeasure, and possibly liability, in the event of an accident, regardless of the innocence of the test systems.

3.3 REVIEW OF VARIOUS CLASSES OF SYSTEMS AND SYSTEM CHARACTERISTICS

3.3.1 Basic System Elements

In discussing passive warnings, the basic function and system element are easy to define. Some sign or other indication is used to convey a simple message to the motorist: "You are approaching a grade crossing." Some special information may be added, but this is the essence. Active systems, on the other hand, require the accomplishment of several functions. The operation can be described in terms of a diagram such as Figure 3.2

Figure 3.2-Block Diagram of Functions Necessary for Active Protection

Various systems may combine two or more of these elements. In the conventional track circuit (section 4.2.2), for example, there is no separation between train detection and communication of that information to the signal processor; this similarly would be true for crossing-located train detection methods such as radar or track impedance. On the other hand, one can easily conceive of systems in which each element is distinct, as when detection is localized at an appropriate distance from the crossing and train-presence information is communicated via cable, telemetry link, etc.

The signal processing is generally rather simple, and typically consists of discriminating between approaching and receding trains, etc. This function can become considerably more complex in the vicinity of sidings, stations, etc., particularly when the attempt is made to compensate for trains of varying speeds. The usual requirement is for activation of warnings 20 to 30 seconds in advance of train arrival. Actuation of warning devices may better be considered a decision than a system element, although that function is typically associated with a specific component, such as a relay. Finally, there are the warning devices themselves - gates, flashing lights, etc. - which may be at the crossing or well in advance of it.

Any of these elements or combinations of elements can properly be the subject of attempts at improvement and innovation. Certainly, one can imagine many means of detecting train presence, although achieving failsafe operation complicates matters somewhat. Systems which require no connection to the rails avoid both the possibility of interference with other signal systems and the use of insulated joints, shunts, etc. If train detection can be accomplished with no violation of railroad right-of-way, one can then consider systems (particularly for advance warnings) which other authorities, such as state highway departments, could operate independently.

It is also desirable to be able to detect both train velocity and direction, so that more complete information can be utilized in the signal actuation decision. A measure of train length (either in space or time) could be of use in those cases where one can consider redirecting motorists to other crossings or grade separations.

The communication link must be reliable, difficult to vandalize, insensitive to environment (in terms of both interruption and injection of false signals), and unobtrusive to the community. Even in most sophisticated cases, the required information rate is trivially low, and the detector need be sampled only a few times per second at most. If operation is not in a failsafe mode, a provision for self-checking should be included.

The signal processing, viewed in terms of logical operations, is usually simple and can be at quite low speed. This function is conventionally carried out by an array of very large, expensive relays of most impressive reliability. It is not clear at present whether these can be replaced by either solid state or telephone-type relays without compromising reliability or increasing cost, but this appears to be a worthwhile aspect to pursue, in view of the cost and reliability characteristics of both technologies.

The type of warning signals to be used is very much an open question. Reference has previously been made to the importance of both uniformity and compatibility with general highway signaling.

Since these elements typically represent a relatively small portion of the total cost, concern here is more with increased effectiveness than economy, and innovation will as often be based on human behavioral studies as on technological innovation. Appropriate concerns of at least a partially technical nature (some now being investigated) include improvement of bulb type and brightness, roundel design for highly efficient patterns, use of alternative light sources, and determination of the optimum roundel color (to maximize transmission while still clearly identifiable as "red".)

Investigation of the general value of active advance warnings has not been common, but warrants serious attention. Basic considerations are not greatly different from those for crossing-located devices, though some special factors are involved. The signal activation function may then involve a second communication link, and power consumption may be an especially important variable. On the other hand, many of the questions of liability and highly reliable operation become substantially less restrictive, permitting greater innovation. Further, it may well be that active advance warnings can significantly decrease the hazard for many crossings, perhaps ultimately coming to serve, at least in the motorist's mind, as the primary protection.

Low power consumption is desirable for all system elements, since batteries are generally provided to give protection in the event of power failure. In particular, if the train detection, communication, and advance warning signals can operate at power levels sufficiently low that batteries alone can be used, with replacement at six-months to one year intervals, significant savings may be possible in installation expense.

3.3.2 Cooperative Systems

Among the many system concepts frequently proposed for enhancement of grade crossing safety are a large number which may be characterized as cooperative systems, techniques which require that special system elements be installed on trains and/or motor vehicles. There are basically three categories of such methods, which are discussed below.

Train-Crossing Systems: The basic concept involves some sort of locomotive-mounted transmitter, with a receiver at the crossing. The means of communication can be radio, optical, acoustic, or other. There are several inherent major defects associated with such systems. All locomotives which might cross the intersection in question must be appropriately equipped, and for most systems the locomotive has to precede all other rolling stock. In general, this will be difficult to ensure, particularly in view of the practice of locomotive interchange among railroads and the common situation of cars being pushed in switching moves. Further, the equipment must be in operating order, which raises the question of what is to be done in the event of a failure during general operation. Also, one then has the undesirable situation that different departments within the company have responsibility for maintenance of different elements of a single system. This problem is even more acute for interchange equipment. Failsafe operation is impossible, as an unequipped train will be indistinguishable from the no-train situation. Finally, one must have both uniform warning time, difficult to obtain for such a configuration, and proper activation regardless of the orientation of the locomotive or its position in the train.

Some of the above objectives are removed if crossing signal activation is accomplished by means of some inherent property of the train, such as vibration, noise, etc., rather than through special apparatus. However, the effectiveness of such means under a variety of environmental conditions for diverse types of rolling stock (with constant warning time) seems an extremely challenging task.

Crossing-Vehicle Systems: A number of concepts have been suggested involving activation by roadside components of special signals located within automobiles. Many of these are applicable to grade crossings. Given that the major part of protection expense is in train detection and signal activation, it is clearly desirable to utilize all possible means of alerting motorists once the basic investment has been made. However, it seems unreasonable to expect installation of the necessary receiving/signal apparatus in all vehicles simply for grade crossing protection, so that it will be necessary to await implementation of such a system for general highway usage before crossing applications are feasible. In addition, since the presence and operability of the vehicle-mounted components cannot be guaranteed, such a warning device can never be considered as more than a secondary system, to enhance the effectiveness of more conventional signals.

Train-Vehicle Systems: The idea of direct communication between train and motorist has strong appeal, but appears to be a very unpromising approach. Essentially, such a method would combine the defects of both previous cooperative systems. The exception to this judgement is found if one chooses to consider as in this class the direct observation of the train by the motorist, either visually or by auditory means. FRA examination of this topic indicates that train horns are at present near or above loudness levels which the public will permit, but considerable improvement is possible in enhancement of train conspicuity through appropriate use of paint, reflective materials, and special lighting. This topic is treated elsewhere in this report. (Section 4.4).

3.3.3 Stalled-Vehicle Indicators

It is a popular notion that a major element of grade crossing safety is prevention of collisions with motor vehicles which have become stalled on the tracks. A conclusion frequently drawn is that means must be found to alert the train crew so that the train can be halted. While it is true that some of the most spectacular accidents are of this type, particularly involving trucks, there are several misconceptions involved. First, a relatively small number of accidents fall into this category (approximately 10%) and few of these result in deaths. Perhaps even more relevant, a very long distance is required to stop a train. The basic characteristics of wheel on rail permit maximum decelerations approximately one-tenth the value for automobiles, for example, so that stopping distances are inherently at least ten times greater. At least as important, the nature of conventional train braking systems, the limitations imposed by train dynamics, and the predominance of lengthly freight trains combine to make even an emergency brake application a slow (and hazardous) process, requiring initiation one-half to two miles in advance of the obstacle. Thus, most cases of stalled vehicles are such that there is either no chance of stopping the train in time, or the vehicle can be moved (or the passengers evacuated) well before arrival of the train. There is, of course, a substantial cost in stopping and restarting a long train, as well as a certain amount of danger, so this course of action would be viable only if the incidence of false alarms were quite low. Unfortunately, this is unlikely to be the case. The possibility for malicious activation (vandalism) might be a particularly severe problem in many areas. Development of low cost but effective and unequivocal stalled-vehicle detectors is not an easy task, nor is the problem of conveying the information to the engineer. Basically, there are few crossings for which it is at all likely that any such system will be cost-effective.

This is not to rule out entirely such an approach. There may well be specific crossings in which trains are at low speeds and vehicle traffic patterns make stalling especially likely. In CTC or continuous cab signal territories, the signaling function may be feasible. However, it remains true that a more effective approach is likely to be via modification of the crossing context and re-examination of mandatory-stop laws, which increase substantially the likelihood of such failures. Research and development efforts in this area appear to be a relatively unpromising investment.

SECTION 4

SPECIFIC CROSSING PROTECTION SYSTEMS

4.1 INTRODUCTION

The guidelines, constraints, and general information developed in the previous sections can now be applied to certain aspects of the crossing protection problem or embodied in specific systems. Certain concepts have been investigated at TSC and have been found to warrant further development and field testing. Other topics, while not studied as extensively, offer promising opportunities. Details of these matters, to the appropriate degree, will be given below.

One characteristic of several system or component concepts considered deserves special comment. This is the relative freedom from interaction with the basic railroad signal system. As mentioned in section 3.2.9 and elsewhere, active advance warnings, being physically separated from the crossing and not on railroad right-of-way, offer a useful circumvention of some of the liability consideration which so sharply constrain the testing and installation of innovative means of protection. However, significant complications do result from the necessity of reliance upon the railroad signal circuits for warning activation. If trains can be detected reliably, and that information conveyed to the warning devices without requiring access to the tracks, or at least without interacting in any significant way with the railroad signal system, then the way is opened for highway departments and other authorities to institute protection completely independent of that provided by the railroad.

This factor applies most strongly to radar train detection (section 4.3.3), but can operate to a degree in all of the systems or approaches described. Such a separation may ultimately prove of great importance in reducing the present tangle of overlapping responsibilities.

4.2 MICROWAVE TELEMETRY, AN ALTERNATIVE TO THE TRACK CIRCUIT

4.2.1 Introduction

The costs of active grade crossing protective systems are largely hidden, in both a figurative and literal sense. The actual signal hardware is typically only 5% to 10% of the total installation expense. Control circuits and components at the crossing are another important part, as is the equipment at trackside necessary for detecting the presence of a train and imparting that information to the control apparatus. Installation labor, of course, represents another major expense. Finally, and least visible, there is the cost of engineering design necessary to take into account the special characteristics of every crossing (the presence of sidings, switches, diamonds, stations, etc.) and the need for compatibility and interconnection with the block signalling system in the area, as well as with other nearby grade crossings. Stations and classification yards in the vicinity can cause particular problems, for under such circumstances a train may approach the crossing and then stop for a lengthy period, or even reverse and leave the scene, and provision must be made for de-activating the crossing signals. (Signals which give frequent false alarms are not only most annoying and costly to delayed motor vehicle operators, but also lose credibility and are apt to be ignored).

The logic and control circuits, which now include many large and very expensive relays, provide rather more potential for cost reduction through use of solid state logic circuits. However, this avenue, which is not without difficulties, is at present being followed by at least one equipment manufacturer. Developments in this area are clearly worthy of our continued strong interest and possible encouragement, and such components might well ultimately form a part of TSC demonstration systems. However, this too seems an inappropriate area for expenditure of our resources. While installation labor is not something which can be attacked directly, the nature of the final system can have important impact on such costs.

As is implied in the foregoing, it is in techniques of detecting train presence, and communicating such information to the crossing control circuits, that there is maximum opportunity for a meaningful improvement. This conclusion arises not simply through elimination of the other aspects of crossing expense, but also from the knowledge that sensing and communication of information is one of the most highly developed areas of modern technology, and therefore represents a resource of great potential value to those activities to which it has not yet been applied. An important goal, then, is development of a sensing and communication system which not only reduces equipment costs, but also has major impact on installation, maintenance, and design costs.

4.2.2 Sensing and Communication of Train Presence

Systems currently in use are based on the track circuit concept first used in 1872, and illustrated in basic form in Figure 3.1. A signal source, either ac or dc, is electrically connected across the rails at a point sufficiently far from the rail-highway intersection to provide sufficient warning. (Typically 25 to 35 seconds is required; for 60 mph rail traffic this necessitates a distance of approximately one-half mile.) A signal detector, perhaps merely a relay, is wired across the tracks at the crossing, so that when a train is between source and detecto the tracks are short circuited, and the detector receives no signal.

This condition, zero received signal, is the operational definition of train presence, and the signals are activated. This system illustrates the essential failsafe attribute necessary in railroad safety systems; failure of the signal source gives the same result as train presence, activating the signals, and there is no danger of a train coming through unheralded under these circumstances. (However, as mentioned previously, false alarms from any cause are highly undesirable.) This system has been used for many years in both ac and dc realizations. Train sensing at the crossing, plus proper logic circuits, turns off signals and resets the system after train passage, and prevents activation by trains moving away from the crossing. Just the same basic system is used for controlling wayside block signals. This fact has caused substantial expense, since the two systems must interact only in very restricted and specific ways. This has been an important part of the engineering design costs. In addition, costly insulated joints or special circuits are needed between adjacent sections of track in order to define the region being controlled.

In ac systems, quite low frequencies have been used (of the order of tens to hundred of cycles per second). However, more recently so-called "overlay" systems have been developed, in which the track circuits utilize audio frequency signals-hundreds to thousands of cycles per second. This is generally seen as a major advance, as these frequencies do not interact with block signaling systems, and high-frequency shunts across the tracks can replace insulated joints in defining the protected area. However, even the audio frequency (overlay) track circuits have weaknesses. The only information conveyed is "train - no train"; either a train is coming or it is not. Velocity information of use in situations where rail traffic can have a variety of speeds must be obtained by other (quite expensive) means. The cost of the receivers and transmitters is substantial, and there can be problems as well as substantial cost in multi-track, multi-crossing areas, where many separate, harmonically unrelated frequencies must be used. Although overlay circuits help considerably, there can be problems with seldom-used track through rust build-up which prevents proper shunting by the train axles. Increasingly important is the vandalism problem. One aspect of this is that vandals can easily short-circuit the tracks, thus activating the crossing protection for indefinite periods. Similarly, water, ice, or slush, particularly when salt has been spread on the highways, can short-circuit the rails. Thus, in terms of both cost (including design and installation) and operational characteristics, there is clear incentive to seek an alternative technique, not based on track circuits. In addition, there is little likelihood of simply improving a basic system which has been undergoing development over such a long period of time.

4.2.3 Consideration of Alternatives

With track circuits, sensing of train presence and communication of that information to the crossing signals are combined. However, the alternatives considered here separate these functions. Train presence can be determined in a variety of ways. Currently available methods, as well as some novel techniques, are under consideration.

The communication task may be simply defined. The basic requirement is transmission of information, at a very low information rate, over a distance typically less than 3,000 feet. The system must possess very high reliability under adverse environment, with essentially failsafe operation and infrequent and inexpensive maintenance. In the track circuit, loss of power triggers the signal, just as would a train axle short-circuiting the tracks. In a similar manner, any replacement must, in essence, be such that loss of communication is interpreted as presence of a train. One can immediately imagine several non-track-circuit methods of approaching this problem:

a. Cable
b. Acoustic
    1. Ground
    2. Air
c. Electromagnetic
    1. Optical
    2. Microwave - UHF
    3. RF

While hasty decisions must be avoided, several of these can be ruled out fairly quickly. According to FRA and railroad specialists, cable suitable for such an application can cost over $2/ft., plus another $2/ft. for installation. The cost is thus prohibitive for systems where economic considerations are so crucial to widespread installation. (This would total $16,000 for a 2,000-ft. two-direction installation). It is for this reason that such an obvious solution has not been utilized in the past, except for low-speed crossings where short distances are involved. A seismic acoustic system would undoubtedly be highly subject to local variation and would be inefficient in terms of power consumption. An air-propagation acoustic system, operating at relatively high audio frequencies would be highly vulnerable to environmental effects. Ice on the antennas would be a particularly troublesome problem and dealing with it would significantly increase cost and complexity. In addition quite high power would be required for the distances involved due to the substantial air attenuation of higher acoustic frequencies.

Of the electromagnetic approaches, optical devices also seem too vulnerable to environment (dust, mud, snow, ice, fog, vegetation, etc). All could interfere drastically with proper operation. On the other hand, radio techniques seem quite suitable. Determination of system parameters requires consideration of permissible frequency ranges, antenna size and gain, availability of efficient, reliable, low-cost signal sources and freedom from either causing or suffering from electromagnetic interference. These points will now be explored.

