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CONSTANT WARNING TIME CONCEPT DEVELOPMENT FOR MOTORIST WARNING AT GRADE CROSSINGS

FINAL REPORT

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16. Abstract One important improvement for achieving greater effectiveness in train-activated warning systems at railroad-highway grade crossings (RHGC) would be to provide a constant warning time (CWT) to the motorist of the impending arrival of a train.

This report describes an investigation that was carried out to identify, evaluate and demonstrate the feasibility of concepts upon which a general purpose CWT system could be developed. The scope of the study includes train detection, signal transmission, and associated logic, but did not include motorist warning devices. Primary emphasis was placed on the development of CWT concepts rather than equipment for such systems.

Train detection techniques with the greatest potential for application to CWT systems are described and evaluated. These include seismic, magnetic, and acoustic transducers; doppler, guided and two dimensional radars, video sensors, strain gages, and proximity switches. The most promising of these are shown to be based on magnetic and acoustic concepts. Field tests carried out to demonstrate the feasibility of these techniques are described and the data is analyzed.

It is shown that a great deal of further testing and development will be required before either of those techniques can be incorporated into a working CWT system.

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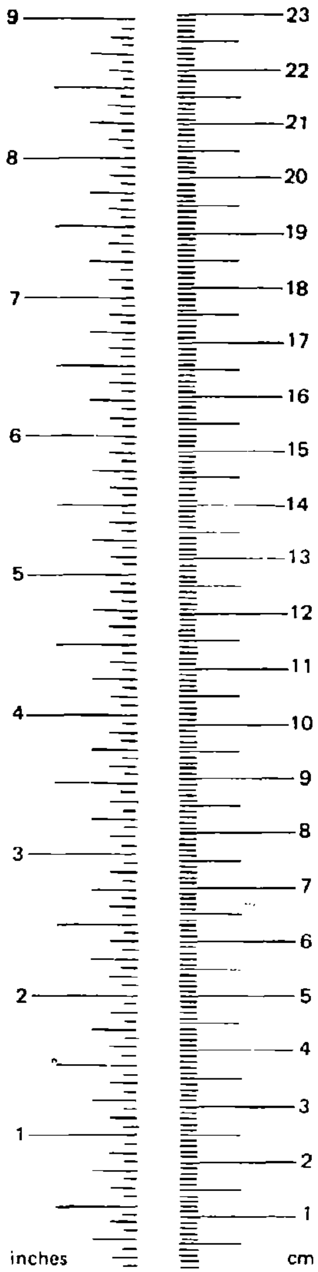
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

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

*1 in. = 2.54 cm (exactly). For other exact conversions and more detail tables see NBS Misc. Publ. 286. Units of Weight and Measures. Price $2.25 SD Catalog No. C13 10 286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	36	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
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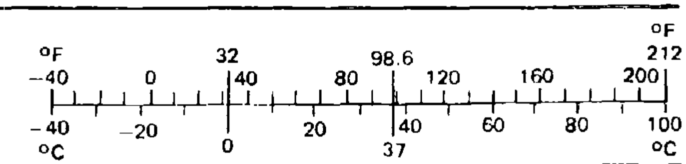
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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EXECUTIVE SUMMARY

The Department of Transportation has directed many studies in recent years with the overall objective of achieving greater effectiveness in train-activated protection at railroad-highway grade crossings (RHGC). It has been found that one important improvement would be to provide a constant warning time (CWT) to the motorist of the impending arrival of a train.

CWT, by definition, requires that the motorist warning signals and their associated gates at the RHGC be activated a specified amount of time before the arrival of the train which is usually 20 seconds. The overall objective of the CWT concept is to provide safety to the motorist while eliminating needless waiting for slow trains or trains which may have stopped on the tracks prior to reaching the crossing.

This report describes an investigation that was carried out by Systems Technology Laboratory, Inc. to identify, evaluate and demonstrate the feasibility of concepts upon which a general purpose CWT system could be developed. The scope of the study included train detection, signal transmission, and associated logic, but did not include motorist warning devices. Primary emphasis was placed on the development of CWT concepts rather than equipment required for such systems.

The report assesses the state-of-the-art of CWT signaling through a review of the capabilities of commercially available CWT devices. The limitations that have prevented general acceptance of these devices by railroad management are identified and discussed. These limitations are: low reliability compared to systems based on conventional warning systems, and poor compatibility with other signaling systems that use the rails and with powerline overbuilds that share the right-of-way.

Train detection techniques with the greatest potential for application to CWT systems are described and evaluated. These include seismic, magnetic, and acoustic transducers; doppler, guided and two dimensional radars, video sensors, strain gages, and proximity switches. The most promising of these were shown to be the magnetic and acoustic transducers. Field tests that were carried out to demonstrate the feasibility of these techniques are described and the data is analyzed. The results of these tests established that the acoustic transducer is the more flexible detection device in that it provides continuous train detection when the train is standing still (engines running) or moving in either direction. Its greatest weakness is that it depends on a continuous, or nearly continuous, path through the rails for the transmission of acoustic energy. The magnetic sensor does not rely on the rails. However, it does not provide continuous train detection which could cause complications in the case of switching operations and in addition may have difficulty detecting very slow moving trains. It was shown during the study that a great deal of further testing and development will be required before either of those techniques can be incorporated into a working CWT system.

1. INTRODUCTION

1.1 BACKGROUND

Credibility has long been recognized as one of the key factors that determine the effectiveness of train warning systems. To be effective in preventing accidents at railroad-highway grade crossings, a warning system must above all be seen and understood by the motoring public. But to be fully effective, it must also be believed by that public. Few things can more decisively reduce the effectiveness of a warning system than the loss of its credibility in the minds of motorists. A warning system that is not believed will eventually be ignored, and accidents will be the inevitable result. Moreover, once lost, credibility cannot be easily or quickly restored.

Train activated warning systems are particularly susceptible to loss of credibility when they cause unnecessary or prolonged operation of flashing lights and automatic gates. Many motorists have had the experience of waiting at a crossing without ever seeing or hearing a train while warning lights were in full display; and many, after waiting in vain for a train to appear, have at one time or another driven around lowered gates - an illegal and highly hazardous maneuver. When inappropriate activation of warning devices at a crossing becomes so frequent and so onerous that motorists habitually drive through or around these devices to the point of actually ignoring them (perhaps unconsciously), then the effectiveness of the warning system has been compromised and sooner or later an accident attributable to this cause will occur.

Accident statistics[1] show that most train-vehicle accidents occur when drivers enter a crossing while warning signals are

[1] Rail-Highway Grade Crossing Accident/Incident Bulletin, No. 43, Federal Railroad Administration, Office of Safety (1977).

properly indicating the approach of a train. Although some of these accidents are undoubtedly due to drivers failing to see or understand the signals, many occurred either because drivers did not believe a train was approaching or because they believed there would be a long delay before the train arrived at the crossing. Thus, one can argue plausibly that lack of reliability is a major factor contributing to a reduction in the effectiveness of train-activated warning systems in the U.S.

Railroads and their suppliers have been well aware of problems caused by inappropriate operation of train warning systems, and since 1963[2], they have attempted to deal with these problems by developing new types of warning equipment that can sense and measure the motion of a train as well as continuously and accurately determine its position. Most warning systems now in use are based on conventional DC track circuits and do not detect train motion. Neither do they determine train position. These DC track circuits only determine the instant when a train moves to within a fixed approach interval from the crossing - an interval that may be more than 5,000 feet in length. They do provide extremely reliable, continuous information that a train is somewhere within the approach interval, but they have no way of determining where the train is within this interval. They cannot sense that a train has stopped somewhere within the approach or that a train, having stopped, is moving away from the crossing. They cannot determine when a train enters the approach at such a low speed that its arrival at the crossing will be delayed for many minutes. In all of these cases, lack of specific information means that warning signals must be activated at the crossing very shortly after the train is first detected and that they must continue to operate as long as the train remains within the approval interval however long that may

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[2] J. G. Frayne. *Theory and Operation of Grade Crossing Predictor is Explained*. Railway Signaling and Communications, Vol. 56, No. 11, November 1963.

be and regardless of the consequences to motorists. Thus, when a motorist approaches a crossing with a warning display in progress, his only sure knowledge is that there is at least one train somewhere within a certain distance from the crossing. He does not know what that distance is; and unless he can see it, he cannot know whether the train is stopped, moving away from the crossing, approaching the crossing slowly, or closing rapidly. In general, he has no way of knowing when or whether a train will reach the crossing.

Equipment capable of relieving some of the motorist's burden of uncertainty and disbelief at grade crossings has been available commercially for more than 10 years. This equipment can supply much of the information that is unobtainable from conventional warning systems (Appendix A). In simplest form it consists of an electronic device called a motion sensor or motion detector which can detect the presence of a train out to a certain maximum distance from the crossing and determine continuously whether it is moving toward or away from the crossing. This device has the capability of alleviating some problems caused by a train that triggers the warning system but comes to a stop before it reaches the crossing. It can be used to clear the crossing when it senses that a train has stopped, or is moving away, thereby preventing prolonged warnings to motorists for trains that either will never reach the crossing or will do so only after a long delay caused by one or more stops.

Other, more elaborate equipment is available that includes features of the motion sensor and adds the capability of measuring train speed and distance. By feeding real-time train speed and distance data to a computer, these so called Grade Crossing Predictors (GCP) are able to compute and continuously update an estimated time of arrival at the grade crossing. This information could, of course, be displayed at the crossing for the immediate enlightenment of motorists. However, to minimize errors in judgement, the device is designed to delay until the estimated time of arrival has fallen to a certain preselected value, e.g., 25 seconds, before signaling the start of warning displays at the crossing. In this way, the motorist does not have a long wait for low moving trains and is given some reason to expect the arrival of a train at the crossing within a uniform and tolerable length of time. For this reason, systems based on this device have been described as constant warning time (CWT) systems. The actual length of the warning may vary somewhat since the train may accelerate or decelerate after the warning has started. However, by waiting until a train closes to the minimum distance consistent with its speed and a fixed warning time before beginning warning displays, the system reduces the probability that a significant change in velocity can or will occur after the warning starts. In effect, the GCP attempts to give motorists a fixed warning time and replace the fixed approach interval of the conventional system, which must be long enough to accomodate the fastest trains, by variable approach intervals with lengths determined by measured train speed.

Although this equipment has been available for many years and it has demonstrated that it can approach a true CWT system in operation, its use in the U.S. has been limited to a few railroads - most notably, the Southern Pacific which has provided the basic financial and conceptual support for its earliest development. The question naturally arises then: Why has the GCP not been widely accepted by U.S. railroads and rail authorities? There is apparently no simple answer to this question. Rather, there are many partial or fragmentary reasons which make up the complete answer. These reasons can be discussed in the general context of reliability, compatibility and cost.

By most industrial standards, the basic GCP module* is a highly reliable piece of equipment. Failure rate data for this device is not generally available to the public in documented form. However, a mean time between failure (MTBF) of 2½ - 3 years is frequently quoted by knowledgeable industry sources. This rate of

*This study of the GCP is based upon the Model 300 series. It must be noted that updated models have been developed since this study was performed.

failure appears to be quite low, and so it is; but by railroad standards, which have been established over many years by the DC track circuit with a MTBF of nearly 10 years, it appears high. In fact, it is uncomfortably close to the maximum failure rate that is usually considered acceptable by railroads (MTBF = 2 years) for critical equipment. There are several reasons why GCP's have not approached the reliability of DC track circuits. In the first place, the GCP is a vastly more complicated piece of equipment with a correspondingly larger number of components. On this basis alone, with other factors being equal, a higher failure rate would be expected due to component damage and malfunction. Not all of this increase in complexity is related to the GCP's primary function of estimating the arrival times of trains at grade crossings. Part is due to the requirement that it operate in a fail-safe manner (See Section 2.1.2.). Fail-safe operation is a burden shared by all train warning systems, but it falls more heavily on the more complicated system. In satisfying the fail-safe requirement, there is a need to add complexity to the system and so in doing, increase the likelihood that a safe failure will occur.[3]

The GCP is also susceptible to failure due to environmental factors that are beyond the control of systems designers. Most important among these are changes in ballast resistance - particularly changes that reduce ballast resistance to relatively low levels. Both track circuits and GCP's lose sensitivity as ballast resistance decreases, but GCP's are much more severely affected. Loss in sensitivity is reflected in loss of accuracy of predicted arrival times. These losses, if continued, will reach a point where the system can no longer function properly. The system is designed to sense when this has occurred, but its only option in the event is to initiate a safe failure mode since there is no way

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[3]J.B. Hopkins, R. Abbott, F.R. Holmstrom, E.F. White, and A.T. Newfell, *A Communication-Link Approach to Actuation of Grade-Crossing Motorist-Warning Systems*, U.S. Department of Transportation, Transportation Systems Center, Cambridge, MA. July 1975.

to adequately compensate for ballast resistance if it is low enough. The most common safe failure mode for these systems is continuous operation of the warning system - a procedure that is extremely disruptive and dangerous to automobile traffic in the vicinity of the crossing. In some cases, the safe failure mode consists of switching to a back-up track circuit which is less likely to be disabled by low ballast resistance. Clearly, the latter procedure entails considerable added expense to the system.

Losses in sensitivity and prediction accuracy can be observed in the GCP when the ballast resistance reaches the neighborhood of 10 ohms per 1000 feet of track.[2] At the 10 ohm level, these losses are usually not significant with DC circuits or low frequency AC circuits, however, they can begin to cause a problem at the higher frequencies employed by the GCP (654 Hz). When ballast resistance drops to 5 ohms or below, the GCP faces serious problems and failures can be expected. If all railroads in this country maintained their track in such a condition that a minimum of 10 ohms ballast resistance per 1000 feet of track could be guaranteed, the failure fate of GCP's would be significantly reduced, and this device would probably be much more extensively employed. Unfortunately, most U.S. railroads can only guarantee minimum ballast resistances in the 2-3 ohm range,[4] and, consequently, there are many areas where the GCP cannot be used without encountering problems.

In addition to carrying the burden of a relatively high failure rate as compared to the DC track circuit, the GCP encounters problems in achieving compatible operations with other systems that also generate electric currents on the rails either intentionally or unintentionally. The GCP can be both the source and the victim of these electromagnetic compatibility (EMC) problems. In the

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[2] Frayne.

[4] A.J. Carey, *Basic Track Circuit Limitations*, Bulletin 261 Westinghouse Air Brake Co. Untion Switch and Signal Division, Pittsburgh, PA.

former category, there is the problem of achieving compatible operation of the GCP with DC track circuits that may be required near crossings for block signaling purposes. One frequently encountered problem is caused by the terminating shunt that is required by the self-check system of the GCP (Appendix A). DC track circuits cannot operate with a direct short circuit across the rails, and therefore another type of shunt must be provided for the GCP.[2] Similarly, battery operated DC track circuits can cause unwanted shunts for the GCP due to the low impedence of the battery circuit when connected directly across the rails.[2] Other compatibility problems arise when insulated joints required by the GCP near the crossing fall within the range of a DC track circuit and, conversely, when insulated joints required by DC track circuits fall within the range of a GCP. It must be emphasized that all of these compatibility problems usually can be solved by one means or another. But this cannot be achieved without penalties (sometimes severe) in the form of increased installation, maintenance, and operating costs and decreased reliability for the GCP and for other signaling systems that must use the rails. The GCP is far from being an "overlay" system in the sense that this word is applied to some audio frequency track circuits (Appendix A).

The GCP is also faced by EMC problems involving large, nonsignaling systems that regularly produce interference currents on the rails, and some of these problems are intractable at present. Since the GCP is usually the victim in these cases, this means that the use of the GCP is generally precluded wherever large current source systems are in place and required. In other words, a basic incompatibility may exist to the exclusion of the GCP. This situation exists on electrified railroads which use the rails to provide a return path for traction currents. Since perfectly balanced rail currents cannot be guaranteed, the very large and rapidly

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[2] Frayne.

fluctuating traction currents will produce time varying differences in potential across the rails at the point where the GCP is attached. These differences in potential may incorrectly interpret the GCP as an approaching train even though the train that produced the traction current is miles away and heading in the opposite direction. Occurrences of this kind are clearly intolerable for any warning system, and therefore, the GCP is regarded by some railroads as being incompatible with electric traction systems. The GCP will be required to undergo considerable further development in order to solve these problems. At present, it is an open question whether or not a satisfactory means will ever be found to render the GCP compatible with AC traction systems.[5] The outlook for achieving compatibility with DC systems is brighter, but both of these goals are likely to become more elusive as more and more thyristor controlled locomotives are put into service on U.S. railroads. Thyristor controlled locomotives (AC and DC) generate traction currents with a higher harmonic content than is associated with currents generated by older types of locomotives and these harmonics can only make the system designer's job more difficult.[6]

A similar problem occurs on railways that are heavily overbuilt with high voltage power lines. These power lines can induce unbalanced currents and voltages on the rails that can affect the GCP in the same way that traction currents can. Where both traction currents and power overbuilds occur on the right-of-way such as along the Northeast Corridor, the problems faced by the GCP are formidable.

In summary, under certain conditions, the GCP can provide virtual constant warning time operation at a cost comparable to

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[5]F.V. Blazek, *Track Circuit Characteristics Associated with Motion Monitor*, Westinghouse Air Brake Co., Union Switch and Signal Division, Pittsburgh, PA, 1975.

[6]R. L. Monroe. *A Survey of EMI Problems Generated by Traction Control Systems Employing Thyristors*, prepared under FRA Contract No. DOT-FRA-8042, Systems Technology Laboratory, Inc., Arlington, VA, July 1979.

conventional systems. The required conditions are: stable ballast conditions with minimum ballast resistance greater than 5 ohms/1000 feet of rail, low levels of interference current on the rails, few other signaling systems near the crossing, and simple track/crossing geometry. If one of these conditions is absent, system reliability will be adversely affected and installation and maintenance cost will be noticably higher than for conventional warning systems. If most are absent, installation and maintenance costs are likely to be significantly higher than for conventional systems. When all conditions are absent, use of the GCP will probably not be feasible due to low reliability and high costs. Since most of these conditions do not exist at most U.S. grade crossings, the GCP, in its present state of development, is somewhat limited as a general-purpose grade crossing warning device.

1.2 SCOPE AND OBJECTIVES

Although state-of-the-art CWT systems based on the GCP do perform adequately under favorable conditions, these systems have not met acceptable standards for general-purpose utility and to date they have found limited employment at U.S. grade crossings. The investigation described in this report was undertaken as a step leading toward the development of a general-purpose CWT system free of the limitations that have so far prevented the widespread adoption of this potentially important train warning technique. The objective of the study is to identify, evaluate and demonstrate the feasibility of concepts upon which a CWT system can be based. The study is limited to train detection for the purpose of motorist warning and does not include warning for the purpose of train signaling or control. The scope of the study includes train detection, signal transmission and associated logic but does not include motorist warning devices. Primary emphasis is placed on the development of CWT concepts rather than equipment required for such systems.

In considering these concepts, the following general characteristics were taken as design goals for an acceptable all-purpose CWT system.

- simplicity
- fail safe operation
- reliability
- compatibility (overlay capability)
- low false alarm rate
- low hardware, installation, maintenance and operation costs
- modular construction (unit replacement of major components)
- damage resistance (vandals, weather and normal track maintenance procedures)

Since not all of these characteristics are attainable to the same degree in a single concept, trade-offs and compromise were a necessary part of the evaluation procedure.

The minimum functional requirements of any CWT system are:

- to reliably detect the presence of an approaching train;
- to accurately determine its position and velocity;
- to predict the time of arrival of the train at the grade crossing;
- to initiate warning displays at a predetermined time prior to the arrival of the train at the crossing; and
- to deactivate warning displays after the train has cleared the crossing.

Although not required for nominal CWT operation, the ability to measure train acceleration and deceleration is considered highly desirable since this feature can greatly improve the accuracy of predicted arrival times when train motion is non-uniform. These requirements are reflected in the basic elements of a CWT system which consist of:

- Train detection devices (sensors

- Train tracking devices (sensors)
- Data transmission subsystems
- Data processing subsystems
- Warning signal activation systems

Ideally, the system should be able to function in all railroad environments; to discriminate and process multiple traffic conditions; be adaptable for all track geometries and directions; and to allow for custom installation as required by the various combinations of train speeds and lengths.

Of the many potential train detection techniques that could be considered for a CWT system, the following were chosen for study in this investigation: seismic, magnetic, acoustic, radar (3 types), video, strain gage, and pressure. Two of these, the magnetic and acoustic, were determined to have the most promise for CWT application and were given field tests. These tests verified their potential in this area but also revealed that a great deal of further testing and development would be required to translate either into a working CWT system.

2. CONCEPT IDENTIFICATION

The effort of identifying various concepts which may be valuable in providing constant warning time to motorists at grade crossings has been divided into three (3) steps. The first step was to establish performance criteria by which to judge the concepts. Secondly, present techniques of technology in the sensing and communications areas were examined. These techniques can be looked at as available components which could be used singly or in combination as an eventual system. Lastly, various candidate concepts were tested in quick-look experiments and addressed according to how well they met performance criteria. Through this three-step process, two feasible CWT concepts were identified.

2.1 PERFORMANCE CRITERIA

As previously defined, a CWT system must provide a reliable and credible length of time so that a motorist at an RHGC knows a train is actually approaching. In order to meet this overall performance standard in a practical and effective manner, certain performance criteria have been established and are outlined below.

2.1.1 Reliability

Of most importance to a CWT system's success is the degree of reliability it possesses. In order to prevent motorist-train accidents, motorists must be able to trust that when a "stop for train" display is activated, a train will in fact reach that crossing within the 20-30 seconds prescribed. Should the "stop for train" display be incorrectly and randomly activated, the entire system will lose its credibility.

