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**INNOVATIVE CONCEPTS AND TECHNOLOGY
FOR RAILROAD-HIGHWAY GRADE CROSSING
MOTORIST WARNING SYSTEMS**

**Volume II: The Generation and Analysis
of Alternative Concepts**

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16. Abstract This report describes the results of a study directed toward the generation, analysis and evaluation of innovative conceptual and technical approaches to train-activated motorist warning systems for use at railroad-highway grade crossings. Particular attention is given to the use of the track as a transmission line in a guided reflection (radar-like) technique operating at audio frequencies. Attention is also given to improve special road surfaces in advance of the crossing, and to optically programmed traffic lights. Volume I consists of 210 pages.					
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PREFACE

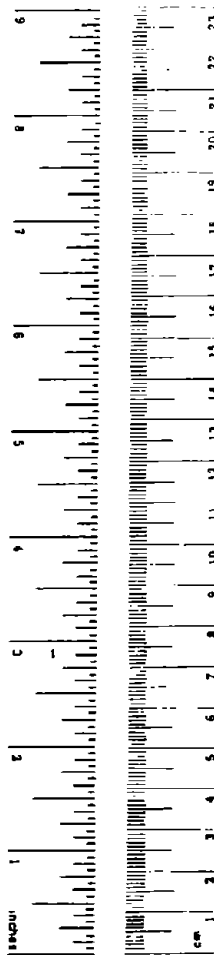
The work described in this report was performed in the context of an overall program at the Transportation Systems Center to provide a technical basis for the improvement of railroad-highway grade crossing safety. The program is sponsored by the Federal Railroad Administration, Office of Research and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

This volume, the second of a two-volume report, consists of a report documenting a process of concept generation and evaluation in the field of innovative grade crossing warning systems. Volume I includes an executive summary for the two volumes, an overview of the subject area, and a similar concept study carried out by another contractor.

METRIC CONVERSION FACTORS

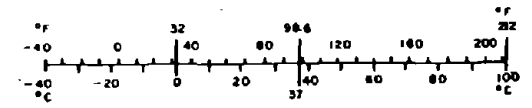
Approximate Conversions to Metric Measures

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



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
LENGTH				
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
AREA				
cm ²	square centimeters	0.16	square inches	in ²
m ²	square meters	1.2	square yards	yd ²
km ²	square kilometers	0.4	square miles	mi ²
ha	hectares (10,000 m ²)	2.5	acres	
MASS (weight)				
g	grams	0.036	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
VOLUME				
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m ³	cubic meters	36	cubic feet	ft ³
m ³	cubic meters	1.3	cubic yards	yd ³
TEMPERATURE (exact)				
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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NOT REPRODUCIBLE

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1. APPROACH

In this section we describe the general approach that we undertook to develop solutions to the problem. The specific steps themselves are described in later sections.

The guide crossing problem is one of long standing. The last century has seen at least an experimental installation of a wide range of ideas for improving some aspect of the grade crossing. As in many areas that have been under investigation over a span of time encompassing great technological changes, failure in a new concept for railroading was as apt to be the fault of experiment design, or lack of suitable materials and hardware to flesh out the bare bones of the concept, as it was to be any fault in the validity of the concept itself. We endeavored, therefore, to search the literature not only to achieve an understanding of the problem's many aspects, but also to rediscover for new consideration ideas whose earlier premature birth had precluded survival at that time.

Our research included libraries (both within and without the transportation community), the Patent Office, interviews with knowledgeable persons, conferences and exhibits. Conferences and exhibits included (a) the 1974 National Conference on Railroad - Highway Crossing Safety, and (b) joint annual meetings of the Communication and Signal Section and the Data Systems Division of the Association of American Railroads, held in conjunction with an exhibit by the Railway Systems Suppliers, Inc.

Concurrently, we assembled in turn different groups of scientists and engineers for a series of brainstorming sessions. We began these with a brief presentation of the problem background in terms of driver behavior patterns, accident trends, and other performance parameters. Then we proceeded to conduct each session according to rules specifically designed to inhibit a negative turn of mind toward the idea under examination. Into the discussion we injected the ideas and background developed in our information search activities, and from the discussion we derived new targets for research. This interplay between brainstorming and research led to a heterogeneous collection of candidate ideas and incipient concepts.

The next step was to develop a set of criteria which would allow us to winnow the initial ideas and concepts to identify those which showed promise of contributing to a solution of the problem as it now stands. In general, these criteria reflected the need for achieving lower cost or greater effectiveness in comparison with existing systems; or they dealt with technological feasibility in the near term (3 to 5 years to operational implementation). These criteria are described in section 2, following.

The concepts which survived this first cut were then formulated in terms of specific function, and their effectiveness examined in detail in the light of the previously derived criteria. This process disclosed a number of problems with each concept, and the nature of these problems figured strongly in the evaluation process. A full description of this evaluation is presented in section 3, following.

The functional evaluation led to the identification of three specific concepts which showed a potential for near-term application far beyond that of any of the others. It revealed, further, that these concepts (TRACS, Open Graded Asphalt Friction Course, and Optically Programmed Traffic Signals) comprise subsystems of the only system warranting serious consideration at this time. Consequently, we concluded that cost analysis of the other concepts should extend no further than a general determination of cost acceptability, and that the more detailed cost analysis effort should be devoted exclusively to the selected subsystems.

2. CRITERIA

This section presents the criteria used in the evaluation of the ideas and concepts developed in this study. These criteria were developed over a period of time in response to the problems and choices presented by the emerging ideas and concepts. They are presented here in a body so that the reader may understand the considerations which led to the recommended system.

Six criteria were developed for application in the general case. They are listed as follows and described in turn under the remaining paragraphs of section 2.

- a) Operational applicability in 3 to 5 years;
- b) Grade crossing specificity;
- c) Cost acceptability;
- d) Constant warning time;
- e) Capability of integration into larger traffic control systems;
- f) Capability of continued operation upon failure of normal power source.

2.1 OPERATIONAL APPLICABILITY IN 3 TO 5 YEARS

This criterion arose from the contract objectives which state that a realistic concept is expected to be one which can be developed and field tested for operational application in 3 to 5 years. We interpreted this requirement liberally, but rejected those concepts clearly beyond realization within 5 years.

2.2 GRADE CROSSING SPECIFICITY

This requires that an acceptable concept should be directed to the improvement of grade crossings as its main purpose. It was formulated primarily to rule out system concepts directed only incidentally to the grade crossing problem. An example is a large communication net for general traffic control. We considered that such a concept was not properly a target for this study.

2.3 COST ACCEPTABILITY

In evaluating concepts for further development, cost considerations were applied in terms of the benefit-to-cost principle. For each concept under study, we determined what it contributed to the grade crossing problem in terms of basic function(s) (train detection, protection and warning at the crossing, impact attenuation, etc.). Similarly, we determined the magnitude of the cost involved. This permitted a benefit (contributed function) to cost comparison which was assessed in the light of known cost for providing similar functions with existing systems and components. Some concepts were found to be clearly unacceptable on this basis.

2.4 CONSTANT WARNING TIME

It was considered that an acceptable concept should have the capability to provide constant warning time at the crossing when directed toward influencing the behavior of the automobile driver. There is a long backlog of experience with existing systems which provide such a variable warning time (depending upon the speed of the train). Experience shows that these systems are not sufficiently effective in achieving their objective of influencing the driver not to cross in spite of clear warning that a train is nearby. The driver remembers

that the train has often been slow; that it has sometimes stopped while the alarm continues; that on occasion the train has reversed direction and never even reached the crossing. He has insufficient confidence in the warning, and he is dangerously tempted both to decide that there is ample time to cross, and to ignore the well-known consequences of being wrong. It is generally accepted that a constant reasonable warning time will be an effective influence upon the driver to wait for the warning to cease before he decides to cross. These considerations led us to conclude that a valid modern day innovative concept of this nature should provide the constant warning time capability.

2.5 CAPABILITY OF INTEGRATION INTO LARGER TRAFFIC CONTROL SYSTEMS

This was considered to be desirable for a grade crossing protection system in an urban area where traffic patterns depend upon a general system of traffic signal control. The primary advantage of such integration was considered to be that it permits the disruption of traffic by a train at the crossing to be minimized through the use of various traffic control techniques (e.g., rerouting the road traffic).

Our discussions brought out a second aspect which deserves consideration in evaluating the effect of the integration of a grade crossing protection system into the larger traffic control system. Such integration may result in the shifting of certain installation and maintenance functions from the jurisdiction of the railroad to the appropriate government agency. For example, a radar installation for train detection may be located at a distance from the railroad right-of-way. This might readily place the responsibility

for installation and maintenance of the train detection device into the hands of Government, rather than the railroad which normally has such responsibility. This would have an impact upon cost, liability, etc., which might or might not be advantageous, depending upon the case at hand.

2.6 CAPABILITY OF CONTINUED OPERATING UPON FAILURE OF
NORMAL POWER SOURCE

This capability was considered desirable in the general case. Only emergency power sources in current general use, such as batteries, were considered to provide the capability acceptably. Intermittent power sources such as solar collectors, windmills, etc., were not regarded as acceptable for this purpose.

3. CONCEPT EVALUATION

3.1 CLASSIFICATION OF CONCEPTS

The concepts identified for evaluation were collected for consideration according to the functional classes listed below.

- a) Train Detection
- b) Communication Systems
- c) Protection and Warning at the Crossing
- d) Advanced Warning Concepts
- e) Arresting/Impact Attenuation Devices
- f) Self-Contained Power Sources
- g) Modification of Driver Behavior

The results of the evaluations are summarized in the following sections.

Other classification schemes were used in the initial stages for focusing on particular aspects. For example, categorizing by applicability to type of crossing as defined by traffic density was examined. Another scheme separated ideas by their appropriateness in one or more categories of intended use (e.g., protection of new crossings, protection of existing unprotected crossings, and upgrading of protected crossings). These classifications had some virtue in the evaluation process, but for expository purposes, the functional categories were found to be the most suitable.

3.2 TRAIN DETECTION

3.2.1 General Considerations. Train detection concepts are discussed in this section according to the following types of train detection:

- a) Direct Sensing—Concepts which employ sensing devices mounted and transmitting separately from the train and track structure.
- b) Sensing via Track Structure—Concepts which accomplish sensing by means of signals transmitted through the track structure.
- c) Train-borne Sensor—Concepts which employ sensing devices mounted aboard the train.

Many new concepts were considered which provided for "point detection," that is, detection of the train only when it arrives at a certain point in the vicinity of the crossing. Concepts which use only one point-detection device in a system are incapable of providing for continuous monitoring of the train's presence in the vicinity, or of providing constant warning time. Consequently they are even less effective than systems already in use, and therefore we considered them to be unacceptable.

Concepts which use two or more point detection devices do offer capabilities for continuous monitoring or for providing constant warning time, and hence may be considered to be comparable in effectiveness to existing systems. However, these concepts were found to require extensive cabling or trackside multiplexers at the detection site, and therefore promise to be at least as costly as existing systems. Consequently we considered them, also, to be unacceptable.

Some of the concepts providing for point detection are of interest, however, and for this reason they are discussed in the following sections.

3.2.2 Direct Sensing Systems. The following sections discuss the direct sensing concepts investigated during this study.

3.2.2.1 Radar. Radar has had an attraction as a means of detection for many forms of traffic because of its ability to provide locational and kinematic information at a distance. Much research is continuing in the field of small, inexpensive short range units, for both military and civilian use. Units for the latter use range from automatic crash avoidance braking systems in motor vehicles, to railroad car velocity measurement devices in classification yards. However, in spite of the potential of radar, it was concluded in the course of this effort that radar systems of more or less classical configuration should not be studied in any detail. We considered that the problems associated with radar for this purpose are already being studied elsewhere in more depth than would be possible here and it was felt that a breakthrough in this area could not be achieved within the scope of this study. The technical problems lie in the line-of-sight nature of the transmitted signal. Railroad crossings are usually characterized by significant obstructions to any practical line-of-sight, and the means for dealing with the attendant problems have yet to be found. However, ongoing research and development should be closely monitored for possible solutions.

3.2.2.2 Seismic. The possibility of using geophones in the vicinity of a crossing was appealing initially, because the location of the apparatus is not critical and may be removed to a distance from the right of way. However, factors such as large wavelengths, long periods, changes due to rock formations, moisture content, and sensitivity to extraneous noise such as that from heavy traffic, require elaborate networks to extract suitable locational information, let alone velocity information. It was considered that a pickup of acoustic energy in the rail might be compared with seismic waves to provide the required information. However, the variation in seismic waves, and the

lack of a practicable method of calibration, made this technique infeasible.

3.2.2.3 Infrared. Two versions of this concept were considered. A trackside system using devices similar to those now used for detecting hotboxes was ruled out owing to deficiencies of single point detection (see section 4.2.1). The other version would employ an infrared detector at the crossing to pick up the approaching locomotive. This scheme fails when an approaching train has a locomotive in a position other than the head end. It might be possible to affix some type of "hot" reflector on the first car, but short of equipping every car with one (at both ends), the problems associated with ensuring that the device was indeed on the lead car in each case seemed insurmountable without gross complexity and cost.

3.2.2.4 Acoustical. This concept utilizes an acoustic pickup transducer at the crossing (or other appropriate trackside location) to sense sound emanating from the approaching train.

The whistle (or other sounding device) on the train could be used as the sound source but this was considered infeasible, mainly because of the unacceptable risk of false alarm. The acoustic spectrum of the whistle is duplicated in sound pressure level over the predominant octaves by other sources such as trucks, motorcycles, emergency vehicles, etc. One could seek to counter this threat of false alarms by resorting to a coded whistle signal. But even for coded signals, a safe warning time requires that the signal be sounded first about a half mile or more away, and then repeated more or less continuously until passing the crossing. This in turn requires that the whistle must be sounded at the proper time. Such additional burden upon

the locomotive engineer could not be accepted from the viewpoint of railroad liability. Additional false alarm risk is posed by train whistles in the vicinity on trains which have already passed a particular crossing, which are on another track line, or which for another reason do not threaten that crossing. This might be countered by assigning a unique code for each crossing, but this could solve only part of the false alarm problem, even if suitable reliability could be achieved.

The noise generated by the moving train might also be used as the sound source to the transducer. But here again the false alarm risk is not acceptable. There is no assurance that even a very sophisticated and costly spectrum analyzer could distinguish (at widely varying speeds) the acoustic signatures of steam trains, electric trains, and diesel trains from those of other sound sources in the vicinity of a grade crossing.

3.2.2.5 Other Methods. Four additional concepts for train detection by direct sensing were studied:

- a) Magnetic detection—Sensing the train's metallic mass through its influence on a locally created magnetic field.
- b) Bow-wave detection—Use of barometric devices to sense the air pressure change at the head of a passing train.
- c) Photo-cell beam—Use of photoelectric cells to sense the interruption of a locally created light beam by the passing train.
- d) Proximity switch—Activation of some type of proximity switch to sense the presence of the passing train.

All of these concepts prove to be unacceptable because of the deficiencies of point detection (see section 3.2.1). Of course bow-wave detection has the additional deficiency of being virtually insensitive to a slow moving train.