4.2.4 Radio Communications Link

Radio communications can be carried out using state-of-the-art apparatus in the frequency range of fractions to tens of thousands of megahertz. As a general rule, antennas must be of the order of (or, for directivity, significantly larger than) one wavelength at the frequency used. Thus, this consideration alone suggests use of a wavelength of 10 meters or less, or a frequency above 30 MHz. However, several other considerations restrict the choice far more. Reduction of electromagnetic interference, as well as low vulnerability to extraneous signals, strongly indicates the desirability of a line-of-sight system, in which signals are either absorbed by obstacles or pass through the ionosphere with no reflection. Further gains can be made by using highly directional receiving and transmitting antennas, which implies antennas with basic dimensions of the order of ten times the wavelength. Another point favoring use of higher frequencies is wider available frequency allocations and reduced commercial use-important in avoiding interference. Finally, a highly directional antenna system is much less wasteful of energy, so that power consumption can be kept at a low level, simplifying power supplies and reducing the size of batteries needed for stand-by use, or eliminating the need for line power. (This is a significant part of the cost of both initial installation and maintenance.) Of course, construction costs and immunity to weather and vandalism limit the permissible antenna size to a radius (for parabolic reflectors) of 2 to 3 ft. (~100-cm.). This implies operation in the microwave range, at wavelengths of less than 10-cm. (Frequencies greater than 3GHz).

Further guidance can be obtained from consideration of available microwave sources. At this lower frequency limit, (3-GHz) transistor oscillators or transistor-varactor circuits are feasible. However, both represent significant cost and complexity. On the other hand, recent developments in solid state microwave technology (heavily supported by DOD and NASA for a decade) suggest the desirability of somewhat higher frequencies. Two types of oscillatory diodes have been realized in practical form, both providing direct conversion from dc to microwave power with no additional circuit elements beyond the diode and its mounting. The avalanche, or IMPATT (Impact Ionization-Avalanche-Transit Time) junction diode is somewhat more highly developed, and more efficient, than the Gunn (Transferred electron) bulk diode, but requires ~80-Vdc compared to the very convenient 12-Vdc for the latter. Costs and reliability are about equal. Either could be used in the proposed system, but the necessity of compatibility with battery operation militates strongly in favor of the Gunn device. The physics underlying the operation of these devices restricts operation to approximately 8-GHz, and number of other markets (police radar, intrusion alarm systems, etc.) at 10.525 imply that devices of minimum cost will be found for 10 to 11 GHz systems (Wavelength approximately 3-cm). This is a frequency range (X-band) at which many components are readily (and inexpensively) available, and very high antenna gain and directionality can be achieved for antennas of only 1 to 2 ft. diameter. An analysis of required transmitter power for antennas and distances considered will be found in Appendix A, and shows state-of-the-art components to be entirely adequate. Specifications for such diodes currently indicate a mean time before failure of approximately five years, with an estimated cost (high volume) of $25.

Higher frequencies would increase cost substantially as both oscillatory diodes and other components require closer tolerances in manufacturer, and commercial and military markets (and hence production volume) are much smaller. In addition, above 20 to 30 GHz attenuation from heavy rainfall can have significant effect on propagation distances. On the other hand, at 10 GHz no problems occur for rainfall of less than 5 inches/hour, a rate at which all motor vehicle traffic would presumably be at a standstill.

4.2.5 Signal Activation by Means of Microwave Telemetry

The basic system which has been designed at TSC is indicated in Figure 4.1, and consists of a solid-state microwave transmitter at the train detection point (typically 1/4 to 1/2 mile from the crossing) with a receiver at the crossing. The normal (train absent) condition is with the transmitter on, pulse modulated at a low repetition frequency, with pulse width sufficiently short to provide a duty cycle of less than 1%. At the receiver, this signal is detected and rectified, giving an output voltage as long as a signal is received. In the absence of such a signal, for whatever reason, there will be no output, and warnings are activated under these circumstances. Thus, it is simply necessary to arrange to turn the transmitter completely off when a train is detected. (Means of train detection are indicated in section 4.2.7). Transistor circuits to realize this mode of operation have been designed and constructed.

The transmitter used is a transferred-electron (Gunn) diode, which is conveniently operated from a 12-Vdc source, such as a storage battery. For 100 mW output power, which is a desirable level, this low-efficiency device requires about 5 watts input. However, the low duty-cycle of the pulse modulator reduced the net power requirement to under 50-mW (.05 W), with a similar or smaller power requirement for the modulator. For a 12-volt system,

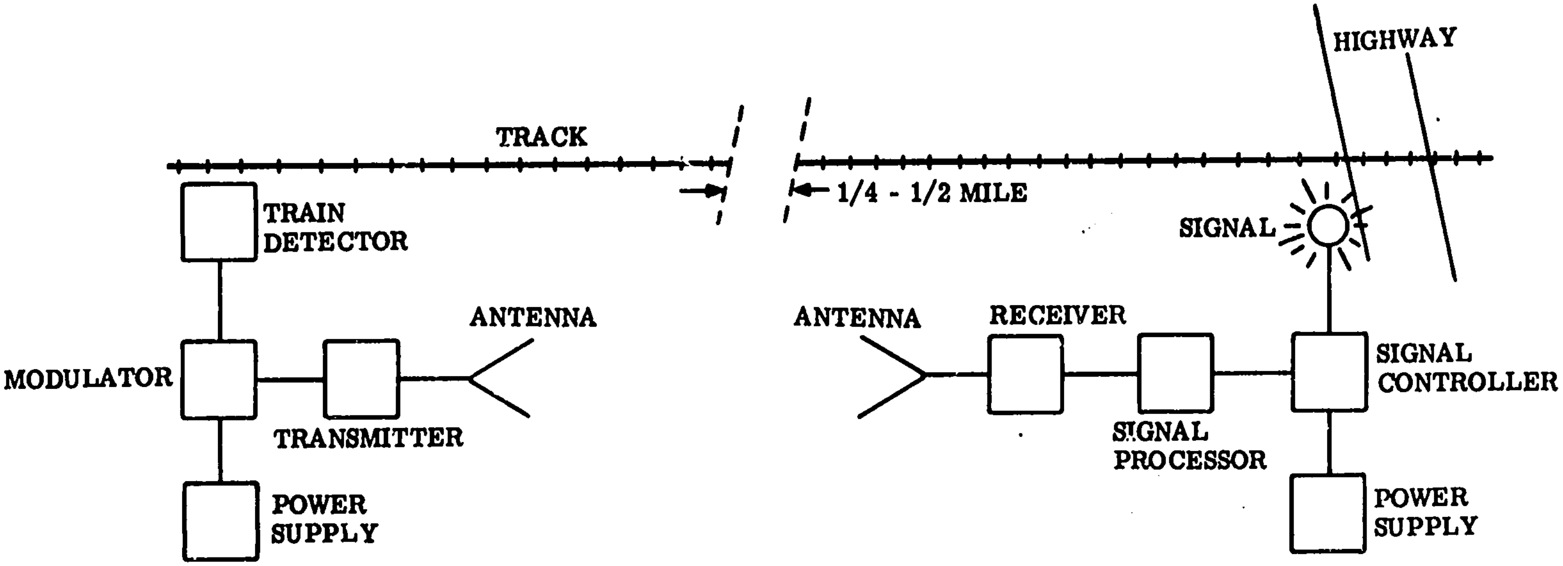


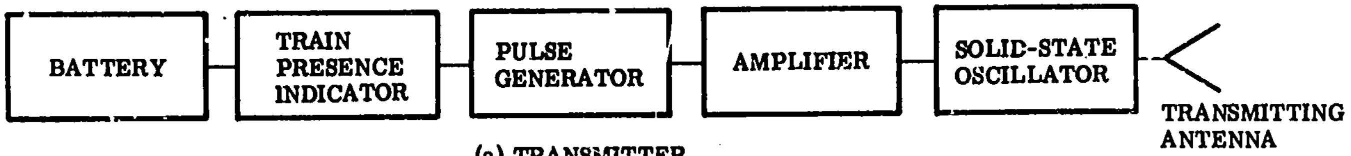
Figure 4.1. - Basic Telemetry System

this represents a current of approximately .01 amperes, or .25 Amp-hours/day. The largest capacity automobile batteries have a rating of approximately 90 Amp-hours, so that this system could run for approximately one year on a single battery. These numbers are intended only to indicate the proper order of magnitude. There is nothing to prevent an oscillator duty cycle so low as to require less than 1 mW average power, and modulator circuits could also be designed for very low consumption. Then, with a low-power consumption train detector (as seems quite feasible) complete battery operation is possible at the down-track point. This could produce significant savings in installation costs. Where line power is readily available and its use is desired, there will still be a significant reduction in the power supply and size of back-up battery needed. (For comparison, conventional systems operate at power levels of watts.)

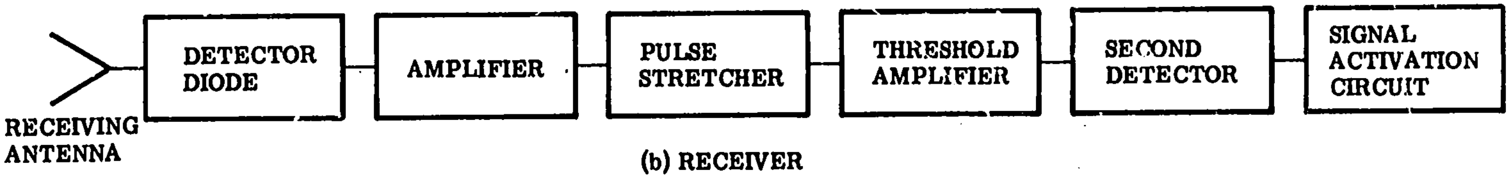
The receiver circuits consist of a detector, a stage of amplification (simple integrated circuit video amplifier), a long-time-constant R-C circuit and a threshold amplifier (to convert the very low duty-cycle input waveform to a square wave, with much higher average power), a power amplifier (integrated circuit), and a rectifier to measure the average received power. Both the receiving and transmitting circuits are shown in block diagram in Figure 4.2.

It should be pointed out that these circuits are intended to demonstrate the concept, and do not necessarily represent final designs. For full-scale demonstration and evaluation, it will be appropriate to have the actual system, particularly the modulator and receiver circuits, designed and constructed by a contractor especially skilled in low-power, high-reliability circuits, and knowledgeable of railroad environment, practices, and standards.

One may better utilize the availability of a full communication channel by designing for a number of possible system modes. As an example, consider the use of six separate (identifiable) modes of operation: transmitter fully off, transmitter on unmodulated, or transmitter on pulse modulated (at a low duty cycle) at one of five repetition frequencies, f_1, f_2, f_3, f_4, and f_5. The receiver would respond to the "off" and "on" (CW) modes with signal activation (failsafe operation) plus system failure indications, while modulation at f_1 would indicate train absence (all clear); f_2, a train traveling less than 20 mph; and f_3, f_4, and f_5 for trains with velocities of 20 - 40 mph, 40 - 60 mph, and above 60 mph, respectively. (Any other frequencies would also give a system-failure response.) The additional cost of such refinement should not be extreme, and would probably be warranted at a substantial number of crossings with a variety of train movements. (Alternatively, the exact train velocity, to whatever accuracy is both necessary and justified by the measurement technique, could be telemetered in fairly simple fashion.)



(a) TRANSMITTER



(b) RECEIVER

Figure 4.2 - Block Diagram of Telemetry Circuits

The system now being demonstrated operates at 10 GHz, as explained. However, this parameter should not be frozen at this stage. The only elements affected by the frequency are the Gunn diode and the antennas. Should diode technology and economics permit, K_u-band (approximately 20 GHz) would give significantly higher antenna gain for the same physical size. (At significantly higher frequencies the possibility of serious attenuation by heavy rainfall becomes a drawback.)

Similarly, considerable attention has been given to the best type of antenna for this application. The familiar parabolic dish is relatively inefficient at smaller sizes (low ratio of aperture to wavelength), and with feed assembly and radome can be rather expensive (over $400). The standard horn antenna, for the gain required, would be bulky, subject to wind damage and attractive to vandals, and would also be fairly expensive. Careful attention is now being given to the use of planar slot-array antennas. Even for small aperture/wavelength ratios they are highly efficient, with small physical size, and can easily be weatherproofed. The structure is simply that of a plate about one foot in diameter, with a thickness of less than an inch. Cost is, at present, difficult to estimate, as the only prior applications have been in military missile systems, with extremely demanding specifications. Informal estimates for a civilian application (such as grade crossings) have ranged from $30 to $250, assuming reasonably high volume, once design and tooling costs are amortized. Since these antennas have such desirable operational characteristics, their use is being investigated further. In addition to studying characteristics and costs, a test is contemplated in which a large number of dummy antennas (wooden or plastic) would be installed along railroad right-of-way, in order to determine attractiveness and vulnerability to vandalism.

4.2.6 Elaboration of the Basic Concept

The use of an explicit communication channel, as well as the nature of the proposed channel, make possible a number of more sophisticated protective systems, for which the additional cost might well be acceptable in certain situations. Some of these will now be delineated.

Multi-Track Systems - In multiple track situations, completely separate track circuitry is used for each track. As an alternative, separate sensors (for each pair of rails) could modulate the microwave transmitter in different ways, so that the crossing receiver can distinguish between them (for example, for interpretation of restart and receding train signals). The additional solid state circuitry could be quite inexpensive, and only one transmitter, antenna, and mounting would be required. This is illustrated schematically in Figure 4.3.

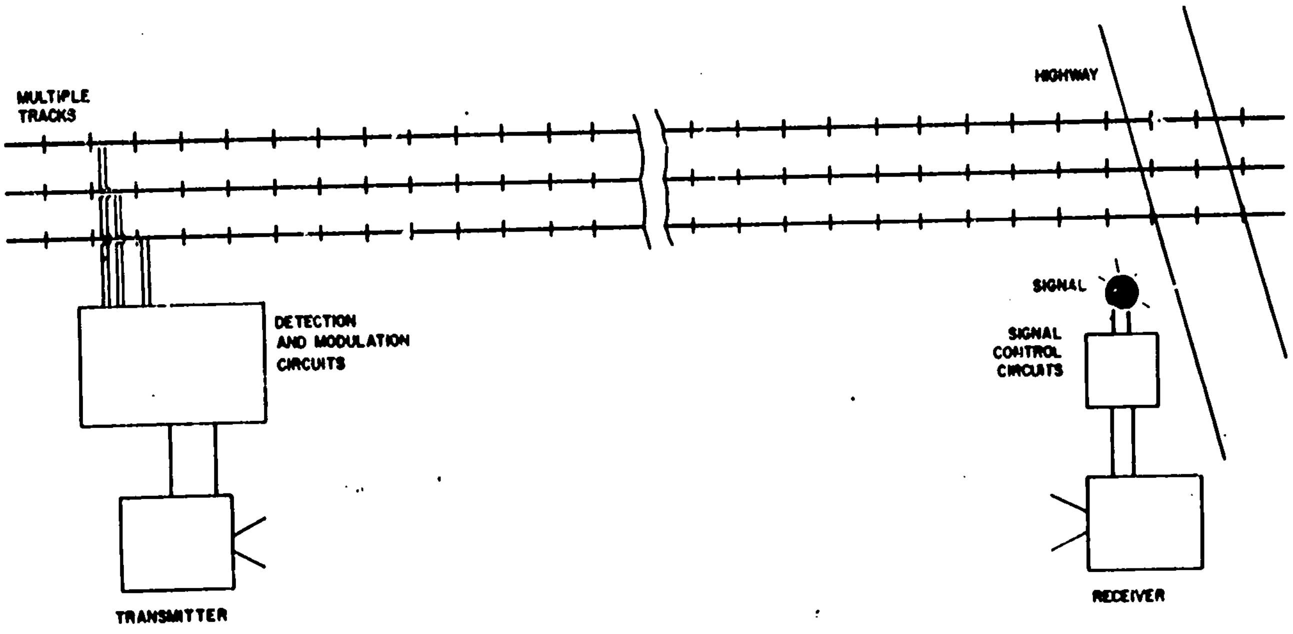


Figure 4.3 - Application of Telemetry System to Multi-Track Case

Multiple Crossings - For a given track in urban or suburban areas, it often occurs that there will be a number of crossings located in close proximity to one another. In such a case, one sensor (per track) and one microwave transmission system (for each direction), supplemented by appropriate time delay circuits, might well be sufficient, as indicated in Figure 4.4.

Non-Uniform Train Movements - The basic form of grade crossing signal activation assumes that all trains pass at the maximum allowed speed, with no velocity changes between the sensing point and the crossing. For a 30-second warning time, with a track speed limit of 60 mph, the signals are activated whenever a train passes a point one-half mile from the crossing. A 15 mph freight will then initiate warnings two minutes prior to passage, occasioning considerable annoyance on the part of waiting motorists. A more dangerous condition results when drivers who consider themselves familiar with the crossing develop the habit of ignoring the signals. Also serious is the situation in which a passenger train has a station stop just prior to the crossing, such that, in absence of special procedures, highway traffic is delayed unnecessarily throughout the stop. An even more difficult situation is a longer stop (perhaps by a switching locomotive). The worst case (which may occur near sidings or classification yards) involves a locomotive moving into the protected region, triggering the signals, and then leaving. The signals may then remain activated indefinitely, or until a timing circuit deactivates them. At present, such occurrences can be avoided or reduced in seriousness (where traffic warrants) by a variety of additions to the basic track circuit. There additions generally raise the overall cost quite substantially, may impose limitations on train operations, and do not always solve the problem. The microwave link provides no remedy. However, the enhanced communication capabilities it furnishes make possible the utilization of more sophisticated sensors and signal processing in a fashion that may well deal with these problems with greater economy and effectiveness.