2.1.2 Failsafe

Any system will fail on occasion. Provision for failure without hazard must, therefore, be incorporated into the design of the system. This provision is referred to as "failsafe," and in terms of the CWT system concept, it entails activating the "stop for train" display should a system malfunction occur. There are two levels of malfunction to be considered: (1) that malfunction which completely disables the system and (2) that which eliminates the system's accuracy or redundancy. An example of level (1) malfunction is loss of primary power to the warning system. This situation is dealt with in a failsafe manner by crossing gates that are designed to remain open when energized and to close under the operation of gravity when power is cut off. It can also be handled by relays which automatically (under gravity or spring loading) switch to an auxiliary power supply when deenergized by a primary power failure. Level (2) malfunction is illustrated by a situation in which invironmental factors or poor track maintenance reduce the ballast resistance to a level below that which is required for safe operation of an Audio Frequency Track Circuit or Motion Sensor (Appendix A). This situation leads to a continuous operation of the warning signals. It can also be handled by switching to a DC track circuit which is less sensitive to low ballast resistance.

2.1.3 Ease of Maintenance

When a failure in the system does occur, it is essential that it be repaired rapidly. To expedite this, the system should be conceived so that it can be serviced easily and quickly. Ease of maintenance will contribute to long-term reduced costs of system ownership, and rapid maintenance will contribute to total system credibility.

2.1.4 Weather and Vandal Resistance

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

2.1.5 System Adaptability

A very important requirement of any CWT system is that it should be able to operate in different grade crossing situations. A system which is able to operate reliably and inexpensively at one particular crossing, yet cannot adapt to a crossing with different traffic patterns, speed, etc., will not be able to meet constant warning time criteria.

2.1.6 Economy

The new grade crossing system should cost no more, and ideally even less, than present systems. The costs of installation, ownership and maintenance are some factors which limit the number of active grade crossing systems which can be installed. However, a new system which costs more than the present is not necessarily undesirable if it provides certain advantages which are unavailable in present systems.

2.1.7 Independence of Track Structure

Initially, it was deemed desirable that the new train detection system should not be connected to the rail or rely on portions of the existing track structure. However, field tests and studies indicate than in diesel territory little is gained by requiring the system to be independent of the rail provided it fulfills all constant warning time requirements and does not interfere with existing track circuitry. In electric territory, the situation is altered by the fact that rails normally carry large, rapidly changing traction currents which can be expected to cause serious interference with most CWT systems (Appendix B). These currents and their associated magnetic fields will cause expecially severe problems for systems like the Grade Crossing Predictor (Appendix A) which attach directly to the rails. In this situation, any CWT system that does not connect to the rails enjoys a significant advantage because the effects of the traction current can then be minimized through proper placement, orientation, and shielding of equipment.

2.1.8 Safety Monitoring Capability

While not a solid requirement, a CWT system with the capability to obtain and monitor safety-related information (i.e., flat wheels, thermal cracks in rail or wheels, dragging brakes, residual stress levels) would be highly desirable.

2.2 CONSTANT WARNING TIME SYSTEM TECHNOLOGY

Technology for constant warning time system concepts can be divided into four categories or subsystems. These subsystems include:

- Sensor Subsystem
- Communications/Control
- Warning Signals
- Remote Power

The sensor subsystem includes the devices by which the train's presence is detected. The communications/controls subsystem interprets the data from the sensor, computes the constant warning time and activates the warning signals accordingly. Moreover, the communications/control subsystem performs self-check diagnostic operations of the complete system. The warning signals subsystem displays the appropriate warnings to the motorist and locomotive engineer. The remote power subsystem may be used to supply power to the sensor only, or to supply power to the entire subsystem, if necessary.

2.2.1 Sensor Subsystem

The first and probably the most important function of constant warning time is the detection of the train. The sensing technique(s) used by any innovative concept must do more than simply detect the presence of the train in a particular block of track. It must provide adequate information to control the grade crossing signals and maintain constant warning time for a great variety of train movement patterns.

Sensing techniques are divided into general classes: continuous and discrete. A continuous sensing technique has the capability of detecting a train's movement on a continuous basis. A discrete sensing technique detects the train only at one or more specific locations (point sensing). Radar and rail impedance characteristics are examples of the continuous techniques, while beam interruption and pressure sensing are examples of discrete sensing techniques.

Continuous Sensing Techniques

Continuous sensing techniques are highly attractive because with these techniques, train presence is known on an uninterrupted basis. There are no "dead spots" where the train cannot be detected, and there is no easy way the train can confuse the control circuitry by irregular movement patterns or by dropping off a locomotive or freight car. Continuous sensing techniques discussed below include track impedance, horizontal radar, acoustics, video and train-mounted transponders.

- Track Impedance Techniques: An interesting approach to continuous detection and monitoring of the train is to use the rails as conductors in a transmission line. An alternating current (AC) signal is impressed on the rails near the crossing and this AC signal is propagated away from the crossing. The axles of the train create a short circuit at the location of the train, thereby altering the impedance. Measurement of this impedance provides information about the distance of the train from the crossing.

A variety of systems based upon this principle are in widespread use (see Appendix A). Movement of the train causes the total track impedance to vary, allowing measurement of both position and velocity. Since this technique utilizes the track as a conductor, its effectiveness can be limited by poorly conducting joints, poor insulation and ballast shunting effects. Also, proper frequency selection at which impedance is to be measured is critical to proper operation of the track impedance technique. This is discussed in the next paragraph.

If the system shown in Figure 2-1 had the input impedance of an ideal transmission line, shorted at distance X and open at the point of measurement, then as X is increased from zero to a quarter wavelength, the impedance is inductive and increases from zero to infinity. As X is increased towards three-quarters of a wavelength, the impedance goes capacitive initially before decreasing toward zero and becoming significantly inductive as X increases toward infinity. This phenomenon indicates that the frequency selected must be low enough to allow the train to be detected when

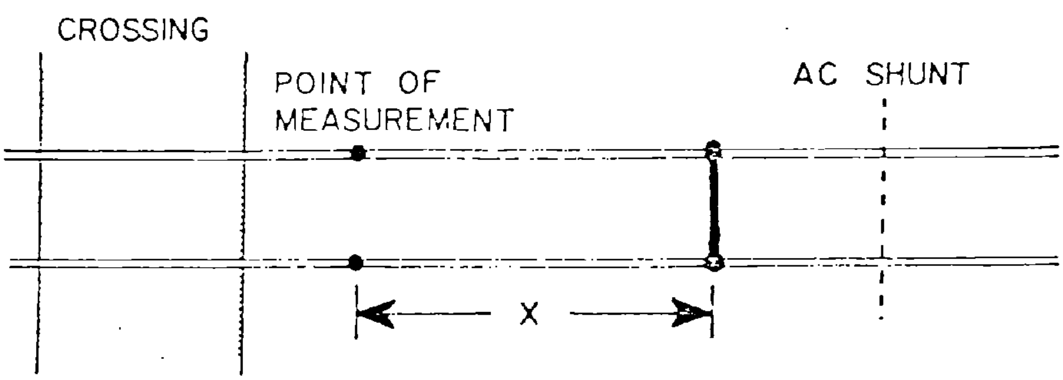


FIGURE 2-1. TRACK IMPEDANCE TECHNIQUE

it is within a quarter wavelength. This will eliminate most ambiguities in the train's position. The detection range is limited by connecting a shunt between the rails at the maximum desired detection distance needed for the CWT requirement. Operating on a frequency low enough to allow the maximum detection range less than a quarter wavelength has another advantage. Suppose that the maximum distance is less than approximately one-tenth wavelength. Then the impedance is linear and proportional to the distance, allowing considerable simplification in the associated electronic circuitry. When the maximum detection is, for example, 1 kilometer, then the maximum frequency should be 30 kHz, which has a wavelength of 10 km.

• Time Domain Reflectometry (TDR): Track impedance is not the only concept for train detection which uses the track as a transmission line. Alternate concepts employ time domain reflectometry (TDR) to locate the train. Basically, a pulse or burst of carrier energy is injected into the track at the crossing and radiates down the track. Upon encountering a short caused by the train's axle, the pulse or carrier burst is reflected back towards the crossing. The time of arrival of the return pulse is proportional to the distance of the train. The nature of the phenomena and the accuracy desired dictates that short pulses and high frequencies must be used. An obvious drawback of the use of either the short pulses or the high frequency carrier is radiation. The track becomes a long and imperfect transmission line at higher frequencies, and radiated signals will interfere with communications services. These techniques suffer from unwanted reflections due to track discontinuities, poor joints, switches, and other deviations from a perfect transmission line.

If these false echoes were the only ones, the system could feasibly operate with the use of a microprocessor to catalog all those which were not train related, and discriminate against them. However, some of these will still move as the train moves, making detection of the correct echo extremely difficult. In summary, time domain reflectometry techniques using either a pulse or carrier burst are:

- subject to all the disadvantages of the track impedance techniques;
- will cause radio frequency interference; and
- will require complex processing to separate the true train echo from ambient noises caused by track irregularities.

• Radar Systems: Another continuous sensing method is based on radar techniques. A radar transceiver is mounted in close proximity to the crossing signal and is directed down the track. Echoes indicate train presence, and doppler shift indicates velocity. Unfortunately, horizontal doppler radar cannot see around curves. Also, it cannot distinguish a train on an adjacent track, and may therefore fail to detect an approaching train beside a receding train.

- Acoustic: Both moving and idling trains generate significant acoustical energy over a wide band of frequencies. As a form of displacement, acoustic train signals are propagated through the air, associated structures and geology, each of which have unique attentuation properties and each of which are also subject to similar acoustic signals from the general environment. In a passive mode, acoustic signals are a potential source for detection and analysis of train motion and characteristics, providing the accompanying acoustic background can be reduced so to minimize the rate of false alarms and extraneous data. Acoustic energy can also be used in an active mode, usually at the higher sonic frequencies. The higher the frequency, the greater the directional capability of the acoustic beam and the smaller the transducers used in the transmitting and receiving. In an active acoustic mode of transmitting, energy can be concentrated in a narrow band in the rail, significantly improving the signal-to-noise ratio of reflected or interrupted acoustic signals.

- Train Borne Transmitters: Train mounted transmitters and transponders could be used in conjunction with receivers and transceivers at the grade crossing. Such techniques might work, but would require the installation of transponders on all rolling stock, since the grade crossing warning concept must respond regardless of whether a locomotive or a box car approaches first. Such an installation would be cost prohibitive.

- Video Motion Sensors: Sensing techniques which rely upon light energy, from infrared through visible light to ultraviolet, are vulnerable to severe attenuation due to atmospheric conditions such as mist, rain, fog and smoke. To filter out these variables, as well as countering changing light levels would require extremely complex signal processing to enable the video motion sensor to function properly for this purpose.

Discrete Sensing Techniques

These are techniques which sense the position of the train at various discrete points along the track within the vicinity of the crossing. With sufficient detection points and appropriate timing mechanisms, the techniques can be used to measure the position and velocity of the train on a basis that approximates a continuous sensing technique.

- Mechanical-Electrical Devices: Mechanical phenomena are generally evidenced by the exercise of force or displacement. Force can be measured in terms of static or dynamic loads imposed by a train on its environment. A train will have a certain signature as evidenced by the static forces applied to the track, ties, ballast and contingent geology, arising from the train's dead weight. This signature can be used to identify the location and length of the train. With the train in motion, the dynamic forces add data to the signature and provide the potential for also determining velocity.

There are three general techniques using mechanical-electrical devices, which utilized the weight of the train to provide an indication of its presence:

- pressure switches
- strain gages
- piezoelectric ceramic crystals

Pressure switches open and close when the weight of a train depresses the rail.

The strain gage is a mechanical sensing device used to monitor the presence of mechanical stress or strain. The device makes it possible to monitor mechanical loads that are present in the rails of a railroad track. As the train's weight is applied to the rail, the rails deflect. The mechanical strain that results from this deflection is transformed into a proportional electrical voltage by the strain gage. Monitoring this voltage identifies the train's presence.

The strain gage is placed in a Wheatstone bridge configuration where strain absence will correspond to a given voltage and maximum strain will yield a higher voltage. The voltage level associated with train presence will initiate the train-presence electronic circuitry. The false alarm rate associated with the strain gage is expected to be very small since virtually the only way the triggering voltage can be produced is by the mass of a train. It also lends itself readily to fail-safe operation whereby the unlocated rail (zero strain) is set to a non-zero voltage whereas power failure corresponds to zero voltage. In this case the system logic is set to trigger the warning circuitry on either the loaded voltage or zero voltage, thereby incorporating the fail-safe feature.

While the strain gage produces a change in resistance in response to applied force, piezoelectric (PZ) crystals have the property of generating a voltage proportional to applied pressure. 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 in voltage, the power level is low. Thus, an attempt to transmit this signal directly to the crossing location would be difficult because attenuation would, for all purposes, destroy the signal. It would appear the primary use of PZ crystals would be to activate some form of relay device for transmitting the signal to the crossing circuitry.

While strain gages and piezoelectrical sensors are considered reliable techniques, they, like pressure switches, suffer from a common problem of requiring exact installation and alignment to the track. Should the railroad track settle or a portion of the ballast wash away, the force applied to the sensor will change, resulting in incorrect operation of the device.

- Seismic Sensing Devices: Seismic sensors can be strongly responsive to heavy moving masses such as trains. However, the substrate through which the pressure wave travels can greatly attenuate and distort the signal. Additionally, the seasonal or daily weather phenomena can distort the signature, making positive detection rather complex.

The normal geophone measures the vertical component of ground velocity and a horizontal geophone measures the horizontal component of velocity. An accelerometer measures local ground acceleration and is used for seismic measurements at short range or in solid rock (especially where frequencies reach several kilohertz or higher). Strain gages are occasionally used for seismic measurement by measuring local strain, that is, the space derivative of ground displacement.

A rough rule for seismic geophone selection is that the natural frequency of the geophone should be less than one-fourth the lowest frequency of interest in the seismic wave form.

- Magnetic devices: Magnetic devices utilize magnetic field variations caused by the train. Several types of magnetic devices can be considered. These are divided into two main categories.

(1) Magnetometers. The term "magnetometer" has been widely used to describe all types of magnetic flux sensing devices, especially those which sense variations of current incuded in a coil or set of coils, or inductive loops.

Magnetometers in the from of portable hand-held devices, can be considered. Magnetometers developed for vehicle intrusion can also be used as train presence detectors. The systems have most of the desirable train sensor features. The devices are capable of being sealed, ruggedized, and buried in compact modules below the trackbed surface, thus offering high protection against severe weather, environment and vandalism. These are also insensitive to standing water, ice, snow or other non-magnetic or non-moving objects in the vicinity.

(2) Magneto-Resistor Sensors. These devices are semiconductors characterized by a resistance which increases in an increasing magnetic field. Electric signals can be derived from the change in magnetic flux density caused either by moving the

magneto-resistor into a constant magnetic field or by varying the magnetic field strength around a fixed magneto-resistor. If the magneto-resistor is attached to the rail then depression of the rail caused by presence of the train will activate the sensor.

2.2.2 Communication/Control Techniques

Conventional systems based on track circuits (Appendix A) use the rails to transmit information concerning train location and/or velocity to control circuitry which operates the warning devices at a crossing. Although all of the detection techniques that were studied could use the rails, this approach is not always the most advantageous. Some detection techniques are better suited to other types of communications systems. Three major categories of communication techniques applicable to CWT systems are: dedicated wire, carrier-shared wire, and wireless. Each of these is applicable in different situations; therefore, the new system may use all three, as fits a particular grade crossing situation.

(1) A dedicated wire is a hard-wired link between the points of transmission and reception of data which handles only the data or information of interest. It is by far the most reliable type of link if properly installed to obviate the effects of environmental stress or vandalism. A buried armored cable represents such a link.

(2) A carrier-shared wire is also a hard-wired link; however, more than one form of data is transmitted either simultaneously or on a time shared basis. It requires extra terminal equipment to properly encode the data at the transmitting end and decode or separate it out at the receiving end. The use of the encoding and decoding equipment lowers the effective MTBF of the system in addition to presenting possible crosstalk or interference from the sharing services.

(3) A wireless link incoporates transmission in the radio spectrum which requires similar encoding and decoding equipment as used in a carrier-shared link;however, the reliability of the system is compromised by the possibility of outside radiated interference.

2.2.3 Warning Signal Techniques

The warning signal display is mentioned here only because it is an important component of any effective CWT system in terms of motorist behavior. Development of warning signal displays, however, is not within the scope of this study.

2.2.4 Remote Power Techniques

Active Systems

An active CWT system would require all transmitters to operate constantly. This wastes both power and channel space.

Passive Systems

A passive CWT system would require power only when activated. One technique would be to interrogate each sensor in turn and ask for a status report. A second technique would have every sensor report its status periodically, thereby requiring power in time pulses. A third method would require power only when the sensor was activated by detection of a train.

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

2.3 CANDIDATE CONCEPTS FOR A CWT SYSTEM

2.3.1 Examination and Evaluation of Candidate System Concepts

In the effort to determine feasible concepts for a constant warning time system, a series of quick-look experiments were performed to uncover and demonstrate promising techniques. Specific ground rules, discussed below, were established to make the quick-look experiments as meaningful as possible.

- Test sites were evaluated in order to select those which were representative of actual situations.

- Experiments were conducted in both passive and active modes (where appropriate).

- Each experiment considered a broad range of parameters, i.e., number of sensors, location of sensors, transmission range, transducers and instrumentation frequencies, ranges and sensitivities of sensors.

- Data was analyzed in both the time domain and the frequency domain.

Constant warning time concepts were divided into three (3) categories for the purposes of the quick-look experiments:

1. Direct Sensing
2. Via Track Structure
3. Train-Borne Transponders

2.3.2 Direct Sensing Concepts

Direct sensing employs sensing and transmitting devices mounted independent from the train and track structure. Several types were investigated and consisted of radar, video motion, magnetic, seismic and beam interruption techniques.

Radar Systems

Using a Page Model 234 microwave source with selected frequency in the radar bands, three methods of radar detection were investigated:

1. guided radar
2. two-dimensional radar
3. horizontal doppler radar

In all cases, the energy source was directed down the track, and when the train broke into its path, a beam was reflected back and the distance of the approaching train was determined. Below is a more detailed discussion of the techniques investigated.

- Guided Radar: This technique has been the subject of much theoretical research in the United States and elsewhere in the world. Practical exploration of it has been pursued primarily in Great Britain and Japan. The technique consists of a surface wave conductor laid parallel to the railroad track. This conductor is provided with holes to permit communication between it and a nearby transmitter or receiver. Research has concentrated primarily on its use for mass transit communication systems. A simple approach to this technique utilizes a leaky coaxial cable where holes have been made in the shielding which permit the two-way transfer of radio frequency energy. This particular technique is used in the Washington Metropolitan Area Transit Authority (WMATA) subway system.

A very interesting form of the surface-wave guide 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 pursued further in the United States. This technique would be ideal for a guided radar detection system. It effectively eliminates the line-of-sight problems as well as the high attenuation from rain and other environmental effects that plague low-power free space radars. A signal propagated down the wave guide is reflected from the leading edge of the train and returned to the crossing processing area where location and velocity are calculated.

Any favorable benefit-cost ratio will have to include communication and traffic control modes. Since research is still underway in these areas, it was not appropriate to pursue any further investigation at this time. From a functional point of view, it would seem to accomplish all that a train detection system would require.

- Two-Dimensional 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. Research is continuing in the field of small, inexpensive short-range units. Civilian units in use range from automatic crash avoidance braking systems in motor vehicles to railroad car velocity measurement devices in railroad classification yards.

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. It was 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 are associated with the line-of-sight propagation of the transmitted signal. Railroad crossings are usually characterized by a significant obstruction to any practial line-of sight, and the means for dealing with the attendant problems have yet to be found.

- Horizontal Doppler Radar: A horizontal doppler radar was used for train detection by aiming it down the track. A typical installation used for radar units (see Figure 2-2). They were mounted on the crossing signals and required no connection to the track or roadbed. The basic principle of doppler radar is that the frequency of the signals reflected from a moving object differs from the frequency of the transmitted signal. An approaching train produces a decrease in frequency. This change in frequency is directly proportional to the train's velocity, allowing easy computation of train movement.

Serious problems arose in applying the radar sensor to the curved and multitrack situation. A train located on a curved track was invisible until it was within the line-of-sight to the crossing. In multi-track situations, the sensor was unable to distinguish trains adjacent to each other. This made it possible for a low or stationary train to mask the echo from a rapidly approaching train on the adjacent track. While the radar sensor was an adequate motion sensing device in some situations, its applicability to grade crossings is very limited.

The development of low cost and reliable doppler radar speed sensing equipment has progressed rapidly in recent years, mainly due to availability of solid state microwave components and a market created by law enforcement use. Capability exists to determine accurately and reliably the velocity of any rail vehicle along a line-of-sight path.

Such a doppler radar system could be readily applied to give the velocity information necessary to transform a conventional occupancy detection system to a CWT system. It possibly may be used to also provide occupancy information by interruption of a microwave "beam" by the rail vehicles or train.

If a system using the doppler radar as an adjunct to a conventional AC or DC track is used, the dependence on the radar as a failsafe subsystem component is greatly reduced. Also, the problem of track curvature and obstructed sight lines are reduced as the track current gives continuous occupancy information.

In such a system, the doppler radar would provide speed information over as much of the approach as conditions would permit and this information could be used to delay the crossing warning start for slower moving trains. Control of the warning would not be passed to the radar subsystem unless a valid velocity signal had been obtained.

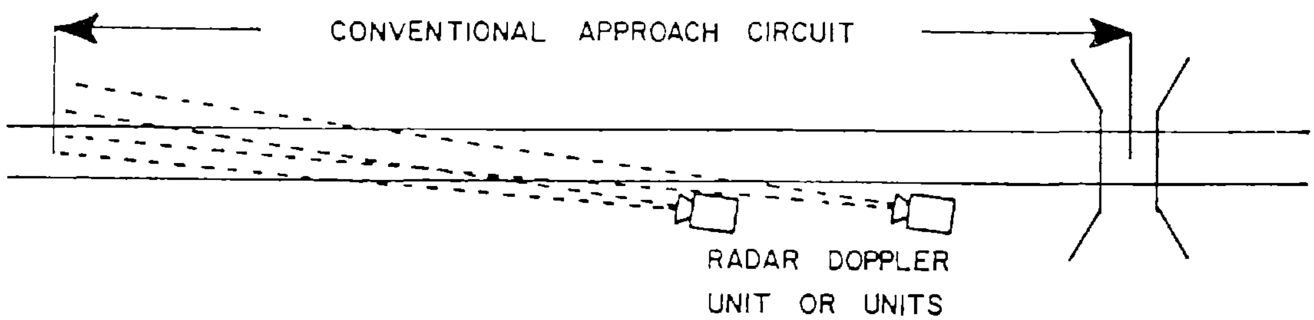


FIGURE 2-2. RADAR DOPPLER SYSTEM

Velocity information could be passed to the crossing control unit by wire or microwave data link. A simple computer, probably micro-processor based, could be used to provide interpretation of the occupancy and velocity information. A dynamic system self-check would be required to provide the required failsafe operation with reversion to the track occupancy circuit if trouble is detected. In an off-the-rail, all microwave system, a transponder would be required to check the integrity of the microwave data link. This system would likely use passive reflectors to improve coverage of the microwave "beam" (see Figure 2-3).