3.2.3 Sensing via Track Structure. The following six sensing concepts which use the track structure were investigated by this study:

- a) Guided radar
- b) Switches
- c) Airgap transformers
- d) Buried loop
- e) Track circuits
- f) Nonelectrical methods

3.2.3.1 Guided Radar. This concept has been the subject of some theoretical research in this country and elsewhere, while practical exploration of it has been pursued primarily in Great Britain and Japan. The system consists of a surface wave conductor laid parallel to the railroad tracks. Such a conductor would be leaky enough to permit communication between it and a nearby transmitter or receiver. Research has concentrated primarily on its use for mass transit communication. A simple concept utilizes a leaky coaxial cable, holes having been made in the shielding which permit the two-way transfer of RF energy. This application is planned for use in the Washington DC Metro subway system.

A continuously leaky system uses a Goubau line or some derivative form thereof. Here, the shape of the conductor, its placement, and electrical characteristics control the amount and direction of the leakage. One of the most interesting forms of the surface-waveline is an open Y-shaped channel running down the center of the track, the Y-channel

serving as an open microwave guide. It was introduced in Japan, but appears not to have been further pursued.

It appears that such a concept would be ideal for a guided radar detection system. It would effectively eliminate the line-of-sight problem as well as the high attenuation from rain and other environmental effects that plague low-power free space radars. A signal sent down the wave guide would be reflected from the leading edge of the train and returned to the crossing processing area where location and velocity could be deduced in the several ways currently available (e.g., Doppler).

This concept does not appear to be feasible within the specified time frame as a cost-effective solution. Any favorable benefit-cost ratio will have to include communication and traffic control modes as well. Since research is under way in these areas, it did not seem appropriate to pursue it further at this time. Should it later prove to be viable, its proponents will certainly ensure a hearing on the merits. From a functional point of view it would seem to accomplish all that a train detection system would require.

3.2.3.2 Switches. Many forms of switches, relays, and other devices which cause current to start, stop, or change magnitude when activated by a passing train were proposed. They all suffer from point deficiency problems but are offered here as a brief summary.

- a) Magnetic reed relays activated by a magnet on the train.
- b) Mechanical limit switches have problems with environment extremes.
- c) Piezoelectric (PZ) crystals - These interesting solid state devices turned out to be a fertile

source of possible systems because PZ crystals have the property of generating a high voltage when pressure stressed. The voltage is proportional to the pressure applied. A PZ crystal attached or imbedded in the track would send out a signal which could then be used for various detection purposes. While the signal is relatively high, 500 to 2,000 volts, the energy is low and any attempt to transmit this signal directly to the crossing would fail because attenuation would effectively destroy the signal. The use of such a signal would have to be at the point of initial detection. One possibility would be to create a spark which could be detected at the crossing. However, the RF interference present in such a system would be unacceptable. Thus it would appear that PZ crystals would be useful only in activating some form of relay and as such are subject to single point detection deficiencies.

3.2.3.3 Airgap Transformers. The basic principle involved with this concept is that a train wheel passing an airgap transformer would increase the transformer coupling. This increase in coupling effect would result in an increase in the transformer secondary current which would be usable in detection circuits. It may be possible to use the rate of current rise to determine train velocity. Most likely, multiple sensors will be required to accurately determine velocity.

The device itself would be rugged and virtually maintenance free. It would not be vandal free, however, as any large piece of iron passing the sensor would produce a signal.

This concept also suffers from single point detection deficiencies.

3.2.3.4 Buried Loop. This concept would utilize induction coils buried in the track bed in much the same way as that used in roadways for demand type traffic signal control. Buried loops are not practical for an extended area and for short distances would suffer from single point deficiency. The loop concept does have some possibility as part of a communication system. Suitable equipment placed onboard the locomotive could be used to induce or receive signals. However, such a larger scope system was not explored here.

3.2.3.5 Track Circuits. Track circuits have been a part of the railroad scene for over a century. They come in a great many forms suitable for diverse functions, such as traffic control, signaling, crossing protection, etc. They were not thought to be a promising area for exploration because of the considerable research already associated with them. They have an appeal, however, because conceptually, they have these advantages:

Communications over existing equipment

Operational over entire travel of train

Provide warning of rail discontinuity

Up to this point they have not been used for ranging and velocity measurement because such functions are not easily performed with the existing systems. The primary reason for this is that all of the AC circuits used are impedance limited. Systems have been devised which use impedance change as a means of ranging but they are not very accurate because the impedance change is not linear over a reasonable distance and is subject to a large variation due to environmental factors such as rain.

In reviewing this area, it was realized that none of the systems were utilizing the one principle that could be made independent of the environment or at least readily amenable to auto compensation. This was the speed of transmission signal propagation. The original idea was to transmit a signal down one rail, pass through a shunt located at the terminals of the danger zone for approaching trains, and then proceed back to the crossing through the other rail. It was felt that this signal transit time could be timed around the track. A train entering would shorten the length of the circuit and this would show as a shorter elapsed transmission time. Needless to say, the concept is not so simple when the practical problems are examined, but this concept led to a variation which was ultimately shown to be feasible and beneficial. Therefore, a much fuller discussion will ensue in section 4.

Another variant of the track circuit approach was to use ground as a part of the circuit. One rail could be well grounded while the other was used for signal transmission. A train would then increase the grounding of the active rail which would in turn be measurable at the crossing. The concept was not pursued because the basic feasibility was not apparent without extensive field testing and because it did not seem to offer any advantages over those track circuits which appeared to have real potential.

3.2.3.6 Nonelectrical Methods. Perhaps the most important in this category were systems which were nothing more or less than acoustic track circuits. In place of an electrical current there would be a sound wave traveling through the rail. Several attempts to pick up signals on a section of B&O track made it evident that these signals were rapidly attenuated in nonwelded track and did not penetrate the isolated joints used for some track circuits.

A number of ideas were considered. Some used the natural vibrating impact of the train. Others used artifice and strategy to produce unique signatures for the purpose of providing range and/or velocity. For example, notches could be cut in the track in some fixed code to give a characteristic sound when the train passed a particular point. Other ideas used special ties which would impact in peculiar ways upon the track, special track cross sections which would change the induced vibration as a function of distance, etc. Some of the ideas failed for practical reasons; notches are undesirable if deep, and are soon peened into ineffectiveness if shallow. However, the major fault of all the above systems is the lack of a telltale failure mode, absence of signal being the "safe" condition. Due to this reason, this concept was deemed unacceptable.

An acoustic system literally analogous to an electrical track circuit was considered. In this form, a transducer would send a signal through the rail which would return, having gone through suitable shunting, in the other rail. A better version uses one rail and the reflected signal from some terminal points (similar to sonar). Tracor Jitco, Inc., has considerable experience in the sonar field and it was the consensus of Tracor Jitco that high power requirements and the necessary signal processing to give range and velocity were not in line with the realities of budgets and maintenance requirements.

3.2.4 Train-Borne Systems. Several systems have already been discussed where operation is enhanced by placing some device on each locomotive. This section deals with those concepts where the train equipment is a necessary and major part of the system.

Before discussing the various proposals under this group, certain advantages and disadvantages should be pointed out. The advantages are:

Velocity information may be directly obtained and transmitted.

System has the potential of integration into larger communications systems.

The disadvantages are:

Locational information and crossing specificity are not directly obtainable without great complexity.

System is not fail-safe in railroad terms, i.e., absence of signal connotes train absence.

Failure of system creates operational problem for railroad.

Difficult to determine train length directly.

These disadvantages are somewhat intertwined in their impact upon design. For example, consider a system in which the transmitter is continually broadcasting information as to its velocity. To determine where that train is in reference to a given crossing, we must either provide the train with a clue as to where it is or we must provide an external detection device. Generally speaking, both cases require some device external to the train although it is possible to conceive of inertial reference systems, satellite triangulation, etc., all of which are not practical for this application at this time. External devices in turn tend to require power and a communication link to the crossing. Accordingly, train-borne systems which meet performance criteria require elements outside the train. In the following

discussion, these systems have been divided into active and passive systems.

3.2.4.1 Reflective Device. The passive device could be a reflective type such as used for boxcar inventory control, only simpler since color discrimination would not be required. There are two objections to this approach. First, any reflective surface is prone to dirt accumulation. Although recent developments with Teflon-type coatings have improved dirt rejection, periodic cleaning would still be required. However, the possibility of dirt accumulation or even damage or removal of the reflective surface plus the vandal prone detector weigh heavily against this approach, especially since it does not lend itself to "fail-safe" operation. The second objection is the same mentioned for many other concepts: it provides detection only at a discrete point and velocity cannot be extracted without multiple sensors.

3.2.4.2 Strobe. Among various active train-borne devices which were considered was a high intensity strobe mounted on the engine with a detector at the crossing. This concept is quite feasible and in fact has been commercially marketed by for use in traffic light control by emergency vehicles. The train velocity could be encoded in the strobe flash rate.

This system has at least three disadvantages. First, the range is approximately one-third mile and is decreased by fog, heavy rain or snow. Secondly, it is not inherently "fail-safe." Lastly, this concept does not give distance away from the crossing and therefore lacks constant warning time.

3.2.4.3 Electromagnet. An electromagnet on the train could be continuously operating or activated upon command to various sensors such as reed switches, variable reluctance, hall effect, or other types of sensing devices. Although the

sensing devices would be small and relatively inexpensive, cabling would be required to connect them to the crossing. Again, the concept is not "fail-safe" and suffers from the deficiencies of single point detection.

3.2.5 Communication Systems. Trains currently use radio frequency transmission for communication. A further extension of this concept would be to use an RF transceiver to transmit the train's presence and velocity directly to the crossing or to a central control station which would in turn signal the crossing. One configuration of this concept suggested by Transportation Systems Center (TSC) personnel has been labeled Multiple Crossing Controller (MCC). The train transceiver would be activated by a passive component buried in ballast or at the wayside a specific distance from the crossing. Once triggered, the train transceiver would transmit a signal indicating presence and velocity to a transceiver at the approached crossing. This information could then be used to activate the motorist warning system at that crossing only, or more generally, the received signal information would be routed to a Multiple Crossing Controller. This controller would consist of a microprocessor/microcomputer which would coordinate the motorist warning at a series of proximate crossings. (This could also be handled by the railroad's central computer system.) Not only train velocity, but also number of cars, destination or other pertinent information could be encoded on the train's transmission. This type of approach, integrating the motorist warning system into a larger system, greatly increases efficiency and should be pursued in a total system concept. Operating alone, one major problem is to provide a fail-safe mode of operation. A continuous communication link which could be established in a total communications system would overcome this obstacle.

Another total communication link which seems to warrant further investigation was suggested by Federal Railroad Administration personnel. This system would use a lossy radiating cable alongside all railroad tracks to serve as a communications link. Every locomotive as well as every railway track would have a unique identification code and mini-transmitter. Although the original concept was for automatic car sorting in the railway yards, it could also provide continuous monitoring of train location. The communication link could also be established to the individual crossing, thus allowing activation signals from the railroad central control center as well as a redundant override directly from the train. Both concepts have considerable potential for efficiency and overall reduced costs and improved reliability, but these can best be achieved as part of a total network, which we feel is beyond the scope and intended time frame of this effort.

3.2.6 Protection and Warning at the Crossing. The concepts generated for this group were generally aimed at providing more sensory information to the approaching driver. Inadequate warning seems to play a major part in grade crossing accidents; thus, improvement in this area seemed desirable. As many of the concepts involve the use of a gate as a warning and also as a barrier, many gate ideas were forthcoming, not all of which were aimed at this goal. Some were frankly an attempt to see if new forms might hold promise of lower cost, minimal maintenance, etc. Because at the time this report was written, a parallel program funded by DOT/TSC directed specifically at gate barrier improvement was ongoing, the subject of gates was not pursued to the degree that other areas were investigated. This section does not deal with restraining barriers but only with those which serve primarily as a visual impedance to progress as opposed to, for example, an arresting cable.

Several gate concepts were proposed using the spiral tube deployment principle as developed for antenna on spacecraft. This was believed to be too costly compared to the conventional gate. Similarly, inflatable gates did not show promise, requiring an extensive powered inflation system.

Dropping a net, flag, mirror, or rubber fingers was also felt to present problems of activation and distraction that would be unfavorable compared to the present gates. It was also impossible to assess the impact upon driver behavior at the crossing without extensive testing.

Scissor or pantagraph gates were suggested. However, these suffer from too rapid an entry into the path of the driver in comparison to their recognition value. That is, the driver does not have very much time to become aware of the gate's movement before it becomes an actual barrier.

The following modifications to existing gate design were proposed, which may have merit but which were not investigated:

- Use of light tube material for arm thus lighting up entire gate

- Use of metalized mylar to enhance conspicuity

- Use of lightconducting fibers, similar to the "fountain of light" sold for the home to create a fuller lighted area surrounding the barrier arm

Another concept, not easily evaluated in terms of effect, was to flood the crossing proper with directed light, possibly alternating red and white. Such illumination, especially in areas not already containing competing light sources, might be an effective nighttime warning. However,

it does not appear to have cost-effective potential because it would only be effective on the nighttime accidents, which are only a third of those which occur. Considerable power, maintenance, etc. were considered to mitigate against it.

Some thought was given to improving barriers on both sides of the track (per lane of traffic) to discourage attempts at beating the train. Problems of this concept include expense, unknown effectiveness, and necessity for placement such that the driver would not feel trapped or encouraged to go around.

It was felt that some investigation of overhead mounted gates which would swing down into the lane might have merit. Such a configuration would have the potential of being able to bounce back from an impact with a vehicle. It was not pursued by us at this time because of other ongoing, more specific DOT-sponsored investigations of gate configurations. A perhaps more serious problem arises from the fact that the plane of deployment is coincident with the longitudinal and vertical axes of the motor vehicle. Thus, perception of lower velocity and closing speed in the last half of travel would seem to hold potential of deluding or misleading the driver about the gate motion.

There are several suggestions in the current literature as to the use of holographic images to serve as a warning or pseudo barrier at crossings. At the present time such devices seem to have potential only as a night warning because of the enormous power requirements needed to make them visible in bright sunlight. Care must be taken to avoid panicking the driver with a suddenly appearing image.

Several audible warnings were considered. A vortex gun similar to the child's toy of several years ago and the type currently being used to pick fruit from trees could be used to hit vehicles with a pneumatic impact which would

certainly be an attention getter. Such a warning would be ambiguous as to meaning, however; and would certainly pose some of the safety problems that have caused the toy to disappear from the market.

Parking lot type spikes leaning up out of the roadway toward the car's tires were considered. Such a device would have significant operational problems from snow, ice, etc. From an effectiveness standpoint, it leaves something to be desired because it is not a real barrier in the sense that it would not slow a vehicle down appreciably unless placed back some distance from the crossing so that the driver would have time to stop his damaged car. An injury to a vehicle can be justified only if it substitutes a damaged car for a car-train collision. Such would not appear to be the case here.

The use of traffic signals was discussed and felt to have merit. This concept is further examined in section 4.