For the simplest case (trains moving below the maximum allowed speed) the sensed velocity can be relayed to the warning signals, so that a time lag may be introduced prior to activation. This may require either that trains be prohibited from significant acceleration just prior to the crossing, or that a small additional time interval be added to the normal advance time to allow for the possibility of increasing speed. One can also conceive of systems using microwave speed-sensing radar at the crossing to detect the speed of an approaching train, possibly canceling the delay if the measured velocity is well above that indicated by the train detector. Such radar could even provide primary coverage in some cases, as described in Section 4.3.3. A two-transmitter system, as in Figure 4.5 could also be used as an advantage.

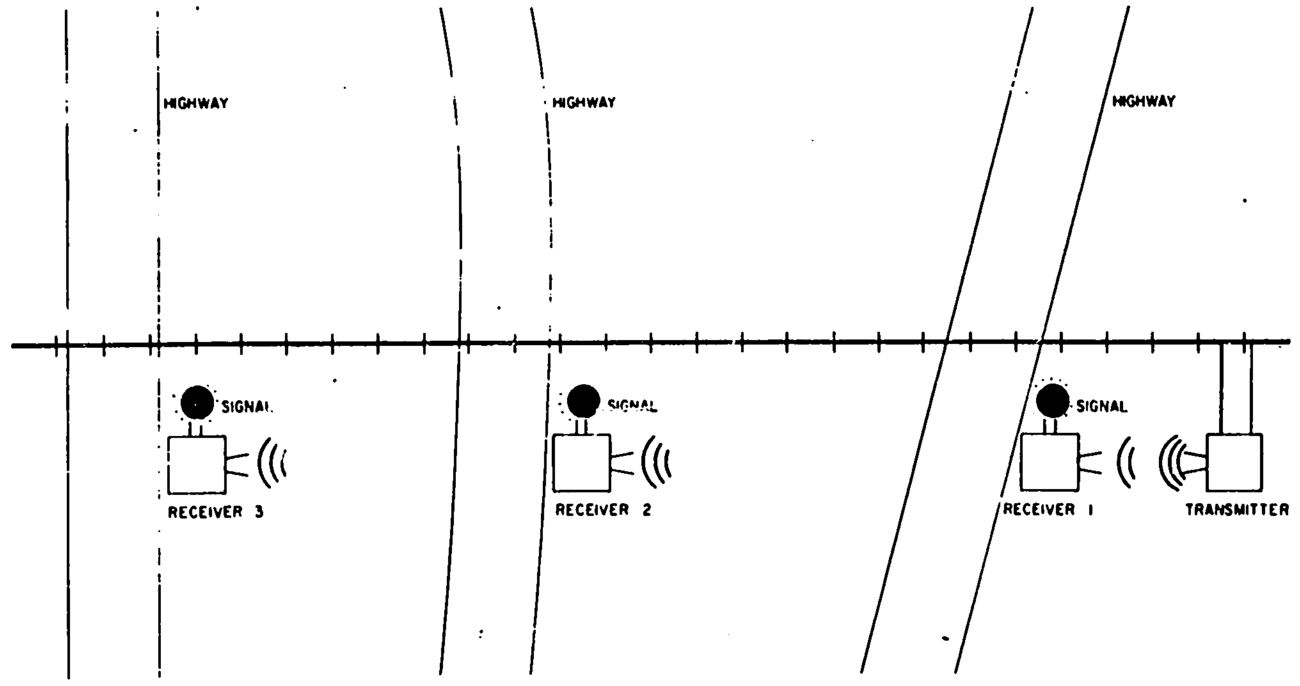


Figure 4.4 - Application of Telemetry System to Multiple Crossing Case

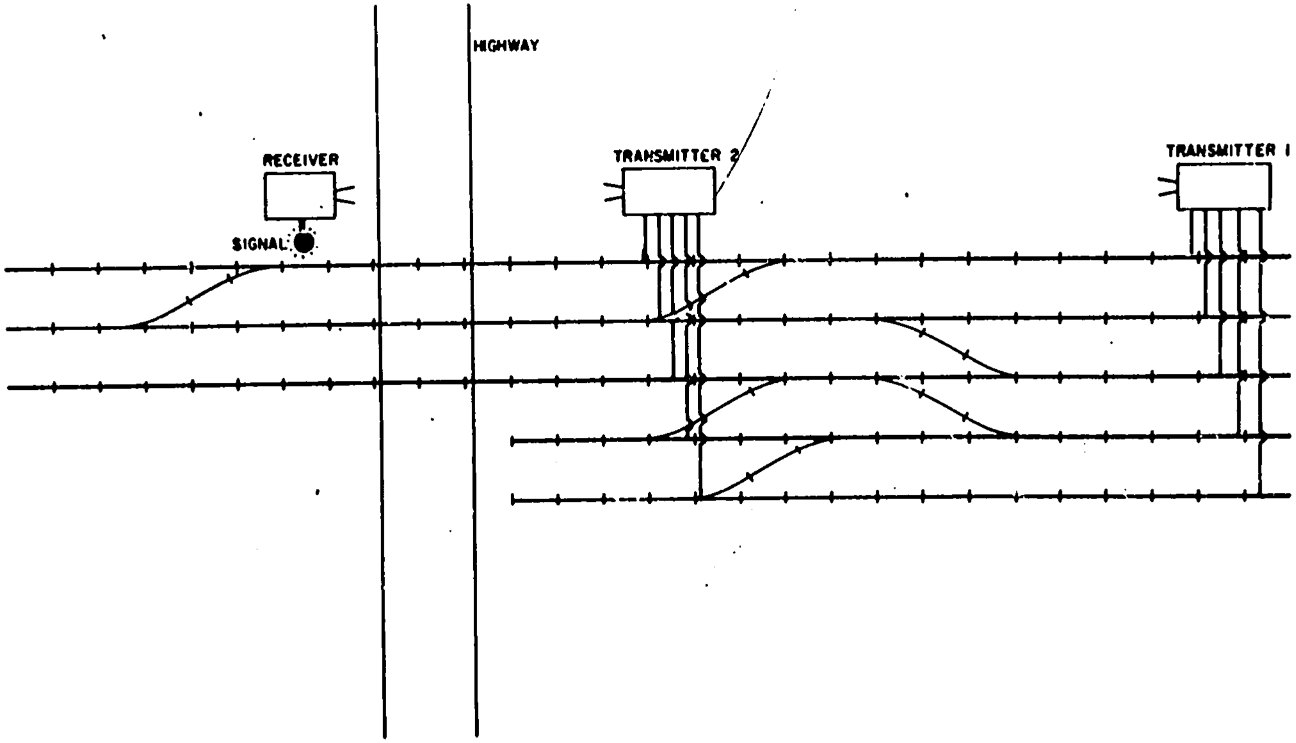


Figure 4.5 - Application of Telemetry System to Non-Uniform Train Movement

Trains that enter a protected region and subsequently reverse direction and leave could be dealt with through direction sensing at the detection point, so that the system is reset if a train is detected first approaching then leaving the sensing point without activation of sensing circuits at the crossing or in the opposite direction. (This requires not only that direction be sensed, but that this specific information be conveyed to the crossing.)

For certain special cases, such as station stops and regular frequent switching movements, it is not unreasonable to consider the possibility of locomotive-mounted transmitters which can override the crossing signals, or activate a special response mode. Alternatively, a second transmitter might be housed at the station, to be activated by the train prior to departure.

Alternative Highway Routings - Under some circumstances, particularly passage of long, slow freight trains, there may be some advantage to motorists choosing, or being directed to, alternate routes such as grade separations in the vicinity. Sufficient advance measurement of train speed and length, and communication of these values, could provide information needed to activate indicators, either at the crossing or well prior to it, indicating suggested evasive action which might significantly reduce the motorist delay associated with passage of the train (illustrated in Figure 4.6).

Advance Warning - It is sometimes the case that terrain, buildings, road or track curvature, or other visual obstacles prevent an approaching vehicle from seeing the crossing (even with lights flashing) until a relatively short distance prior to the rail-highway intersection. A driver who is speeding, inattentive, or fatigued, particularly under conditions of inclement weather, may fail to stop in time. Such situations could be avoided by use of active advance warnings (special flashing lights, or signs illuminated only when a train is present). It is quite possible that in many cases such signs could be activated either directly by the original microwave transmitter (perhaps using reflectors) or by a second slave transmitter. (See Figure 4.7.)

4.2.7 Train Detection

A number of means can be used to switch the transmitter into the proper "train present" mode when appropriate. Although track circuits are used almost universally for crossing protection, other means suitable for classification yard use or operation of various scanners are available. The principal characteristics desired are:

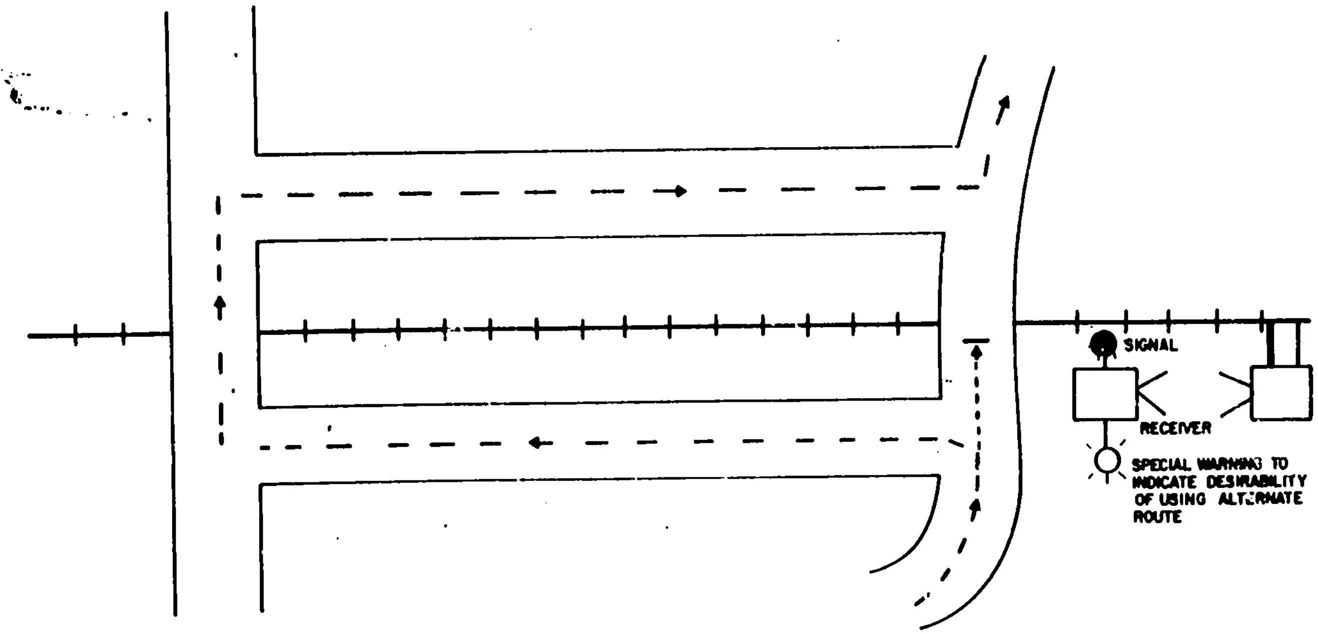


Figure 4.6 - Use of Telemetry System to Indicate Alternative Routings

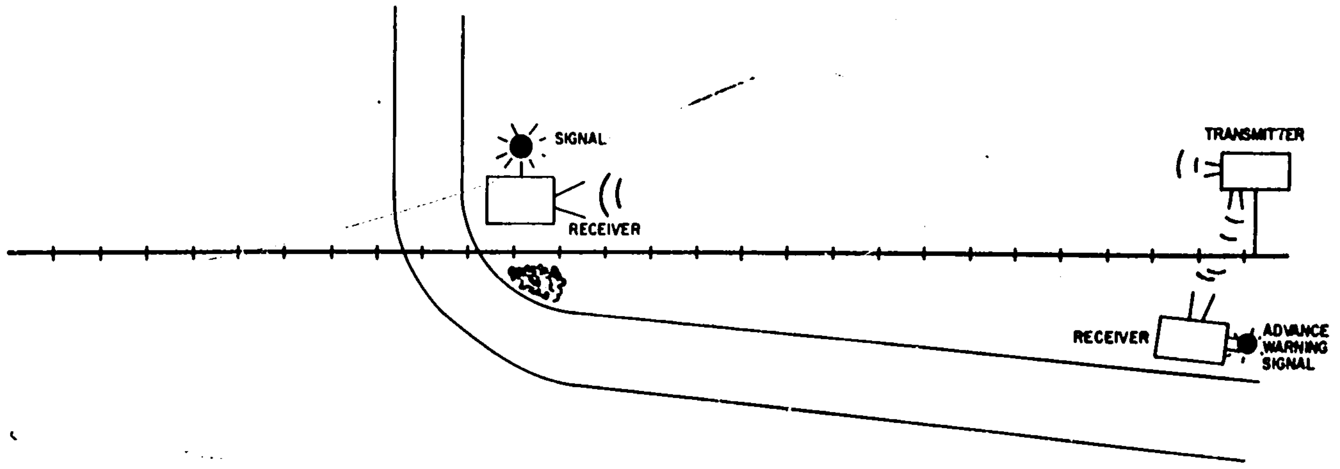


Figure 4.7 - Use of Telemetry System to Provide Advance Warning

a. low cost
b. low power consumption
c. very high reliability
d. failsafe operation
e. minimal interaction with railroad signal system
f. direction and velocity sensing

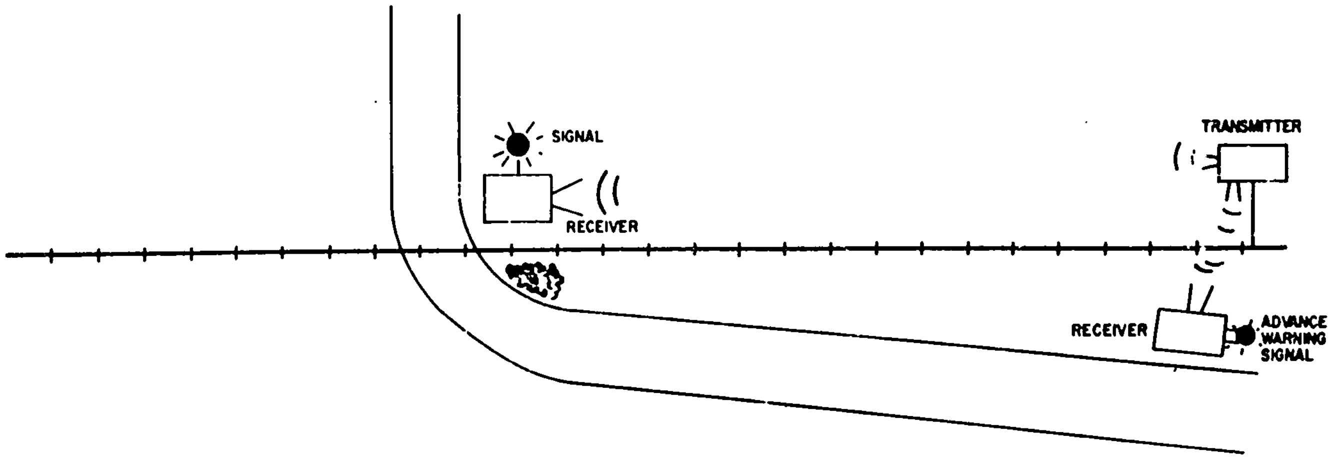
Items a. and b. are obviously necessary if the overall system is to have those properties; minimal installation labor and maintainance is included in this requirement. Item c. needs no elaboration here, and d. can, as suggested in section 3.2.7, be dispensed with, although it remains a highly desirable characteristic as long as it is consistent with a. and b. To the degree that failsafe operation is compromised, reliability must be even greater. The reason for e. was indicated in section 4.1; it permits active protection to be introduced by non-railroad authorities. Such a restriction is, to a degree, implicit in the desire for low-cost operation. There are, of course, many other desirable attributes which apply to all systems-widespread applicability, relative invulnerability to environment and vandalism, etc. The properties of f., while not required, are desirable in order to take advantage of the available communication link.