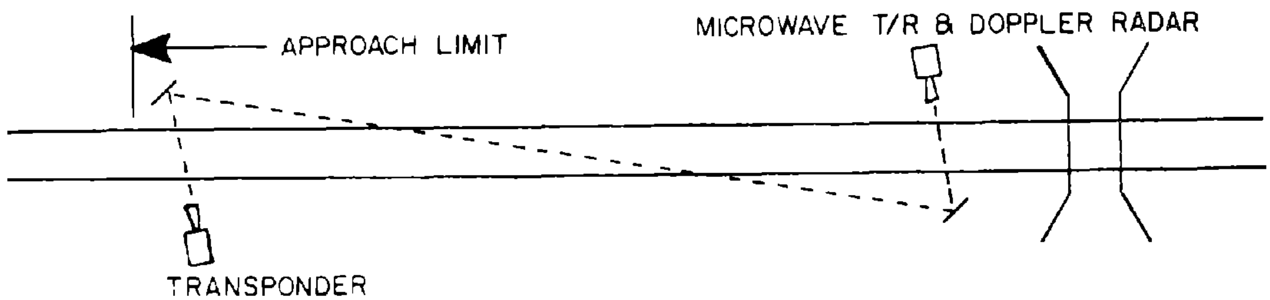


FIGURE 2-3. TRANSPONDER SYSTEM TO CHECK MICROWAVE LINK

In summary, while radar systems have capability for providing occupancy and velocity information, they do all suffer from line-of-sight problems which severely restrict their reliability and adaptability to grade crossing warning systems.

Video Motion Sensing

The visual image of a train may be discriminated from other objects passing the field of vision of a closed circuit television camera. Using a VC100, VCR recorder 210 and 200, and an RCA Model 400 camera (with associated panning motors), a train was monitored visually by the equipment upon its grade-crossing approach. Velocity was amply computed from two cameras. This concept proved unacceptable due to the fact that the camera could not compensate for changes in light levels and although the technology to solve this problem is available, the cost appears to be prohibitive. Consequently, this technique was not consdered feasible for constant warning time application.

Magnetic

Several types of magnetic concepts were investigated. These were in two general categories--magnetometers and magneto-resistor transducers. Since the magneto-resistor was attacked to the track, this id discussed in the section on track structure concepts. (See Section 2.3.3.) Quick-look experiments were carried out on three types of magnetometers: a hand-held magnetometer developed by Ballantine Laboratories; a self-powered vehicle detector initially developed for the Federal Highway Administration for traffic control purposes; and an encapsulated magnetic coil device initially developed for military applications as a vehicle intrusion device. Descriptions of these devices and the associated quick-look experiments are described below.

- Portable hand held magnetometer: Using a portable Ballantine Laboratories hand-held device, a voltage signal was produced by integrating the flux change in the loop caused by the phenomena being measured, such as the change in the earth field when the train is present. An inherent problem with this method is the device's extreme sensitivity to the surrounding environment. Consequently, it could not be considered as a viable CWT detection device.

- Self-Powered Vehicle Detector (SPVD): As part of this effort, the SPVD system developed for the Department of Transportation, Federal Highway Administration (FHWA) by the United States Naval Surface Weapons Center was evaluated. Although the SPVD system was designed for traffic control at highway intersections, application of the SPVD system as a possible concept for CWT was investigated. Evaluation and testing were conducted at the U.S. Army Rail Transportation Facility at Fort Eustis, Virginia.

The SPVD is capable of operation on AC or internal DC power. The unit detects vehicular presence by measuring its magnetic signature relative to the earth's magnetic field. A dual axis Brown Fluxgate Magnetometer is used as the transducer incorporating a digital nulling loop to perform sensor offset nulling and logic functions. An FM telemetry link containing three encoded tones transmits vehicular presence information to a roadside receiver/control unit which interfaces with the existing traffic control electronics.

The SPVD telemetry link consists of an encoder/RF transmitter module and the receiver/control unit, which contains the decoder and receiver modules. (A block diagram of this link is shown in Figure 2-4.) Vehicle presence is sensed by the encoder control logic which selects the appropriate tone generator for a leading or trailing edge and determines the transmitter pulse length. A modulated crystal oscillator producing a 40 MHz frequency modulated signal is amplified by the radio frequency amplifier, resulting in a transmitter output of approximately 100 milliwatts. The transmitter output load is a spiral helix antenna with a 50 ohm impedance which provides omnidirectional converage.

The SPVD is housed in a 22.8 cm (8.97") x 15.2 cm (5.98") enclosure. The housing is placed inside a weatherproof container. The internal DC power supply is a 6.75 volt, 13 ampere hour rated mercury battery. The battery module contains two batteries in a parallel configuration. The module is fabricated from acrylonitrile butadience stylene (ABS) providing isolation of potential electrolyte leakage. Photographs 2-1 through 2-3 illustrate various aspects of the SPVD test.

The sensor/transmitter package was buried approximately 2" under the surface of the railroad ballast on a centerline equidistant between the railroad tracks. A Hewlett Packard Model 141T spectrum analyzer main frame along with a Hewlett Packard Model 8552B intermediate frequency plug-in and a Hewlett Packard Model 8554B radio frequency plug-in were used to display and measure the radio frequency spectrum from the transmitter.

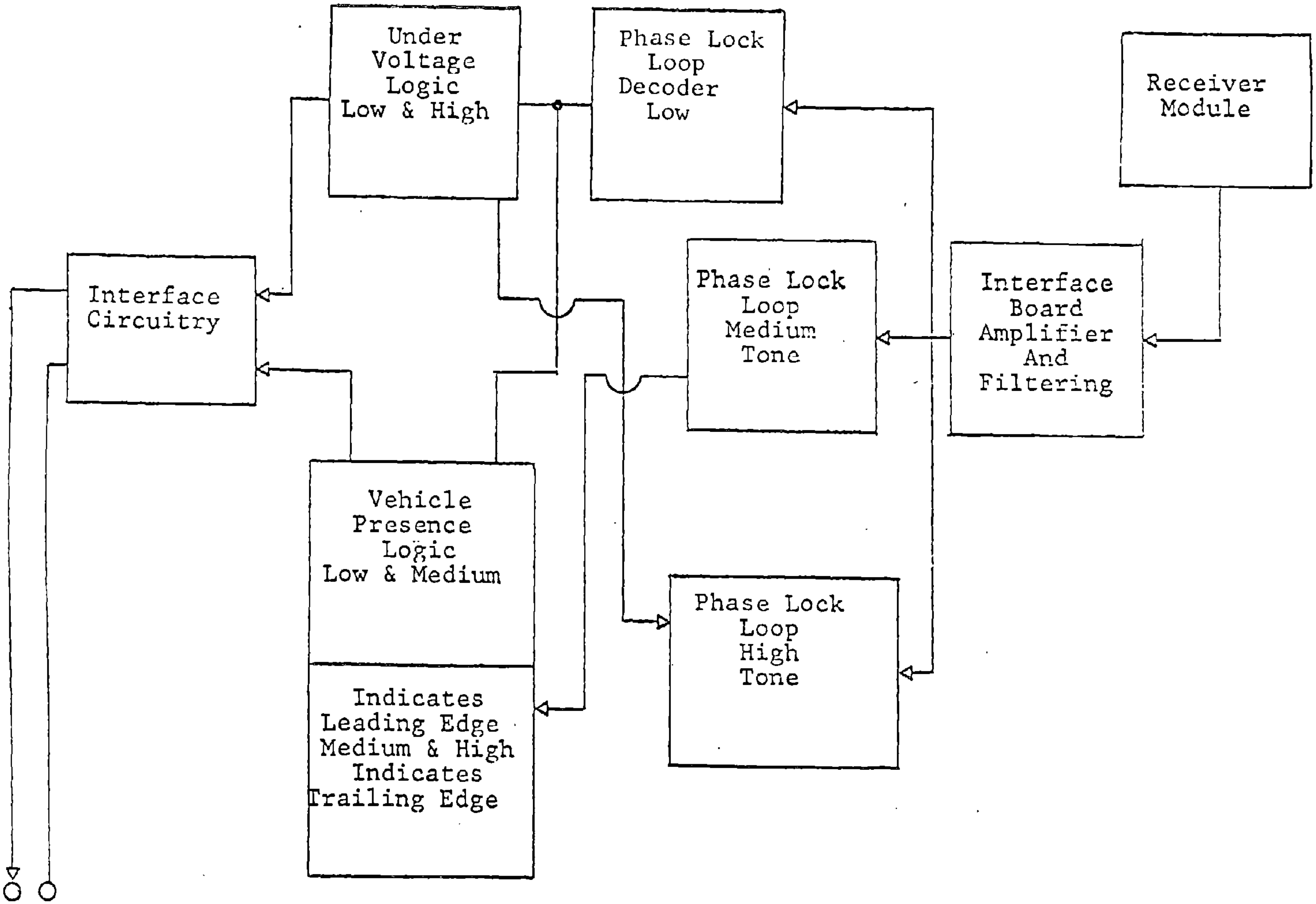
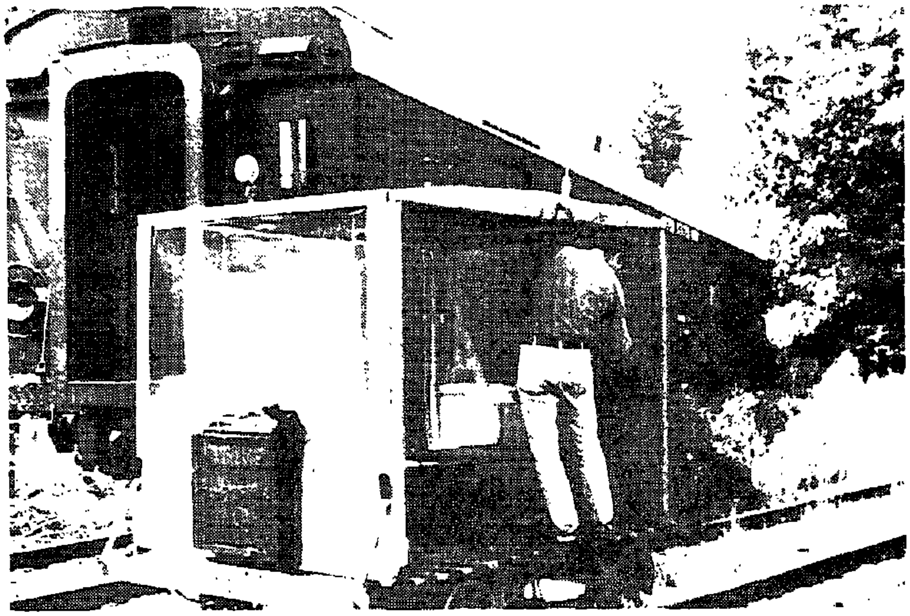
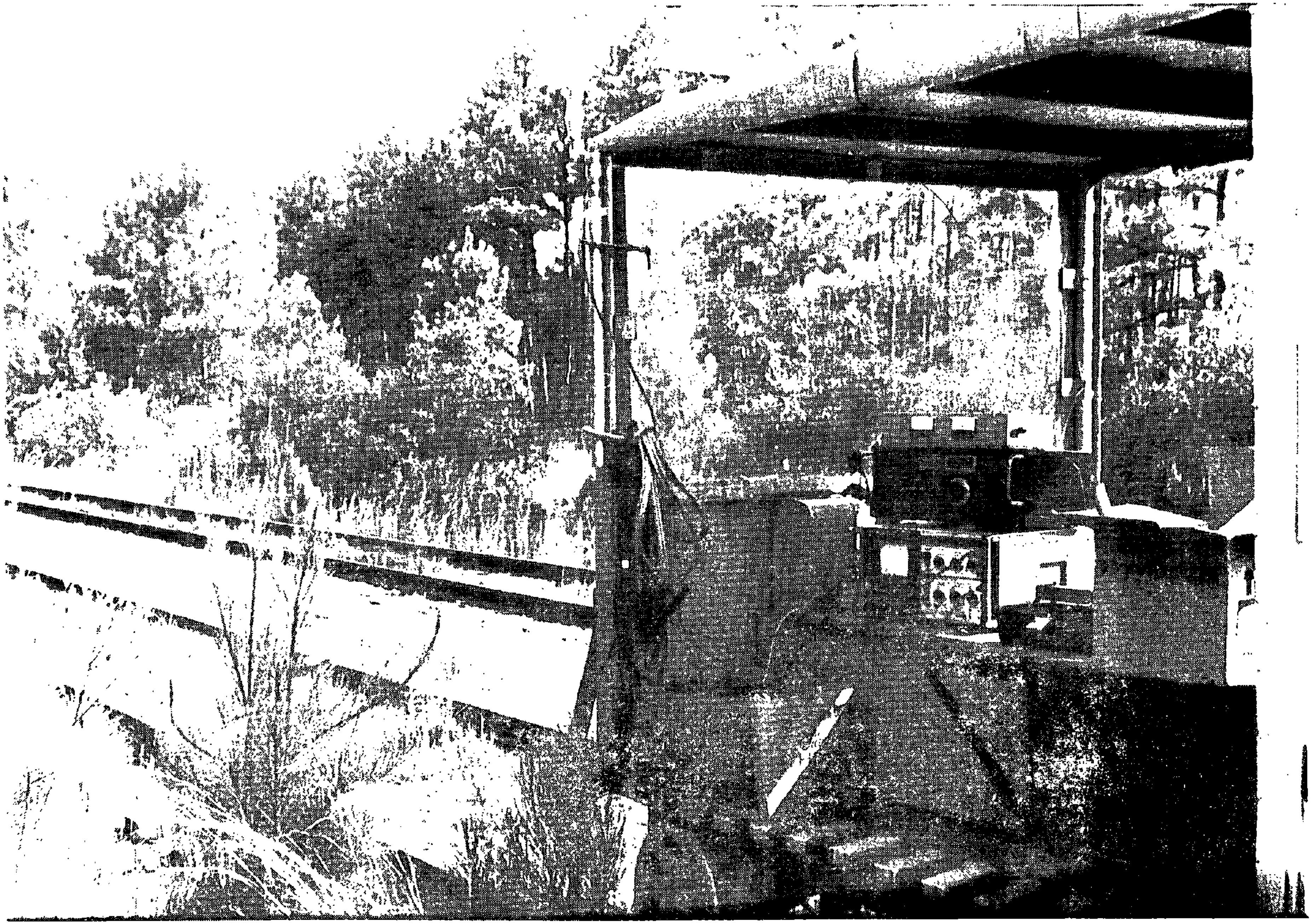


FIGURE 2-4. SPVD BLOCK DIAGRAM



PHOTOGRAPH 2-1. STL REPRESENTATIVE MOUNTING SPVD ANTENNA ON STL ENGINEERING VEHICLE

PHOTOGRAPH 2-2. TEST TRAIN PASSING OVER IMPLANTED SPVD



PHOTOGRAPH 2-3. SPECTRUM ANALYZER DISPLAYING TRANSMITTED PULSE FROM SPVD

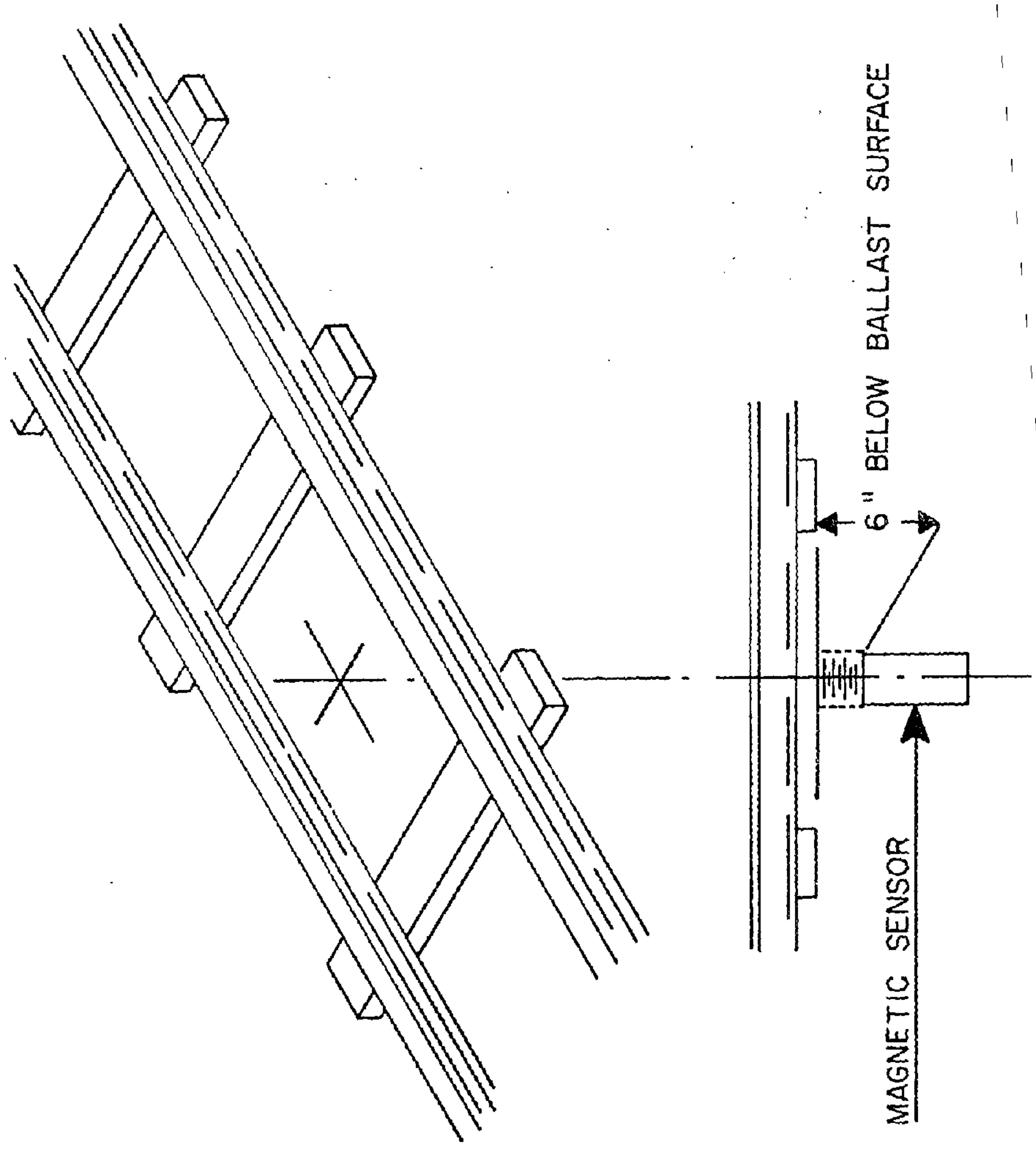
The output power of the SPVD was measured at +3dbm(2mw). This appears excessively low. An apparent conclusion for the low output power may be the driver stage leaking through a faulty final amplifer state. It was also noted that due to environmental effects the antenna became untuned and the voltage standing wave ratio (VSWR) had to be absorbed by the final amplifier. (The SPVD utilizes an RCA 2N3866 transistor as the final amplifier.)

In view of the limited range of the transmitter and other potential maintenance, reliability and weather resistant problems, the SPVD was not considered to be a feasible CWT detector.

- Encapsulated Magnetic Coil Sensor: This sensor was developed as an intrusion monitoring device for the Department of Defense and is capable of being sealed, ruggedized and buried in a compact module below the trackbed surface, protected from environmental elements and vandalism. The technique tested utilizes the natural magnetic field which is concentrated by the presence of a train. The movement of the train causes a change in the magnetic field and generates a voltage in the coil of the sensor. By measuring this induced voltage, the train's presence can be detected.