One concept that generated initial enthusiasm was using the weight of the train to stress piezoelectric crystals which in turn would fire strobe lights at the crossing. Though theoretically possible, the output of present crystals does not have the energy potential for the task.

While these crystals can be stacked to increase the energy developed, the number required would seem to render the concept unreasonable at this time.

3.2.7 Advanced Warning Concepts. A major portion of the grade crossing accidents are caused by driver's unawareness of the situation. Advance warnings consist of the round sign and frequently the painted roadway. Both have serious deficiencies in their ability to keep the driver alert to the presence of the crossing and the danger it represents. As elaborated earlier, such warning has traditionally been

located some distance from the crossing although there seem to be no fixed guidelines that are generally accepted. The "Manual on Uniform Traffic Control Devices for Streets and Highways" (MUTCD) establishes a minimum distance of 100 feet "where low speeds are prevalent." Again, as earlier noted, the use of a concept to reduce stopping distance also reduces warning time requirements and permits the use of warning systems placed at the crossing proper where with adequate target value they serve as advance as well as onsite warnings.

One method is to communicate with the car through the use of an in-vehicle warning system activated by either radar or RF. Such systems have been found to be non-cost beneficial unless made a part of a system addressed to larger interests. For example, an RF communication system for advising the motorist of road conditions, routing, etc., or an FM radar for crash avoidance are possibilities under evaluation elsewhere.

Many of the suggested concepts used strobe lights for increased conspicuity. One device available on the market places the light on the end of a retractable stalk, helical in form, which extends up from a compressed height. The device is promoted for mounting on the roof of a police vehicle or as a warning device to be placed in the road at the scene of an accident. One can readily envision such a device at a crossing with the strobe light flashing while moving up and down. However, beyond such speculation, no attempt was made in this program to utilize the device because its effects are problematical and its effectiveness ranking among competing devices is unknown. Its evaluation is more properly within the scope of a directed evaluation of visual warning devices. This statement is generally true for strobe and other flashing or moving light concepts.

Before considering the implications of the last sentence, it would be well to differentiate between classes of advance warnings:

Passive

Active

Nonspecific

Specific

Passive types have historically been inefficient, losing their impact to the frequent passerby and going unnoticed by the new traveler along the way. Active but nonspecific (nonspecific in the sense that the warning informs only as to the presence of the crossing but not as to the presence of a train) types are in use at a number of crossings in this country. One form is the overhead suspension of two amber lights which continually alternate. A sign indicating the presence of a crossing is placed adjacent to them. Our observations indicate that the newcomer is warned of the presence of a crossing, but that its effect on the frequent crosser is unknown. Certainly, driver behavior did not outwardly show significant differences in behavior from crossings without such a device. However, it is not known whether a state of heightened consciousness existed as a result of the signs.

It is reasonable to posit that an active specific sign could be effective in warning the driver. None of the concepts for placement of devices at some distance from the crossing, however, seemed particularly innovative nor did their effectiveness stand out. One immediate disadvantage is the necessity for providing a multitude of such devices, one, or preferably two, per direction of traffic flow for each road leading to the crossing. These must all be linked to the crossing with some type of communication system with appropriate fail-safe precautions, etc. Such an approach did

not appear to warrant effort when weighed against some of the other concepts generated under this program.

The advanced warning concept of rumble strips was incorporated into the concept of improving the pavement so as to decrease the design stopping distance. Through use of an open graded friction course, this concept has the potential of doubling the coefficient of friction in wet weather. Such an improvement makes possible the use of in-situ warning as advance warnings. The two concepts which are deemed useful here, the above-mentioned road improvement and optically programmed signals, are treated in detail in section 4.

3.2.8 Arresting/Impact Attenuation Devices. Several barriers were proposed including the oft-mentioned aircraft arresting cable. A variant was the use of a net in place of the cable. These suffer from the deficiencies noted by Hopkins,* i.e., capital costs approaching grade separation, highway blockage from malfunction, etc.

One possible configuration might be based upon an air bag principle with deflation after actuation. Such a system would not be "fail-safe" in the conventional sense, however, and would be subject to the criticism of high cost.

3.2.9 Self-Contained Power Sources. To provide active warning at grade crossings not serviced by normal power lines, some type of remote power source is required. Such a local, self-contained source of power would also have potential for use as an emergency backup at grade crossings supplied by power lines. Emergency electrical backup is presently provided at grade crossings by a system of batteries, but these require regular maintenance and periodic replacement.

The present national awareness of energy supplies and the need for new sources have generated a number of concepts of which at least two are worth considering for this

* FRA-ORD & D-74-14 Hopkins.

problem: the use of wind powered generators, and the conversion of solar energy. It is our opinion that there is enough ongoing research in this field that, should a viable scheme for power in the 1- to 5-kw range become available, it would receive attention for use in the context here.

Some thought was given to diverting some of the power available from the train itself and storing it for use at the crossing. The problem with this approach is the short time available in many instances to transfer energy. If the transfer is performed at one point on the track, short train lengths would necessitate a large quantity being transferred. On the other hand, a long transfer system would appear to be prohibitively expensive, requiring installation along each track. Again, it may be possible to achieve the transfer of energy but none of the concepts proposed during this effort appeared promising.

3.2.10 Modification of Driver Behavior. Driver behavior and theories for modifying it have produced a number of hardware concepts over the years. This program was no exception and several of these were proposed. However, as noted before, the effect of these systems can only be speculated upon without extensive research, unlike, for example, a hardware system to activate a gate. Accordingly, these ideas were not pursued beyond their formulation. However, they are presented here as possibilities for research in this area.

- a) The use of automatic cameras to record traffic law violators at grade crossings as is now done with some radar speed detectors.
- b) As vertical roadside objects provide a clue to vehicle speed, it is hypothesized that altering the spacing of objects such as telephone poles might provide an illusion of speed. Regular

spacing would establish a correlation in the driver's mind between his speed and the rate of poles flashing past. By gradually reducing the distance between, the driver would have a sense of speeding up and would compensate accordingly. Possibly his then reduced speed would lessen the chance of an accident.

- c) The use of barriers, red lights, or other devices on the far side of the crossing to reduce the reward for beating the train

4. RECOMMENDED CONCEPTS

This section develops and analyzes those systems which were shown to have initial promise of fulfilling the need for improved grade crossing protection. These are:

- Train Ranging and Correlation System (TRACS)
- Open Graded Asphalt Friction Course
- Optically Programmed Traffic Signals

4.1 TRAIN RANGING AND CORRELATION SYSTEM (TRACS).

The use of rails themselves as a carrier of electrical energy for purposes of sensing, warning, and communications has a long history; the classic dc track circuit dates back to the 1870's. In the interim, many variations upon this system have evolved and are being marketed by a number of railroad equipment suppliers. In analyzing the principles of operation of these, it was found that constant warning time, although available, was not widely in use. This omission results from several factors.

- a) There has not been a great demand for such a system.
- b) Most systems which have the potential either do not have the capability of providing velocity information at all points in the affected area since they provide it only at the entry of train into the system through means of a "time trap," or they are adversely affected by the changing electrical characteristics of the track/ballast system. This latter deficiency can be compensated for in present equipment by adding complex sub-systems to the basic design.

- c) Many require active equipment at the site of train entry into the affected area with the attendant need for extra-track communication with the crossing.

The TRAC system proposed here requires nothing at the entry point beyond an electrical short (at the operating frequency) between the rails, thus obviating the requirement for additional cabling. It is internally compensating for changes in ballast characteristics that affect impedance. And it provides continuing position and velocity information for the trains at arbitrarily chosen increments of distance, e.g., every 100 feet.

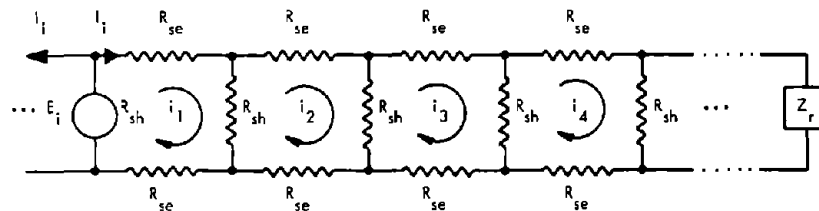
TRACS provides the same protection against broken rails as present systems do. It is compatible with a fail-safe mode of operation. It has the advantage of not requiring an "island" at the crossing to detect the presence of the train at that location.

To understand the principle of operation, it is well to begin with a description of the rail/ballast system.

4.1.1 Rail/Ballast System. Physically, the railroad track bed appears as a simple structure comprised of parallel steel rails supported by cross ties that are in turn embedded in some type of stone ballast material. Variations in materials are found, but the same basic structure remains. Rails are available in a range of weights and in a number of different alloys, cross ties are generally wooden but concrete ties are sometimes used, and in some cases the rails are directly embedded in concrete slabs. Electrically, however, the structure is a rather complex one. This complexity stems from the fact that the steel rails present both series resistance and inductance to currents flowing in them; the ballast

provides a shunt current path between the rails that is both resistive and capacitive. Axles of trains serve effectively as moving short circuits between the rails and weather conditions (wet/dry) cause ballast resistances to vary from 1/2 to about 200 ohms per 1000 feet of rail bed.

At dc, the rail/ballast structure can be modeled by a resistive ladder network² as shown below in Figure 4-1.



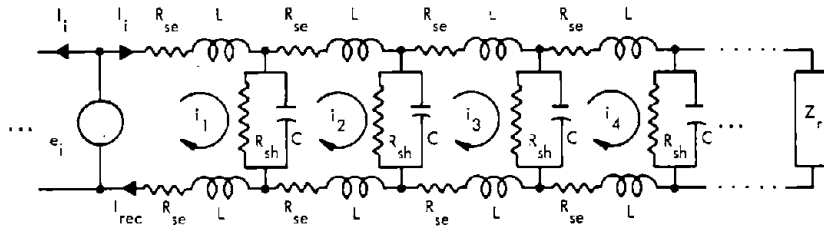
- $R_{sh} \cong$ ohm/1000 ft (wet Ballast)
- $R_{sh} \cong$ 200 ohms/1000 ft (dry or frozen Ballast)
- $R_{se} \cong$ 0.015 ohms/1000 ft (Welded Rail) dc
- $R_{se} \cong$ 0.08 ohms/1000 ft (Web Bonded Rail) dc

FIGURE 4-1. MODEL OF RAIL/BALLAST STRUCTURE (dc)

At audio frequencies the rail ballast structure can be modeled² generally as shown in Figure 4-2.

This data indicates several factors which affect the parameter values. For instance, the resistance to ac current and inductance are both affected by increasing frequency. It can be shown that the resistance increases and the inductance decreases with increasing frequency,² commonly called skin effect.

As frequency increases, the current becomes non-uniformly distributed over the conductor (rail) cross section, concentrated near the surface. This results from magnetic flux lines increasing the reactance near the center, thereby reducing the current at that portion of the cross section.



$$R_{se} = 0.23 \text{ ohms/1000 ft (loop) at 60 Hz}$$

$$X_{sh} = 1/wC \cong 30 R_{sh} \text{ at 100 Hz and } R_{sh} \approx 5 \text{ ohms}$$

$$X_{sh} = 1/wC \cong R_{sh} \text{ at 10 kHz and } R_{sh} \approx 200 \text{ ohms}$$

FIGURE 4-2. MODEL OF RAIL/BALLAST STRUCTURE
AUDIO FREQUENCY

This redistribution of current increases the ac resistance and decreases the inductance. These effects increase with frequency and with conductivity, magnetic permeability, and size of the conductor. Since these last three physical properties are all relatively large for a steel rail, it is not surprising that the effects are significant at low frequencies.

Another factor affecting the parameter values is a change in capacitance with varying ballast conditions and frequency, the capacitance being largest at low frequencies and with wet ballast.² The total change cited was from 10 μ fd (at 100 Hz, wet ballast) down to 0.08 μ fd, the latter under conditions of dry ballast and 10 kHz frequency. This is evidently due to change in the dielectric permittivity of the ballast with both moisture and frequency. These variations indicate that our model is not, in fact, complete, and other stray resistance and capacitance effects are present. Not only that, but all component values are a function of frequency, moisture, or both. However, it is convenient to use the model of

Figure 4-2 because of the transmission line equation which then applies. Also, no data on a more complex model was found in the literature. "Worst case" conditions of ballast will be used, however, which should help compensate for the deficiencies of the model.

In both Figures 4-1 and 4-2, the shunt impedance Z_T at the right-hand side of the figures is intended to indicate a termination of the track circuit. This termination can be either in the form of a physical shunt network designed to allow signal currents to flow in the track circuit loop, or in the form of a short circuit presented by an approaching locomotive.

4.1.2 System Configuration. If we assume that the track circuit is an appreciable portion of the signal wavelength, it would be convenient to consider the railroad track as electrically equivalent to a transmission line. The model shown in Figure 5-2 will still apply in this case. Considering a two-wire parallel transmission line, the analogy seems even more appropriate. If a voltage is impressed at the crossing and the tracks shorted some distance away, the short will result in the signal waveform being reflected from that point. It should be noted that a similar reflection results from an open circuit, such as a broken rail. The circuit electrical parameters of inductance, capacitance, resistance, and in our case, particularly conductance, affect the attenuation and speed of wave front (or phase) propagation. To effect a ranging system, we need to measure only the round trip elapsed time for a particular wave front and keep account or compensate for any change in phase propagation velocity.

Measuring this time interval does indeed only measure the electrical length of the track circuit, but since the train acting through its wheels and axles effectively controls the electrical length of the track circuit, this time

measurement is sufficient to locate the train's position. A general system configuration is shown in Figure 4-3.

The attenuation, or loss, in the signal during the round trip is a primary constraint on the range. This attenuation increases with increasing frequency, wet ballast, and higher rail resistance, inductance, and capacitance. Another constraint on range is the sensitivity of the receiver and its signal processing circuitry. One approach toward measuring the time interval, which also provides sensitive detection, is to use a correlator.

In the classic correlator configuration shown in Figure 4-4, the transmitted signal, $f_{tr}(t)$, is routed to both the rails and a delay line. The current flowing in the rail is detected, $f_{rec}(t)$, and this received signal is routed to a parallel array of signal multipliers. The delay line is constructed with multiple outputs, each providing replicas of the transmitted signal that are delayed respectively by specified time intervals; the first output gives a delay of τ , the second 2τ , and so forth. Each of these delay line outputs is routed to a multiplier and is multiplied with the received signal. The multiplier outputs are routed to integrators and integrations are performed over a period of time, t_{int} . Outputs from the integrators, identified as $C_n(n\tau)$, are then sensed to determine the train location at any time, t .