There are many means of detecting such an obvious object as a train; potentially suitable techniques now available fit into the following categories:

a. track circuit
b. track impedance
c. inductance
d. magnetic
    1. rail-mounted
    2. independent
e. radar
f. sonar

The first three techniques, particularly if designed for relatively high frequency operation (so that detection is well localized) generally are of relatively high cost and power consumption in present embodiments. Inductive techniques also generally involve substantial labor for burying of cable loops, etc. Magnetic methods appear quite promising, and rail-mounted units, used for hot-box and ACI detectors, can sense both direction and velocity of trains in more expensive realizations. These can be nearly failsafe (i.e., safe with respect to most failure modes) and cost factors look promising. Further development would be necessary for general use in the crossing-protection application. Magnetic detectors not rail-mounted also have potential, but have not been developed for such use.

Radar and sonar techniques (e and f) are used in yards and could be suitable. Velocity information is likely to be readily



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Radar and sonar techniques (e and f) are used in yards and could be suitable. Velocity information is likely to be readily attainable. However, cost and non-safe failure modes are a problem, and weather-proofing a sonar system for remote use presents definite difficulties.

This brief summary is intended only to outline relevant constraints and techniques; other methods are possible and may prove optimal. However, these represent currently-available detectors most suitable to early field test of a telemetry system. For reasons indicated in section 3.3.2, no detectors requiring train-mounted apparatus have been considered. The possibility of using no explicit train detector, but relying simply on beam-interruption, is discussed briefly in section 4.3.3.

4.3 CROSSING-LOCATED SYSTEMS

4.3.1 Introduction

It has been shown previously (section 2.4) that there are many crossings for which a protection expense in the range of $3000 to $10,000 is the maximum justified. Such an investment could often permit use of conventional (or quasi conventional) signals (barely), provided that some very inexpensive means of activation can be found. Here it is likely that there must, for the sake of economy, be some compromise of the failsafe requirement, with all the attendant problems, but the substantial number of crossings in this category suggests the value of considering such methods. (Nor is it necessarily true that reliability or overall effectiveness need be reduced.) Realization of this objective requires that effective train detection be accomplished for only a few thousand dollars. This will be possible only through extreme simplicity. The entire system almost certainly must be located at the crossing with little or no track modification, and preferably no other physical structure necessary in addition to the signal poles. (Relay houses, for example, cost approximately $500 plus installation.) The required simplicity of control logic may be possible only for single track cases, but these are sufficiently common that this is not a severe drawback. (Indeed, multiple track would require automatic gates, adding at least $4,000 to the cost, and raising the level of discussion to the higher cost classes of crossings.)

Implementation of the concept of a simple, crossing-located system is being carried out at TSC by consideration of two techniques. The first is use of a variation of the conventional (though recent) motion or presence sensor, now manufactured by several companies as a secondary system or for non-vital applications, as in classification yards. These operate by measurement of rail impedance at the crossing and either note simply the decrease brought about by the approach of a train (presence detector), or the rate of decrease of impedance, which is approximately proportional to train velocity (motion detector).

The other means of train presence detection being considered is the use of radar, located at the crossing and directed in both directions along the tracks. Major relevant considerations for both systems are described in the following sections.

4.3.2 Train Detection by Rail Impedance Measurement

A section of railroad track may be thought of as electrically equivalent to the transmission line of Figure 4.8. The series inductance is due to the rails; the shunt resistance is that of the track ballast. Typical values for 1000 feet of track are 0.5 mH and 5 ohms, although ballast resistance in particular can vary considerably. The basic equation for the input impedance of a transmission line, in the configuration of Figure 4.9, is

$$Z_{in} = Z_o \frac{Z_L \cosh(\gamma \ell) + Z_o \sinh(\gamma \ell)}{Z_o \cosh(\gamma \ell) + Z_L \sinh(\gamma \ell)}$$

where Z_o = line characteristic impedance

$= \sqrt{jwLR} = \sqrt{\frac{jwL}{G}}$

ℓ = line length

G = shunt conductance per unit length = $\frac{1}{R}$

L = series inductance per unit length

Z_L = load impedance

and γ = propagation constant $= \alpha + j\beta$

$= \sqrt{\frac{jwL}{R}} = \sqrt{jwLG}$

In this model an approaching train is represented by a Z_L of .06 ohms at a distance ℓ. The actual rail-rail impedance measured at a given point is the parallel sum of the impedance looking in each direction, so that the true situation is that shown in Figure 4.10. (A lossy line of sufficient length has an input impedance of Z_o regardless of termination).

For the case common to present motion detectors, a constant current is fed into the track, and the voltage developed is measured. Thus, for one ampere injected, the voltage is numerically the same as the impedance in ohms (V = IZ), and impedance data is sufficient to describe the situation.

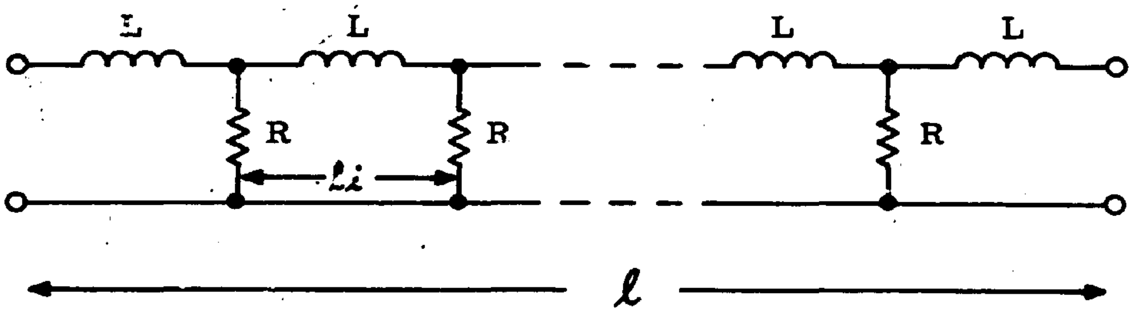


Figure 4.8. - Track Equivalent Circuits

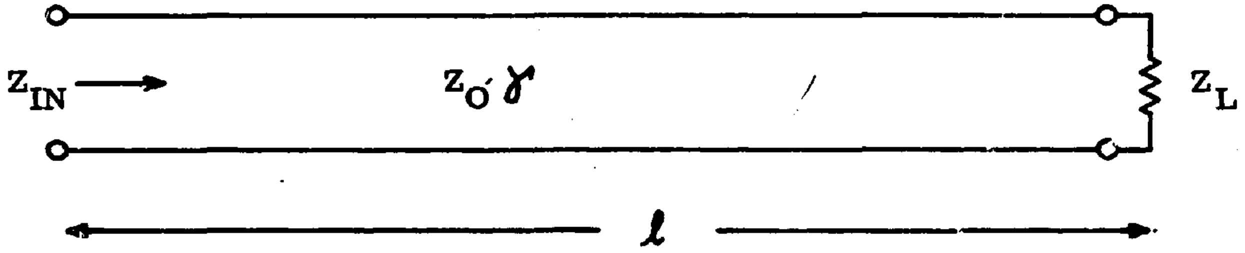


Figure 4.9. - Basic Transmission Line

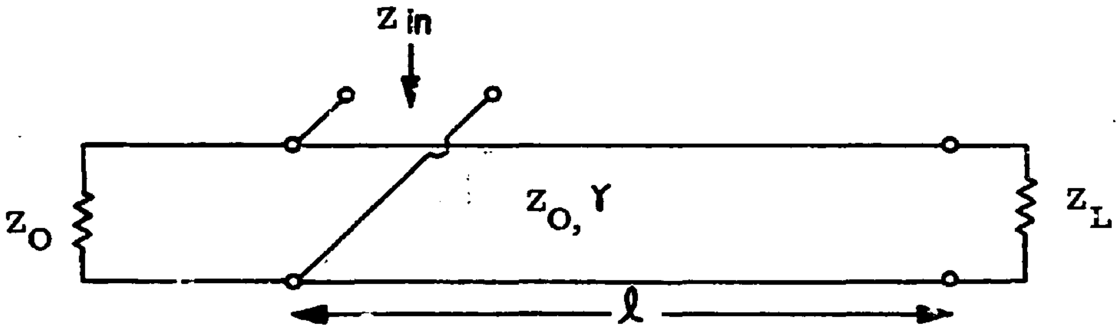


Figure 4.10. - Transmission Line Circuit Used for Calculations

However, impedances are often measured by bridge methods, which offer greatly improved sensitivity. The basic Wheatstone bridge is shown in Figure 4.11. The ratio of output voltage v_o to input voltage v_i is given by

$$\frac{v_o}{v_i} = Z_d \frac{\dfrac{Z_x}{Z_x + Z_s} - \dfrac{Z_a}{Z_a + Z_b}}{\dfrac{Z_x Z_s}{Z_x + Z_s} + \dfrac{Z_a Z_b}{Z_a + Z_b} + Z_d} \approx \frac{Z_x}{Z_x + Z_s} - \frac{Z_a}{Z_a + Z_b} \text{ (for large } Z_d\text{)}$$

where the variables are as defined in Figure 4.11. For the case of present interest, Z_x, the unknown, is the rail-rail impedance at the measurement frequency. Maximum sensitivity for such a system occurs for the condition

$$Z_a = Z_b = Z_s$$

The relevant equations have been programmed for computer solution for any desired range of parameters, including measurement frequency. Computer calculations have been made so as to provide data for both track impedance and output of a bridge

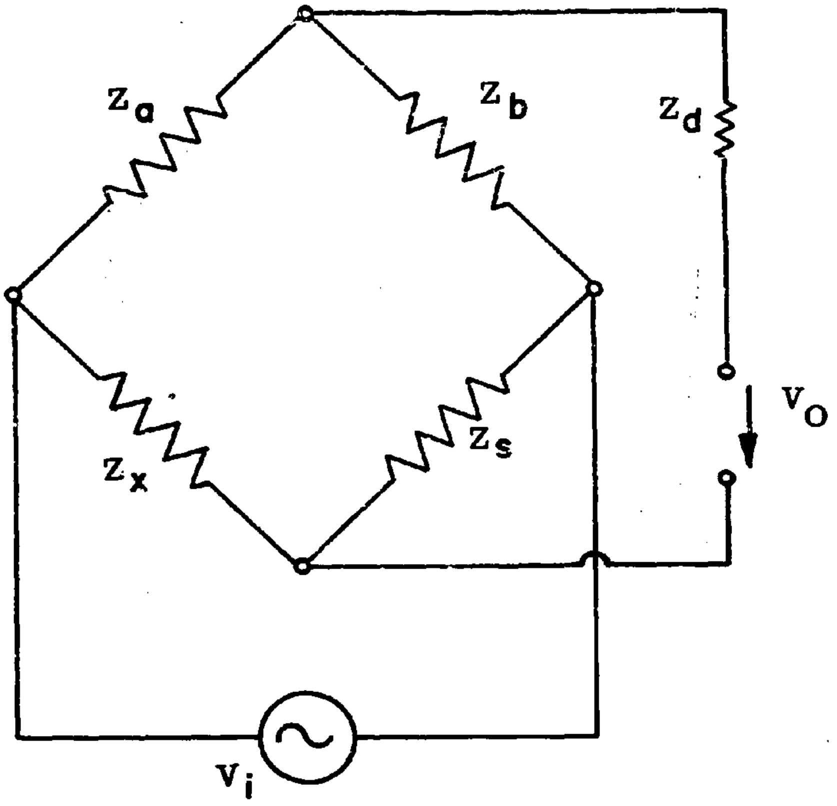


Figure 4.11. - Basic Impedance Bridge Z_x is Unknown Impedance

circuit balanced for the train-absent condition. Data for typical cases considered are presented graphically in Figures 4.12 to 4.15. Most of these plots eliminate the need for presenting variation with one of the parameters by combining two of them, frequency ($f = \omega / 2\pi$), and rail inductance (L) into a single parameter, merely the product fL. This is possible because the two parameters ω and L appear only as a product in the basic transmission line equation, above. Typically the plots show variation of Z_{in} or v_o with distance to train for various values of the product fL and of the ballast resistance R. In all cases the train is taken as a load impedance of 0.06-ohms and bridge input voltage is 10-volts. Slope of these curves (rate of change of impedance or output voltage) has also been calculated, to permit consideration of velocity measurement. An impedance slope plot is included as Figure 4.16. It can be seen in these graphs that bridge methods offer the possibility of considerable improvement in sensitivity, i.e., in sensing distance, but are not well suited to velocity measurement, since the curves are not linear. (Rate of change of impedance is not proportional to train velocity, but depends also on train distance.) On the other hand, a bridge could readily sense the abrupt change in slope associated with passage through a grade crossing, so that for single track, one could conceive of a system requiring very simple logic. Signals are activated upon

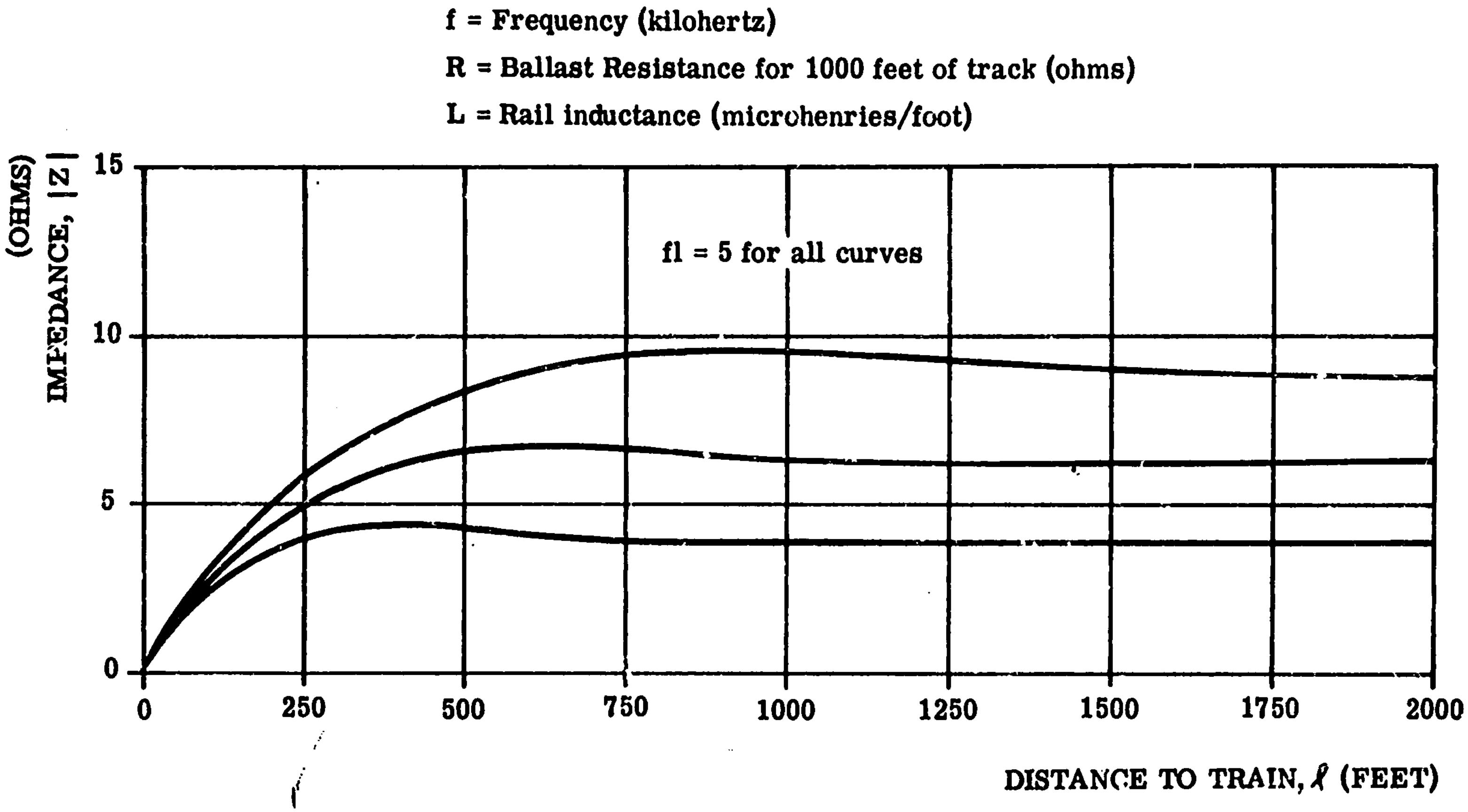


Figure 4.12. - Impedance Versus Distance to Train For Various Ballast Resistances