Two magnetic/seismic sensors* were placed on a center-line beneath the ballast along the axis of the track at the Ft. Eustis railroad center and tested (see Figure 2-5). Initial reference spacing between the units was 22 feet. A strain gage attached to the track was used to define the position of the train during the test. Output data from the units were recorded on a Honeywell 5600E instrumentation recorder (see Figure 2-6) with a tape speed of 7.5 inches/second. Channels 1, 2, 3, 4, 7 and 8 were recorded in FM-FM, IRIG wideband group 1 mode. The center frequency was 27 KHz plus a minus 40% deviation. Channels 13 and 14 were recorded in the direct mode. The data showed this magnetic coil

*The sensor used in this investigation has a dual capability and can be used as either a magentic or seismic (geophone) device (see Section 5.1)


6 " BELOW BALLAST SURFACE
MAGNETIC SENSOR

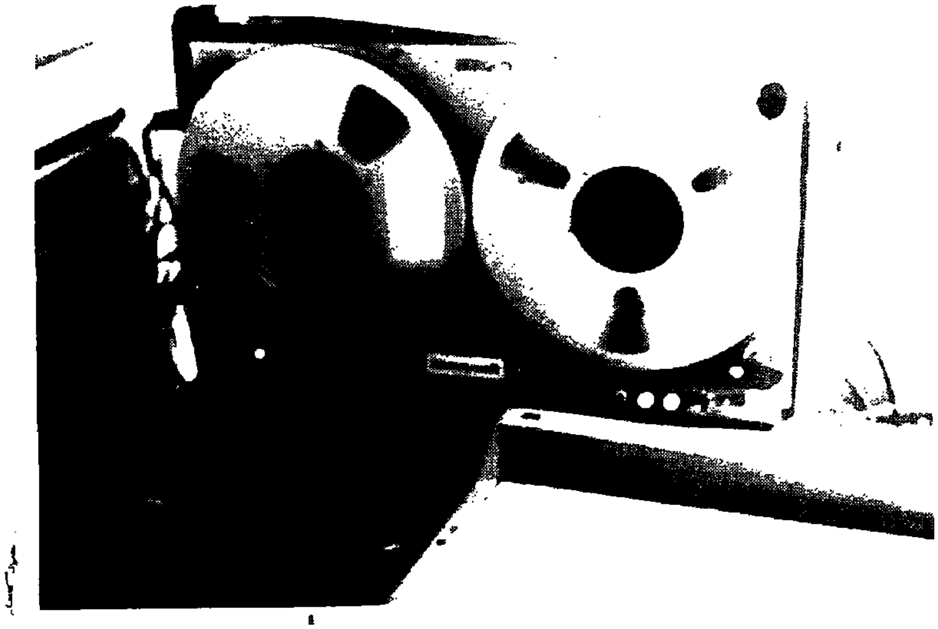


FIGURE 2-6. HONEYWELL 5600E TAPE RECORDER

TABLE 2-1. TAPE RECORDER CHANNEL ASSIGNMENTS

Channel	
1	magnetic sensor
2	magnetic sensor (1/10 gain)
3	seismic sensor
4	seismic sensor (1/10 gain)
7	strain
8	strain (1/10 gain)
13	IRIG B Time code
14	Voice Channel

(Channels 9-12 unassigned)

device to produce a repeatable signature of the train (amplitude) levels are dependent on speed) and to have good reliability, maintainability and weather resistance characteristics. Consequently, it was felt to be a viable choice for a CWT sensor and was subjected to further detailed testing in a subsequent phase of this project as discussed in section 5.1.

Beam Interruption:

Using a helium neon laser (2.5 watts), a beam was reflected across the track to a mirror. Fringe lines were used to calculate the velocity of the object passing through them by using a photo-multiplier tube. The output of the photo-multiplier tube was input to a Hewlett Packard frequency counter, which measured the period of beam interruption. Two lasers were used and the elapsed time was calculated which provided information on velocity and physical length of the train. Although theoretically this concept was very interesting, it was extremely expensive and the mirror reflector is vulnerable to environmental conditions and vandalism. Consequently, this technique was not pursued further for constant warning time application.

Seismic

The use of geophones buried in the right-of-way near the crossings was investigated (see Figure 2-7). Initially, this technique appeared to be promising. The damping of the geophones, however, proved to be extremely critical and placement is required to be very precise between the track and right-of-way areas. Factors such as large wavelengths, changes in ballast formation, moisture and the inability to discriminate between adjacent vehicular traffic noise and train noise did not reflect favorably on this technique of detection. For example, the signatures of a train approaching and a tractor-trailer on an adjacent highway a fair distance away are almost indistinguishable (see Figure 2-8). An excessive amount of electronics would be necessary to filter out the signatures to avoid false alarms in the system as it cannot distinguish a train from adjacent traffic and environment noise. Consequently, this technique was not considered for further study.

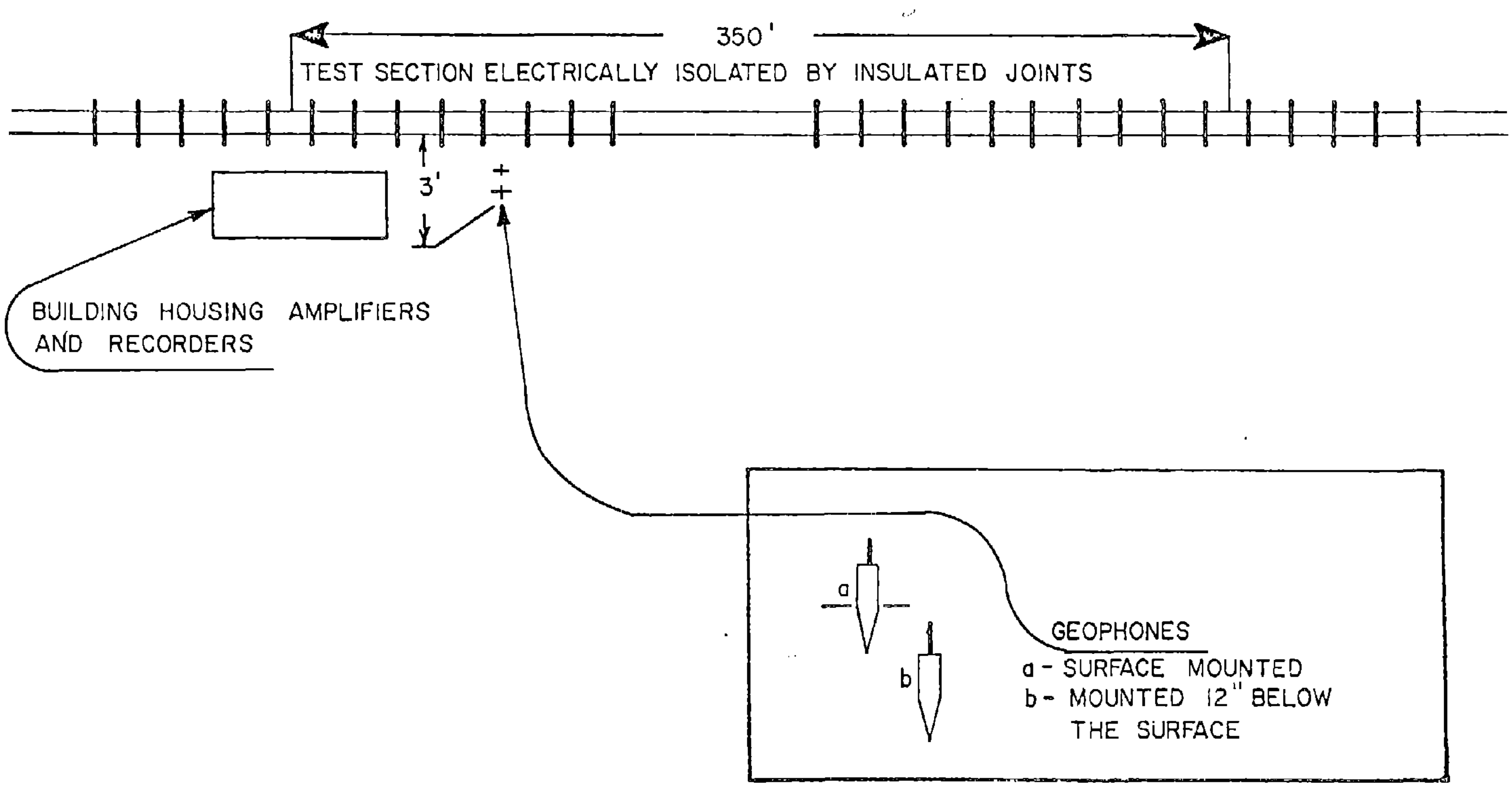


FIGURE 2-7. QUICK LOOK SEISMIC EXPERIMENT

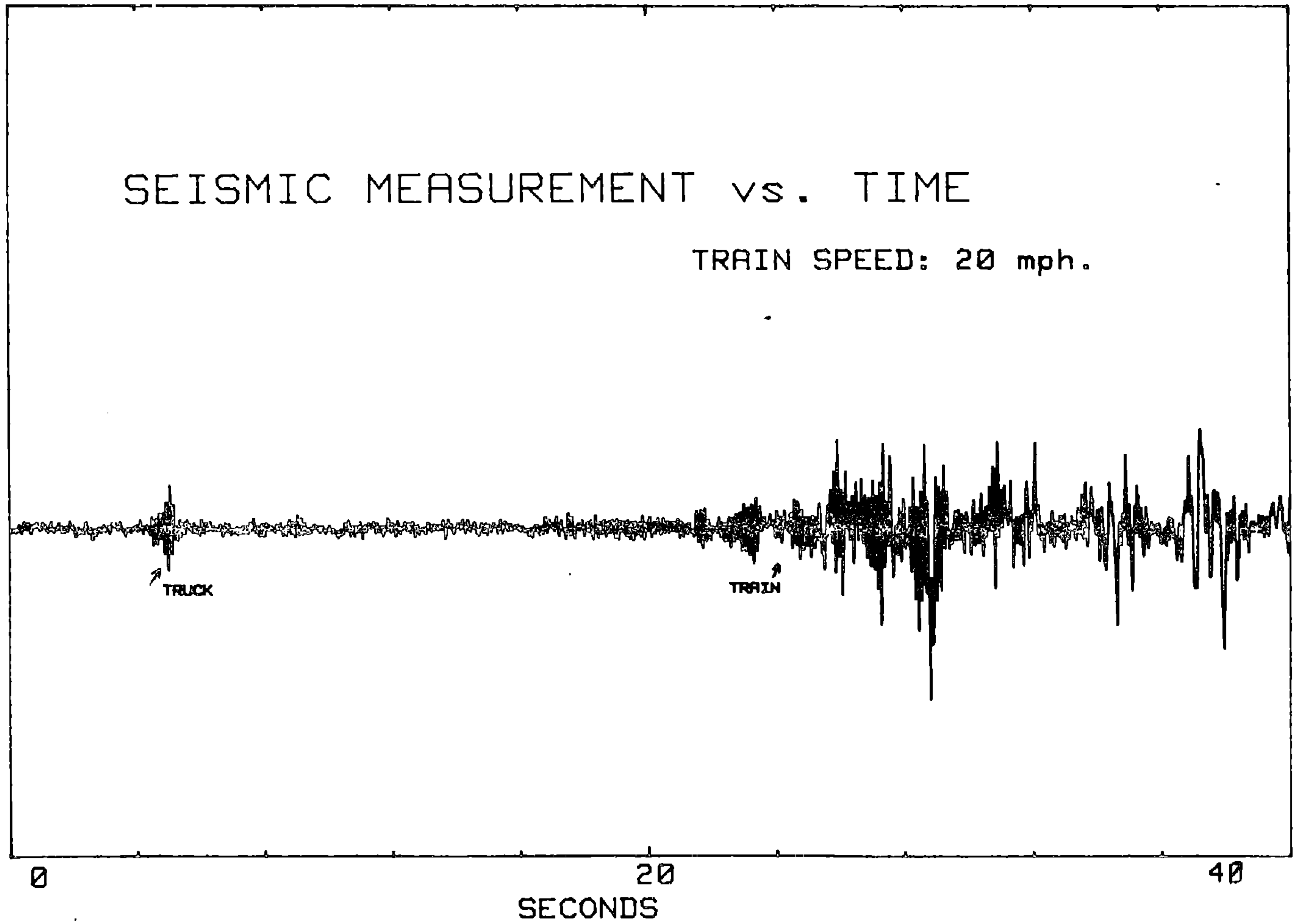


FIGURE 2- 8. SEISMIC INSTRUMENT PICKING UP HIGHWAY TRUCK INTERFERENCE

2.3.3 Via Track Structure Concepts

These concepts use the track structure (rails, ties, ballast) or its immediate vicinity as the medium for detecting the presence of the train. Several concepts were investigated in quick-look experiments to determine their viability for constant warning time application. These included induction loops, track impedance systems, magneto-resistor sensors attached to the rail, proximity switches and acoustic devices.

Induction Loop

The electromagnetic loop detector is currently used in vehicular traffic control. The detector senses the presence of a motor vehicle and converts this to an electrical signal.

Basically, the loop is energized with a high frequency current; the presence of a train or any other conducting object within the loop's electromagnetic field will cause a reduction of the self-inductance of the loop. This change in the loop self-inductance is due to eddy currents induced into conducted material of the train.

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

In the bridge-balance detector, the loop is one leg of a balanced-bridge circuit. The change in the voltage on the sensing loop will cause an imbalance in the bridge circuit and hence indicate the presence of conducting objects.

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

The induction loop has to be mounted in the track ballast between the rails or planted in a rectangular form above the ties between the rails. The supporting electronics has to be safely located with the power supply and communications transmitter, off to the side of the track. These installation requirements suggest that the device would be subject to vandalism, have poor weather resistance and be awkward to maintain. Consequently, the concept was dropped from further consideration as a viable CWT device.

Track Impedance

As indicated earlier, a railroad track can be modeled as a leaky parallel wire transmission line. The series resistance, inductance, and shunt capacitance are due to the rails; the shunt resistance is the result of the track ballast. The rails are driven by a constant current (I) from the track circuit, which results in a voltage being developed across the track circuit designated as E=IZ. This voltage can be processed and filtered and a voltage, E_D, which is directly proportional to the distance from the crossing to the train can be obtained. Differentiating the distance voltage to obtain E_V provides the velocity of the train. The polarity of E_V determines train direction: a decrease in voltage is an approaching train; a positive voltage indicates a train is leaving the crossing. From the velocity and distance voltages a microprocessor can be used to compute the arrival time in a continuous manner, and when the arrival time reaches a predetermined value, the warning signals are activated. This is the basis of a constant warning time system.

In a test evaluating this concept, an audio oscillator (Hewlett Packard 204C with a range of 5 Hz - 1.2 MHz) was used at various cycles (from 1 KHz down to 100 Hz) to inject an audio signal into the tracks. The AC current was found to change as the shunting effect of the locomotive increased while approaching the AC source.

A major challenge with this system is that the input impedance does not remain constant for a given distance but is dependent upon the ballast resistance. The track ballast is subject to extreme environmental conditions which causes changes in its resistance. The end result is different input impedance and a corresponding computed distance for a given distance depending upon the environmental effect of the ballast. Input variations are severe enough to require ballast compensation for accurate train detection. Compensation for ballast variations adds to the complexity and reduces the accuracy of the basic system. In some cases, low ballast impedance will make the train invisible beyond a short distance, and the system must detect such situations to maintain constant warning time requirements.

In addition, the presence of conducting material between or near rails, even if not directly connected, will cause changes in the characteristic impedance of the rails. This will be true of switches, crossings, and metal bridge structures and reinforcements. This change in characteristic impedance will result in a reflected wave and a change in the impedance at the measuring point. The impedance rate of change with train distance will then have different rates for trains on either side of the conductor, confusing the measurement technique. Reliable operation depends on low impedance connections from measurement equipment to the rails, from one rail section to another, and from rails to wheels.

Thus, due to the system's dependence upon ballast conditions, its reliability is impaired. Moreover, the system requires all sidings, switches and crossings to be insulated from the measured track circuitry. Complex and dedicated electronics would be required to adapt this concept to tracks with switches. Fail-safe, self-check circuitry would also have to be developed to detect system malfunctions, further adding to system complexity. Consequently, this system was not considered further as a viable CWT concept.

Magneto-resistor Sensor

The magneto-resistor is a semiconductor component characterized by a resistance which increases in an increasing magnetic field. Electric signals can be derived from the change in magnetic flux density caused by moving the magneto-resistor into a constant magnetic field.

A constant magnetic field circuit is fixed beneath the rail as shown in Figure 2-9. The magneto-resistor is connected to a rod that is bonded to the underside of the rail. As the train passes overhead, the rails deflect causing the magneto-resistor to be displaced within the stationary magnetic field.

Several problems were inherent with this technique; the fixed magnetic field did not remain at the desired distance from the magneto-resistor (changing track ballast is one cause for such a shift), and attachment to the rails of this sort is not vandal or weather resistance. Consequently, this system was not explored furtheras a viable CWT concept.

Thermal

In this quick-look experiment, thermocouples were inserted into 1" x 1" x 1" stainless steel blocks which were bonded to the track. It was thought to be feasible to measure the friction of the train's wheels against the track in the form of heat conducted through the rails. Because of the low signal levels, this was not successful at all, and the concept was not considered further.

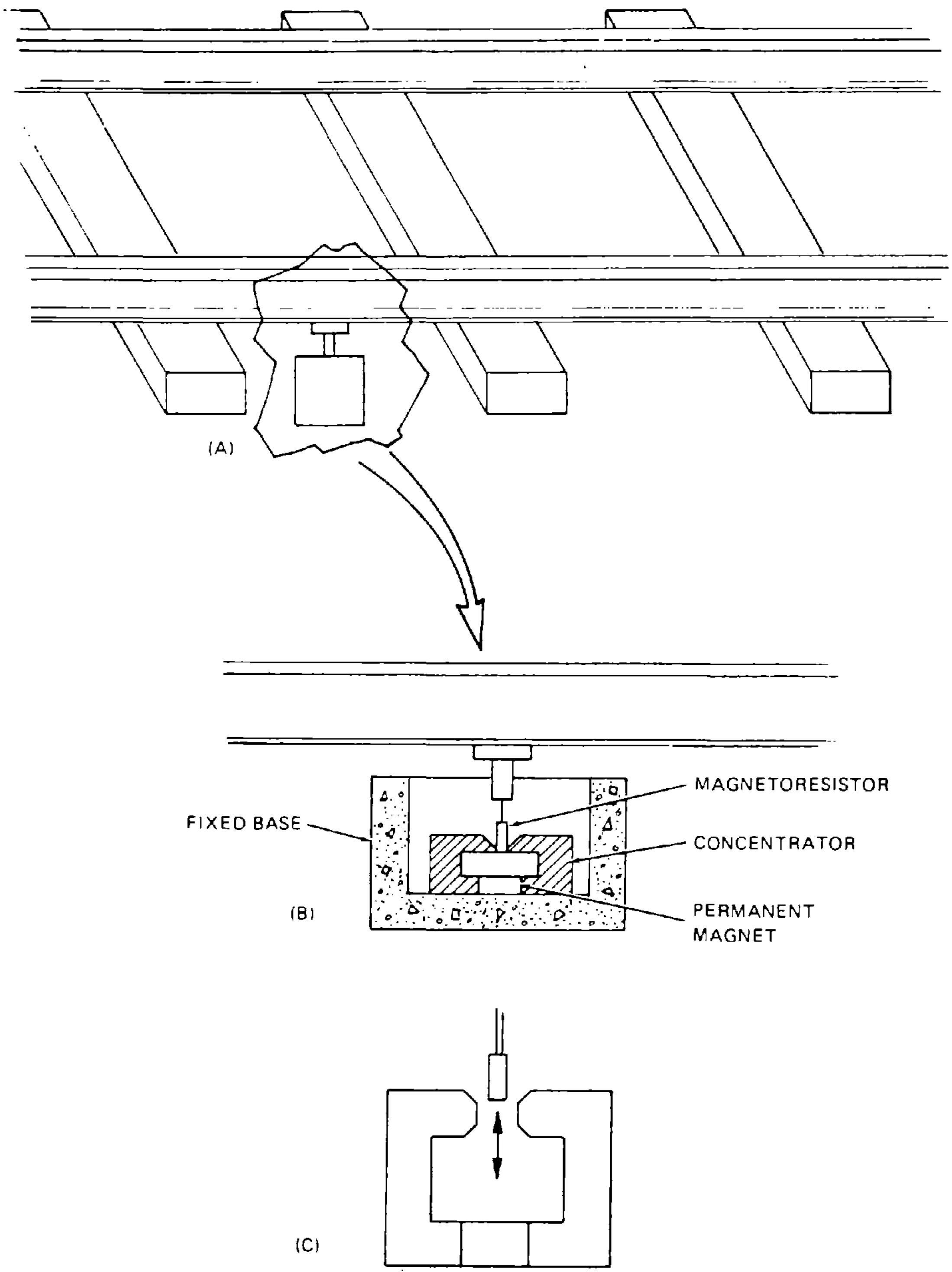


FIGURE 2-9. MAGNETORESISTOR UNDERNEATH RAIL

Proximity 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.

- Mechanical Pressure Switch: The weight of the train can be detected very simply by using a mechanical switch. A switch was mounted underneath one rail, and when the train passed over the rail it activated the switch. The switch was mechanically limited to react only to a very large force, such as generated by the train.

While the device worked satisfactorily, it had all the disadvantages of requiring a direct connection to the rails and critical packing of the roadbed. Erosion of the ballast in time will cause this device to malfunction. In addition, a mechanical device of this type will have reliability problems. Ice and dirt may become packed around the switch, causing problems. Consequently, these switches were not recommended for further studies.

- Piezoelectic Crystals: Piezoelectric crystals are able to generate voltages when subjected to mechanical pressure. They are used in phonograph pickups, accelerometers, butane lighters, and as pilot lights in gas heaters. The tremendous weight of the railroad train may be used to actuate a piezoceramic electric sensor (see Figure 2-10).

The sensor was placed in a mechanical arrangement beneath the rail (see Figure 2-11) so that the changing/force of the moving train on the rail produced a change in mechanical pressure on the sensor, thereby generating a voltage. It was found that, while the voltage induced by a passing train was relatively high (500-2,000 volts), the signal power for transmission remained low and would be susceptible to attenuation before reaching the working signal relay. Consequently, it was not explored further.