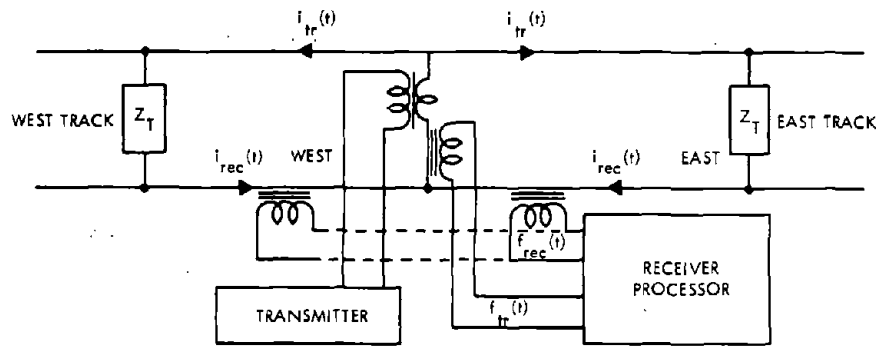


FIGURE 4-3. RANGING SYSTEMS CONFIGURATION FOR CONTINUOUS STEEL RAIL APPLICATION

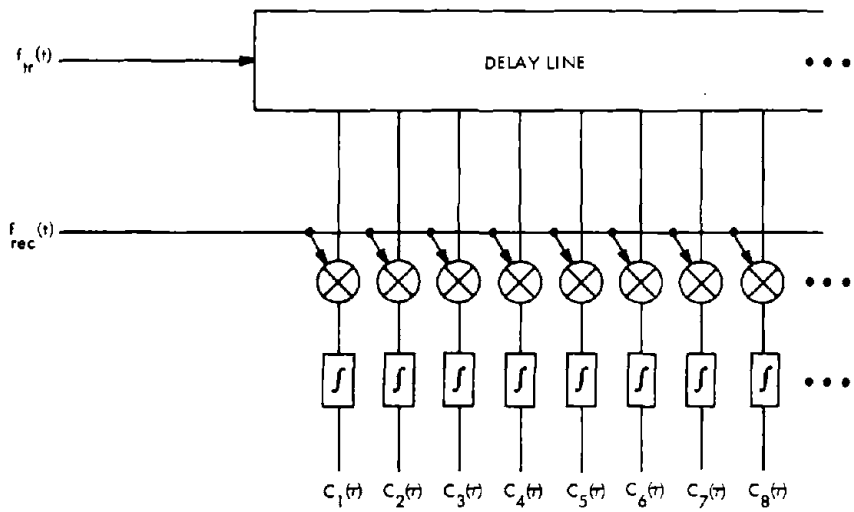


FIGURE 4-4. RANGING SYSTEM CONFIGURATION

The magnitude of the ballast impedance and the location of the train will determine the relative amplitudes of the outputs from the integrators with nonthreshold value outputs. The largest output will correspond to the signal delay returned through the train axle, thus indicating its location. With high ballast resistances and short track circuit lengths, the output from the $n\tau$ integrator may significantly exceed the outputs from the remaining integrators and thereby allow unambiguous decision making. With low ballast impedances and long track circuit lengths, however, the output from the $n\tau$ integrator may not differ significantly from the $(n-1)\tau$ and $(n+1)\tau$ integrators. However, comparison of several outputs and the use of pattern matching techniques should still allow the determination of the train location.

4.1.3 System Performance. Without considering specific hardware configurations (to be discussed later), this section will consider the performance of the system as derived from theoretical considerations.

4.1.3.1 Range Resolution. Referring to the system configuration shown in Figure 4-5, the distance from the transmitter site to d_{\max} is first divided into range segments of d_s length. Assuming that these segments are all of equal length, then

$$\sum_{s=1}^n d_s = d_{\max} = nd_s \quad (1)$$

For this case as shown in Figure 4-6, the output from the first integrator will provide an output for a train detected at a distance d_s ; the second integrator will provide an output for a train detected at a distance $2d_s$, and so forth. Thus, the n^{th} integrator will provide an output for a train detected at a distance d_{\max} .

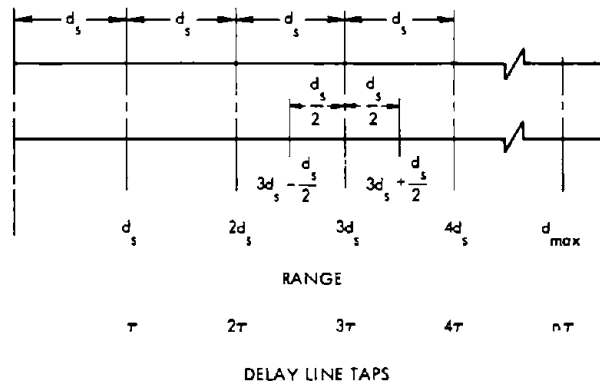


FIGURE 4-5. DEFINITION OF RANGE SEGMENTS AND DELAY LINE TAP OUTPUT

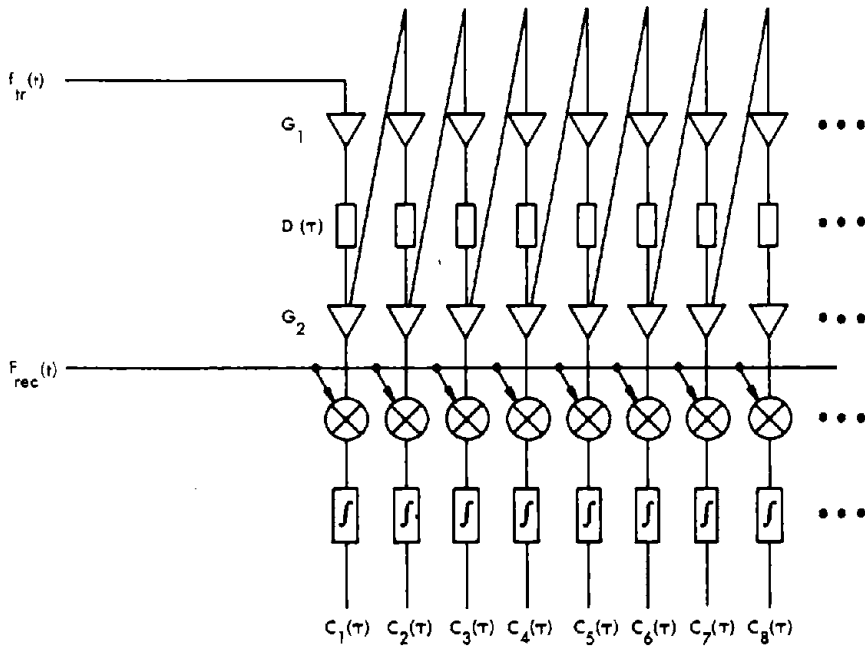


FIGURE 4-6. RANGING SYSTEM SIGNAL PROCESSOR, MODULAR CONSTRUCTION

From this it can be seen that the required range resolution directly defines the number of: (1) delay line taps, (2) multipliers, and (3) integrators that are required in the correlation processor. For example, assume that a locomotive is to be located to within ± 50 feet. Each range segment is then one hundred feet long; $d_s = 100$ feet, and

$$n = \frac{d_{\max}}{d_s} = 52 \text{ or } 53 \text{ stages} \quad (2)$$

In general, for equal length range segments, the delay line taps would be equally spaced at intervals defined by

$$t_s = \frac{2d_s}{v_p} \quad (3)$$

where v_p = propagation velocity of the signal.

For the case where the delay line tap spacings are equal, another configuration of the correlation receiver is possible, as shown in Figure 4-6. Shown in this figure is an array of identical modules. Each module performs the functions required in one stage of the correlation processor and consists of a delay line, two interface amplifiers, a multiplier, and an integrator. The length of the delay line in each module is again equal to t_s and is defined as in equation (3). The merit of this modular configuration is that the processor comprises standard modules. In significant quantities, these modules should be of reasonable cost. Assuming that the range solution can be standardized, the appropriate maximum range for a specific application may then be selected in the field by the installation crew simply by plugging in the required number of modules in a standard rack assembly.

4.1.3.2 Integration Time (Maximum). The purpose of the integrators in the correlation processor is to achieve a

detection gain by adding repetitive signal components and cancelling random noise components in the received signal current, $i_{rec}(t)$. To achieve maximum detection gain, it is desirable to integrate over as long a period, t_{int} , as possible, but to detect a train in a given range segment, a decision must be made based on a given integrator's output before a train can leave that respective range segment. Maximum integration time, t_{max} , is therefore limited by the maximum train velocity, v_{max} , expected and the required range resolution of the system, $\pm d_s/2$. This time is defined by:

$$t_{max} = \frac{d_s}{v_{max}} \quad (4)$$

For example, if the maximum train velocity is 100 miles/hour and the range resolution is ± 50 feet, then the maximum integration time is

$$t_{max} = \frac{100 \text{ ft}}{100 \text{ mph}} \times \frac{1 \text{ mile}}{5280 \text{ ft}} \times \frac{3600 \text{ sec}}{1 \text{ hour}} \quad (5)$$

$$= 0.67 \text{ seconds}$$

As will be shown later, it may not be prudent to extend the integration time to as long as t_{max} , but in any event, the integration time can be no longer than that defined in equation (4).

4.1.3.3 Transmission Line Equations (Infinite Line).

Referring to Figure 4-2, transmission line theory can be applied to the model to predict the behavior of the system. We can utilize the "infinite line" case since the length of the line is an appreciable portion of a wavelength ($> 0.1\lambda$).

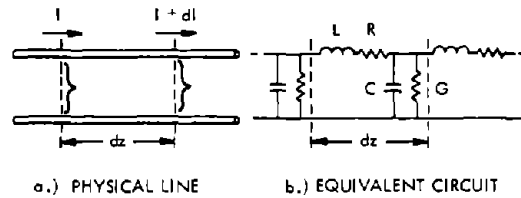


FIGURE 4-7. TRANSMISSION LINE MODELLED AS ITERATIVE NETWORK

From circuit theory, the voltage drop, V , is proportional to line current, I . Thus, using the notation of Figure 4-7,

$$dV = -IZdz \quad (6)$$

where

$Z \triangleq$ series impedance per unit length of line

The shunt current is defined by

$$dI = -VYdz \quad (7)$$

where

$Y \triangleq$ shunt admittance per unit length of line

Now dividing the above two equations by dz gives the ac transmission line equations

$$\frac{dV}{dz} = -IZ$$

$$\frac{dI}{dz} = -VY$$

Using equations (6) and (7), the one-dimensional Helmholtz equations are obtained by differentiating:

$$\frac{d^2V}{dz^2} = \frac{-IdZ}{dz} - \frac{ZdI}{dz}$$

$$\frac{d^2I}{dz^2} = \frac{-VdY}{dz} - \frac{YdV}{dz}$$

Assuming no variation in Z or Y with z, then

$$\frac{dZ}{dz} = 0 \text{ and } \frac{dY}{dz} = 0$$

Thus,

$$\frac{d^2V}{dz^2} = -Z\frac{dI}{dz}$$

$$\frac{d^2I}{dz^2} = -Y\frac{dV}{dz}$$

And from (7),

$$\frac{d^2V}{dz^2} = -Z(-VY) \text{ or } \frac{d^2V}{dz^2} - ZVY = 0 \quad (8)$$

And similarly from (6)

$$\frac{d^2I}{dz^2} - YIZ = 0 \quad (9)$$

The solution to these equations is a sum of two traveling waves—one traveling in the +z and another traveling in the -z direction. These waves have a propagation constant of γ , where

$$\gamma = \sqrt{ZY}$$

Then, working with one of the waves, the solution to the +z wave is

$$V^+ = V_0 e^{-\gamma z} \quad (10)$$

and

$$I^+ = I_o e^{-\gamma z} \quad (11)$$

Returning to equations (6) and (7), we have

$$\frac{dV}{dz} = -IZ = -\gamma V_o e^{-\gamma z} \rightarrow V_o = \frac{IZ}{\gamma e^{-\gamma z}}$$

$$\frac{dI}{dz} = -VY = -\gamma I_o e^{-\gamma z} \rightarrow I_o = \frac{VY}{\gamma e^{-\gamma z}}$$

$$Z = \frac{-dV}{I dz} \quad Y = \frac{-dI}{V dz}$$

$$\begin{aligned} \frac{V^+}{I^+} &= \frac{V_o e^{-\gamma z}}{I_o e^{-\gamma z}} = \frac{Z}{Y} \text{ for case 1} \\ &= \frac{Y}{Z} \text{ for case 2} \end{aligned}$$

Case 1

$$\frac{Z}{Y} = \frac{-1}{Y} \frac{dV}{I dz} = \frac{1}{Y} \left[I_o e^{-\gamma z} \right] \left[-\gamma V_o e^{-\gamma z} \right] = \frac{V_o}{I_o}$$

Case 2

$$\frac{Y}{Z} = \frac{-\gamma V dz}{dI} = \frac{-\gamma \left[V_o e^{-\gamma z} \right]}{-\gamma I_o e^{-\gamma z}}$$

Substituting equation (11) into equation (10) gives

$$\frac{V^+}{I^+} \triangleq Z_o = \frac{Z}{Y} = \frac{Z}{\sqrt{ZY}} = \sqrt{\frac{Z}{Y}} \quad (12)$$

$Z_o \triangleq$ Characteristic impedance of the transmission line

For the case where series inductance and resistance plus shunt conductance and capacitance are all significant, the propagation constant has the following form:

$$\begin{aligned}\gamma &= \sqrt{ZY} = \sqrt{(R+j\omega L)(G+j\omega C)} \\ &= \alpha + j\beta\end{aligned}\quad (13)$$

where

α \triangleq attenuation constant in nepers per unit length;
1 dB = 0.115 neper

β \triangleq wavelength constant in radians per unit length

The corresponding characteristic impedance has the following form:

$$Z_0 = \sqrt{\frac{Z}{Y}} = \sqrt{\frac{R+j\omega L}{G+j\omega C}}\quad (14)$$

The next section will develop the constants for these equations.