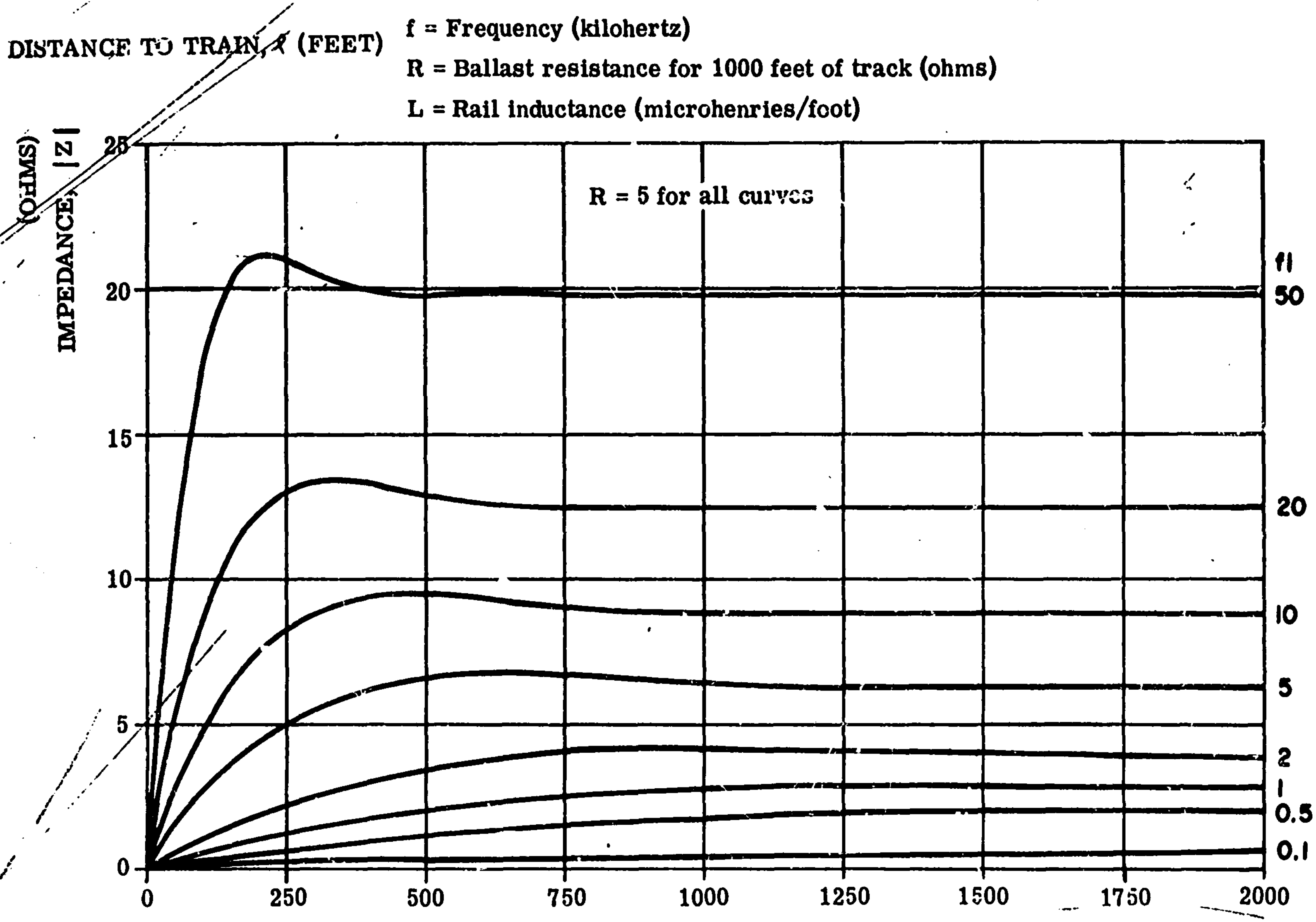


Figure 4.13. - Impedance Versus Distance to Train For Various Values of the Product fL

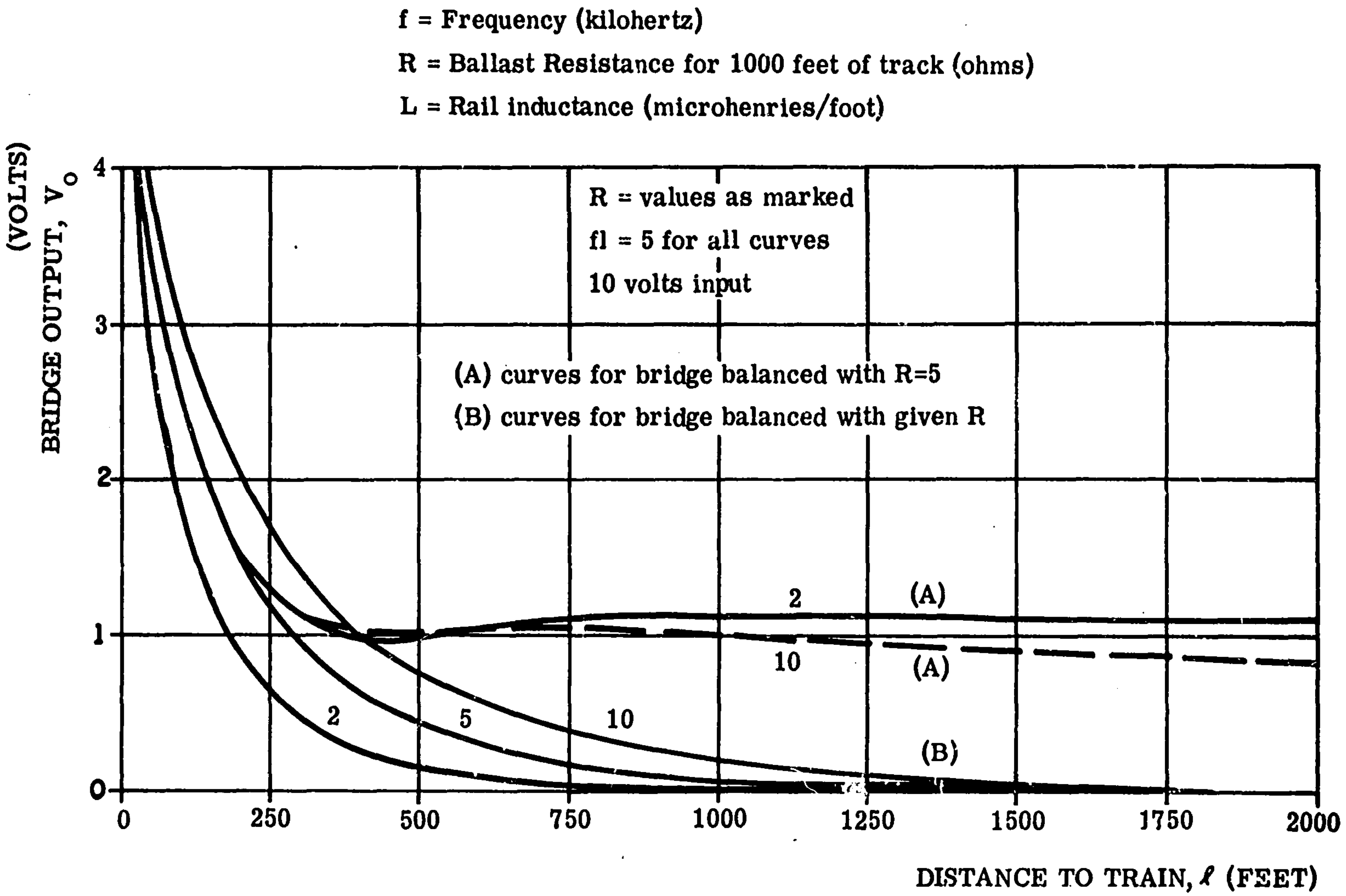


Figure 4.14. - Bridge Output Voltage Versus Distance To Train For Various Ballast Resistances

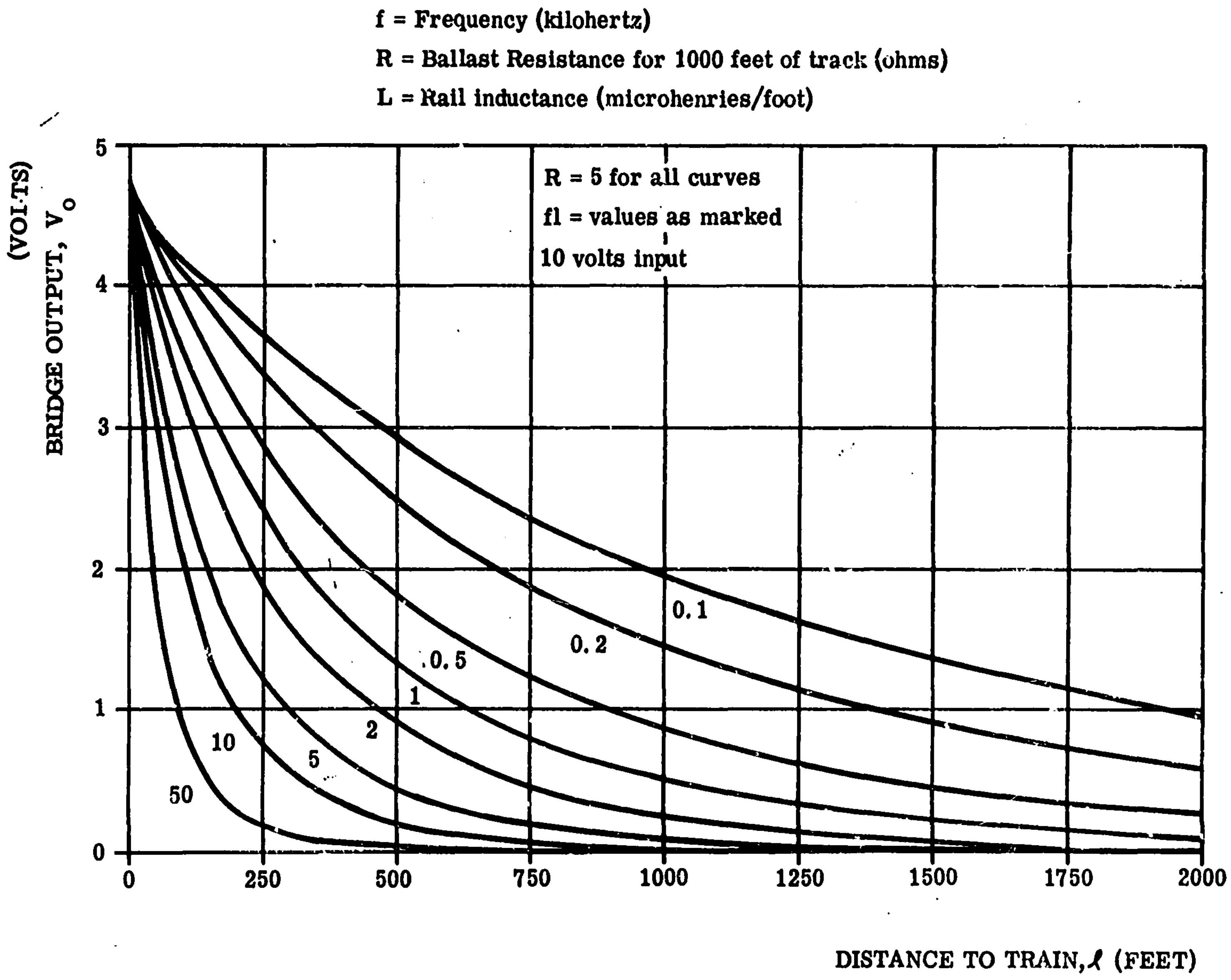


Figure 4.15. - Bridge Output Voltage Versus Distance To Train For Various Values of the Product fL

f = Frequency (kilohertz)

R = Ballast Resistance for 1000 feet of track (ohms)

L = Rail inductance (microhenries/foot)

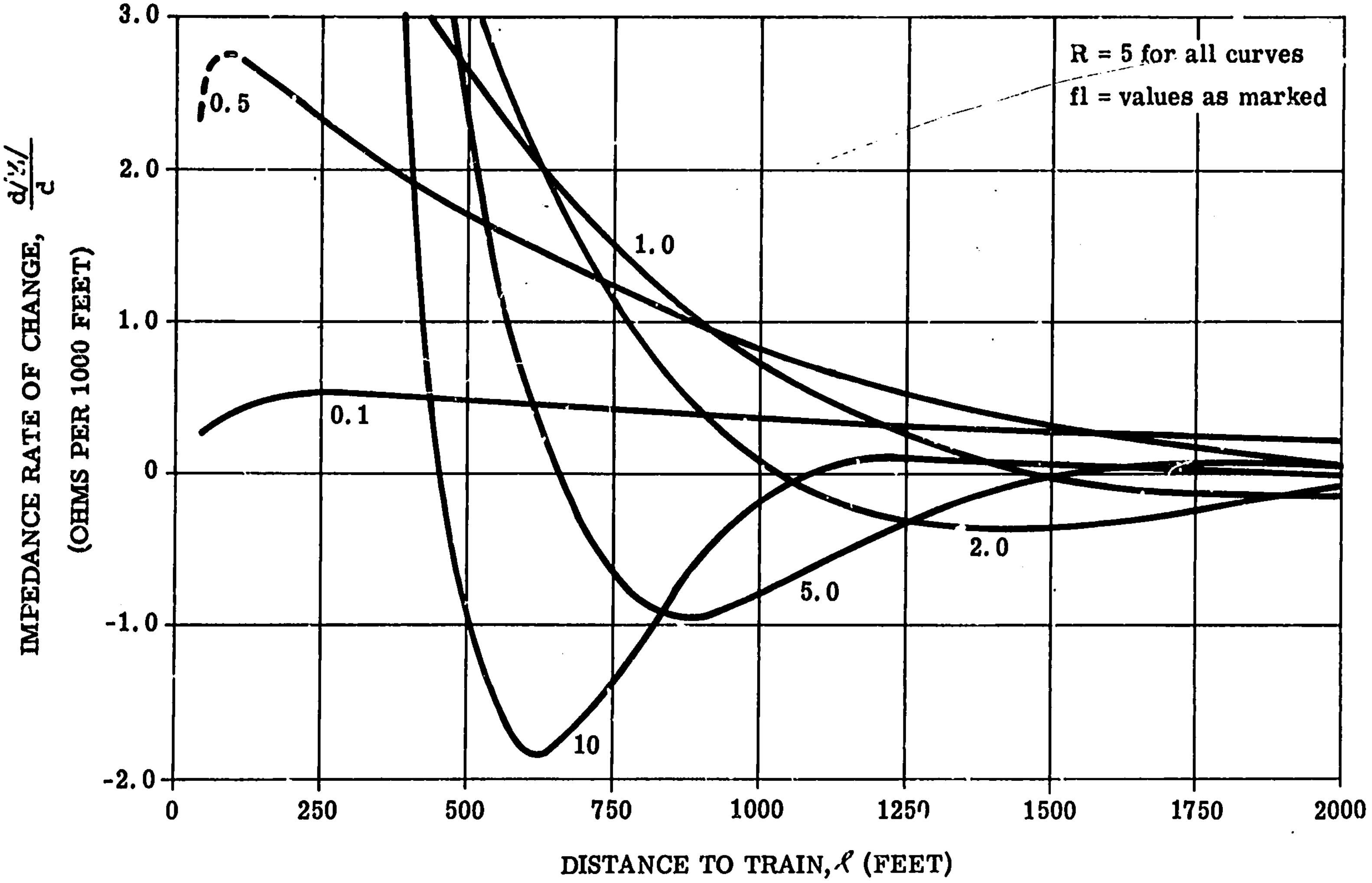


Figure 4.16. - Impedance Rate of Change Versus Distance To Train For Various Values of the Product fL

detection of a train, and remain so until track impedance shows positive time derivative, indicating that the train is moving away from the crossing. Experimental confirmation is required before graphs suitable for system design are calculated.

Such a system does not provide closed-loop broken-rail detection. However, a second set of computations were carried out assuming a very high load impedance, a good approximation to the broken rail case. The results are shown in Figures 4.17 to 4.20 (Z and v_o for a broken rail a distance ℓ from the sensing point), and indicate that there is, in fact, an effect approximately equivalent in magnitude to that seen for train presence, so that broken rails can be detected as far away as trains. Here the bridge system does seem to have a considerable advantage, for the same result occurs in either case: imbalance, and an increased output voltage. A simple impedance measuring device would show an opposite effect than for train approach, and more sophisticated circuitry becomes necessary to provide an indication for the two possible cases.

A major difficulty with bridge circuits is the need to maintain a balanced condition under varying conditions, when ballast resistance may change drastically in short time intervals. (This is illustrated by the (A) curves in Figures 4.14 and 4.19.) Figure 4.21 shows variation in train-absent impedance ($Z = Z_o/2$) as a function of the product fRL. For a constant value of fL, the relationship to R is a fairly sensitive one, so that one could imagine using a high-frequency bridge (100 - 500-kHz) to make periodic measurements of the ballast resistance, which would then provide information to permit automatic adjustment of the lower-frequency train-sensing circuit. This higher-frequency circuit might be rendered inoperative during periods when the longer range bridge had detected a train. The advantage of such compensation is seen in the (B) curves of Figures 4.14 and 4.19, which assume bridge rebalancing for the different ballast resistance values. It remains to be determined whether the cost of providing automatic bridge balancing is low enough to make this a practical approach to low-cost protection.