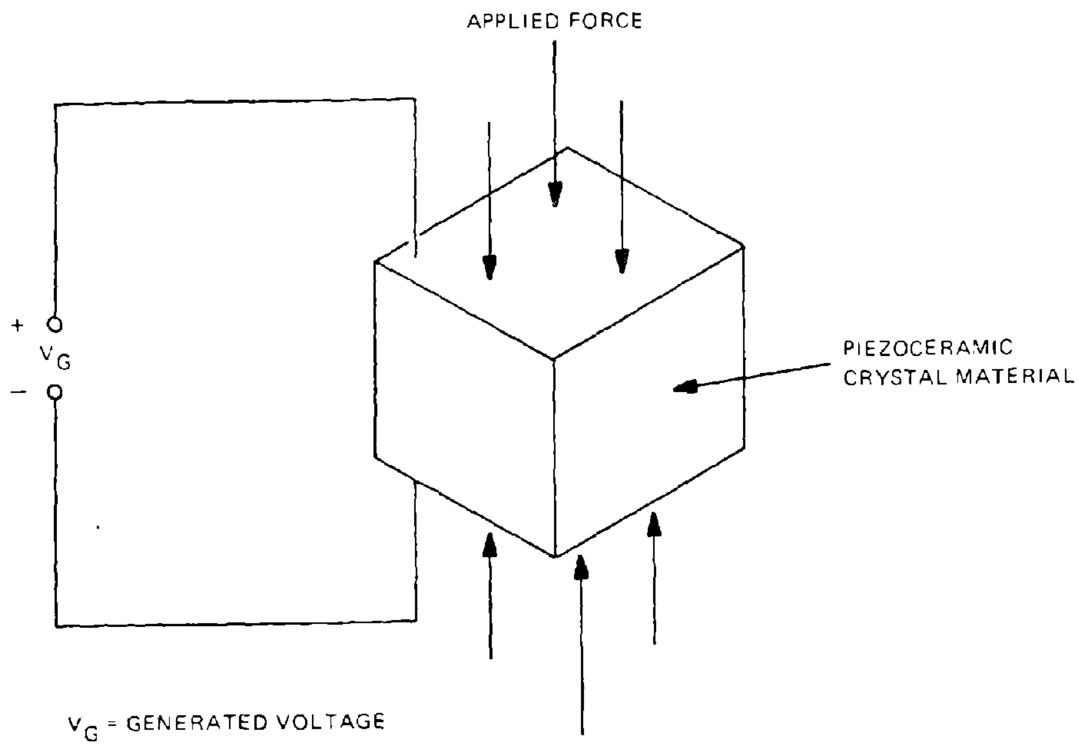


FIGURE 2-10. PIEZOELECTRIC TRANSDUCER

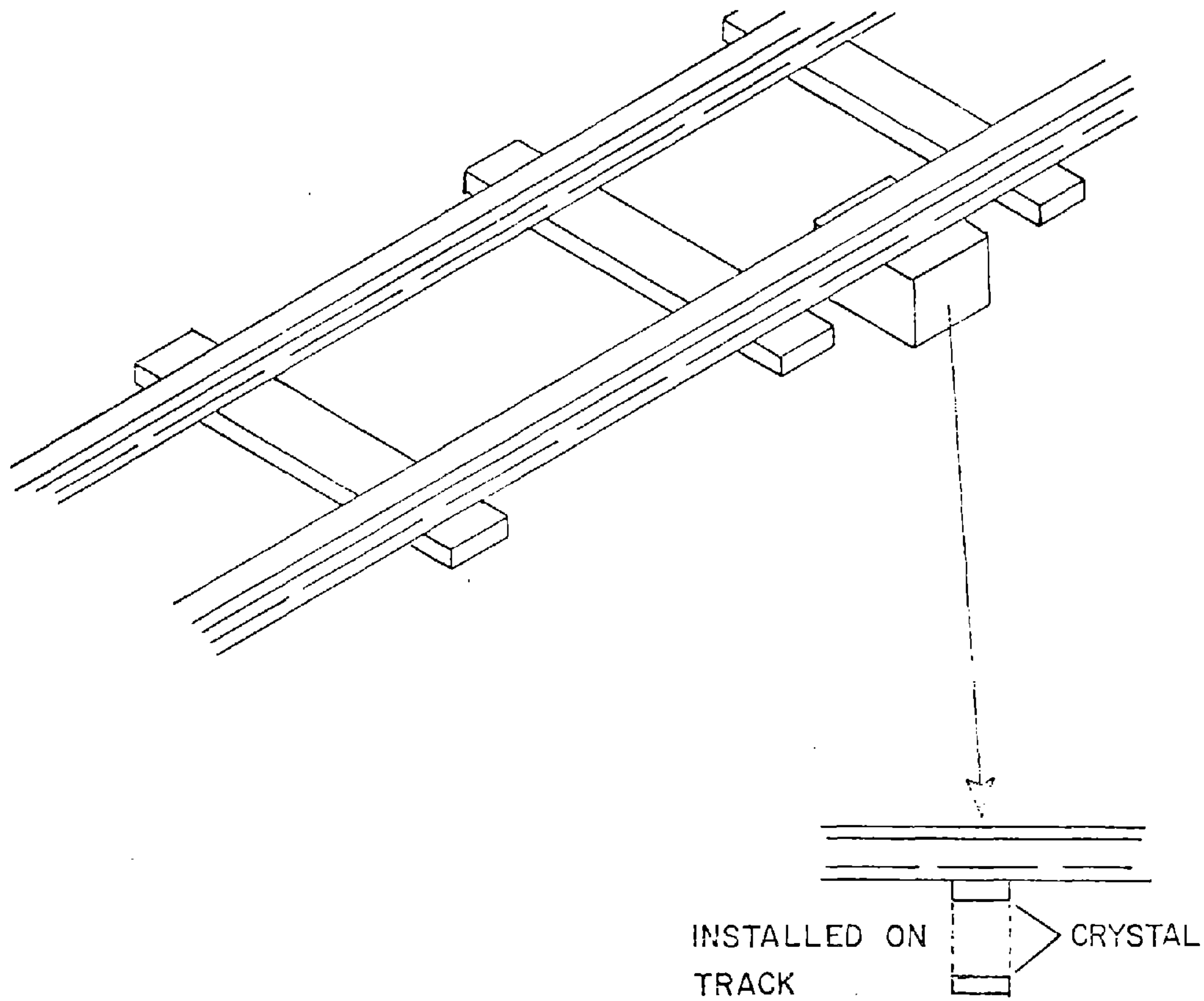


FIGURE 2-11. PIEZOCERAMIC MOUNTING ARRANGEMENTS

Strain gages

Tests involving strain gage measurements were conducted at the U.S. Army Rail Center in Fort Eustis simultaneously with the initial magnetic coil sensor tests. A strain gage with a DC resistance of 350 ohms was affixed to the track (refer to photograph 2-4). The purpose of the tests was to investigate the train signature and determine whether it could be used repeatably to monitor train presence and velocity. The gage was set so that the axles ran north to south, and runs were made to determine if a pulse could be obtained. Figure 2-12 illustrates that a signature could be obtained and defined as to the train consist. Run RN 1 breaks down in the following manner (reading from left to right):

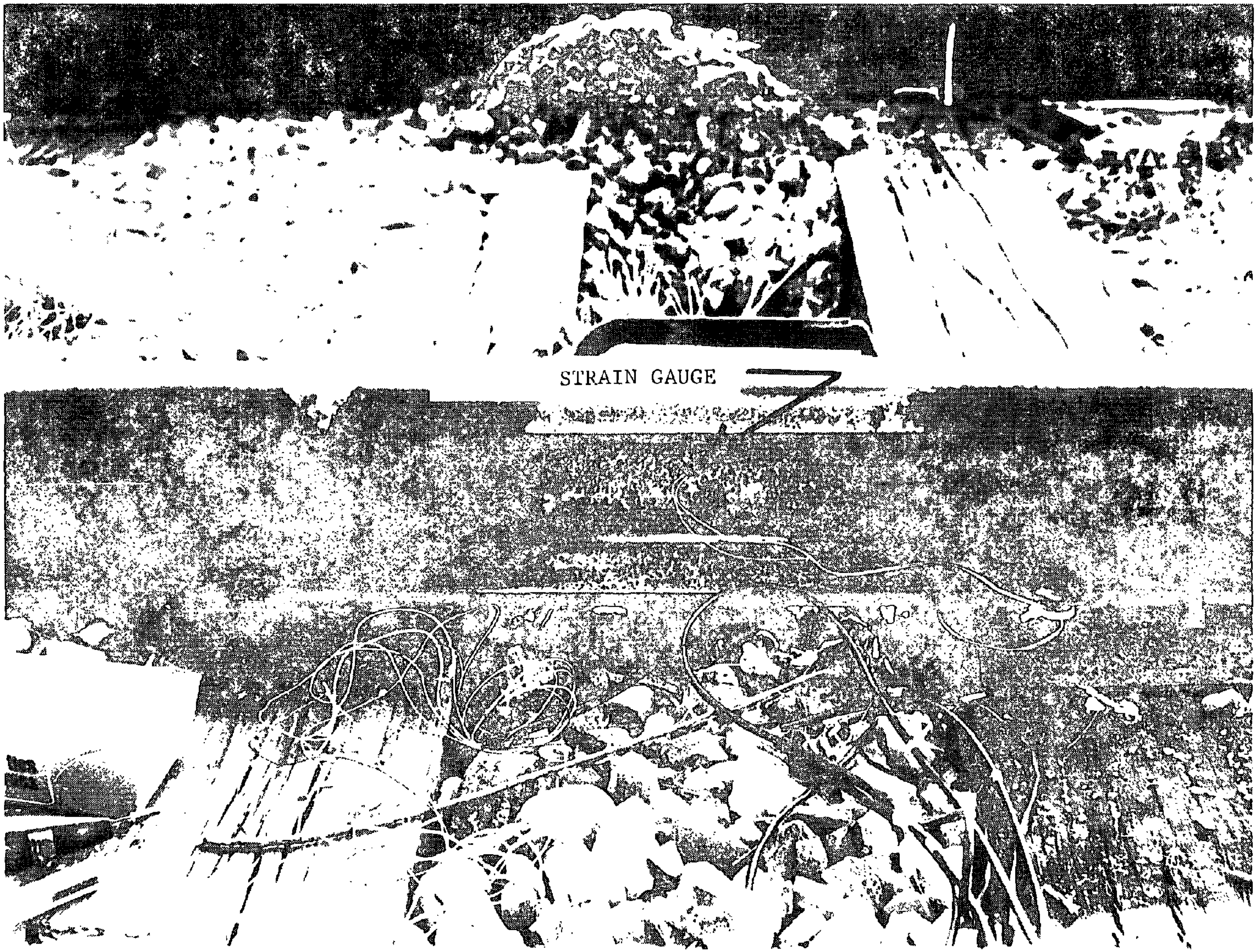
Locomotive:	Overhang of locomotive identified by negative amplitude, 4 ticks = 4 axles
Flat cars:	Long and short Two ticks-time line-two ticks
Coach cars:	Three ticks-time line-three ticks

Short time lines between series of ticks are couplers

Figure 2-13 illustrates that if the distance between the first wheel of the rolling stock is known (see Test Train Dimensions - Figure 2-14) and the time base is known, velocity can be computed. Although this type of sensor does have promise for position and velocity determination it has to be attached directly to the rail, which makes it vulnerable to the weather and vandals. Also, it is expected that such a system would require frequent attention to make sure the strain gage was properly affixed to the rail to measure the rail strain. Because of these deficiencies in terms of weather and vandal resistance and the frequent maintenance requirements, this concept was not considered to be feasbile for application as a CWT sensor.

Acoustic

Several types of transducers were considered. These vary from an acoustic pick up to sense the sound from the train to an acoustic pick up monitoring sound in the rail.



PHOTOGRAPH 2-4. STRAIN GAUGE MOUNTED TO TRACK

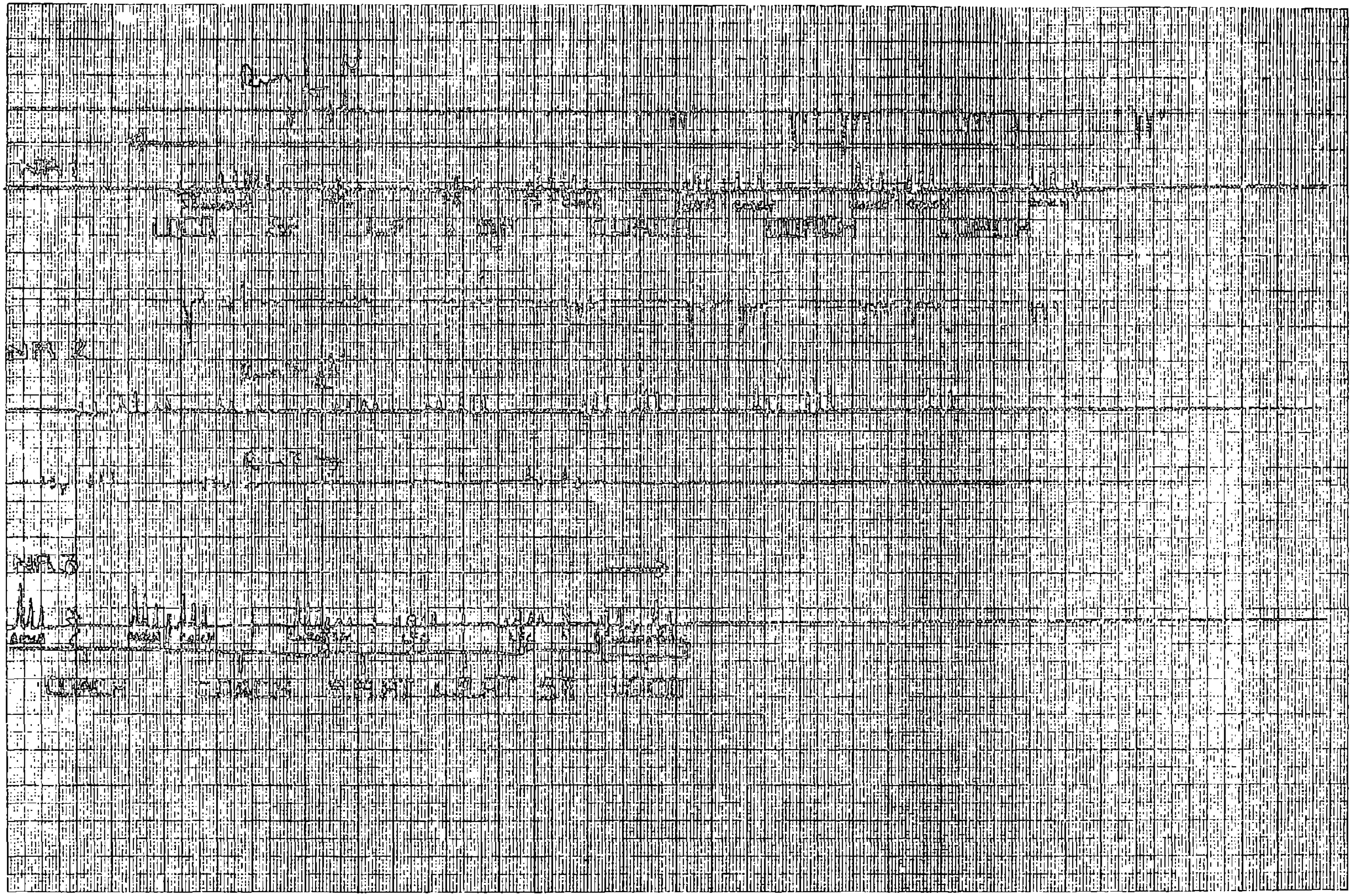


FIGURE 2-12. STRAIN GAUGE TEST-TRAIN SIGNATURE IDENTIFIED

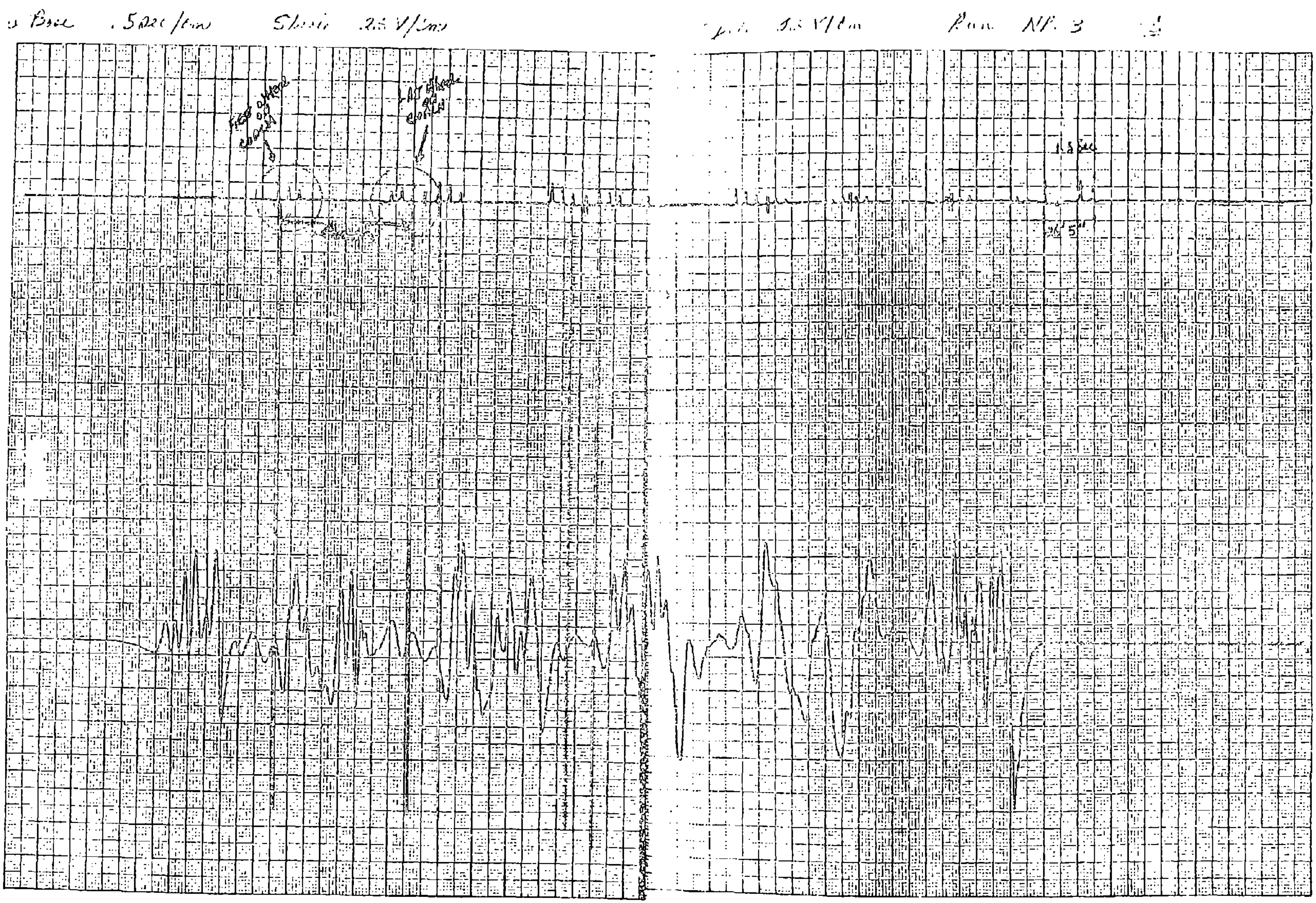


FIGURE 2-13. STRAIN GAUGE VELOCITY CALCULATOR

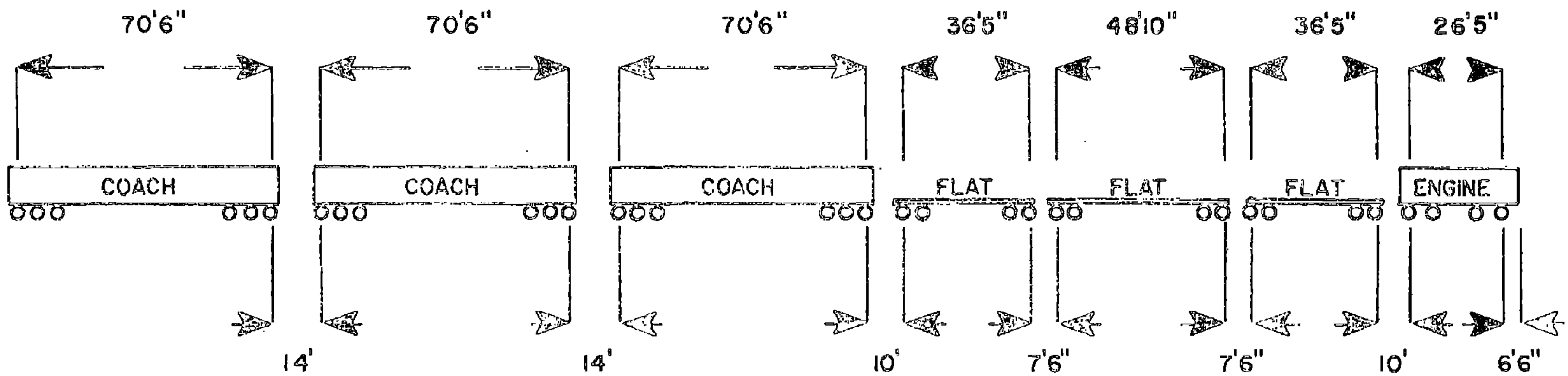


FIGURE 2-14. TEST TRAIN DIMENSIONS

For the concept that utilizes an acoustic pick-up transducer at the crossing to sense sound emanating from the approaching train, the whistle (or other sounding device) on the train could be used as the sound source. However, this was considered not to be realistic due to the 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 alarm by resorting to a coded whistle signal. For coded signals, a safe warning time requires that the signal be sounded first, a sizeable distance from the crossing, and then repeated more or less continuously until the crossing is passed. This requires that the whistle must be sounded at the proper time. The additional burden upon the locomotive engineer would not be accepted from the viewpoint of the railroad's liability. Additional false alarm risk is posed by train whistles that are in the vicinity of 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 more promising acoustic device entailed listening to a train's approach through the rails by using various acoustic pick-ups (see Figure 2-15). From the data collected it was demonstrated that usable acoustic signals can be detected at least 400 feet from the transducer. (see Figure 2-16). Subsequent analysis indicated that this range could be increased; also that an acoustic device incorporating an active input to the rail coupled with this passive device would constitute a very viable CWT system. This is discussed more fully in section 5.2.