4.1.3.4 Wavelengths, Wave Velocity, and Signal Attenuation.

Since the reflected wave adds vertically with the initial wave where they overlap, it will probably be necessary to pulse the transmission. In this situation, only the reflected wave should be received back at the initiation point. Intuitively, the shorter the transmission the better; hence, the higher the frequency the better. However, attenuation also increases with frequency. To investigate this further, we will conduct an analysis with the highest frequency for which data was found. Frielinghaus² shows some data at 10,000 Hz. The graphical data shows the resistance at 10 kHz to be 1.5 ohm. The inductive reactance, X_L , is shown to be 22.5 ohms. The inductance would therefore be

$$L = \frac{X_L}{2\pi f} = \frac{22.5}{2\pi \times 10^4}$$

$$L = 0.36 \text{ millihenries}$$

The capacitive impedance is given as 150 ohms at 100 Hz and 5 ohms ballast resistance, and 200 ohms at 10 kHz and 200 ohms ballast resistance. If capacitive impedance is taken to mean capacitive reactance, X_c , then

$$X_c = \frac{1}{2\pi f C}$$

and thus

$$C = \frac{1}{2\pi f (X_c)}$$

At 5 ohms ballast and 100 Hz,

$$C = \frac{1}{2\pi \times 10^2 \times 150} = 10.6 \text{ } \mu\text{fd}$$

At 200 ohms ballast and 10 kHz,

$$C = \frac{1}{2\pi \times 10^4 \times 200} = 0.08 \text{ } \mu\text{fd}$$

Because pertinent data regarding the effect of frequency and ballast resistance upon capacitance was unavailable, the following assumptions are made. Given a frequency of 10 kHz, assume wet ballast capacitance of 0.8 μfd . This should provide a worst case value. Ballast resistance is assumed to be 2 ohms. Although ballast resistance is occasionally found at values down to 0.5 ohms, 2 ohms is a generally accepted worst case in the literature. To summarize, the parameters to be used are:

$$f = 10,000 \text{ Hz}$$

$$G = 0.5 \text{ mhos/1000 ft (corresponds to 2 ohm/1000 feet ballast resistance)}$$

$$R = 1.5 \text{ ohms/1000 loop ft}$$

$$L = 0.36 \text{ millihenries/1000 loop ft}$$

$$C = 0.8 \text{ } \mu\text{fd/1000 ft}$$

Substituting into equation (13) for the propagation constant,

$$\begin{aligned}\gamma &= \sqrt{[1.5 + j(2\pi \times 10^4)(0.36 \times 10^{-3})]} \\ &\quad \times \sqrt{[0.5 + j(2\pi \times 10^4)(0.8 \times 10^{-6})]} \\ &= \sqrt{(22.67)(0.503)} \angle \frac{(86.21^\circ + 5.74^\circ)}{2} \\ &= 3.375 \angle 45.97^\circ \\ &= 2.35 + j2.43\end{aligned}$$

Therefore, the formula for the attenuation constant becomes

$$\gamma = 2.35 \text{ nepers/1000 ft}$$

And for the wave length constant,

$$\beta = 2.43 \text{ radians/1000 ft}$$

The wavelength, λ , of the propagated signal is defined by the wavelength constant as

$$\lambda = \frac{2\pi}{\beta}$$

For the assumed parameters, then,

$$\lambda = \frac{2\pi}{2.43/1000 \text{ ft}} = 2.586 \times 10^3 \text{ ft}$$

The phase velocity, v_p , of the signal is

$$v_p = \lambda f = \frac{\omega}{\beta} \quad (15)$$

The fact that the velocity is proportional to frequency is significant in the choice of signal waveshape. For any signal waveform with multifrequency components, each component would arrive with a different delay, thus distorting the waveform. Although compensation is possible, a single frequency sinusoid will be assumed for the purpose of this initial analysis of the problem.

The phase velocity, v_p , for this case is then from (15)

$$\begin{aligned} v_p &= \frac{2\pi \times 10^4 \text{ radians/sec}}{2.43 \text{ radians/1000 ft}} \\ &= 2.586 \times 10^7 \text{ ft/sec} \end{aligned}$$

This value of v_p , it should be noted, is only about 2.5 percent of the speed of light. For dry conditions, G and C will become smaller. Maintaining the same frequency, the velocity can be shown to increase up to an order of magnitude change. It should be noted that this is not a true velocity in the sense of something tangible traveling at this speed. Instead, it refers to the fact that the relative phases at different places along the rail are such as to give the appearance of velocity.

From transmission line theory,³ the ratio of voltages in the initial wave, V_R^i , and reflected wave, V_R^r at the receiving end can be expressed as

$$\frac{V_R^r}{V_R^i} = \frac{Z_R - Z_0}{Z_R + Z_0} = \rho$$

This ratio is called the reflection coefficient. For our case, the train axle impedance is assumed to be less than the rail impedance. Hence, $\rho \approx 1$, indicating very low loss at the axle. The total attenuation for the signal is therefore approximately twice the one-way attenuation.

For our example,

$$\alpha = 2.35 \text{ nepers/1000 ft}$$

For the loop, the attenuation expressed in decibels is

$$\begin{aligned}\alpha_{\text{loop}} &= (2) (8.68 \text{ dB/neper}) (2.35 \text{ nepers/1000 ft}) \\ &= 40.8 \text{ dB/1000 ft of track}\end{aligned}$$

Before range can be estimated, it is necessary to evaluate the detection gain that can be achieved.

5.1.3.5 Detection Gain. Having obtained estimates of the attenuation loss per unit track distance suffered by a signal propagated along a rail/ballast structure, the problem now is to determine the receiver threshold and thus define the maximum distance at which a train can be detected.

Receiver threshold refers to the minimum signal level, at the input of a receiver, that can be usefully detected. This threshold is a function of both the detection process and the type of signal used. The detection process considered here is autocorrelation, in the manner shown in Figures 4-4 and 4-6. The signal type considered here is a pulsed sinusoid.

Detection gain refers to the improvement in signal-to-noise ratio achieved in a detection process. For example, let

$$S_i/N_i \triangleq \text{signal-to-noise ratio at input of detector (rms)}$$

$S_o/N_o \triangleq$ signal-to-noise ratio at output of detector (rms)

then

$$\text{detection gain} = \frac{S_o/N_o}{S_i/N_i}$$

By expressing the signal-to-noise ratios in decibels,

$$(S/N)_{dB} = 20 \log(S/N)$$

the detection gain can also be expressed in decibels. In the autocorrelation detector discussed below, the detection gain results from the averaging process performed by the integrators. Assuming that the noise is random with zero mean, then the noise power reduces as the averaging or integration time is increased. Since the noise is reduced, the signal-to-noise ratio is increased, therefore resulting in a detection gain.

In the following discussion, detection gain refers to the gain expected for each stage of the receiver shown in Figures 4-4 and 4-6. By stage is meant the series chain of devices shown in Figure 4-8, consisting of two buffer amplifiers, a delay line section, a multiplier, a low-pass filter, and an integrator.

Note that the gain computed later is therefore achieved in each stage and that the detection gain for the receiver is not a function of the number of stages used in the receiver. The number of stages is important only in defining the range resolution of the system, as discussed previously.

Considering now the use of sinusoidal signals, the transmitted, $f_{tr}(t)$, and received, $f_{rec}(t)$, signals have the following form

$$f_{tr}(t) = E_m \sin (wt + Q)$$
$$f_{rec}(t) = AE_m \sin (wt + Q + \Delta Q)$$

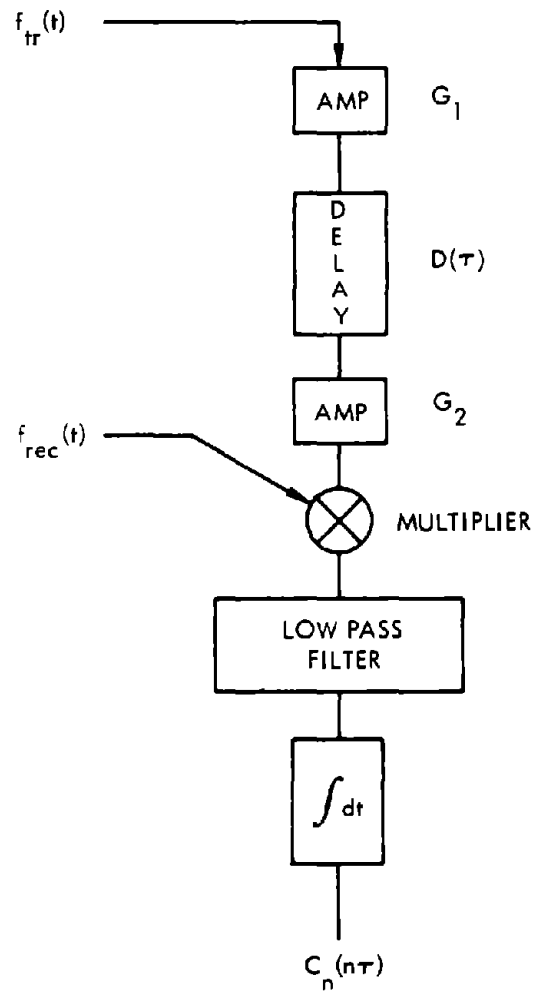


FIGURE 4-8. SINGLE STAGE OF CORRELATION RECEIVER

The rms value of the transmitted signal is $E = E_m/\sqrt{2}$.

Under these conditions, Lee⁶ has derived an expression for the output signal-to-noise ratio in decibels, R_{Oa} , for an autocorrelator; this expression is

$$R_{Oa} = 10 \log \left\{ \frac{n}{1+4\rho_i^2+2\rho_i^4} \right\} \text{ dB} \quad (16)$$

where

$$\rho_i \triangleq \frac{N_i}{S_i} = \text{input noise-to-signal ratio (rms)}$$

$n \triangleq$ number of samples of the input signals used in the correlation process

Using these definitions, the input signal-to-noise ratio in decibels, R_i , then is

$$R_i = 20 \log \left\{ \frac{1}{\rho_i} \right\} \text{ dB} \quad (17)$$

From equations (16) and (17), note that

$$\text{detection gain} \triangleq (R_{Oa} - R_i) \text{ dB}$$

Also note that for a fixed threshold value for R_{Oa} , the threshold value for ρ_i is controlled by the number of samples used, n . As a first case condition, the integrator output is assumed to be usable when the output signal power exceeds the output noise power by six decibels.

or

$$R_{Oa} = 6 \text{ dB}$$

Now the problem reduces to defining values for n and ρ_i .

In previous sections the potential operating frequency which has been considered is 10 kHz. Possible

sample rates are, of course, a function of the type of high frequency components present in the noise that appears at the input to the receiver, but we will consider sample rates equal to six times the signal frequency. In section 3.3, the relationship between train velocity, range resolution, and maximum integration time was considered and it was determined that for a maximum train velocity of 100 miles/hour and a range resolution of +50 feet, the maximum integration time, $t_{int(max)}$, is

$$t_{int(max)} = 0.67 \text{ sec}$$

To allow for other processing, let's use

$$t_{int} = 0.5 \text{ sec}$$

Therefore, the number of samples processed by the correlator is

$$6 \times f \times t_{int(max)} \text{ samples}$$

$$n = 6$$

However, we are considering a pulsed sinusoid. If the duty cycle is assumed to be 25 percent, we must divide the number of samples by 4.

$$\begin{aligned} n &= \frac{6(10^4)(0.5)}{4} \\ &= 7.5 \times 10^3 \text{ samples} \end{aligned}$$

Returning now to equation (16) and using the identity

$$\ln x = \frac{1}{M} \log x; \quad \frac{1}{M} = \ln 10 = 2.303$$

Equation (16) can be expressed as

$$0.2303R_{oa} = \ln \left\{ \frac{n}{1 + 4\rho_i^2 + 2\rho_i^4} \right\}$$

Taking the natural logarithm of both sides gives

$$e^{0.2303R_{oa}} = \left\{ \frac{n}{1 + 4\rho_i^2 + 2\rho_i^4} \right\}$$

and after rewriting, gives

$$\rho_i^4 + 2\rho_i^2 + 1/2 (1 - ne^{-0.2303R_{oa}}) = 0$$

Using the quadratic formula,

$$x = \frac{-b \pm \sqrt{b^2 - 4ac}}{2a}$$

then

$$\rho_i^2 = -1 \pm \sqrt{\frac{1}{2} (1 + ne^{-0.2303R_{oa}})}$$

For real solutions,

$$\rho_i = \left\{ -1 + \sqrt{\frac{1}{2} (1 + ne^{-0.2303R_{oa}})} \right\}^{\frac{1}{2}} \quad (18)$$

For our example

$$\text{Let } R_{oa} = 6 \text{ dB}$$

$$n = 7.5 \times 10^3$$

then from (18)

$$\begin{aligned} \rho_i &= \left\{ -1 + \sqrt{\frac{1}{2} \left[1 + (7.5 \times 10^3) (e^{-0.2303(6)}) \right]} \right\}^{\frac{1}{2}} \\ &= 5.45 \text{ (rms)} \end{aligned}$$

and the input signal-to-noise ratio in decibels is from (17)

$$\begin{aligned} R_i &= \left\{ 20 \log \frac{1}{5.45} \right\} \\ &= -14.7 \end{aligned}$$

For this case, the detection gain is

$$\text{Gain}_{\text{det}} (1.0 \times 10^4 \text{ Hz}) = 10 + 14.7 = 24.7 \text{ dB}$$

It is now possible to predict the range through the use of a power budget. Power budget refers to a bookkeeping procedure used to account for the available transmitter signal powers, the required received signal powers, the system noise powers, the detection gains, and the propagation losses predicted for a communication system.

Assuming a threshold post-detection signal-to-noise power ratio of 6 dB as used in the previous section and a noise temperature of $T = 300^{\circ}$ Kelvin, the input signal limitations will now be examined. Only noise associated with the input first stage will be considered since the noise contribution of succeeding stages is divided by the gain.

There are several sources of noise, as follows.

1. Johnson or thermal noise is caused by thermal agitation of electrons in the resistive portion of impedances. A voltage is produced by the corresponding random movement of charge through the resistance. Thermal noise is proportional to the temperature and the resistance. The rails have a relatively small resistive component and should not contribute significant thermal noise.

2. Schottky or shot noise is created when current passes through a semiconductor junction. Shot noise is a function of material and manufacturing processes. A noise current is produced from the random arrival time of the

charges when an operating current is flowing. The input stage device(s) should be carefully selected for superior noise characteristics.

3. Flicker or 1/f noise is also unique to semiconductor materials, although the origin is still in question. It is often the dominant noise component at frequencies less than 100 Hz. Since its magnitude decreases with increasing frequencies, it is not expected to be significant at the operating frequencies discussed in this report (approximately 10 kHz).

4. Popcorn noise is peculiar to some transistors, especially in integrated circuits. It is thought to result from the transistor current gain (h_{fe}) jittering between two values. It does not occur in all devices and testing can eliminate those which exhibit this effect.

5. Environmental noise sources include harmonics of rail signalling and power line inductive pick up, switching transients and noise generated by the train wheels slipping on the track and passing over the joints, lightning, etc. Because of lack of available characterization of these noises, it is not possible to include them in the calculations at this stage. The TRAC's operating frequency should be chosen to reduce interference from harmonics. Narrowband filtering will minimize the other effects.

The only one of these noise sources that can be estimated, at least in part, is the thermal noise. The other effects either are totally device-dependent or no information is available to use. Basing an estimate on just thermal noise will lead to an optimistic value for maximum range. This will provide insight into TRACS's theoretical upper limits.