Power consumption for such a system could be kept quite low. Pulsed operation, perhaps 1 to 10 pulses-per-second, would be adequate, and the ballast-resistance-measuring circuit need operate only occasionally, either every few minutes, or perhaps only when some change is indicated by the primary system.

An alternative mode of operation has been investigated. This is based on balancing the bridge for the train a specified distance away. The normal (train absent) situation will then represent imbalance, and a non-zero output voltage will occur. This will go approximately to zero when the locomotive reaches the specified approach distance, providing zero output as an indication of train presence, a useful failsafe characteristic. While further study is necessary to determine the utility of this mode, calculations indicate that it is too highly sensitive to ballast

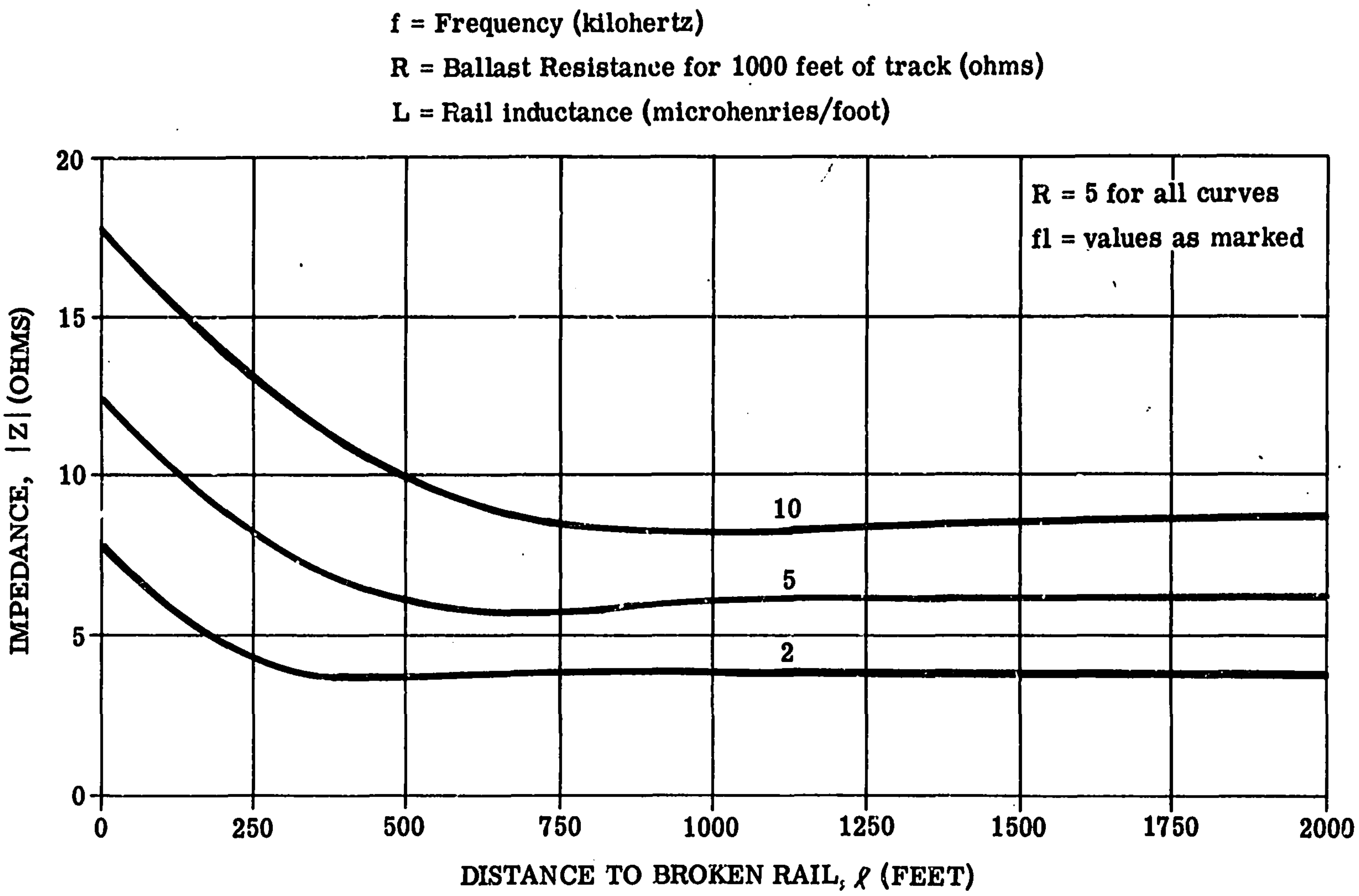


Figure 4.17. - Impedance Versus Distance To Broken Rail For Various Ballast Resistances

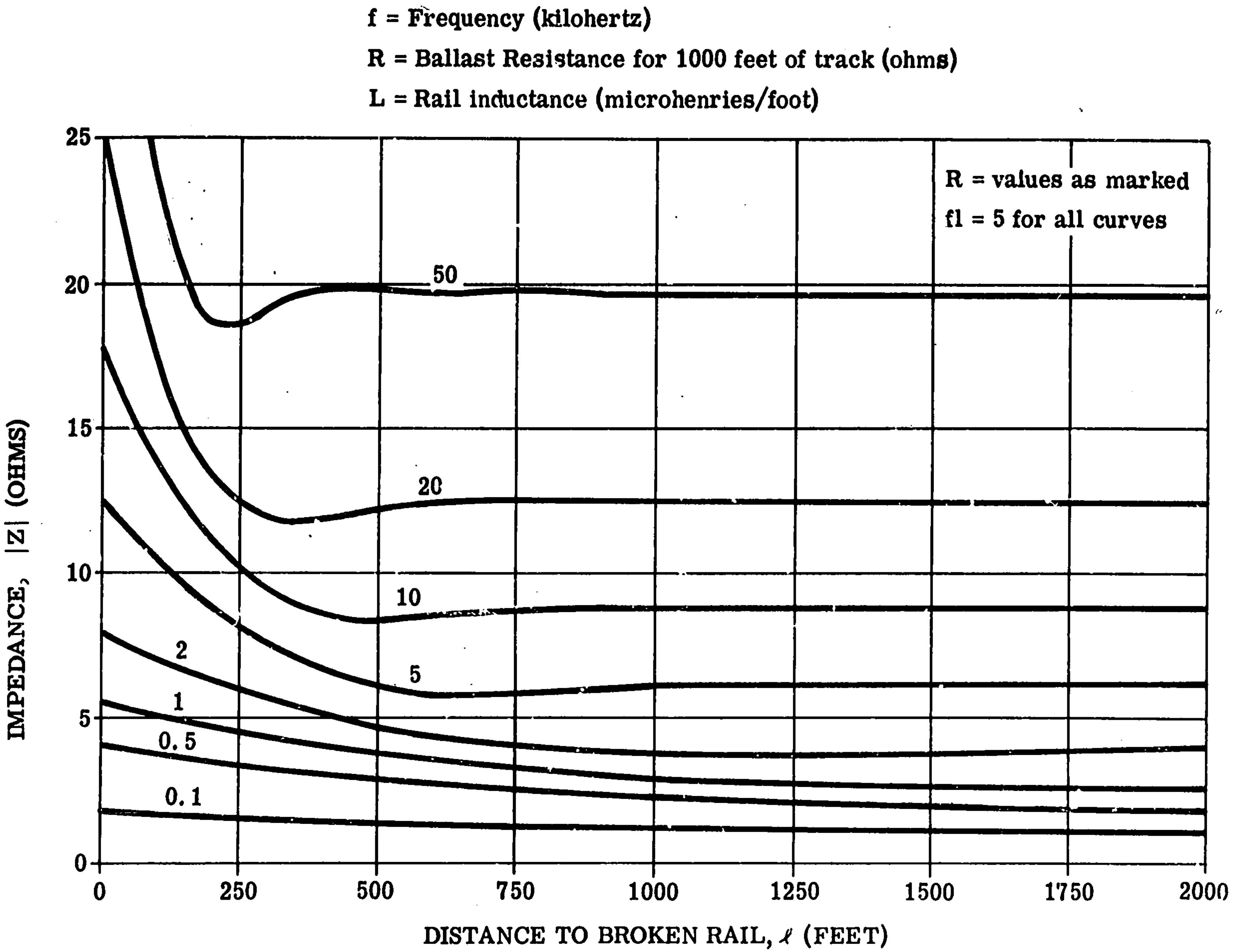


Figure 4.18. - Impedance Versus Distance To Broken Rail For Various Values of the Product fL

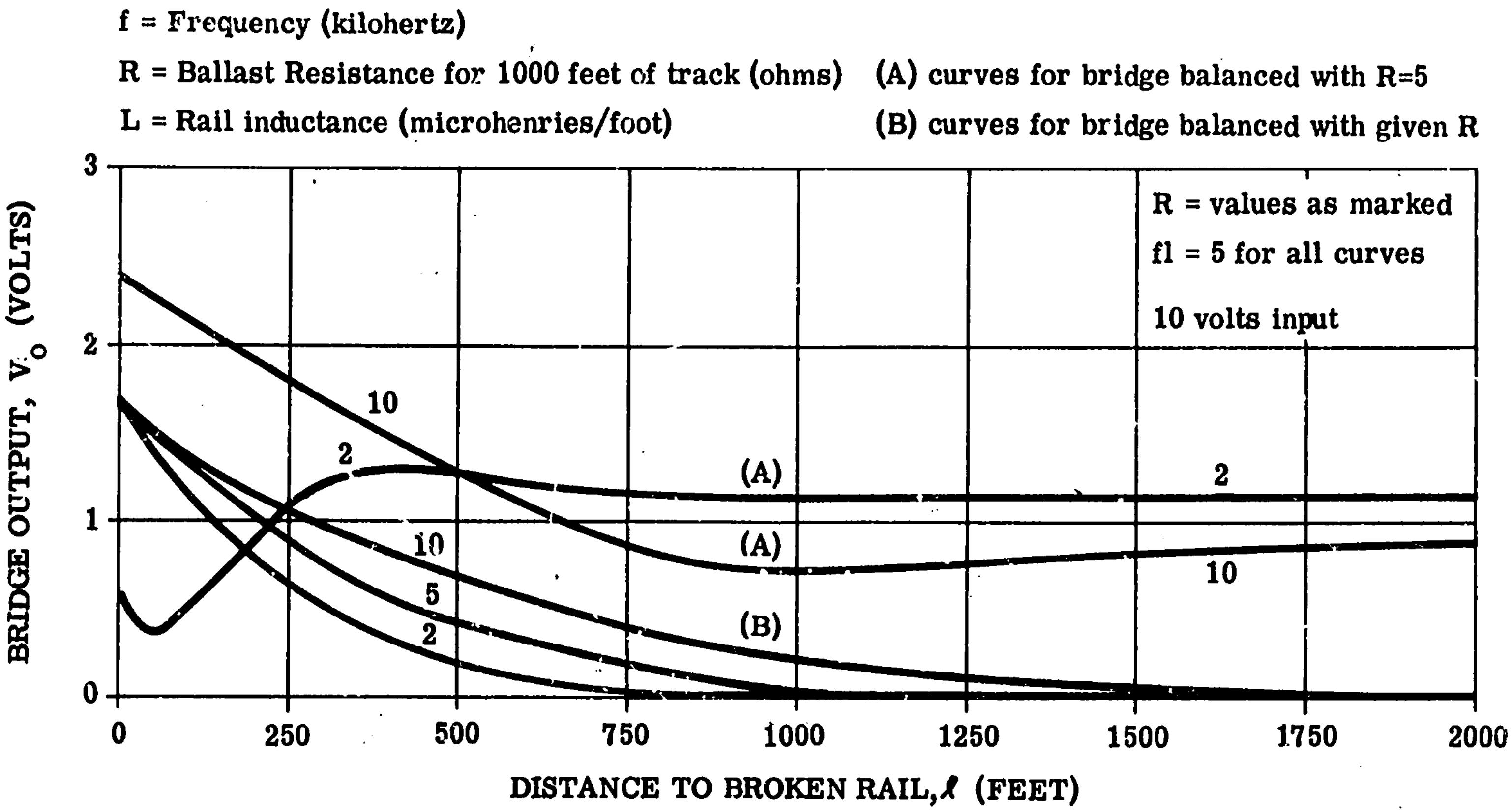


Figure 4.19. - Bridge Output Voltage Versus Distance To Broken Rail For Various Ballast Resistances

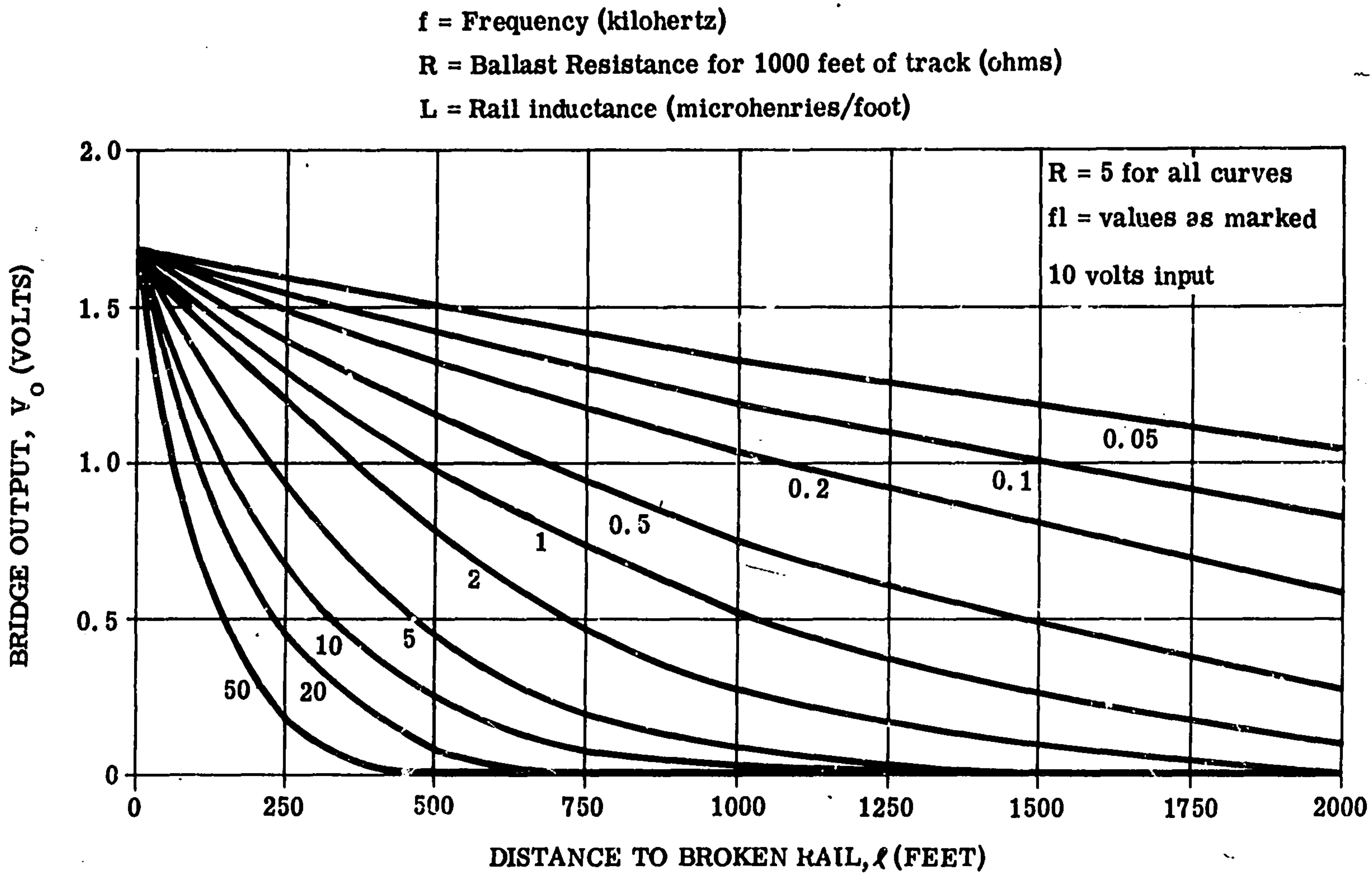


Figure 4.20. - Bridge Output Voltage Versus Distance to Broken Rail For Various Values of the Product fL

f = Frequency (kilohertz)

R = Ballast Resistance for 1000 feet of track (ohms)

L = Rail inductance (microhenries/foot)

NOTE: Phase angle is a constant 45°.

Figure 4.21. - Steady-State Impedance Versus Product of Frequency, Ballast, and Inductance (Train Absent)

resistance to be usable without a very effective compensation (automatic rebalancing) circuit.