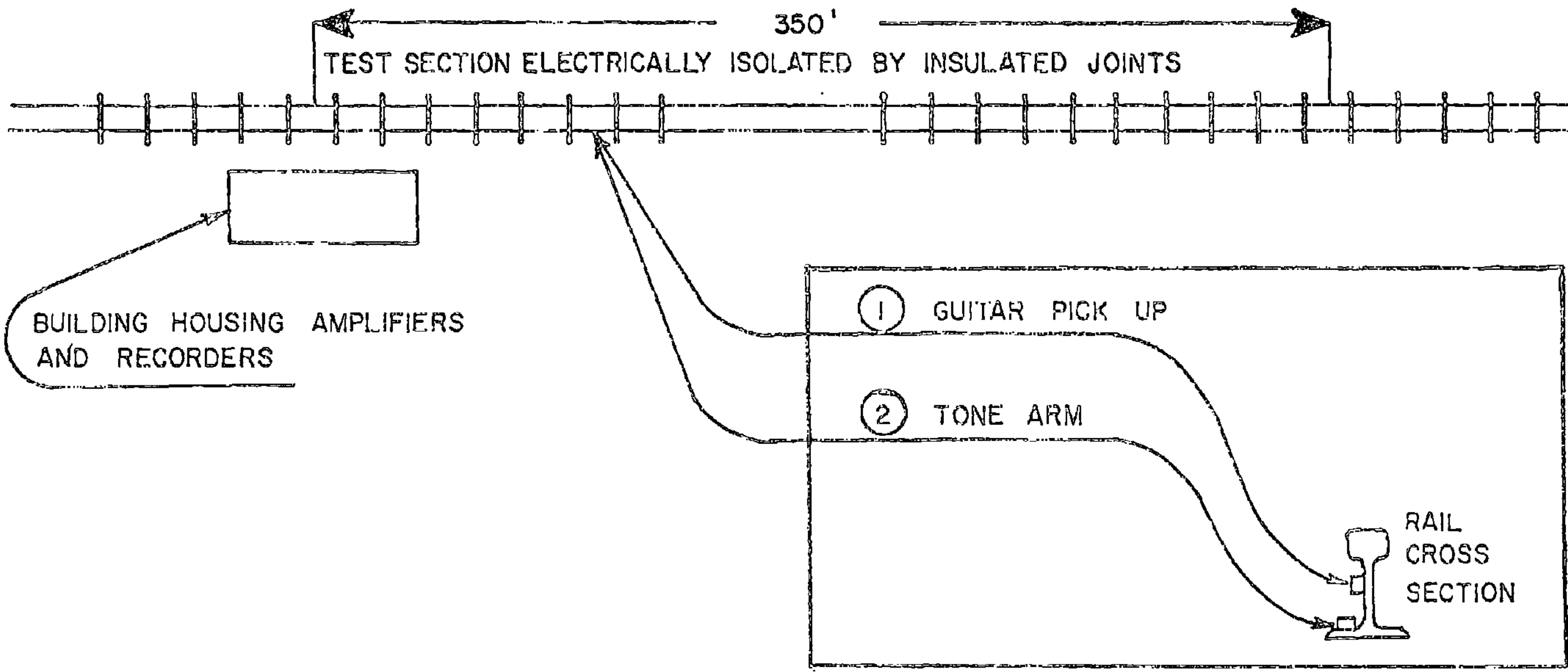


FIGURE 2-15. QUICK LOOK ACOUSTIC EXPERIMENT

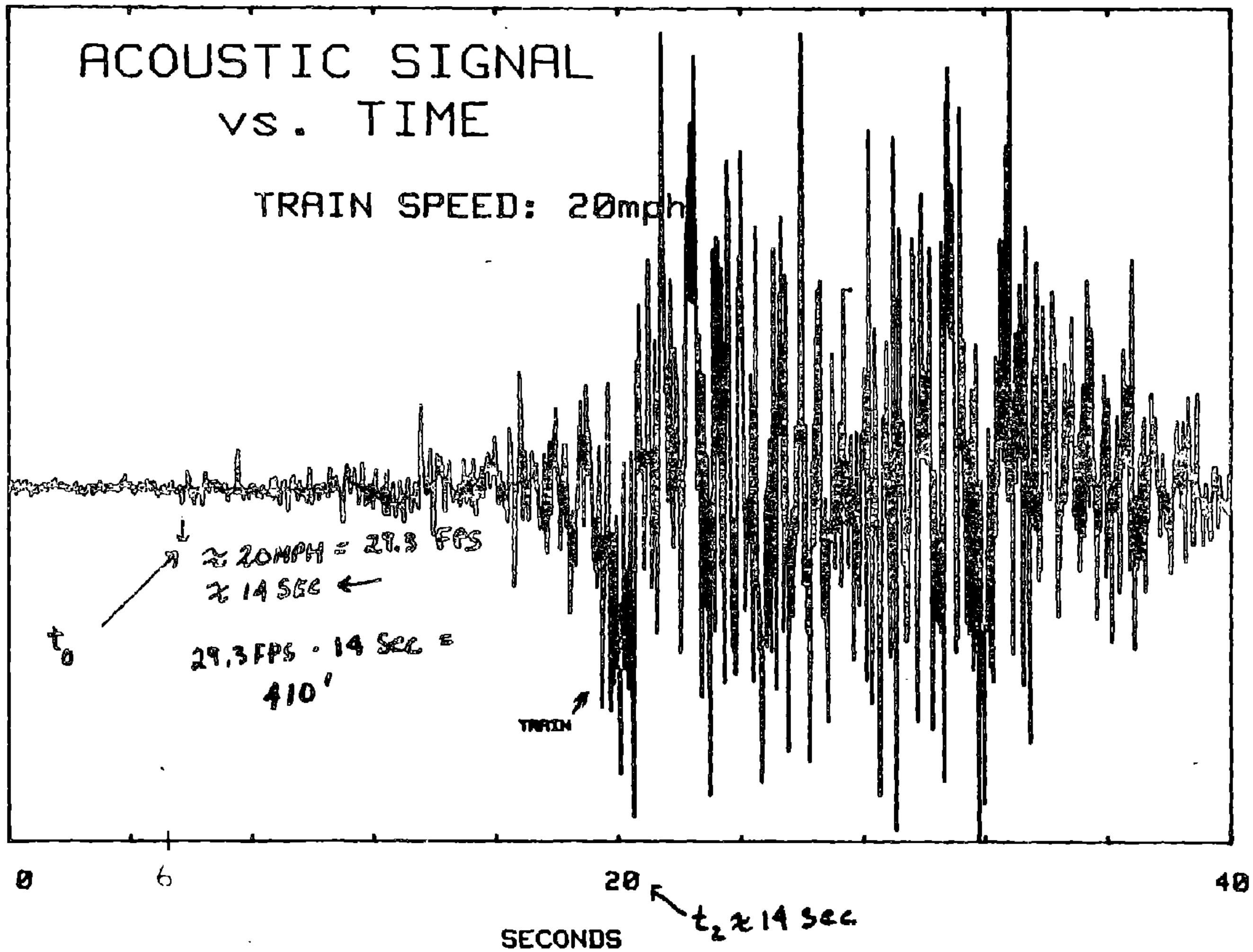


FIGURE 2-16. ACOUSTIC SIGNAL VS. TIME

2.3.4 Train-Borne Transponder Concepts

Several concepts were tested based on attaching systems to the locomotive. There are certain advantages and disadvantages to such systems. The advantages are:

- The velocity information may be directly obtained and transmitted.
- The total system has the potential of integration into larger communications systems.

The disadvantages are:

- Train location information and grade crossing arrival times are not directly obtainable.
- The system is not fail-safe in railroad terms, i.e., absence of signal does not necessarily denote train absence.

The following systems, were investigated:

Stroboscope

Among various active train-borne devices which were considered was a high intensity strobe mounted on the locomotive with a detector at the grade crossing.

Xenon-type lights were mounted directly below the headlamp of the locomotive and were pulsed at various rates from .5 seconds to 1 second. Photocell diodes located at the crossing were used to detect the beam. The concept worked fairly well at night; however, during the daytime, light level variations posed problems.

A second test had the strobe light mounted at the crossing where pulses were sent out to a reflector shield mounted on the locomotive. As the locomotive came within range, the beam reflected back towards the crossing to the photocell diode array. Problems arose in that the photocell diodes are difficult to keep clean. Furthermore, the concept was limited by line-of-sight detection.

Reflective Device

One passive device considered is a reflective type device used for boxcar inventory control. There are two objections to this approach. First, any reflective surface is prone to dirt accumulation. Although recent development with Teflon-type coatings have improved reflection, periodic cleaning would still be required. The possibility of dirt accumulation or even damage or removal of the reflective surface plus the vandal prone detector weighs heavily against this approach, since it does not lend itself to "fail-safe" operation.

In summary, both of the train-borne transponder concepts have deficiencies particularly associated with dirt build-up on the detector and reflector devices makes them unacceptable for CWT systems in terms of poor reliability and fail-safe operation.

3. CONCEPT ASSESSMENT

The CWT concepts investigated can be divided into three categories: direct sensing (i.e., independent of the train and track structures); sensing via track structure, and train borne transponders. These concepts are discussed and evaluated in Sections 2.3. Of the seventeen various concepts and techniques that were investigated, only two concepts, the magnetic and acoustic, showed a practical, timely potential for meeting present requirements for a CWT system. An evaluation summary of all seventeen concepts is given in Table 3-1.

Although guided radar and two-dimensional radar systems were considered, their potential could not be effectively determined in this study due to the time frame of the contract and the lack of off-the-shelf components in these areas. Ongoing research and development in these areas may provide a basis for future reassessment of these techniques. The remaining radar technique, horizontal doppler, was investigated by STL and dropped from further consideration because of its failure to meet all of the performance criteria listed in Table 3-1. It was not considered reliable or failsafe because of its line-of-sight mode of operation and because it was unable to distinguish between trains on adjacent tracks. These objections could be overcome by utilizing the doppler radar as an adjunct to a conventional AC or DC track circuit, but this still leaves open questions as to the practicality or economics of such a combined system.

Video motion sensing was investigated, utilizing a close circuit video system to monitor a train during its grade crossing approach. This concept proved unacceptable becuase of the sophisticated, costly technology required to develop it further.

Of the three magnetic concepts evaluated, only the magnetic coil sensor was deemed suitable for further investigation as a practical, reliable and cost-effective CWT system. Besides the magnetic coil sensor, a portable magnetometer was tested and

TABLE 3-1. MATRIX OF SENSING TECHNIQUES VS. CWT REQUIREMENTS VS. OVERALL PERFORMANCE

	RELIABLE	FAILSAFE	EAST TO MAINTAIN	VANDAL/ WEATHER RESISTANT	ADAPTABLE	ECONOMICAL	POWER REQUIREMENT	OVERALL PERFORMANCE
DIRECT SENSING								
Horizontal Doppler Radar	NO	NO			NO			NO
Video Motion Sensing	NO					NO		NO
Portable Magnetometer	NO				NO			NO
SPVD			NO	NO				NO
Magnetic Coil Sensor								YES
Beam Interruption				NO		NO		NO
Seismic	NO		NO		NO			NO
VIA TRACK STRUCTURE								
Induction Loop			NO	NO				NO
Track Impedance				NO	NO			NO
Magneto-Resistor	NO			NO				NO
Thermal	NO			NO				NO
Mechanical Switch	NO		NO					NO
Piezoelectric Crystals				NO	NO			NO
Strain Gage			NO	NO				NO
Acoustic								YES
TRAIN BORNE TRANSPONDERS								
Stroboscope	NO			NO				NO
Reflectors	NO	NO		NO				NO

found to be too sensitive to ambient noise in the railroad environment. Lastly, another magnetic sensor, the Self-Powered Vehicle Detector (SPVD), was tested and evaluated, as discussed in Section 2.3. The SPVD detects the presence of a vehicle by measuring its magnetic signature relative to the earth's magnetic field. Though the SPVD approach has merit, its performance in a railroad environment was considered inferior to that of the STL magnetic sensor concept.

The beam interruption technique was investigated, utilizing two helium neon lasers, each transmitting a beam across the track to a mirror and back to a photo-multiplier tube. This concept, though interesting, was discarded because of its cost and its vulnerability to vandal and environmental conditions.

The final direct sensing technique investigated was the seismic concept, utilizing geophones buried in the right-of-way near the crossings. This technique proved unfeasible for a number of reasons: lack of ability to distinguish between adjacent vehicular traffic and train noise; critical placement of the geophones; and sophisticated, expensive electronics to provide seom assurance against false alarms.

A number of CWT concepts whose signaling is accomplished through the track structure were investigated. These concepts included induction loop, track impedance, magneto-resistor, thermal, proximity switches, and·acoustic. Of these, all but the acoustic sensor concept were considered unacceptable for various reasons, as discussed in Section 2.3.3. See Sections 4.2 and 5.2 for further examination of the acoustic concept.

The track impedance concept is limited by ballast resistance, which can vary appreciably under changing environmental conditions. The magneto-resistor senses a change in magnetic flux density caused by a passing train; it requires a bias magnetic field that is difficult to maintain at a constant value and provides only a small dynamic range of resistance change.

The thermal concept depends on heat produced in the rails from the friction of the train's wheels. The quick-look exercise showed this technique to be ineffective.

Several proximity switch concepts were investigated by STL including mechanical switches, piezoelectric crystals and strain gages. They all suffer from point deficiency problems as well as requiring critical connection or alignment with the track structure. The mechanical switch requires direct connection to the rails and critical packing of the roadbed; ballast erosion and a dirty rail enviroment will cause severe reliability problems. The piezoelectric sensor responds only to a change in mechanical pressure; thus, it would fail to respond to a stationary train. The strain gage sensor is probably the most reliable of the proximity sensors; however, it still requires careful connection and alignment to the rail and in addition is not vandal proof.

The only track structure concept that is considered to have potential for a CWT system is the acoustic sensor. This concept utilizes an acoustic pickup transducer at or near the crossing to sense sound emanating from the approaching train. Air transmitted sound was considered initially, but discounted due to the probability of false alarms caused by sound from extraneous sources. Acoustic sensing through the rails was then investigated with promising results. These are presented in Section 3.3.3. (Also Sections 4.2 and 5.2). The acoustic sensor concept is a viable concept for a CWT system and warrants further study.

Finally, some train borne transponders were considered for a CWT system. These included an active (stroboscope) device and a passive (reflective) device. Both types, naturally, require train borne devices which is a serious disadvantage in itself. The stroboscopic system experienced problems during the daytime and has the limitation of requiring line-of-sight. The reflective device concept provides detection only at a discrete point and therefore has the disadvantages associated with discrete sensors. Train borne transponders were not considered practical or reliable for a CWT system.

4.0 ADDITIONAL INVESTIGATION OF PROMISING CONCEPTS

This section describes further investigation of the two most promising concepts. These are based on magnetic and acoustic principles, respectively.

4.1 MAGNETIC COIL SYSTEM

This system consists of a series of discrete magnetic sensors which are implanted in the trackbed underneath the ballast. As the locomotive passes over each individual sensor, a change in the magnetic field causes a voltage to be generated. The voltages from each sensor are transmitted to a receiver and recorded. The time sequence of these signals enables the location of the locomotive to be plotted as a function of time. Using this data, a microprocessor computes the velocity and acceleration of the locomotive between the various sensor points, enabling the time to the crossing to be accurately calculated. The time to the crossing is carefully monitored by the microprocessor so that when it falls below a pre-established threshold which can be set beween 20 and 30 seconds, a signal to initiate the warning light system is transmitted.

4.1.1 Sensor Details

The sensor package consists of a 1/4" diameter, high permeability material rod approximately 12" long which is wound in the middle with a coil of Number 40 gage wire. The inductance of the system is relatively high (150-175 H) and experiences a peak-to-peak amplitude change of approximately 250 mV when passed over by a medium road switcher locomotive (60 tons) at 20 mph. The sensor itself is contained in a 3" - 4" diameter tube (48" long) which is buried 6" below the ground (see Figure 4-1). It is easily installed with a post hole digger. While the particular sensor used in this investigation is no longer manufactured, similar sensor packages can be obtained commercially.

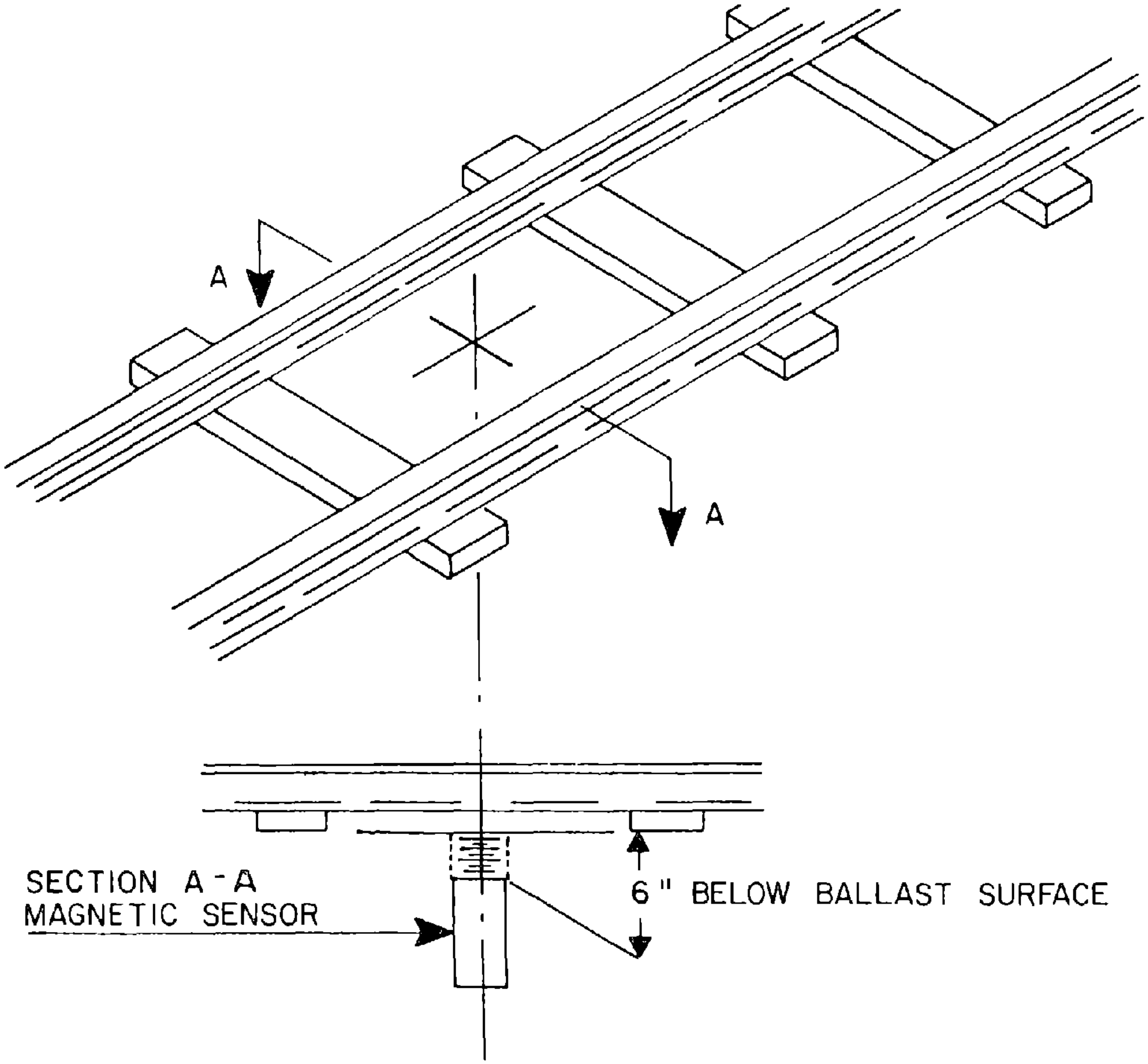


FIGURE 4-1. MAGNETIC SENSOR PLACEMENT

4.1.2 Sensor Layout

The magnetic concept is designed around a series of five discrete sensors S_1 through S_2 placed through the signal block. (See Figure 4-2). Placement of the sensors relies upon establishing the worst case (highest) speed for each grade crossing, converting the speed in miles per hour to feet travelled per second, and multiplying that figure by the desired constant warning time (20-30) seconds Thus, if in a given grade crossing the worst case speed is 70 mph and the desired constant warning time is 20 seconds, the first detection point (d) is given by

$$d = 70 \times \frac{88}{60} \times 20 = 2053 \text{ ft. (622 m) from crossing}$$

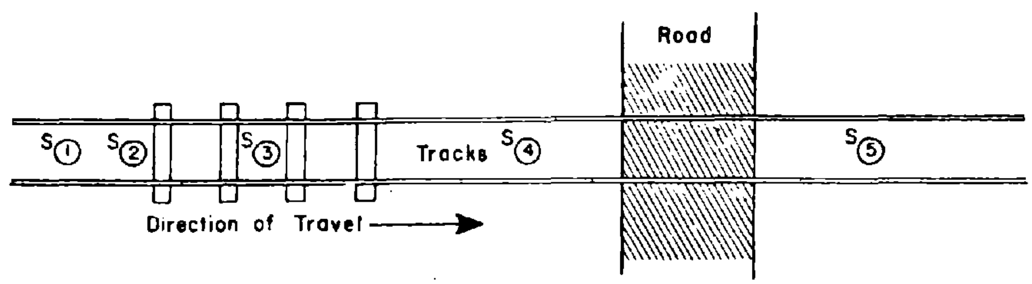


FIGURE 4-2. PLACEMENT OF MAGNETIC SENSORS

4.1.3 Signal Transmitter Description

The entire sensor and transmitter unit is powered by a DC source with an extremely low self-discharge of 3 to 5 percent in ten years together with a capacity of over 100 Ah. An external DC source is used to charge Nickel Cadmium (NiCd) batteries which are used to supply the peak current requirements of the transmitter. The voltage is monitored during each transmission to determine if the unit is still able to maintain its charge. During transmission is the best time to check battery capacity since it includes a DC source internal impedance in the measurement which will rise rapidly as the cell capacity is exhausted. This approach provies a highly reliable transmission/ power self-check capacity for the transmitter.

Transmitter Timing

Basic system timing is derived from a crystal oscillator and divider. The basic oscillator frequency will be approximately 200 MHz followed by a divide-by-9 circuit. This must be further subdivided to give a basic time frame which is used to check out the entire system.

A test transmission is indicated by a special data bit transmitted after each data word. If any portion of the system is inoperative, the system will not transmit, and this lack of transmission will be noted and recorded by the receiver and processor servicing this particular transmitter.

Timing is arranged to prevent two closely spaced or overlapping pulses from being transmitted at the same time by adjusting the timer sequence so that the test transmission is always delayed a fixed amount of time from any transmission, whether it is a test or "presence" (of a rail car) signal. The low energy condition is transmitted as part of the data sequence as a constant transmitter validity check.