Then the thermal noise power at the input of the receiver is

$$N_{in}(B_{in}) = kTB_{in}$$

for

$$k = \text{Boltzmann constant} = 1.38 \times 10^{-23} \text{ watts/}^{\circ}\text{Kelvin}\cdot\text{Hz}$$

$$T = \text{Receiver noise temperature} = 300^{\circ} \text{ Kelvin}$$

$$B_{in} = \text{Input noise bandwidth of receiver}$$

With these definitions, and assuming a ten cycle input noise bandwidth for the receiver then the input noise power is

$$N_{in}(1) = kTB_{in} = (1.38 \times 10^{-23})(300)(10) = 4.14 \times 10^{-20} \text{ watts}$$

or in decibels

$$\begin{aligned} N_{in}(\text{dB}) &= 10 \log (4.14 \times 10^{-20}) \\ &= -193.83 \text{ dBW} \end{aligned}$$

For our example

$$\text{Let } f = 10^4 \text{ Hz}$$

$$R_{oa} = 6 \text{ dB}$$

In section 4.1.3.5, the threshold input signal to noise ratio under these conditions was determined to be

$$R_i = -14.7 \text{ dB}$$

the threshold signal level at the receiver input is

$$S_{in}(\text{dB}) = N_i(\text{dB}) - R_i = (193.83 - 14.7) = 208.53 \text{ dBW}$$

Now considering a transmitter power of 1 watt -- 0 dBW, the allowable system propagation loss, L_p is

$$L_p = 208.53 \text{ dB}$$

Using the example of section 4.1.3.4, the propagated signal for this case is expected to be attenuated by

$$\alpha_{\text{sys}} = 40.8 \text{ dB/1000 feet of track}$$

thus the estimated maximum range for the track circuit operating under these conditions is

$$\text{Range}_{\text{max}} = \frac{208.53}{40.8} \times 1000 = 5111 \text{ feet}$$

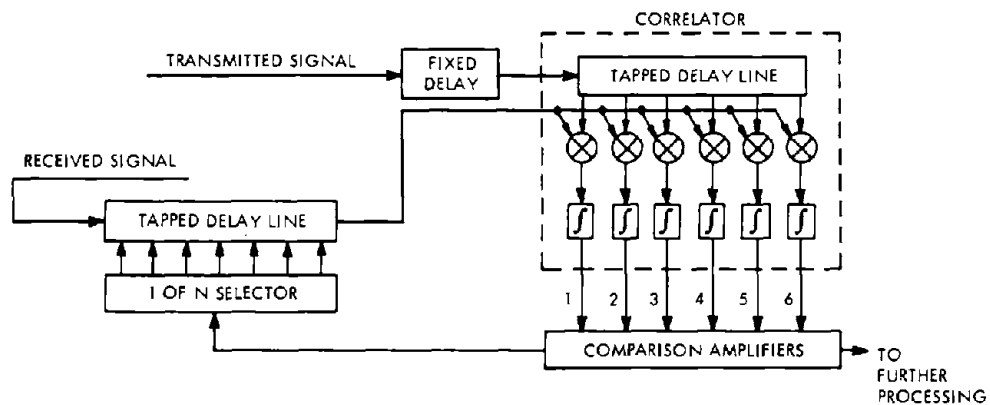
This is quite close to our original proposed range of one mile (5286 feet).

Recall that this range is based on 2 Ω /1000 feet ballast, and represents the maximum distance to the shunt. However, there are several factors such as noise which may produce a decrease in the actual range. More extensive data on the values of track electrical parameters, and a more accurate model may further increase or decrease the range. Such data is particularly needed to predict higher frequency operation.

4.1.4 System Implementation. The overall system description in the system introduction involved a classic auto-correlator. This concept, however has difficulty with long wavelengths as the maximum integrator output corresponding to the train location is difficult to separate from adjacent outputs. Also, a considerable number of sections would be required. For example, a one mile range with 100-foot segments would require 53 multipliers and integrators. However, a more fundamental problem is that each tap of the delay line is setup to correspond to a fixed number or fraction of degrees of a cycle. The distance between taps is to also correspond to a fixed distance. As we saw earlier the propagation velocity changes with change in electrical parameters due to weather conditions. This means the value of the

equivalent distance for each delay line tap is a function of weather! To compensate requires a continuous measure of some type. One such measure would be of the complex impedance.

A more straightforward method is to simply maintain a constant time lapse when no train is present. This is the concept to be developed here. It is not presented as a complete optimized system but rather as a concept which will require the normal design and development cycle to finalize. First, examine a system without regard to the change in ballast. Figure 4-9 shows a simplified system diagram. The transmitted signal pulse is fed directly into a fixed delay line whose delay corresponds to a fixed percentage of that required by the signal to travel to a fixed shunt at the maximum distance and return. The signal then goes to the tapped delay line portion of a correlator whose length corresponds to the remaining percentage of the transmit time.



⊗ MULTIPLIER

∫ INTEGRATOR

FIGURE 4-9. SIMPLIFIED TRACS CONCEPT (NO BALLAST COMPENSATION)

The received signal is fed into a second delay line. This received signal delay line also introduces a maximum delay corresponding to that required to transverse the rail to the fixed shunt and return. The delay line output is fed into the correlator and multiplied by each tap on the transmitted signal delay line. Each multiplier output is then integrated. All the integrator outputs together produce a detectable pattern.

One such pattern would be the 225° to 285° portion of a raised cosine wave, corresponding to the inflection point $\pm 15^\circ$. This portion of the waveform may be easier to detect. It corresponds to the maximum rate of change in the produced sinusoid at the integrator outputs, and has no repeated values. This pattern would then be detected by comparing the integrator outputs with a fixed pattern, and a "majority vote" circuit to allow detection when, say, 90 percent of the amplifier outputs have exceeded a preset level. The transmitted signal delay line taps, multipliers, and integrators may only require seven or eight sections for detection. In this case, each tap would be 5° increments of the transmitted signal. Thus each tap would have a time delay equal to

$$\tau_t = \frac{1}{f} \frac{5^\circ}{360^\circ} = \frac{1}{10^4} \times \frac{5}{360}$$

$$= 1.39 \times 10^{-6} \text{ seconds}$$

Each tap then corresponds to a distance equal to

$$d_t = v_p \tau_t$$

For our example case,

$$\begin{aligned}d_{\tau} &= (2.59 \times 10^7 \text{ ft/sec}) (1.39 \times 10^{-6} \text{ sec}) \\ &= 35.9 \text{ feet}\end{aligned}$$

The received signal delay lines total delay corresponds to the elapsed time to the shunt and return. For a range of one mile, the total round trip is two miles. Hence the total time delay, T_t , is

$$\tau_t = \frac{2 \times d_{\max}}{v_p}$$

for the example using the conditions and values developed with the power budget

$$\tau_t = \frac{2 \times 5111 \text{ feet}}{2.59 \times 10^7 \text{ feet/sec}} = 3.9 \times 10^{-4} \text{ seconds or } 0.39 \text{ millisecond}$$

The number and spacing of taps in the received signal delay line is dependent on the desired resolution. As shown in section 4.1.2, for a range segment of 100 feet (± 50 feet), the number of taps, n , is

$$n = \frac{d_{\max}}{\Delta s} = \frac{5111}{100} \approx 52 \text{ stages.}$$

For the example conditions, each tap, T_t , would be

$$\tau_r = \frac{3.9 \times 10^{-4} \text{ seconds}}{52} = 7.5 \times 10^{-6} \text{ seconds}$$

Hence each delay of 7.5 microseconds corresponds to 100 feet distance. For a train within the shunt, the circuitry uses the outputs from the comparing amplifiers on the integrators to control the tap section on the received signal delay line, selecting the tap which produced correlator outputs with the best pattern match.

One difficulty remains to be resolved. As the ballast conditions change, the propagation velocity, v_p also changes. Thus, although each tap of the transmitted signal delay line is still τ_t , 1.39 microseconds in our example, the corresponding distance, d_t , has now changed directly proportional to the change in propagation velocity,

$$v_p, (d_t = v_p \tau_t).$$

To compensate for this, one approach is to vary the incremental delay in the received signal delay line, τ_r , such that the distance, d_t , remains constant. For our example,

$$d_t = 100 \text{ feet} = v_p \tau_r$$

Hence as the velocity increases with drier ballast, the incremental delay must decrease to maintain the product $v_p \tau_r$ constant.

The tapped delay line with variable incremental delays can be implemented with at least two techniques. One method is to digitize the received signal and enter it into a shift register array with periodic outputs corresponding to taps, Figure 4-10. The signal is then clocked through the shift register at a rate to produce the required τ_r incremental tap delay. The tap selector then feeds the digital signal from the selected tap to a digital-to-analog converter before being routed to the multipliers.

A simpler method utilizing an analog delay line technique has been recently developed. It used a "charge coupled device" (CCD) which allows the sampled analog signal to be stored and shifted along a series of elements as an analog voltage (Figure 4-11). This is sometimes referred to as a CCD "bucket brigade". By varying the clock rate, the incremental delay between taps can be varied as required.

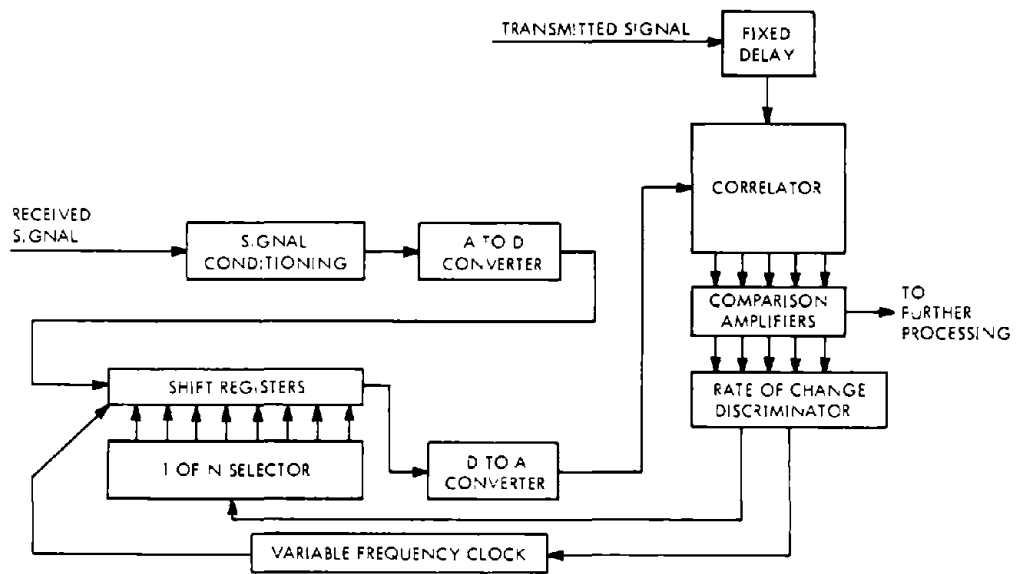


FIGURE 4-10. TRACS USING DIGITAL DELAY COMPENSATION

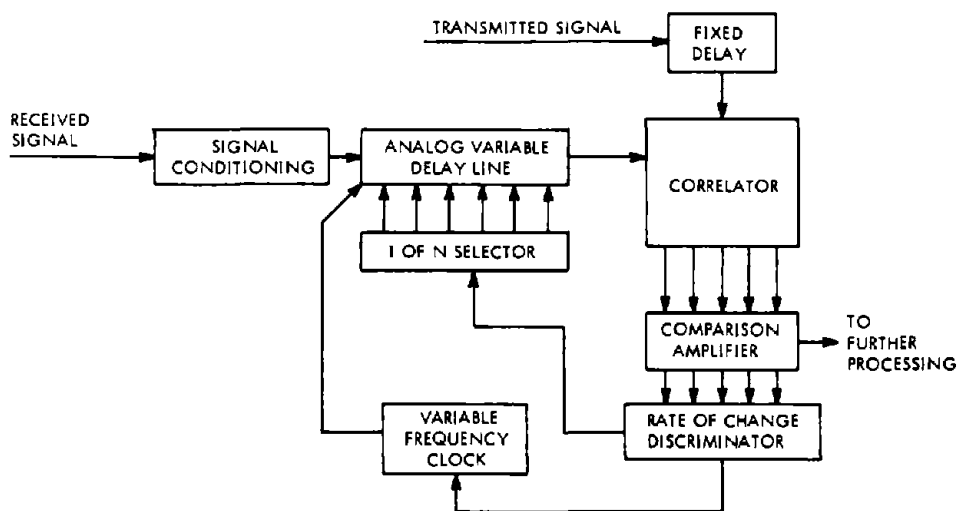


FIGURE 4-11. TRACS USING ANALOG VARIABLE DELAY COMPENSATION

The next question concerns how to know what τ_r to set. This is accomplished by a circuit that is sensitive only to very slow changes in the total delay, such as would be caused by change in ballast. With no train present, the signal waveform is reflected at the shunt, a known distance away. The tap selector on the receive signal delay line is set on the maximum delay tap, which then corresponds to the distance to the shunt. The system is set up so the integrators from the correlator are producing the desired pattern, indicating matched delays. If a very slow shift begins to occur, the differential amplifiers in the pattern recognition circuit indicate the shift after it exceeds a preset level, and produce an error signal to change the clock frequency in the receive signal variable delay line in such a way as to decrease the error voltage. In this way, the error voltage for very slowly varying signals is never allowed to exceed the higher threshold which would indicate an approaching train.

More rapid changes will be assumed to be caused by an approaching train and will be tracked by selecting taps on the delay line. Once the higher threshold is exceeded, the tap selector moves to the next tap, producing a shorter delay. Thus the system tracks the train location; the polarity of the error signal dictates whether the tap selector should move to longer or shorter delay. This same signal can be used to indicate direction of motion. The time of arrival, which dictates when to activate the warning system, must also be determined.

One approach is to measure the time between adjacent tap selections which is inversely proportional to train velocity. For our example, the taps represent an incremental distance, ds , of 100 ft. If the lapsed time between tap change is one second, the velocity is 100 feet per second. If the

constant warning time criteria, t_{cw} , for the system is 30 seconds and a velocity of 100 feet per second is detected, the system would activate at the tap corresponding to 3000 feet (tap number 30 for $d_s = 100$ feet). In practice, there would be a different time threshold, T , for the elapsed time measured between each pair of adjacent taps. The threshold velocity v_t can be expressed

$$v_t = \frac{d_s \times \text{tap number}}{t_{cw}}$$

but

$$v_t = \frac{d_s}{T}$$

Therefore the elapsed time threshold can be expressed

$$T = \frac{d_s \times t_{cw}}{d_s \times \text{tap number}}$$

or

$$T = \frac{t_{cw}}{\text{tap number}}$$

Thus knowing the train position, direction, and time to the crossing, appropriate criteria can be applied to activate or deactivate the warning system under any conditions.

The system can be used to control multiple crossings. In Figure 4-12, a TRACS unit is placed at crossings A and B. The distance between A and B must be less than the range of the basic system, here shown as one mile in each direction. The unit at A is able to detect and monitor the train through the distance S_1 . As it passes through A, the head end is picked up by the TRACS at B, the distance S_3 being monitored. The tail end continues to be monitored by the TRACS at A, so that S_2 is always known. Finally, when the tail end of the train passes through B, the distance S_4 is monitored. Here, however, the function is to determine when to open the crossing to traffic.

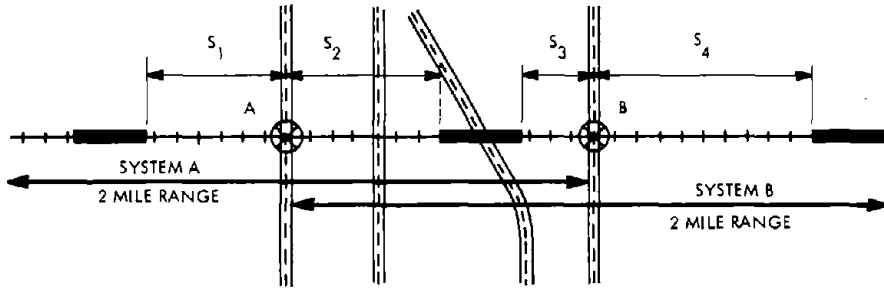


FIGURE 4-12. MULTIPLE CROSSING CONTROL

Thus the information necessary to the control of the crossings between A and B is available in two TRACS units. The actual control of the intermediate crossing can be done through a variety of communication links to the protection equipment per se.