A number of technical questions remain to be answered concerning the various possible realizations of impedance techniques. Careful consideration is required of such aspects as noise immunity, estimated cost, reliability, etc. TSC work at present is concentrating on analytical studies of the type already described, and should encompass experimental verification as test circuitry is developed. The close relationship between such systems and conventional techniques suggest that consultation with rail signal equipment suppliers can be particularly beneficial in this area. As design concepts and constraints are further defined, development of operational circuitry may be a task better left to suppliers well versed in the arcane art of rail signal electronics.

4.3.3 Train Detection by Radar

The rail-impedance approach described above, is considerably handicapped by dependence on the electrical properties of the tracks. Variation of ballast resistance, broken rails, and accidentally or maliciously short-circuited tracks can cause unreliable operation, even if failsafe design is achieved, and the credibility of these systems is sacrificed, along with much of their effectiveness. Thus, it is desirable to consider less conventional alternatives, which are completely independent of the rails.

The task of locating objects, characterizing relative location and velocity, is one that has been solved in many applications over the last thirty years by the use of radar. In essence, a radio signal is transmitted and the required information is obtained by analysis of any reflected return signal. A closely related application of this technique is that of highway speed monitoring, used by many police departments. The concept as applied to grade crossings consists basically of the use of two such radars, located at the crossing and directed down the track in both directions, to indicate the approach of trains, so that warning signals can be activated. A number of variations are possible, typically involving a compromise of cost with effectiveness or with complexity of function. These are described below:

a. In the basic mode, the radar unit would provide a fixed output voltage except when the reflected return signal is that associated with approach of a train. Unless obstacles, curves, etc. sharply define the point at which the train comes into view, there will be some uncertainty in the approach distance for which the system triggers, and a conservative design will thus lead to undesirably long warning times. An island track circuit at the crossing would probably be required for restart, although alternative methods are possible. As is true of all radar systems, failsafe design is not inherent, since misalignment of the antenna could prevent detection. (A response to this problem is indicated below.) This operating mode is that which probably represents minimal cost, with some concomitant compromising of reliability and warning characteristics.

b. With slightly greater sophistication, one can measure velocity (presumably by doppler shift) and thereby accurately predict arrival time, so that warning time can be constant regardless of train velocity. Effective operation and true simplicity are obtained only if the train-acquisition point is known and constant, as for the case in which a track circuit is used as a primary system with the radar merely providing constant warning time.

c. With more elaborate modulation and signal processing, the radar system could measure both velocity and range, so that no auxilliary track circuit or other distance discrimination system is necessary. Cost is a crucial aspect of the feasibility of this approach.

d. The need for an island track circuit for restart of signals after train passage can be eliminated if the radar, through more elaborate circuitry, can distinguish between approaching and receding trains. In this case, an approaching train will activate the warnings, to remain active until only a receding train is observed.

Systems such as these have several common characteristics. They can be operated on a low duty cycle, with a 1 to 10 $\sec^{-1}$ sampling rate, so that power consumption can be very low. As indicated, none of these modes is designed in a fully failsafe manner, unless used as a supplement to a conventional track circuit. (This form of application might permit significant cost reduction of present constant-warning-time detectors, which are also secondary to track circuits, and quite expensive.) The crossing-located antenna must have line-of-sight view of trains for a sufficient distance to provide the required warning time for permissable train speeds, which is a serious limitation. It is likely that such systems can be applied only to single track situations, or at least to cases in which one can be certain that only one train can approach from a given direction at one time. It is by no means inconceivable that a system could be developed for the multitrack case, but it would almost certainly involve substantially more complicated circuitry and greater cost. Similarly, usage for tracks closely paralleling highways, with no difference in elevation, could be a problem, since radar is most unlikely to discriminate well between trucks, busses, and locomotives.

The considerations for optimal frequency discussed in connection with the microwave telemetry link (section 4.2.4) are equally valid here; a 10 to 20-GHz microwave system permits use of solid state oscillators and antennas which combine high gain and reasonable size (approximately 30-dB gain for 12" aperture). As an indication of the present state-of-the-art, two companies are now marketing a basic radar module containing oscillator and detector diodes and necessary filters, etc., requiring only a 12 vdc DC power supply, for less than $200 in unit quantity. The range of such systems is quoted as one-half mile or greater, with no significant reduction for less than cloudburst intensity rain. If a particular application requires enhanced range capability, this can easily be provided at modest cost either through higher transmitter power or larger antennas.

The use of a reflector to improve system reliability is illustrated in Figure 4.22. Passive structures can be designed to provide very high microwave reflectivity for a specific frequency and direction, higher than will be found for any object or surface normally likely to be in the vicinity. This reflector, since it is stationary, will reflect a signal with zero doppler shift, so that the radar receiver output will be, in a simple cw-system, a dc-voltage. Signal processing circuitry can then be such that absence of this dc-signal activates the signals, providing failsafe operation with respect to transmitter or receiver failure, as well as antenna alignment or interposition of some man-made or natural obstacle. For systems in which range measurement is also possible, an even more reliable indicator is obtained. Of course, as is generally true, introduction of more-nearly failsafe design increases the likelihood that failure will occur (as by movement of the reflector or damage to it), thus activating the signals even though the train detection system is actually working perfectly. Also, while such a reflector could be quite inexpensive, materials and labor of installation for two mounting poles (one for each direction from the crossing) might add as much as $500 to $800 to the total cost of protection. Of course, the use of existing structures for reflector mounting would reduce this drastically, and should often be possible since the distance between radar and reflector is not at all critical.

Some alternative related modes are also possible, but appear to be of limited applicability and questionable reliability. In these, train detection is accomplished by interruption of a microwave beam by the train, either using radar or separate transmitter and receiver, as in Figure 4.23. The radar method permits installation of all active (power consuming) components at the crossing, but requires that the passive reflector give a far stronger return than any train. However, both systems depend on choice of relative locations of transmitter, receiver, reflector, and train such that train presence always interrupts the transmission path sufficiently to guarantee signal activation. It is not likely that many crossing locations will be such that reliable detection occurs at a proper time interval before the train reaches the crossing. Figure 4.24 indicates both radar and single-path systems which

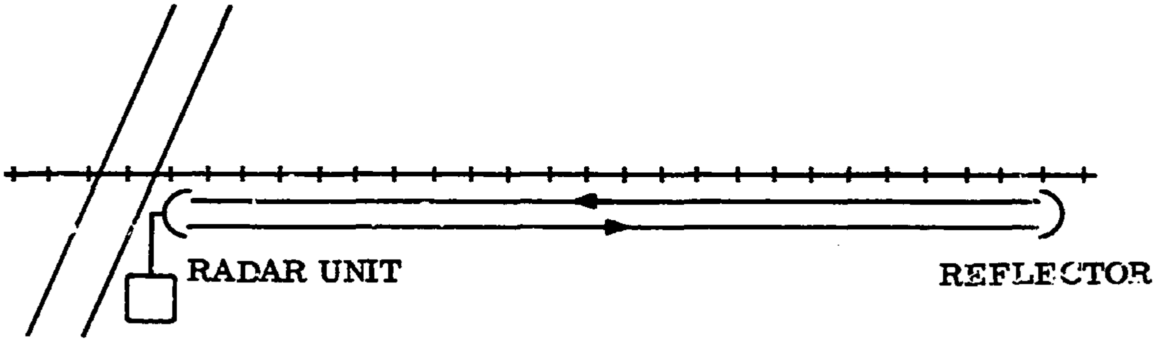
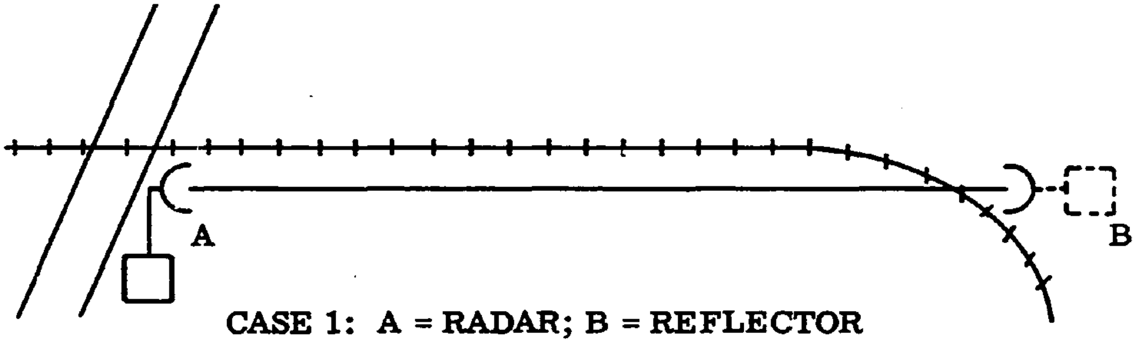


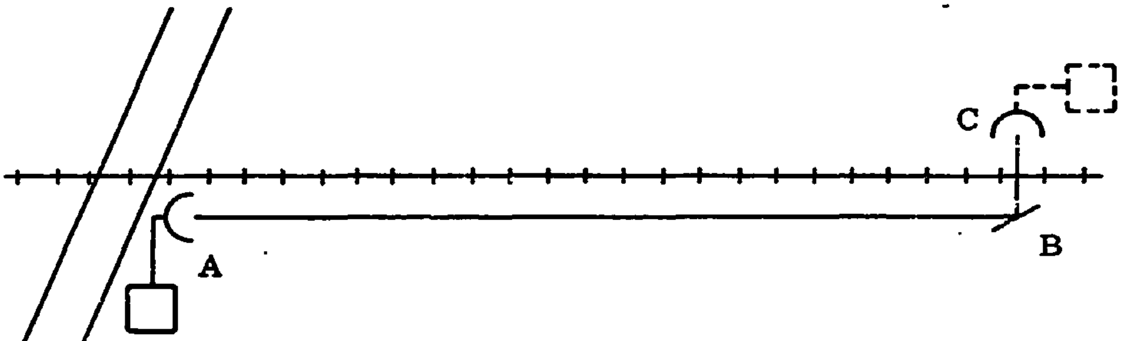
Figure 4.22. - Basic Radar Configuration Using Reflector



CASE 1: A = RADAR; B = REFLECTOR

CASE 2: A = RECEIVER; B = TRANSMITTER

Figure 4.23. - Basic Beam - Interruption Method



CASE 1: A = RADAR; B, C = REFLECTORS.
PATH IS A-B-C-B-A

CASE 2: A = RECEIVER; B = REFLECTOR; C = TRANSMITTER
PATH IS C-B-A

Figure 4.24. - More Elaborate Beam Interruption Method

overcome this last objection, but would presumably further compromise reliability. Also, such methods will almost invariably require the additional expense of an island track circuit at the crossing to reset the system. (Velocity information is not obtained in this configuration.)

All of the beam-interruption techniques indicated above are clearly imperfect, but could offer quite simple, low cost detection, and are included here for completeness. Their actual feasibility can better be judged after further development and test of both radar and microwave telemetry systems.

4.4 IMPROVEMENT OF TRAIN VISIBILITY

A common cause of grade crossing accidents is failure of motorists to see an approaching train. This is of particular importance at crossings with only passive protection, where direct view and audibility are the only cues to train presence. A recent FRA study[7] explores the possibility of visibility (or conspicuity) enhancement by means of appropriate painting or marking of locomotives and mounting of high intensity flashing or rotating lamps on them.

The advantages of use of conspicuous patterns, colors, etc. in marking locomotives seem fairly clear, although it is most important that large areas be involved; patterns which utilize a particular color over areas of less than approximately five feet in the smallest dimension are unlikely to be effective at typical distances. However, there are few sophisticated technical questions associated with this approach; the next meaningful step is organization of a large scale demonstration.

There are approximately 4000 grade crossing accidents per year in this country, and over 25,000 locomotives, implying a mean time between accidents for a given locomotive of approximately six years. Undoubtedly there are parts of the country in which, for a variety of reasons, a substantially shorter interval is found. Thus, a test in which 50 to 100 engines are marked so as to increase conspicuity should provide meaningful evidence as to effectiveness within a few years.

The same argument is equally valid when applied to experimental evaluation of the merits of special locomotive illumination.

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[7] "The Visibility and Audibility of Trains Approaching Rail-Highway Grade Crossings", J. P. Aurelius and N. Korobow, Computer Applications, Inc., New York. Prepared for the Federal Railroad Adminstration under Contract DOT-FR-00006. July 1970. In press as FRA report. FRA-RP-71-1

However, a number of aspects of this concept remain to be investigated. A basic question concerns the relative merits of rotating incandescent lamps versus xenon flash tubes. Optimum color (taking account of lamp color, temperature and power, human eye response, and interpretation given to specific colors) must be determined. Costs, including expense and frequency of maintenance, will be most important if widespread (or universal) installation is to be sought and obtained. The most suitable mounting position, beam characteristics, and repetition rate should be found, and study is required to delineate acceptable nuisance levels for both train crews and the general public. Appropriate means must be determined for adequate variation of intensity with ambient illumination. (Required daytime intensity may be as much as 200 times that needed at night.) Automatic adjustment would be expensive and possibly prone to failure, but a number of problems could arise if this task is left to the train crew.

The primary effectiveness of this system will be direct alerting of the motorist, often through his peripheral vision. However, it appears quite possible that nighttime effectiveness can be significantly enhanced by use of properly designed reflectors at the crossing. The basic concept is illustrated in Figure 4.25. Design of the reflector is not a trivial matter. A simple scattering surface would reradiate all incident energy isotropically, so that very little light would be directed down the highway. On the other hand, a true mirror would be too sharply aimed, and the reflected image of the high intensity light would be confusing to many motorists. The basic goal is a sign with essentially the appearance of standard interstate highway signs. However, that type of surface is retro-reflective, directing almost all incident energy back toward the source, with only a few degrees of spreading. Thus, research and development is needed to determine the best techniques for obtaining the desired result. It should be noted that such a reflector will also operate effectively when illuminated by a locomotive headlight, particularly if it is of the oscillating type so that an intermittant light is seen. However, the very narrow beam width of conventional headlights prevents their being effective for direct viewing.

It is important that such a program not be seen as a replacement for flashing lights. The reflectors, etc., must not give the impression that absence of such a reflected signal is a guarantee of train absence. One then comes into all of the safety and legal problems associated with non-failsafe systems, plus the deficiencies noted in section 3.3.2 for train-vehicle systems. For example the reflector might simply be a symbolic crossbuck, or be inscribed with a legend such as LOOK FOR TRAINS or, simply, TRAINS.

Some compromise may be necessary between the two means of utilizing the system-direct view of the train, and a moving or flashing reflection at the crossing. Preferred colors, shapes,

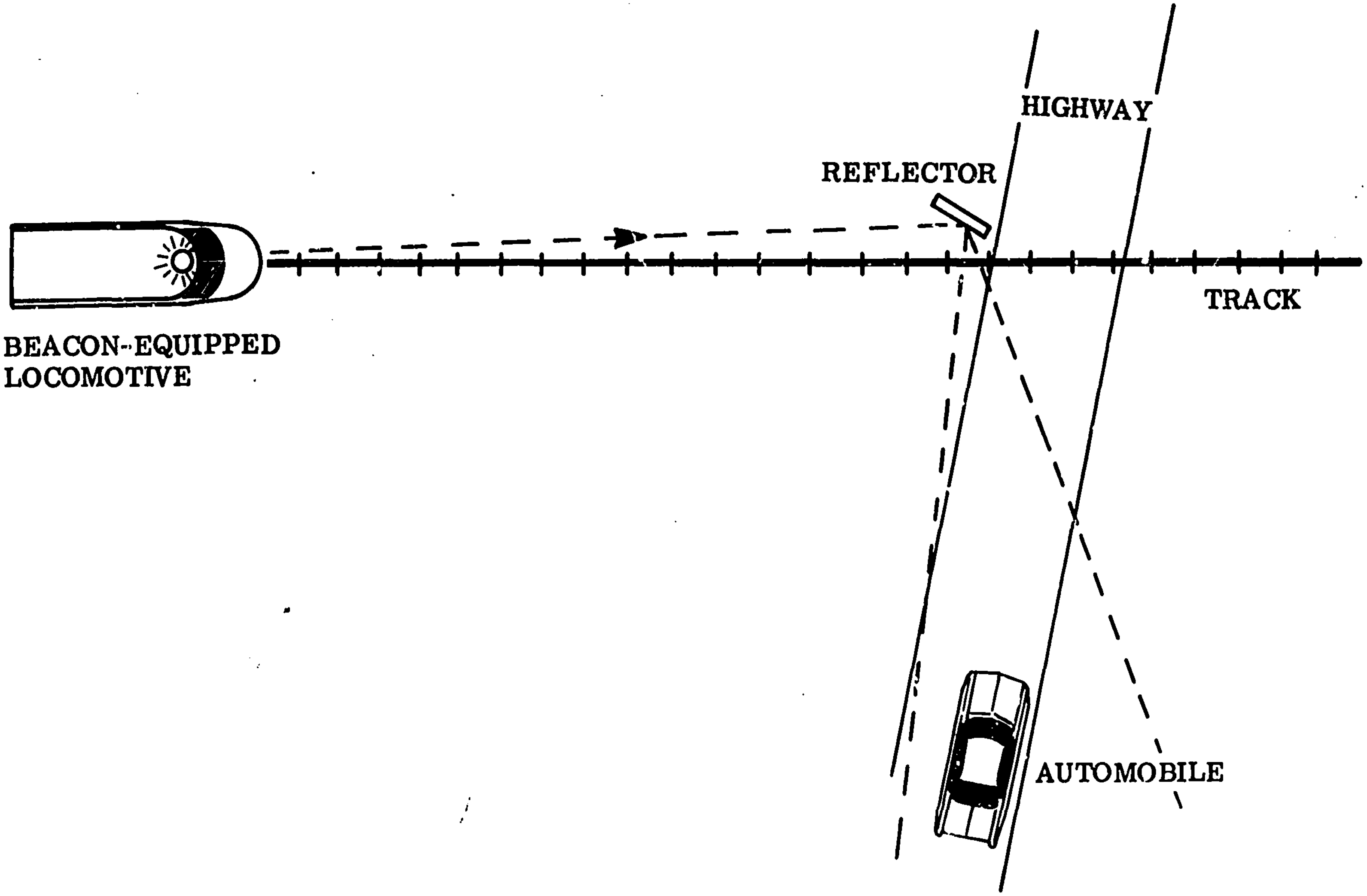

Figure 4.25. - Use of Reflector to Enhance Effectiveness of Locomotive Beacon

and other reflective sign characteristics must be determined. It is also worth noting that such a warning, particularly the light, might have significant impact on the substantial death toll among trespassers. A locomotive-mounted light of high conspicuity would, of course, be of benefit at virtually all crossings, though probably not with effectiveness approaching that of conventional active signals. As a measure of the feasibility of this approach, note that an investment of $1,000 per locomotive (approximately $27,000,000) may be thought of as an expenditure of $150 per unprotected crossing, and an additional several hundred dollars might be warranted at many crossings to provide proper reflectors. These numbers, though merely estimates, arise from a preliminary examination of the topic, and are probably of the right order of magnitude.