For all practical purposes, the transmitter is in a passive mode for the majority of the time. Basically, this requires that only the internal "test" timer and the sensor pre-amplifer and threshold detector can be continuously powered. The remainder of the transmitter can activate when an actual "presence" transmission is desired.

Test Transmitter

The configuration of the test transmitter design is shown in Figure 4-3. The design approach has been intentionally conservative

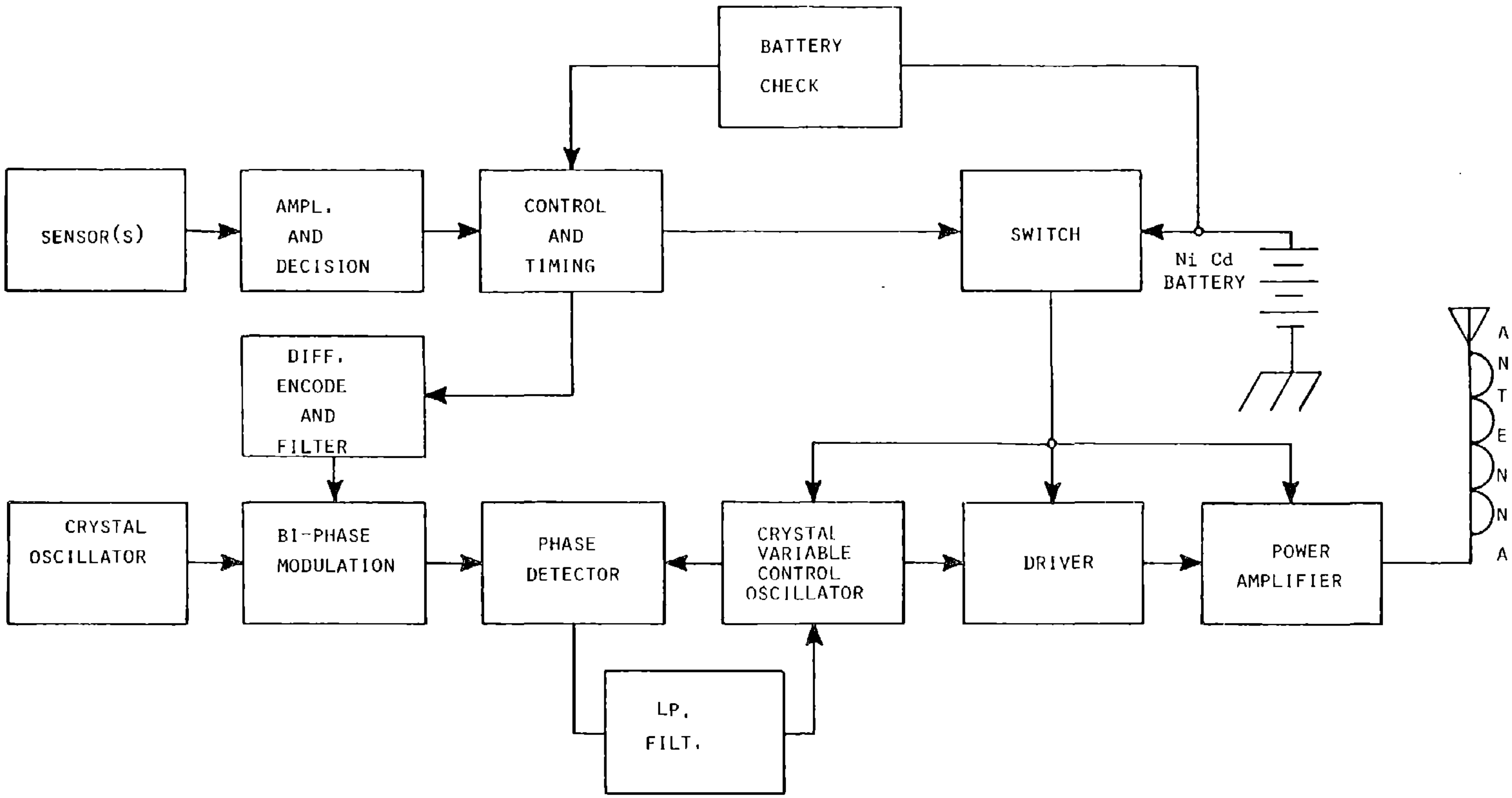


FIGURE 4-3. TRANSMITTER BLOCK DIAGRAM

to compensate for the expected deterioration that will occur over the long-term installation of the system and because of the wide antenna load variations expected. (These involve the antenna working in dry ballast surrounded by large air gaps to situations where the ballast is under water corresponding to a near electrical short.)

For any given application, the system performance parameters must be examined to design the optimum balance between power, distance and antenna gain. The present design is capable of delivering 5 watts into a 50 ohm load with a DC input of 1.25A at 7.5V (53 percent efficiency). This should be sufficient for the present application. Obviously, more RF power could be generated at the expense of greater input power, however, this seems to be an inefficient approach. For example, an increase to 50 watts input would only increase the antenna power by 10 db. This increase to input power would hardly overcome variation in other system variables which can easily amount to 20 or 30 dB (noise, train loading, etc.). Therefore, the present transmitter design which has been checked against FCC rules seems to be a good trade off between size, power and performance requirements for use in a CWT system.

Modulation Scheme

The transmitter system was chosen since it can accomodate the data rate, allow close channel spacing, and still employ optimum bi-phase modulation. To the elementary bi-phase modulator, a "clean-up" phase-lock loop (PLL) has been added to ensure phase measurement accuracy. Since the phase modulator is modulated with square waves, its spectrum has a Sin X/X form. Also, since the data is filtered before applying it to the modulator, the spectrum is bandlimited, but has a large AM component. When passed through the class C transmitter, functioning as a limiter, the spectrum is spread as before. The clean-up PLL takes care of both of these problems since it has no AM component and rate of change of phase, and thus, bandwidth is controlled by its loop filter. Because of the narrow loop filter bandwidth, both oscillators are crystal controlled to ensure receiver aquisition of the transmitter signal.

Transmitter Power Budget

In estimating the transmitter power budget, three operating states must be considered. These are stand-by, operate, and self-test. In considering these items, important variables are:

- Number of trains per day
- Transmission tine
- Transmitter current drain
- Quiescent current drain

For example, assume that a crossing has 40 trains passing through it in any 24-hour period; the electronics in the passive state (quiescent) draws on approximate 300 μA current; the transmitter current drain, when in the active mode, is approximately 1.25A; and the transmitter on-time per train is estimated at 50 msec., per detected train, per sensor. The energy consumption can then be calculated as follows: The stand-by current drain becomes:

$$= 300 \times 10^{-6} \times 24 = 0.0072 \text{ Ampere hours/day}$$

The presence transmission becomes: $= \dfrac{1.25 \times 40 \times 50 \times 10^{-3}}{3600}$

$= 0.0007$ Ah/day

The test transmission becomes: $= \dfrac{1.25 \times 24 \times 60 \times 50 \times 10^{-3}}{3600}$

$= 0.025$ Ah/day

Consequently, the total energy consumption is:

$= 0.0072 + 0.0007 + 0.025$

$= 0.0329$ Ah/day

Since the capacity of the NiCd power pack is 100 Ah, this means the system has a capacity for powering the device for over 8 years provided it is built with sufficient quality.

Transmission System Requirements

The system must, of necessity, be configured with the sensors located at a considerable distance from the protected crossing.

crossing. This distance increases as the anticipated train speeds increase and could extend approximately one mile on either side of the protected crossing. Although reliable communication over such a distance is a prime requirement, it is not the sole requirement. Other factors must be considered and, although they do not directly affect the communications link, they do affect the configuration of the system. These factors include:

Protection against vandalism: If a system is to operate reliably for long periods, it must be immune to vandalism or it will be rendered inoperable before it is used. It is nearly axiomatic that anything that can be erected can also be torn down. To date, no amount of shielding or armoring has been effective against casual vandalism, much less against deliberate destruction. Vandalism in all such forms must be considered in any reliable system.

One might consider using the rails themselves as a conductor from the sensor to the crossing protection circuit. The rails have been shown to be a low impedance transmission line which is, of necessity, continuous, especially at higher frequencies. However, the characteristics of the "rail transmission line" are quite variable due to wet ballast, snow or actual water. At the time they are to be transmitting they could even be shorted by the train itself right at the sensor transmitter.

For positive protection against vandalism, the only transmission medium considered worthy of serious consideration is an underground system. This provides protection in two ways, in that the potential vandal does not know (1) that such a system is installed, and (2) where the sensors or wires are actually located. Burial also gives protection from natural hazards. Of course, deep burial is the most invulnerable, but deep sensors lose sensitivity and costs start escalating sharply for deeply buried cables.

Ease and cost of installation: Again, assuming communication distances of a mile or more, buried wire systems (co-axial cables, fiber optic or single pairs) would require two miles of trenching and two miles of armored waterproof cabling. This is quite costly both for the cost of the cable itself, and for the installation. Again, deeper installation increases installation costs and has the potential to increase maintenance costs also. This is the first juncture where an underground radio transmitter is quite simple by comparison. In addition to being required to transmit from underground, such a system also requires a reliable long life battery.

When using a single cable or fiber with a multiplicity of sensors connected along its length, the single transmission link is extremely vulnerable to mechanical damage. A single break, depending on its location, can take out the entire system, not just one sensor. Physical breaking of such a cable is a distinct possibility considering the projected long lifetime of such a system and the mechanical movement of the earth in the vicinity of the train. Of course, multiple cables (one for each sensor) could be utilized to improve reliability, however, this would lead to increased cost.

Reliability of the package: For system reliability, the sensor package must be hermetically sealed and impervious to moisture if it is to have a long operating life and be a feasible system. For a cable, the physical penetration of the package to make connection to either wire or fiber optic cables increases the vulnerability of the package seal. For this reason a radio-based system is superior since the signal can be radiated without need for an additional penetration of the package.

For all of the reasons cited above, the buried transmitter radio system appears to be the most desirable. The only other medium worthy of consideration is the fiber optic which offers a noise-free transmission medium at the expense of installation costs and package reliability. For either the radio or fiber optic systems, self-powering batteries are, of course, a necessity.

Characteristics of the RF System

It is found that the information and drift rate can be accommodated within a pre-detection bandwidth of 1 KHz. In order to determine the minimum signal level it is necessary to evaluate the system noise performance. This is estimated as follows for a 10^{-5} error rate:

KTB (thermal noise)	-174 dBm
Galactic noise (ITT Handbook)	20 dBm
Noise bandwidth	30 dBm
Error rate of 10^{-5}	11 dBm
TOTAL	-113 dBm

Thus, without any system margin considerations the minimum signal level is -113 dBm.

Because of the nature of the system and the deterioration of the signal-to-noise ratio that can occur due to a variety of causes, at least 20 dB of margin should be assumed indicating a minimum signal level of -93 dBm is required. A minimum signal level of -100 to -120 dBm represents a very small signal (2 to .2 μV) as may be understood when comparing to .5 μV sensitivity (-113 dBm) for a high quality FM receiver with a 15 KHz (42 dB/Hz) predetection filter.

Some sort of automatic noise limiter will have to be utilized. Most likely the sources of excess noise will be of the pulse type, i.e., electric motor brushes, ignition, power lines, lighting, etc.

In the present study which involved railroad testing at Ft. Eustis, it was noted that a single transmitter in close proximity to the receiver destroyed communications. The current frequency band of 30 MHz includes some other bands which could reasonably be expected to be active. These are:

- 26.96 - 27.41 MHz - Citizens Band
- 27.41 - 27.54 MHz - Industrial Land Mobile
- 28.0 - 29.7 MHz - Amateur Band
- 30.56 - 32 MHZ - Industrial, Land Transport Public Safety

Although the gain will be restriced in the RF section to prevent intermodulation, this should not be a severe problem since the probability that two transmitters will be on simultaneously is extremely small. As previously mentioned, there is a requirement for extreme dynamic range requirement to allow reception in the presence of transmitters adjacent to receiver.

Utilizing a 10.695 MHz first IF allows the use of a standard synthesizer. The second injection is derived from a separate crystal oscillator. The second IF processing is at 455 KHz with a narrow band ceramic filter to achieve a 2 KHz noise band-width. While this is not sufficient to completely reject the adjacent channel, it does provide sufficient attenuation to allow signal gain to be achieved.

Finally, the 455 KHz is mixed to 10.455 KHz for final selectivity, gain and demodulation. All of these engineering decisions are interrelated compromises to effect a cost-effective design. It is necessary to go to such a low frequency to achieve the required selectivity.

There has been considerable investigation of how the Phase Shift Key (PSK) data might best be demodulated. The classic concept of PSK demodulation is to store the previous bit and compare it with the current bit. Up until recently, such a technique was only applicable to very high speed data since practical delay lines were so short. However, it is not possible to achieve long audio delays through the use of various charge-coupler devices which function as variable length delay lines, depending on the frequency at which they are clocked. Since it is only required to provide one bit of delay which can be set accurately at the transmitter, it does not require work synchronism. To achieve the required one-bit delay, it is necessary to provide a clock of approximately 155 MHz which gives good fidelity to the 10 KHz signal which is is processing.

The one-bit delayed data and the current received data are continuously applied to the phase detector which makes the decision of whether the phase was changed during a one-bit interval. The advantage of this demodulation technique is that it is sensitive to the actual frequency, thus frequency aquisition is not required.

Receiver

Since a logical arrangement is for six transmitters per track and the frequency assignments are arranged to fit into a standard wideband communications channel, the receiver is configured along similar lines. The receiver is configured to cover a band of 30 to 33 MHz through front end tuning and selection of the synthesizer division ratio. The group of six track channels is 12 KHz wide with groups stepped in 5 KHz steps by the synthesizer.

False Alarm Considerations

Nearly as important from an overall systems operational standpoint is the consideration of the false alarm rate. Although the concept of low probability of error during transmission assures that the message will most likely be received and correctly decoded, it does not guarantee any performance criteria during the time the transmitter is off. The receiver must have the ability to positively identify the transmission and to conclude if it is actually a valid transmission rather than noise. If the receiver is continually recognizing noise bursts as data and activating the crossing signals, the motorists will soon come to ignore them. The approach is a simple, unique encoding of the signal so that the receiver can positively separate any output from noise or interference. (If any interference is present in the operating band, an overriding signal level from the companion transmitter will overcome it and have the possibility of being recognized as a valid transmission.) The coherent demodulator is able to distinguish coherent from incoherent signals and thus provides the required level of noise discrimination.

4.1.4 The Processing System

The processor configuration shown in Figure 4-4 is an overall block diagram of all the inputs and outputs required in a microprocessor based processing system for a single direction track warning system. Because of the complexity associated with six signal receivers, two slave processors are utilized to receive the data directly (each accommodating three channels). A master processor is used to control overall system timing and process the logic decisions.

The track loop signals shown in Figure 4-4 are in connections to the local track to sense whether the train has actually entered or left the crossing island.

For each of the six transmitters the presence of a signal is noted and the transmitted data word is passed to one of the two slave processors to validate the data (parity-redundancy) and to extract the information message. Also, the presence of the transmission itself on a regular basis signifies that the transmitter and battery are still functioning.

The fixed distances are set into the unit at the time of installation and denote the actual distance from the sensors to the protected crossing. This information, in conjunction with the time of arrival of the train at each sensor/transmitter allows prediction of the proper time to give the warning and close the gate. The reset is a manual input to clear the outputs should it be necessary to re-initialize the system.

The "close gate" and "warning" directions are the prime outputs of the microprocessor subsystem and the system itself and are calculated from various inputs.

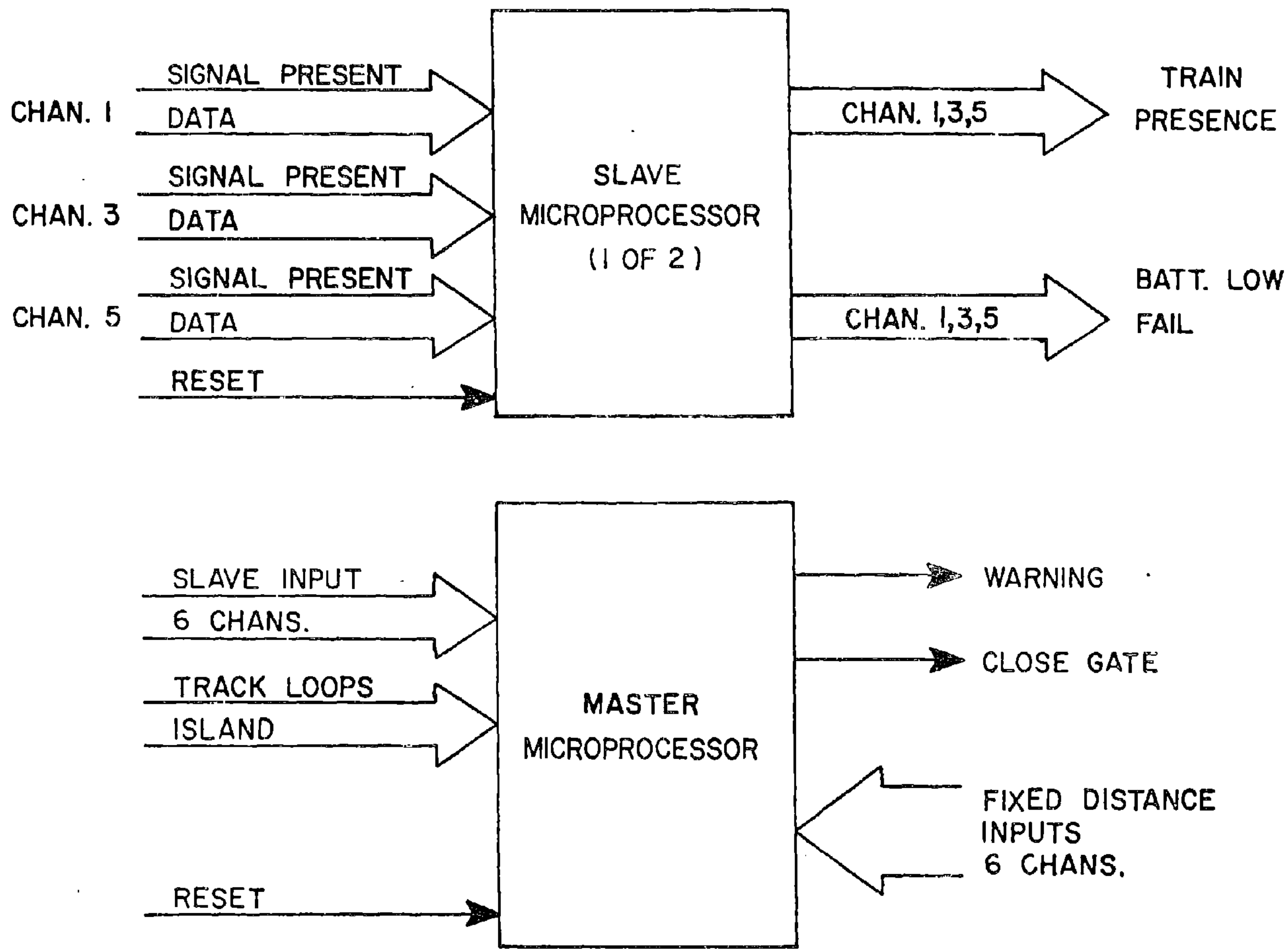


FIGURE 4-4. MICROPROCESSOR

For each transmitter there are two status lights to indicate that the battery is low and that the transmitter itself has failed. Both of these are activated from the test word.

4.1.5 Algorithm for Generating Constant Warning Time General Description

Described below is the manner in which the basic outputs from the individual sensors are processed by the microprocessor to provide a warning signal to the crossing gate system which has a constant warning time prior to the train's arrival.

Referring to the flow chart shown in Figure 4-5, the sequence of events is as follows:

1. The train is initially sensed at S_1, which is placed far enough ahead of the crossing to allow sufficient warning time for trains traveling at the maximum speed for the crossing.

2. The time is measured between sensor S_1 and S_2 to obtain the average velocity between S_1 and S_2. Since S_1 and S_2 are positioned relatively close together, this can be taken to be the velocity at S_2 to a good approximation.

3. The velocity (V_2) at S_2 is then compared to a parameter V_{min} which is the train velocity below which d_2 (the position of sensor S_2) is the sufficient stopping distance.

4. If V_2 is greater than V_{min}, then the gate closing is initiated and the gate is set to close based on the train continuing at the velocity V_2 until reaching the crossing, and allowing a constant warning time of 20 seconds.

5. If V_2 is less than V_{min}, the gate closing sequence is not initiated and the system waits for the train to pass over the sensor, S_3.