4.2 OPEN GRADED ASPHALT FRICTION COURSE

As noted earlier, the criteria for warning time are dependent in part upon the time required for the driver of a motor vehicle to come to a safe comfortable stop. This in turn is a combination of reaction time and actual deceleration time. This latter is based upon wet weather conditions because typically, the coefficient of friction for pavement decreases fifty percent or more under such conditions. If the wet weather coefficient of friction can be raised from a typical 0.30 to 0.60, the stopping distance from application of brakes can be halved.

In looking for a means of increasing the coefficient of friction, or, as it is generally referred to, skid number,* the use of grooved pavement suggested itself. However, such grooves are expensive to cut in existing pavement, are prone to spalling, i.e., degradation, and do not greatly increase the skid number, their main purpose being the channeling of water away from the tire footprint, thus minimizing the dangers of hydroplaning. The grooves have another advantage in that they have a distinctive sound when passed over. This effect is sometimes used in much the same manner as rumble strips, although the sensation is less abrupt.

Research disclosed a new means of deslicking pavement which seems to have none of the disadvantages of grooving and all of the advantages. Called open graded asphalt friction course, it is a thin (under one inch) layer of aggregate and sand using asphalt as a binder. The difference between the proposed friction course and the common dense mix deslicking course lies in the proportions, open graded having a more uniform aggregate size. Through proper proportioning of the ingredients, a porous structure is achieved, (Figure 4-13).

Such a structure has the ability to allow the surface water to drain through onto the shoulder of the road, thus keeping the surface comparatively dry. In other words, the condition avoids the build-up of both the smaller quantities of water which increase the lubricity of the pavement as well as the larger puddles which contribute to hydroplaning. The rapid drainage precludes the formation of ice crystals on the surface while the void area dissipates the hydraulic pressure developed by any ice in the matrix.

* Skid number, SN, is the wet weather coefficient of friction X 100 as measured with a skidding tire per ASTM Standard #.274-70.

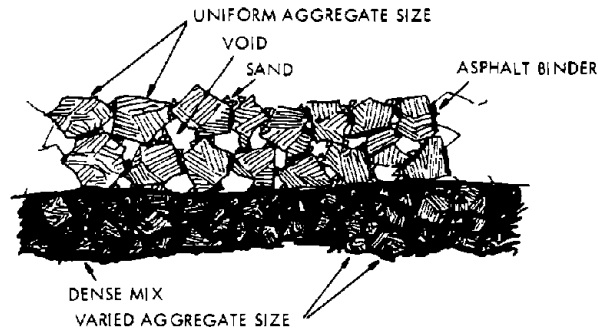


FIGURE 4-13. OPEN GRADED ASPHALT FRICTION COURSE OF DENSE MIX

The use of the open graded asphalt friction course has been oriented towards the deslicking of curves, gore areas, exit and acceleration lanes, and other areas where a low skid number is particularly dangerous. Its recommended use at grade crossings represents a smaller quantity per installation than these "conventional" placements. Consequently, the use of aggregates whose cost or characteristics would not be suitable for long stretches becomes acceptable here. For example, the skid number may be raised as much as 50 points through the use of such aggregates. Two approaches are possible. One is to use very sharp aggregates which are not now used because of excessive tire wear. This is not a factor over short distances.

The other approach lies in the use of finer aggregates, still in a porous mix, whose presence in a conventional mix render the course structure too susceptible to breakdown. This flaw can be corrected through the use of epoxy type binders which are, of course, more expensive than asphalt. Again, the limited area of overlay minimizes the extra material cost, making this concept also potentially feasible. It has been suggested that phosphorescent materials be incorporated into

the roadway to produce a glowing surface beginning at dusk. This idea has not been pursued, but is mentioned here as one of the possibilities offered by the use of an open graded friction course at grade crossings.

Returning to the basic characteristics of the material, the variagated surface, together with the absence of surface water, greatly eliminates glare and splash from the road. Such a feature is made more important by the fact that the surface offers better paint retention by virtue of the open pores. The greater surface area exposed to paint and the greater verticality of much of the surface permits the painted line to be observed at a much greater distance than is normally the case. Coupled with the decrease in glare and splutter, this visibility characteristic is outstanding in wet weather compared with normal markings which disappear from view under such circumstances. Presently, signs and markings painted on the road in the wheel tracks are subject to excessive wear and aforementioned lack of visibility in wet weather. The superior performance of open graded friction course in this regard should warrant renewed investigation into the intrinsic value of road surface warnings.

Another advantage to this material lies in the acoustic properties. The open structure reacts with the tire to produce a sound that is different than that experienced on typical pavement. The difference may manifest itself as either a reduction in intensity for bias construction tires or as an increase in sound and a decrease in tone for radial ply construction. At first, consideration was given to using this feature as an audible warning by alternating strips of the material with strips of dense mix. Investigation into the installation procedures disclosed that because of the course structure of the material, it could not be readily feathered and so the normal practice is to not attempt any gradual introduction but to start the material abruptly. The result is that the motorist encounters a bump in the pavement the height of the overlaid course. Such a characteristic turns a strip of

the material into a rumble strip (see Figure 4-14) although for reasons of adhesion, the course must be somewhat wider, perhaps 6 or 8 feet, compared with the conventional rumble strip.

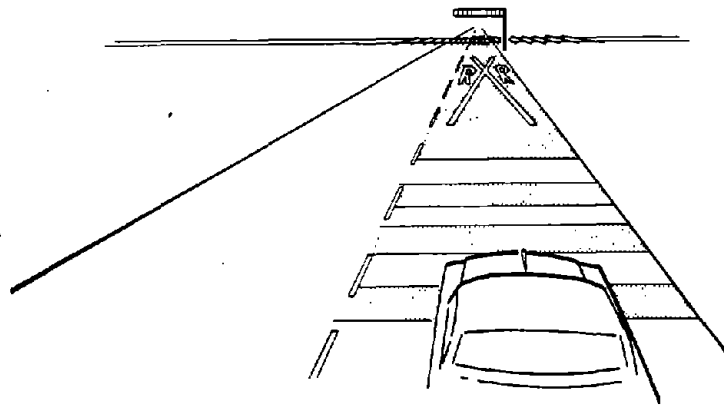


FIGURE 4-14. OPEN GRADED FRICTION COURSE WITH RUMBLE STRIP EFFECT

4.3 OPTICALLY PROGRAMMED TRAFFIC SIGNALS

Optically programmed traffic signals are a relatively new version of the familiar red-amber-green traffic light. As Figure 4-15 shows, they have the ability to sharply limit the viewing angle, the area in which the light can be seen, by optical means. This viewing area can be of any conical shape.

The basic argument for using this system grows out of the following rationale:

- a. Many drivers are unaware of the advance warning signs because of poor placement, low visibility, overexposure to the sign with attendant loss of impact, and other reasons.

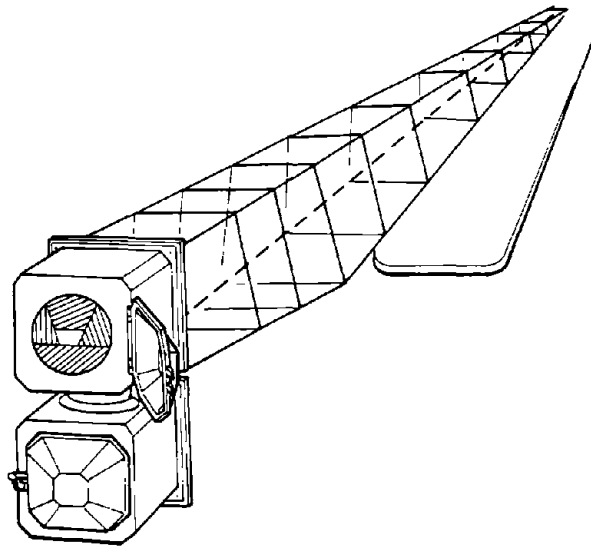


FIGURE 4-15. OPTICALLY PROGRAMMED
SIGNAL PROPAGATION

- b. Present site crossing warnings are not highly visible from a distance because they are designed for low power consumption. Lens design techniques have made efficient use of the light produced, but the system is essentially power limited.
- c. Traffic lights have not been used to any great extent because they have relatively higher power consumption, have a specific meaning whose content may not be applicable to grade crossings, and the fear that the wide spread current disregard for grade crossing signals may be transferred to traffic lights.

- d. A grey period exists for those vehicles in the immediate vicinity of the crossing when the protection is activated. Many go through the crossing because they realize that there is sufficient time from initiation of the signal until actual passage of the train. Others, slightly more distant from the crossing are uncertain. Still others at a greater distance may not be aware of the condition at all.

It was proposed that a system built around optically programmed traffic lights could be addressed to the above considerations in that:

- a. Their greater visibility would serve an advance warning function.
- b. The zoning capability permitted different messages to different drivers.
- c. Signals unique to railroads could be incorporated if desired.
- d. The crossing could be integrated with an urban traffic set-up.
- e. A flashing mode with low power consumption could be utilized during power line failures when battery back-up power would be required.

The principal of operation may be analogised to a slide projector.

From a distance all that can be seen looking into the projector is the color emitted from the projector. For example, in an area which projected red on the screen, all that could be seen looking back into the projector would be red. If a silhouette is projected, the driver's eye placed within the black portion of the silhouette will see no light

emitted from the projector. Thus, by simply masking with tape the desired areas of the signal head's limiter surface, Figure 4-15, it is possible to selectively control the roadway zones where the signal is not seen.

The front surface of the signal is a fresnel lens with a high line count. The result is a very uniform color saturation across the face. This "lighted lollypop" has been shown to have greater target value to the driver than the conventional traffic signal. As an optional feature, the lens is available with a molded-in prism of various shapes, conventionally an arrow for turns. The prism is not visible to the driver whose view lies in the programmed light "cone". However, through proper prism design, the arrow or other shape is visible to the driver whose line of view to the signal lies below the nominal light cone. Thus, a driver would see the colored ball which would abruptly change to a colored symbol when his distance from the signal has decreased enough. The value of this scheme lies in the fact that symbols do not have sufficient target value at a distance, but are very effective when properly viewed.

To illustrate the concept, a program of light changes is suggested here. The optimum program will probably have to result from field testing as driver reaction is not known at this time. However, the scheme proposed here should serve as a starting point.

1. When no train is approaching both amber lights are in the flashing mode. as shown in Figure 4-16.
2. When a train is detected and is, for example, 30 seconds from the crossing, the far zone red light would come on, replacing the amber. The near zone amber would change from a flashing to a continuous mode. as shown in Figure 4-17.