4.5 SIGNAL IMPROVEMENT

4.5.1 Introduction

While the TSC program has been directed in other directions, some consideration has been given to the question of improved warning signals. As the signals themselves do not represent a major cost and present flashing lights have relatively high effectiveness, it is not clear that this is a particularly fruitful area of research. The topic can be subdivided into three elements: improvement of conventional signals, innovation of signal devices, and application of new technologies.

4.5.2 Improvement of Conventional Signals

This avenue does not appear to be a promising one for governmental research. It is a natural area for railroads and suppliers, and, indeed, development is constantly being carried out to produce brighter bulbs, more efficient roundels, etc. Use of quartz-halogen bulbs appears beneficial if various difficulties are overcome. A basic obstacle to use of higher intensity lamps is the general requirement for emergency batteries; higher power consumption means greater battery expense. In addition to some of the concepts alluded to in section 3.3.1, use of a dual filament bulb (or dual-bulb light) has been suggested, in which switchover to emergency power would activate a lower intensity (but otherwise very similar) light.

4.5.3 Innovation in Signal Devices

This category raises questions which can be answered only through behavioral studies. For example, it is often proposed that flashing lights be replaced by conventional traffic signals. Even if one assumes that legal difficulties can be overcome, the motorist's response is unclear. It may, for example, prove confusing to present a familiar warning in an unaccustomed setting. (There would be no reduction in cost, nor in brightness.) Finally, the value of the driver's experience with flashing lights is lost. In any event, the basic questions raised are not those of technology. Similarly, one might consider using xenon flash tubes in place of conventional signals. While some technical questions do arise here, the greater issue is motorist response, particularly since such lights have very little output in the red portion of the spectrum, so that white or blue lights would be used where red has been standard for many years. Thus, TSC involvement in these debates has been small, and will generally be limited to questions of technical feasibility, rather than desirability.

4.5.4 Application of New Technologies

This topic is, to a degree, related to 4.5.3. A number of developments in recent years are relevant, and examination of such concepts will be a part of the TSC program as appropriate. No significant effort has gone into this at present. Technologies of relevance include liquid crystal signs, holography, and use of light-emitting diodes, although only the first seems particularly promising at present, and all raise a number of technical questions.

SECTION 5

CONCLUSION

5.1 PROBLEMS OF POLICY DETERMINATION

As delineated in Sections 2 and 3, the numerous constraints, guidelines, and characteristics associated with grade crossing protection place many limitations on viable technical innovation. At the same time, a number of possibilities have been examined and found promising, with still others awaiting thorough investigation. While it is clear that technology cannot, in itself, provide a solution to the grade crossing problem, it is equally clear that the fruits of modern science and engineering can offer substantial assistance in reducing the death, injury, and indirect (but large) costs arising from the intersection of track and highway. This situation is common to most of the major problems now facing industrial societies.

As various innovations and improvements (both technical and otherwise) move from conceptualization to widespread implementation, there will be many difficult decision points for those with policy making responsibility. Technology will offer no easy answers, and, indeed, may make the task still more difficult. The variety of grade crossings, the complexities of human behavior, the weakness of existing data, and the basic rarity of crossing accidents (approximately 70 years between deaths at an average crossing) reduce any test and demonstration program, even if fairly elaborate, to little more than a good indicator, rather than difinitive proof of effectiveness. It will be necessary, from time to time, to make decisions with quite inadequate information, based as much on intuition, experience, and wisdom as on engineering data.

5.2 APPLICATION OF VARIOUS PROTECTIVE SYSTEMS AND DEVICES

Some of the specific concepts described in this report may hold the key to significant improvements. Further analysis, development, and, where warranted, field testing and demonstration will be necessary, probably followed by a long, difficult period of gradual acceptance into general usage. To provide a general summary of the potential spectrum of protection devices and systems, in terms of the classes of crossings at which they are warranted Table 6 (modified from Table 5, section 2.4) has been prepared.

In this table, and the accompanying discussion, only hardware aspects of protection are considered: signs, signals, detection and activation systems, etc. This is not to imply that there are no alternative (perhaps better)

Table 6. Relevant Protection Devices for Various Classes of Grade Crossings

Class	Warranted Expense	Number of Crossings	Appropriate Protection Devices
1	Under $300	65,100	Improved Passive Devices Enhanced Train Visibility
2	$300-$1000	48,350	Improved Passive Advanced Warning; Train-beacon Reflectors
3	$1000-$3000	32,540	Crossing-located Actuation; Conventional Signals (Marginally Feasible)
4	$3000-$10,000	15,510	Crossing-located Systems Telemetry Actuation Minimal Cost Conventional Systems
5	$10,000-$30,000	13,950	Conventional Systems of Improved Effectiveness - Gates, Uniform Warning Time
6	$30,000-$100,000	3,480	Combinations of Above; More Complex Installations
7	$100,00-$300,000	1,530	More Elaborate Installations; Interconnection with Highway Signals; Emphasis on Reduction of Motorist Delay
8	$300,000 $1,000,000	630	Grade Separations and Sophisticated Traffic Control Systems; Typically Computer Controlled.

ways to invest protection funds, such as improvement of sight lines or road surface, more rigid enforcement, educational compaigns, highway or rail relocation etc. This study has simply been focused on the more explicity technological aspects of the problem. Also, in the table and associated discussion, it is partially implicit that protection suitable to lower cost installations may also be desirable, perhaps in more elaborate form, at more expensive installations as well. Only successively more costly systems are made explicit for each category.

Class 1 (under $300) includes approximately one-third of the passively protected crossings in the country, but apparently contributes a near trivial amount to the death toll. The low probability of an accident makes it difficult to justify elaborate protection and one finds, in fact, (as indicated previously) that simple crossbucks may equal or exceed the warranted investment. Thus, it is difficult to anticipate any realistic improvement beyond more effective signing (reflectorization, etc). (This topic has been investigated extensively by Voorhees, as indicated in V-HPB.) Substantial additional benefits could also ensue from implementation of locomotive visibility enhancement. As indicated previously, an investment of $1000 per locomotive is equivalent to an expenditure of the order of $150 per unprotected crossing.

Class 2 ($300 to $1,000 range) still does not permit use of quasi-conventional active protection; material and installation costs for the simplest flashing lights will generally exceed $1,000, and, as suggested above, there is little likelihood of significant reduction. A locomotive-mounted light of high conspicuity would, or course, be of benefit at virtually all crossings, though probably not with effectiveness approaching that of conventional active signals. However, if the impact of train-mounted beacons can be significantly increased by use of properly designed and located reflectors at each crossing, an additional several hundred dollars might be spent effectively on Class 2 crossing to provide them. Alternatively, one must seriously consider use of passive advance warning, which is at present seldom implemented in an effective manner.

Class 3 involves sufficient investment to permit use of conventional or quasi-conventional signals (barely) provided that some very inexpensive means of activation can be found. The basic guideline here is that achieving effective train detection for an additional $1,000 to $2,000 (beyond the cost of the signals) will be possible only through extreme simplicity. It is difficult to imagine achieving such a goal unless the entire system is located at the crossing, with little or no track modification, and preferably no other physical structure necessary in addition to the signal poles. (This topic was discussed extensively in section 4.3)

In the case for which somewhat greater investment is possible (Class 4) two approaches are possible. The first is more elaborate implementation of Class 3 protection, with greater reliability, possibly more and/or brighter lamps, lightweight gates, etc. (As has been stressed, each crossing is a special case, and the details cannot be predetermined.)

Alternatively, at the upper end of the scale, one can begin to think of utilizing a more conventional (failsafe) train detection system, on a minimal scale, such as the microwave telemetry system in connection with a low cost means of train detection, for signal activiation. It is hoped that such an approach will be of significantly lower cost than audio frequency overlay circuits, and that the down-track equipment, the detectors and transmitters, can be operated entirely from a battery no larger than for present standby units. This can provide significant savings on both rectifiers and installation, as well.

Other incremental cost reductions, such as use of an out-of-order signal (section 3.2.8), may help to bring conventional systems, even using overlay track circuits, into this cost class. Development of solid state logic circuits, now being carried out by rail signal supply companies, offers not only the possibility of significant savings over present relays, but elimination of the large, expensive housing now required.

Classes 5 and 6 (the ranges spanning $10,000 to $100,000) cover most present automatic signal installations. A wide range of options exists, depending on the compexity of the intersection, single or multiple track, number of traffic lanes, pattern of rail and highway traffic, and special factors. Most of the improvements suggested for lower cost installations can be applied here, so that, with cost of detection and control circuits reduced, signals of greater effectiveness can be used. Motion sensors, whether track circuit or radar, used in conjunction with failsafe track circuits, can provide information as to train speed, etc., so as to permit signal operation with constant warning time regardless of train velocity, station stops, switching moves, etc. (This is especially important to maintenance of system credibility.) Similarly, a microwave link can transmit a variety of information, describing the condition of several tracks, switches, etc., replacing a number of expensive track circuits, and providing improved performance as well.

While more definite conclusions await better inventory and accident data, it appears that signal effectiveness can be enhanced by use of cantilever arms (to place a flashing light in each lane, a basic traffic engineering principle), automatic gates (even for single track), and active advance warning signs. The question of the cost-benefit relationship for these devices remains unclear, since it may be wiser in many of these cases to spend much less than warranted, in order that more crossings be protected.

With a justifiable investment of $100,000 to $300,000 (Class 7), a grade separation will usually not be feasible. (However, the numbers developed in this report do not include motorist delay costs and other factors which are often quite important for high traffic density crossings; careful study is required for each case.) On the other hand, one will typically find it appropriate to utilize the range of devices indicated previously: gates, flashers in each lane, active advance warning, train speed measurement for uniform warning time, etc. Here it becomes particularly relevant to consider relatively elaborate interconnection with highway traffic signals in the area to minimize disruption of traffic.

In the above $300,000 category, one is dealing with a small number of highly specialized cases. A separation would generally be justified, but there may be special factors which prevent that solution. In that case, in addition to the steps indicated in Class 7, one can think seriously about fairly elaborate means of informing motorists of their optimum course of action: waiting, detouring to a nearby separation, or using a different crossing which will not be blocked when he arrives. In addition to the substantial expense of necessary signals and interconnections, such a system would typically require a modest computer to evaluate the situation for each train, and a large number of sensors of both rail and highway traffic. It would be particularly important to know train speed, length, and even intentions, as well as the likelihood of another train's arriving in time to affect many of the same motorists. Thus, information concerning both forms of traffic would have to be fairly extensive. No substantive TSC effort has gone into development of this type of system as yet, but consultation with FHWA is planned to facilitate choice of a realistic program. (This is, to a large degree, a traffic engineering problem.) However, it should be clear that the variety of information to be sensed and communicated makes devices discussed earlier (such as the radar and microwave link) particularly useful. Existence of a microwave system, for example, cannot only facilitate information flow, but also permits communication of train with crossing. Thus, the crossing signals can be informed of a station stop or planned switching move in rather simpler fashion than is typically the case with conventional apparatus.

5.3 SUMMARY

Some of the more important constraints on innovative grade crossing protective systems have been delineated, and guidelines for development indicated. Grade crossing inventory data has been examined and arranged in such a manner as to permit a very approximate but still adequate estimate of the classes of systems needed, the allowable costs, and contribution of various types of crossings to the overall accident toll. It is found that a very large number of crossings warrant only very limited expense and account for a very small percentage of deaths. A number of approaches are possible for the intermediate cost classes generally based on use of conventional signals with low-cost activation systems, typically raising the challenge of at least a slight compromise with the basic failsafe requirement. Use of similar elements, singly or in combination, can also contribute significantly to improvement of effectiveness of more conventional systems. The very high cost locations may well benefit from a high degree of interconnection of rail and highway signals, with use of elaborate train (and possibly vehicle) detectors, and small computers.

Extensive analysis and laboratory investigation have been carried out relating to a microwave telemetry alternative to conventional track circuits and possible crossing-located radar and impedance train detection systems.

APPENDIX A

Symbols

A_r = Area of receiving antenna

c = Propagation velocity of electromagnetic waves

f = Frequency

f_{GHz} = Frequency in GHz

g_r = Antenna gain (receiver)

G_r = $10 \log (g_r)$

g_t = Antenna gain (transmitter)

G_t = $10 \log (g_t)$

K = Antenna factor

LdB = Total loss between transmitter and receiver

$= 10 \log \left(\frac{P_r}{P_t}\right)$

P_r = Transmitted power

P_t = Received power

R = Transmitter - receiver distance (meters)

λ = Wavelength

The received power is given by:

$$P_r = P_t \cdot g_t \cdot A_r \cdot \frac{1}{4\pi R^2}$$

but $g_r = k \frac{4\pi}{\lambda 2} A_r$; so $A_r = \frac{\lambda^2 g_r}{4\pi K}$

and P_r can be written

$$P_r = P_t \frac{g_r\, g_t}{k(4\pi R)^2} \lambda^2$$

However, $\lambda = \frac{c}{f}$; so

$$\frac{P_r}{P_t} = g_r\, g_t \left(\frac{-c}{4\pi}\right)^2 \frac{1}{R^2} \cdot \frac{1}{k} \cdot \frac{1}{f^2}$$

or

$$LdB = 10\ \mathrm{Log}\ \frac{P_r}{P_t} = G_r + G_t + 20\ \log\left(\frac{c}{4\pi}\right) - 20\ \log R - 20\ \log f - 10\ \log k$$

k = .65 for typical antennas
c = 3 x 10^8 m/sec.
convert f to f_{GHz}

$$LdB = 30.6 - G_r - G_t + 20\ \log R + 20\ \mathrm{Log}\ f_{GHz}$$

For R = 1000 meters, f_{GHz} = 10 GHz,

$$LdB = 110.6 - G_r - G_t$$

For a 1' diameter parabolic reflector antenna at 10 GH_z, G is approximately 28 dB; for 2'; 34 dB. A reasonable value for $G_r + G_t$, then, is 60 dB, and L_{dB}= 50 dB; i.e., there is a loss of 50 dB for the specified system. If the transmitter power is 100 mW (20 dBm), the received power is 20-50 = 30 dBm

A useful way of characterizing microwave detector diodes is in terms of Noise Equivalent Power (NEP), the received power (in dBmj),for 1 cycle per second bandwidth, necessary to increase the output of the diode by 3 dB above noise. This, then, is a measure of the minimum detectable signal.

For a bandwidth B = 1 KHz, the effective sensitivity is reduced by 10 log B = 30 dB. Typical detector diodes have NEP of approximately - 90 dBm, so that for a 1 KHz system the minimum detectable signal is of the order of - 60 dBm For the case described above, P_r is - 30 dBm, so the safety margin is 30 dB. There are a number of elements which can be adjusted to improve this if necessary.

REFERENCE

1. Fields and Waves in Communication Electronics, Ramo, Whinnery, and Van Duzer, John Wiley and Sons, N.Y., 1965, Pp. 716-717.