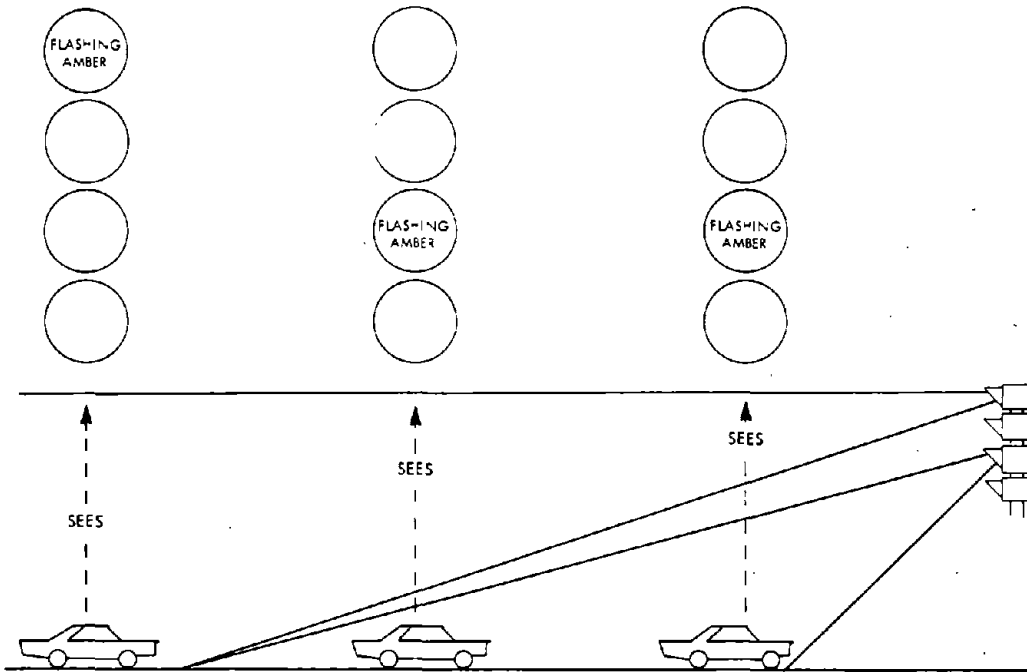


FIGURE 4-16. OPTICALLY PROGRAMMED SIGNALS - NO TRAIN APPROACHING

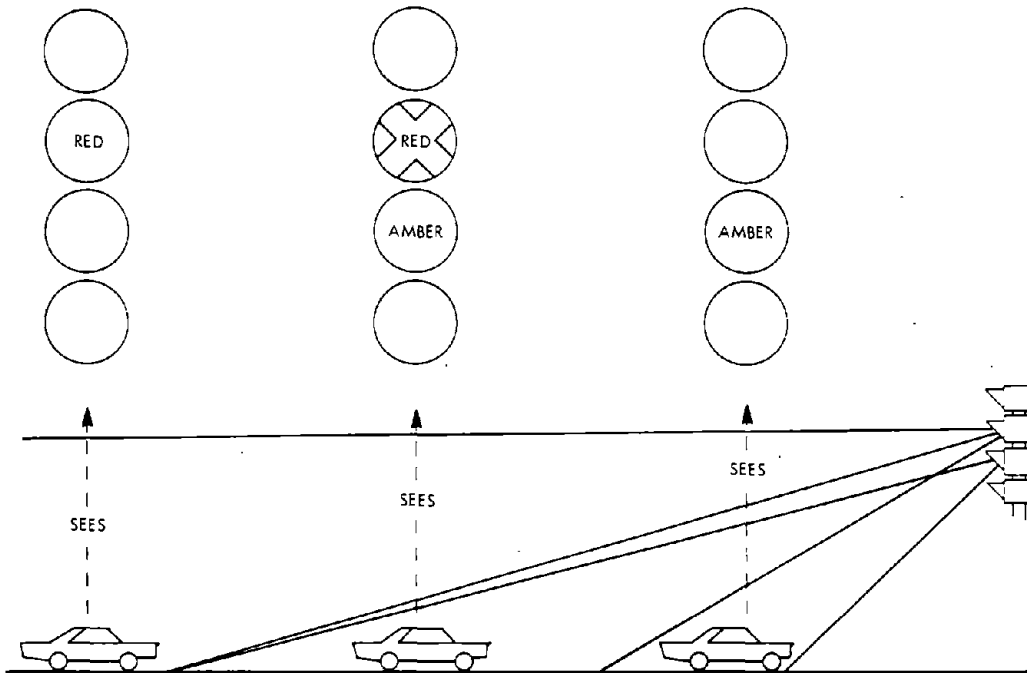


FIGURE 4-17. OPTICALLY PROGRAMMED SIGNALS - TRAIN DETECTED AT A DISTANCE

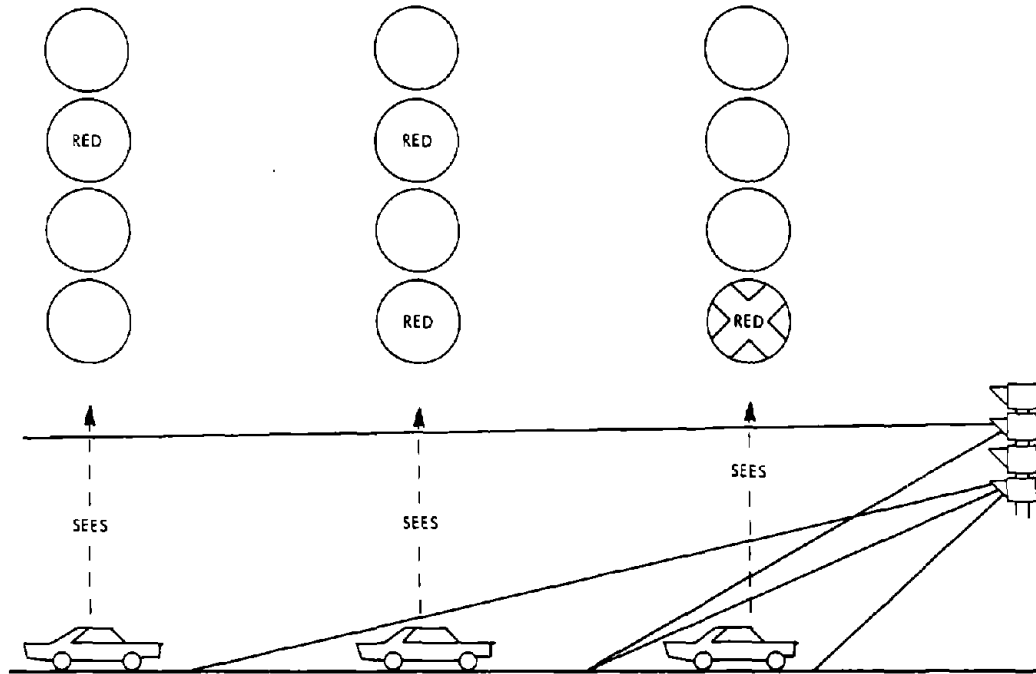


FIGURE 4-18. OPTICALLY PROGRAMMED SIGNALS - TRAIN APPROACHING CROSSING

3. After a sufficient time to permit the leading cars to cross, by 10 seconds, the near zone red would come on, replacing the amber, as shown in Figure 4-18.

The use of a molded-in prism in the shape of an X, the traditional crossbuck of the grade crossing, would be a useful addition to the red sections of both zones. Its use in the far zone would be to relieve some of the ambiguity that would otherwise result when a driver went from the far zone to the near zone in the period when they were showing different colors. Ordinarily, he would see a red light, amber light, and a red light in that order, a possibly confusing sequence. If, however, the driver were to see a red X in conjunction with the now visible amber, the indication of the need to stop would persist until reinforced by the change to red in the

near zone also. The X prism in the near zone is not as necessary, but would reinforce the association of red X with the crossing. This system performs the functions of both advance warning and crossing warning with an effectiveness that would diminish the requirement for gates at many crossings where they might otherwise be considered. Traffic lights could be in the province of the local jurisdiction rather than the railroads and thus could be tied into the general traffic control pattern where warranted.

5. COST ANALYSIS

One of the contractual requirements necessitated a cost analysis of the proposed system(s). It was not possible to perform a detailed analysis of each concept within the budgetary limitations of the contract because of the lack of data with respect to present railroad acquisition, installation, and maintenance costs of present equipment. Such data is not only sparse but, where obtainable, is so widely divergent between the railway systems as to be unhelpful in detailed evaluation. Data was available for some of the hardware acquisition, as well as the cost of similar installations outside the railroad, particularly from highway departments. Given the above circumstances, the analysis presented here, while recognized as noncomprehensive, is felt to adequately delimit the cost areas of the suggested concepts for the purpose of evaluating future programs for their implementation.

5.1 TRAC SYSTEM

Accurate cost assessment of TRACS is difficult at this time because of the unknown nature of the exact configuration and electrical parameters. One of the largest areas of uncertainty lies in the nature of the subsystem for looking down the track in both directions. It is felt that some of the functions for each direction could be shared by a single piece of hardware. The extent of this multiplexing, or whatever, is presently unknown. Again, the technology suggested is in some cases fairly new and the reduction in present costs over the next several years can only be guessed at. One example here is the use of charge coupled devices. It is assumed that as production increases, the costs will

greatly decline, for this has been true for most solid state devices. How much they will decline is still an unknown, however.

In comparing the complexity of the system with the more advanced nonconstant warning time motion detectors, it would appear that TRACS is of the same order of magnitude in cost. Because of its excellent sensitivity, TRACS appears to have the potential for a sizable cost-benefit improvement over the most advanced techniques presently available for constant monitoring at track circuits. For example, TRACS abilities compensate for varying ballast conditions in one step by the use of elapsed time measurement. This is an advantage over present systems which attempt to compensate for the changes in each of the individual electrical parameters. Further, the mechanism for doing so is of the same order as only one of the compensating mechanisms elsewhere employed. Thus, there appears to be the promise of cost reduction over comparable systems even though the magnitude of the reduction is not precisely obtainable at this stage of development.

5.2 OPEN GRADED ASPHALT FRICTION COURSE

This material has been placed in a number of locations throughout this country for evaluation purposes. During the evaluation process, an FHWA study developed a procedure for the design of these courses¹ that should permit the widespread use of this material by highway departments. Two of the most recent applications have been in the State of Ohio. The costs of these have been made available to this program.

Experience in Ohio in laying the open graded friction course provides cost estimates in the area of \$.80 per

¹R.W. Smith et al., Design of Open Graded Asphalt Friction Courses, Report No. FHWA-RD-74-2, Jan., 1974.

square yard at 7/8-inch thickness installed over a solid, level roadway. However, because this estimate was based on resurfacing an entire stretch of roadway, which was quite a bit larger than grade crossing requirements, the estimated cost for grade crossings is in the neighborhood of \$2.00 per square yard for a 7/8-inch thickness. If the roadway were unsound, then the corrective measures would vary. Assuming a road does not need complete restructuring, a 1-1/2-inch layer of dense mix would most likely be used to strengthen and seal the existing bed.

Such a treatment would cost approximately \$1.00 per square yard in addition to the cost of the friction course. However, as the size of the job increases, a corresponding decrease in the friction course expenditure should occur.

A typical expenditure for a four-lane road with 12-foot wide lanes and a 50 mph posted speed limit might be as follows.

Using the following formula based on AASHO policy on geometric design, the safe stopping distance is:

$$d = 1.47 Vt + \frac{V^2}{0.3SN}$$

where

d = safe stopping distance

V = speed in mph (50)

t = reaction time (2.5 seconds)

SN = skid number (70, dry pavement)

Substituting in the appropriate values, we have

$$d \approx 300 \text{ feet}$$

Note the permitted use of a skid number, 70, approaching that of dry weather rather than the 30-35 common to wet pavement.

Now, assuming 15 linear feet of rumble strip, we see that the road area is then:

$$\begin{aligned} & 2 \text{ approaches} \times (300 \text{ ft} + 15 \text{ ft}) \times 2 \text{ lanes} \\ & \times 12 \text{ ft/lane} \times \frac{1 \text{ sq yd}}{9 \text{ sq ft}} = 1680 \text{ sq yds} \end{aligned}$$

At \$2.00/sq yd, the installed cost of the surface is \$3360.

Since many crossings are now in need of repair, the additional benefits to be realized in safety may be obtained at a lower cost than the above, as mentioned earlier.

5.3 OPTICALLY PROGRAMMED SIGNAL LIGHTS

Since the proposed railroad grade crossing system can be viewed as analogous to a traffic controlled intersection, an approach toward the use of using existing traffic control equipment for the system was pursued. The traffic control equipment field is highly competitive, with many companies in the business. There are 29 firms listed in Thomas Register alone and many manufacturers do not advertise in the Register.

Several manufacturers of modern traffic controllers were contacted regarding the adaptation of their equipment toward the proposed crossing protection system. Their response was one of complete confidence in their abilities to match requirements using mostly existing equipment with a minimal amount of modification. This is largely due to the extensive use of solid state logic circuits and the flexibility associated with such devices. For example, one respondent stated that they have "a complete line of solid state logic cards that can be used to generate any combination of sequences that may be required using our standard product line as the main timing and control unit."

In addition to exploring the possibilities of using controllers with manufacturers, the Traffic Operations Division of Montgomery County, Maryland, was also contacted. Using prices and information supplied by these two sources, an installation for a two-lane, single-track crossing analogous to a traffic intersection runs in the neighborhood of \$17,000, as shown in Table 6-1. This price, which does not include track circuitry, consists of 3M programmable signal heads (\$6,800), a controller (\$4,000), support structure (\$3,300), and labor (\$2,900). Keep in mind,

TABLE 5-1
ESTIMATED COST OF TRAFFIC CONTROL EQUIPMENT AND OPEN GRADED ASPHALT FRICTION COURSE FOR A TWO-LANE SINGLE TRACK CROSSING

Item	Cost
Signal Heads	\$6,800
Controller	4,000
Support Structure (Pole)	3,300
Labor, Installation & Service	2,900
TOTAL	\$17,000

however, that these estimates are effective at present, but that costs have risen sharply over the past 3 years. Just how much this \$20,200 total figure will increase over the next 5 years is dependent upon inflation.

Using two mast arms instead of the four poles would add about \$800 to the cost. It should be remembered that these mast arms are of the traffic intersection type and not the single or double cantilevered type with walkway often employed by the railroads. At \$2,000 for each mast arm, an equivalent traffic intersection would necessarily require

four, increasing costs to \$5,840 over the \$17,000 figure. The controller estimate is based on a complete solid state unit, including solid state switching and flashers. The old style electronic type of controller utilizing relays is approximately \$2,500. Controllers that have been recommended for this system are either two-phase semiactuated units used in conjunction with a detector, or a similar controller used with a preemptor. So-called conflict monitors or fail-safe devices are also available. These devices check the operation of the signal heads as compared to prearranged sequences. Should a "conflict" occur, the device automatically switches the controller to a flashing phase. Presumably, any other indication could be programmed into the system. Some monitors "scan" the system after a preset delay to determine if the conflict still exists. Conflict monitors range from \$300 to \$500, depending upon input and scan capabilities.

However, railroad grade crossings apparently do not neatly fit the analogy of traffic intersections, insofar as estimating costs of material and installation. Those manufacturers of existing railroad crossing protection equipment that we contacted were reluctant to even attempt to guess at the cost of an "average" crossing protection system. They firmly stated that there is no such thing as an average crossing and any estimate would be misleading or erroneous when considering any particular grade crossing. The best indications from conversations and material received from these firms suggest that an analogous railroad grade crossing system is within the same order of magnitude as our example, but perhaps two to three times the proposed system when considering a two-track, four-lane crossing. Upon reviewing the literature received from the railroad crossing protection manufacturers, we noted many aspects of the crossing which could affect costs either way, depending how extensively they become part of the picture. An example of the parameters

concerning the equipment manufacturer is shown in the accompanying specification chart, supplied by courtesy of WABCO (Figure 5-1).

Additionally, Part 149 of the AAR Signal Manual "Automatic Highway Grade Crossing Signals and Devices" lists many items that the "purchaser" must furnish or allow for that may affect costs substantially, depending upon the variety of such work that must be done. These are listed below:

- 1) Ties for support of apparatus
- 2) Move ties as may be necessary
- 3) Move switch and tie rods as may be necessary
- 4) Insulated rail joints
- 5) Bridge insulations
- 6) Switch-rod insulations
- 7) Tie-rod insulations
- 8) Gauge-plate insulations
- 9) Concrete:
 - a) Transit mixed
 - b) Mixed at site
 - c) Precast
- 10) Gauge-plates and rail braces
- 11) Necessary grading and drainage
- 12) Excavation of solid rock
- 13) Poles, guy wires, anchors and bracing for serial lines
- 14) Cross-arms, pins, insulators and fittings
- 15) Line wire

1 OF 4

**HIGHWAY CROSSING PROTECTION
PROJECT SPECIFICATIONS**

CUSTOMER _____

LOCATION OF INSTALLATION _____

DATE _____

1. NO. OF TRACKS _____

SINGLE

DOUBLE

OTHER

2. TYPE OF OPERATION _____

AUTOMATIC

MANUAL

IF AUTOMATIC _____

AREA WARNING

DIRECTIONAL CONTROL

ONE WAY

TWO WAY

3. TYPE OF HIGHWAY TRAFFIC _____

4. MAXIMUM SPEED _____ MPH

5. TRAIN SWITCHING OR STOPPING IN APPROACH ZONES _____

YES

NO

1

2

3

4

FIGURE 5-1. TYPICAL CHECK LIST FOR SPECIFICATION OF GRADE CROSSING PROTECTION

- 16) Housings:
 - a) Instrument
 - b) Battery
- 17) Cables:
 - a) Aerial
 - b) Submarine
 - c) Underground
- 18) Conduits:
 - a) Main
 - b) Branch
- 19) Manholes
- 20) Track bonding
- 21) Sand, clay or loam for cable trench, including protection plank
- 22) Necessary attachments to signal apparatus in service
- 23) Make necessary alterations of any part of existing structures or apparatus
- 24) Make necessary alterations to existing circuits
- 25) Unload and properly house material that arrives on the ground before the contractor's force; this work to be done under the supervision of the contractor's representative
- 26) Distribute material
- 27) Buildings

- 28) Tools, fixtures for building and supplies
required for the maintenance of the system
- 29) Communication system
- 30) Control panel for manual supervision
- 31) Power supply

It should be noted that many of these items mentioned in the two specifications are also included in the material and installation costs of our estimate. Exactly how extensively all of these items affect costs is also dependent upon jurisdictional authority, dictating who should accomplish the actual installations and under what specifications.

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APPENDIX A

REPORT OF INVENTIONS

In this report a number of new concepts are explored. Several involve a special application of existing techniques, such as use of the open graded asphalt friction course (Section 5.2) and optically programmed signal lights (Section 5.3) at grade crossings. Others provide substantial analysis of a novel train ranging and correlation system for train detection at grade crossings, described in Section 5.1.

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