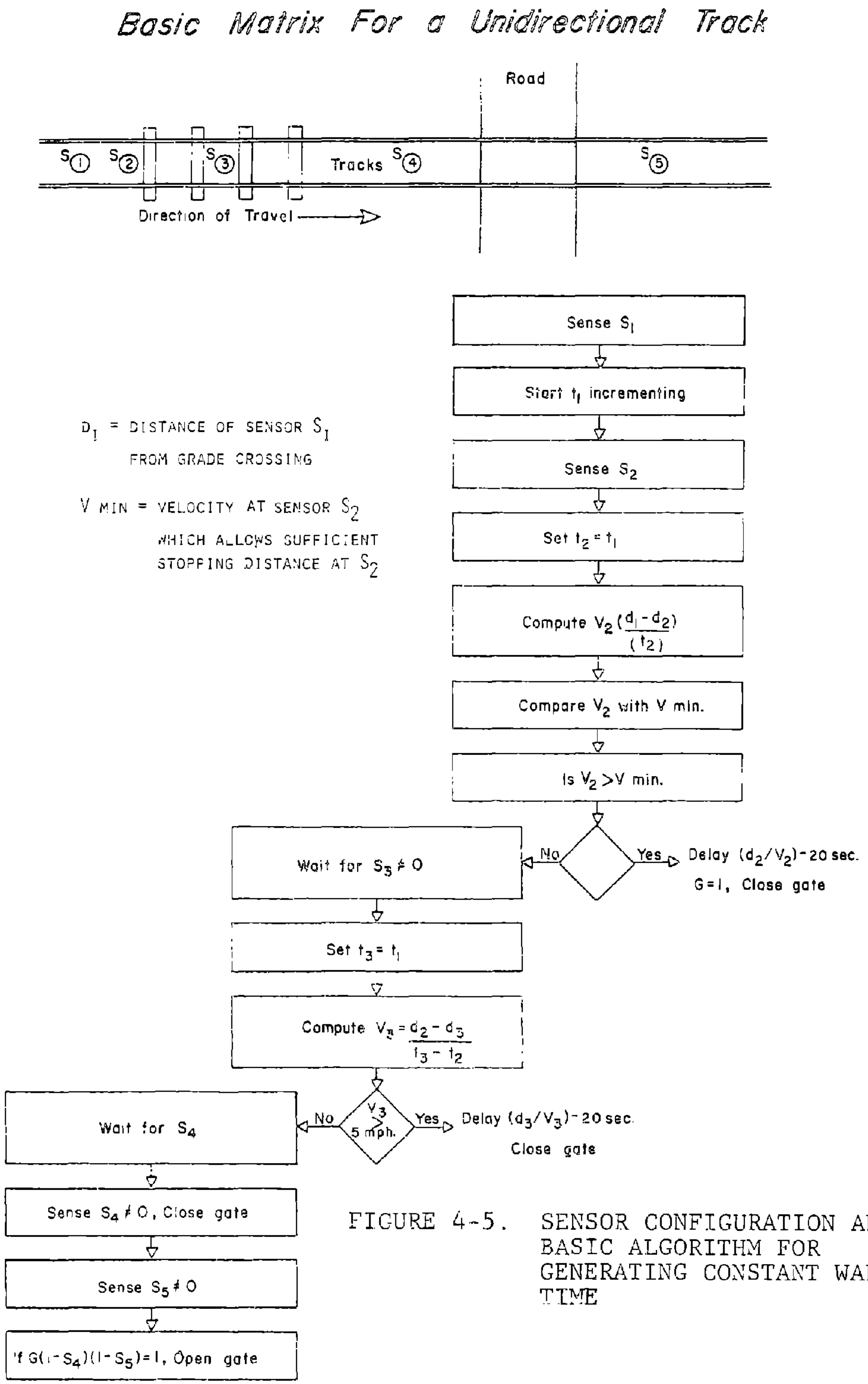


FIGURE 4-5. SENSOR CONFIGURATION AND BASIC ALGORITHM FOR GENERATING CONSTANT WARNING TIME

6. The average velocity between sensors S_2 and S_3 (V_3) is then computed. Comparing V_3 to V_2 allows it to be determined whether the train is accelerating or decelerating.

7. At this point, another decision is made. If V_3 is greater than 5 miles per hour, then the sequence to close the gate is initiated (the exact timing is predicated on whether the train is perceived to be accelerating or decelerating); if the train is traveling less than 5 miles per hour, then there is a possibility it may stop before reaching S_4, in which case closing the gate would totally defeat the notion of constant warning time. In this situation, the sensor S_4, which is placed relatively close to the crossing, is utilized. When this sensor is activated, the gate closing sequence is initiated. This technique protects the motorist against slow-moving trains, however, it does not cause the motorist to wait indefinitely for a train which will never reach the crossing.

8. The final portion of the algorithm concerns resetting the gate mechanism after the train has passed through the crossing. This is done using the output of a sensor (S_5) positioned on the other side of the crossing.

Sensor Placement for Providing Sufficient Warning Time At a Given Crossing

The sensors (S_1, S_2, etc.) must be located at pre-determined distances from the crossing location in order to provide adequate warning time for all trains which are likely to approach the crossing. This means that at the time for the fastest train is detected at the sensor S_2, there must be at least 20 seconds before the train reaches the crossing. Consequently, if the worst case speed for the particular crossing is V_{max}, then the distance d_2 is given by

$$d_2(ft) = V_{max}(ft/sec) \times 20\ (sec).$$

For example, if V_{max} is 110 mile/h (176 km/h) and a warning time of 20 seconds is required, then the location of sensor (S_2) must be

$$d_2 = (110 \times 88/60) \times 20$$
$$= 3227 \text{ ft } (968.1 \text{ m})$$

ahead of the crossing.

The sensor S_1 is always located up-stream of sensor S_2 since it is used for initial detection and monitoring the velocity at S_2 by calculating the time taken to travel the relatively short distance between S_1 and S_2. Sensor S_3 is placed at a distance d_3 which is used to determine if the train is accelerating or decelerating after passing sensor S_2. Sensor S_4 is placed such that if the train reaches the sensor at 5 mile/h (8 km/h) and the gates are not already closed, there is sufficient warning time to close the gates. Thus, distance d_4 is given by

$$d_4(\text{ft}) = (733 \text{ ft(sec)}) \times 20 \text{ sec}$$
$$= 147 \text{ ft } (44.1 \text{ m})$$

Solution Process Used by Microprocessor for Gate Closing

Assume the train is approaching the grade crossing and is detected at sensor S_2 to be moving with a velocity, V. If $V \geq V_{min}$, the gates must close. This will occur after some computed procrastination time defined as T_m,

$$T_m = T - T_C - T_R$$

where T is the time to reach the crossing, T_C is the constant warning time and T_R is the gate response time.

If $V < V_{min}$, the procrastination time to close the gate is computed as follows:

First of all, the average velocity between S_1 and S_2 is determined through

$$V_{1,2} = \frac{d_1 - d_2}{t_2}$$

and since d_1 and d_2 are relatively close, this can be assumed to be V_2, i.e.,

$$V_2 \simeq \frac{d_1 - d_2}{t_2}$$

Next, the average velocity between S_2 and S_3 is determined through

$$V_{2,3} = \frac{d_2 - d_3}{t_3 - t_2} = V_3$$

Comparison of $V_{1,2}$ and $V_{2,3}$ allows determination of whether train is travelling at constant velocity, accelerating or decelerating.

Case 1: If $V_{1,2} = V_{2,3}$, the train is traveling at constant velocity and the time required for the train to reach the crossing is given by

$$T_1 = \frac{d_3}{V_{2,3}}$$

Using this time, the microprocessor system determines if the train is moving at a rate that will not allow it to stop in ample time. It then puts the gate system into a state of procrastination until a modulation time is reached at which time the gate closing sequence is initiated. The modulation time, T_m is given by

$$T_m = \frac{d_3}{V_{2,3}} - T_C - T_R$$

Case 2: If $V_2 \neq V_3$, then the train is not traveling at constant speed and the acceleration or deceleration is given by

$$a = \frac{V_{2,3} - V_{1,2}}{\Delta t}$$

where Δt is the time between the mid-point, i.e.,

$$\Delta t = t_3 - t_2$$

The time T_2 required for the train to reach the crossing is given through the equation

$$d_3 = V_{2,3}T_2 + 1/2\ a\ T_2{}^2$$

Assume that the train is accelerating (i.e., a > 0), then the above equation is solved for t_3. This will give a slightly conservative result for the warning time in that if the train starts to decelerate after S_3, the train will take longer than the constant warning time to arrive at the crossing. This is considered to be a failsafe approach. The microprocessor uses a modulation time as before, which in this case is calculated from

$$T_2 = \frac{1}{a}\left[-V_{2,3} + \sqrt{V_{2,3}^2 + 2ad_3}\right] - T_R - T_C$$

Case 3: In cases of deceleration where $a < 0$, the same equation is used except here the modulation or procrastination time is much longer since the term $a(d_3)$ is now negative. In the extreme case when the train decelerates drastically, the fourth sensor, S_4 is used to determine when the gate should be closed or if the train actually stopped before reaching S_4, in which case the gate is not closed.

4.1.6 Magnetic Hybrid System

An important improvement to the magnetic system concept would be to use it in conjunction with an existing motion sensor device. In this configuration, the number of magnetic sensors could be reduced to say S_1, S_2 and S_3 or possibly S_1 and S_2. Here, the magnetic portion (S_1, S_2, S_3) provides the precise distance and velocity information during normal approach to the crossing, whereas the motion sensor device provide continuous information on the location of the train while in the vicinity of the crossing. This provides proper coverage if the train stops, slows down excessively, or reverses. In essence, this hybrid approach can be used to combine advantages of point sensors (magnetic system) and continuous sensors (motion sensors) to come up with a very cost-effective constant warning time.

4.2 ACOUSTIC SYSTEM

4.2.1 General Principle

This system relies on monitoring the passage of acoustic waves through the rails to find the position of the locomotive. The basic principle relies upon the fact that the speed of acoustic compressional waves through an elastic medium is a known function of the material properties of the rail (Young's Modulus, E; density, ρ). Consequently, if the time of travel of these waves can be measured it is possible to work back to deduce the distance from the point where they were reflected and consequently locate the position of the locomotive. Referring to Figure 4-6, the acoustic energy is sent out via a piezoelectric generator attached to the rail, and when a locomotive is present, the axle provides a return path for the waves as shown in Figure 4-6.

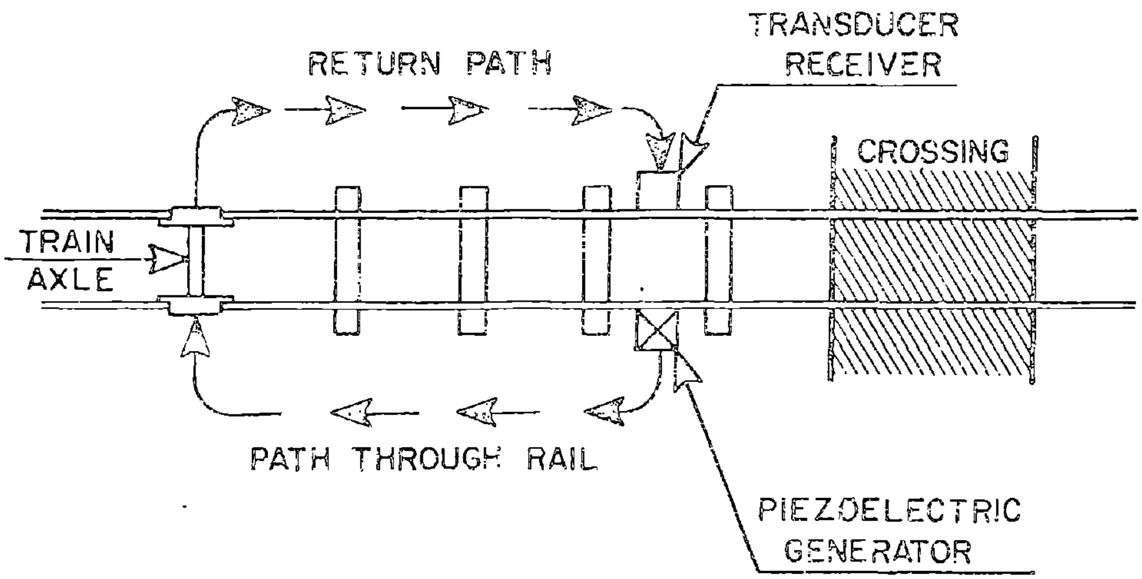


FIGURE 4-6. ACOUSTIC SYSTEM

If the time of travel of the waves is t, then the position of the locomotive from the location of the generator and the transducer is given by

$$S = V \frac{t}{2}$$

where V = the velocity of acoustic waves through the rail.

Cross-correlation processing of the input signal with the return is to be used to deduce the time lag, t. This system provides continuous information on the position of the locomotive as a function of time.

4.2.2 Constant Warning Time Processing

The acoustic system uses the same algorithm and processing systems for computing constant warning time as the magnetic system and has the ability of providing continuous updates on the location of the train.

4.3 SUSCEPTIBILITY OF MAGNETIC AND ACOUSTIC CONCEPTS TO ELECTROMAGNETIC INTERFERENCE (EMI)

The susceptibility of the two selected systems to EMI from diesel-electric traction motors has been examined and analyzed in conjunction with another study.[6] Here, a survey and analysis of EMI problems was conducted for new types of traction control systems, namely those involving thyristor control of traction motors. This examination considered the EMI effects on the selected CWT systems for both diesel-electric and all-electric railroads. Although these effects can be significant in the case of all-electric railroads due to very large return currents on the rails, it was shown that the EMI effects were likely to be insignificant in the case of diesel-electric locomotives. The reason for this is the much smaller rail currents associated with diesel-electric locomotives (1 amp vs. 300-600 amps). Thus, any EMI countermeasures required to assure reliable operation of the selected systems in the case of all-electric railroads will be more than adequate to assure reliable operation on diesel-electric railroads.

In view of the foregoing, it was considered unnecessary and unwarrented to conduct extensive tests on diesel-electric locomotives or to evaluate specialized EMI countermeasures for these locomotives. The EMI problems associated with the new types of locomotive controls, for both all-electric and diesel-electric railroads, are analyzed and evaluated in Appendix B to this report.

4.4 METHODOLOGY FOR DATA HANDLING AND ANALYSIS

The data was recorded, digitized and analyzed using several standard digital signal processing techniques. This approach was

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[6] R. L. Monroe

chosen over direct analysis of analog signals because of the greater speed and flexibility of digital techniques. These techniques include time averaging, linear spectral analysis, and some auto-and-cross correlation.

Figure 4-7 is a flow diagram showing the overall data processing scheme used in these tests. Details of the process changed frequently during the tests, but this figures gives the general approach that was taken. Here, signals from the sensors (magnetic/seismic, acoustic and strain gage) are first amplifed, detected and passed through a low pass, Chebyshev filter with a cut-off of 10 KHz. Output from the filter is recorded by a Honeywell 5600E magnetic tape recorder after passing through a log amplifier. Fidelity of the magnetically recorded data is checked with the aid of an analog display device shown to the right of the tape recorder. A record of the filter output can also be generated by a HP 7046A, X-Y plotter operating in parallel with the tape recorder. The X-Y plotter is used primarily to provide a hard copy record of magnetic/seismic sensor* and strain gage data in the field.

With the data recorded, the magnetic tapes are returned to the laboratory to be processed by an analog to digintal converter and then analyzed. This is done with an HP 5240-B digital signal analyzer. The latter incorporates a microprocessor which employs a FFT algorithm to carry out a numerical evaluation of the Fourier Transform of the signal. That is, the FFT algorithm evaluates

$$X(f) = F\left[x(t)\right] = \int_{-\infty}^{+\infty} x(t)e^{-2\pi jft}\,dt$$

$$\approx \int_{-T}^{T} x(t)e^{-2\pi jft}\,dt$$

where t is the time, f is the frequency, x(t) is the signal amplitude as a function of t and 2T is the time interval of interest.

*The sensor tested is a combination magnetic/seismic transducer and can be used in both modes or one mode (e.g., magnetic only).

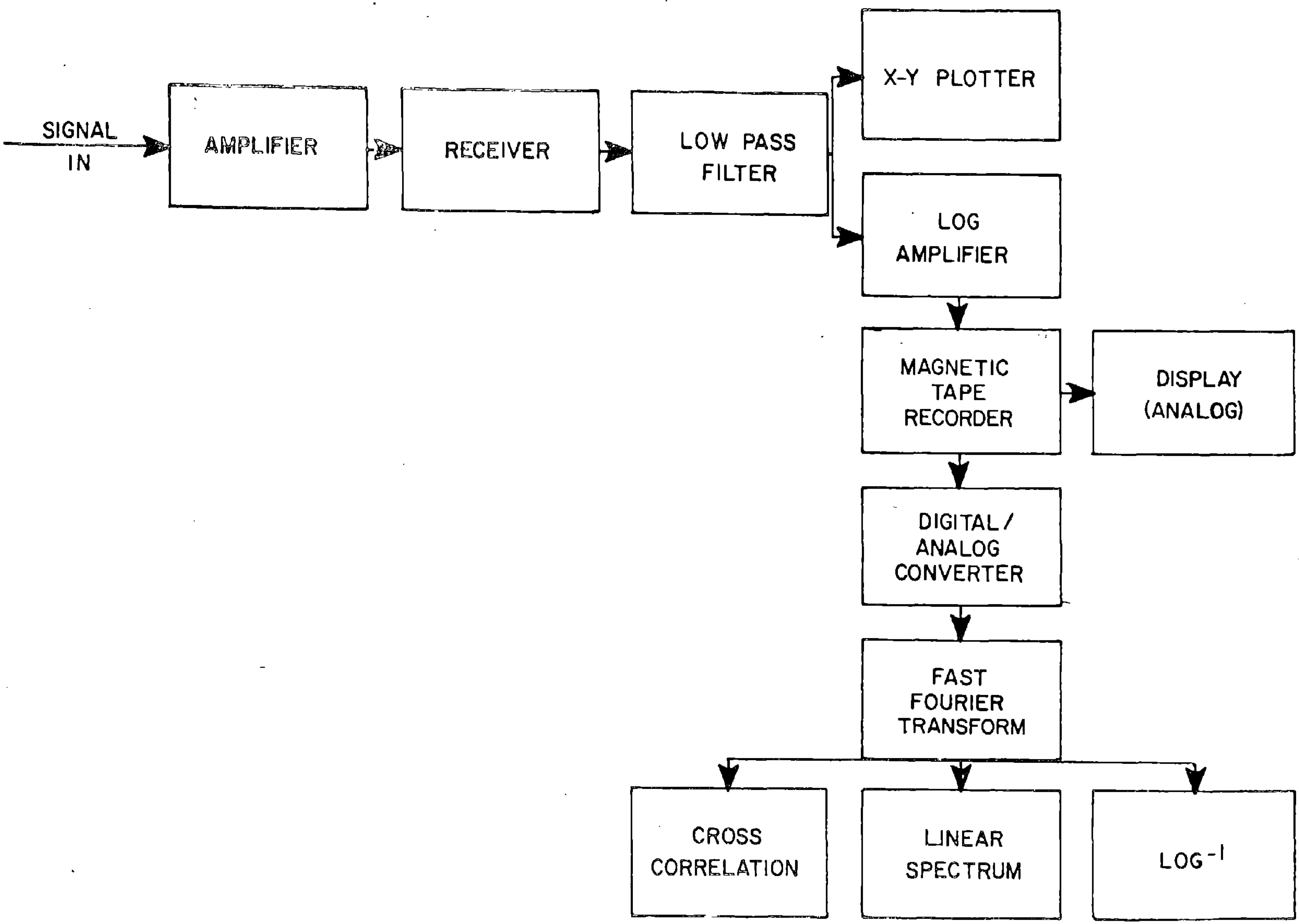

FIGURE 4-7. DATA PROCESSING FLOW DIAGRAM

The linear spectrum S(f) is then determined from the relation:

$$S(f) = |X(f)|$$

The microprocess also computes the time average:

$$\bar{x}(t) = 1/2T \int_{-T}^{+T} x(t)\,dt$$

the autocorrelation function:

$$\phi(\tau) = 1/2T \int_{-T}^{+T} x(t)\, y(t+\tau)\,dt$$

and cross-correlations:

$$\phi_{xy}(\tau) = 1/2T \int_{-T}^{+T} x(t)\, y(t+\tau)\,dt$$

where y (t) is any other digitized signal of interest. The capabilities of this system were used to produce the magnetic, acoustic and strain gage data plots shown in the following sections.

5. CONCEPT FIELD TESTS

The following sections describe testing conducted to evaluate the potential effectiveness of the magnetic and acoustic concepts as field implementable devices. The preliminary tests of both system concepts were discussed in Section 2.3, Candidate Concepts. Some of the information and data in this section may be slightly repetitive as the tests build upon one another. Section 5.1 discusses the test plans, reports and data for the Magnetic/Seismic Sensor. Section 5.2 similarly discusses the test plan, report and data involved in the Acoustic Concept.

Analysis of the test data taken with the magnetic/seismic sensor indicates that when operated in the magnetic mode, the sensor was highly sensitive to moving trains (powered or coasting), although relatively insensitive to nonmoving trains. The seismic mode was found to be susceptible to background noise from trucks and other vehicles operating in the area. Attempts to use the sensor in a joint magnetic-seismic mode in which the output of the magnetic detector was combined additively with that of the seismic detector were largely unsuccessful.

The acoustic concept proved to be effective in dealing with both stationary (engine idling) and moving trains; however, results indicate that further frequency domain analysis needs to be carried out to verify the appropriate frequency bands required for operational use.

5.1 FIELD TESTS OF THE MAGNETIC/SEISMIC SENSOR

An operational CWT system employing the magnetic/seismic sensor would consist of one or more buried magnetic/seismic transducer packages, each of which would feed data to a buried FM transmitter and antenna. The transmitter/antenna would in turn relay the information to a remotely located microprocessor.

In these tests, the complete data gathering and transmission system was not tested as a unit under actual operating conditions. Instead, the magnetic/seismic transducer package and the FM transmitter/antenna package were tested separately under restricted conditions at Ft. Eustis, Virginia. Figure 5-1 is a map of the general test area, showing the track layout and the speed restrictions which were in effect during the tests. Figure 5-2 provides a detailed map of the test area which was located within the 40 mi/hour zone. As shown, this test location had many of the features one could expect to find at any grade crossing in diesel territory, such as two sets of track, an adjacent roadway and AC power lines running within 50' of the sensors. In view of this, it is felt that the chosen site provided a fair test for any detection concept. It is, however, assumed that more field tests under a much greater variety of grade crossing environments will be required in order to evaluate a complete CWT system.

5.1.1 Test Plan

The test was divided into two separate efforts relative to the two devices referred to above:

1. A magnetic/seismic transducer package
2. An FM transmitter/antenna

The magnetic/seismic transducer package consisted of a combination magnetometer and geophone contained within a tube 3 to 4 inches in diameter and 48" in length which was buried 6 inches below ground level as described in Section 4.1.1. The transmitter/antenna described in Section 4.1.3 consisted of a buried 5 watt, battery-powered transmitter operating at 30 MHz driving a buried loop antenna. Additionally, output from the strain gage (described on page 51) was used to supplement data from the magnetic/seismic sensor and to assist in correlating this data with train movements.

The consist used in these tests was made up of a 60-ton 6-axle diesel-electric locomotive with 3 coaches and 3 flat cars in the configuration shown in Figure 2-14. Tests were conducted with the train driven forward (north run) and backward (south run) past the sensors at speeds of 5, 10, 15 and 20 mph. Since the locomotive is at the head of the consist, it would be the first element of the consist detected by the sensor on north runs, but the last element detected on south runs. Therefore,

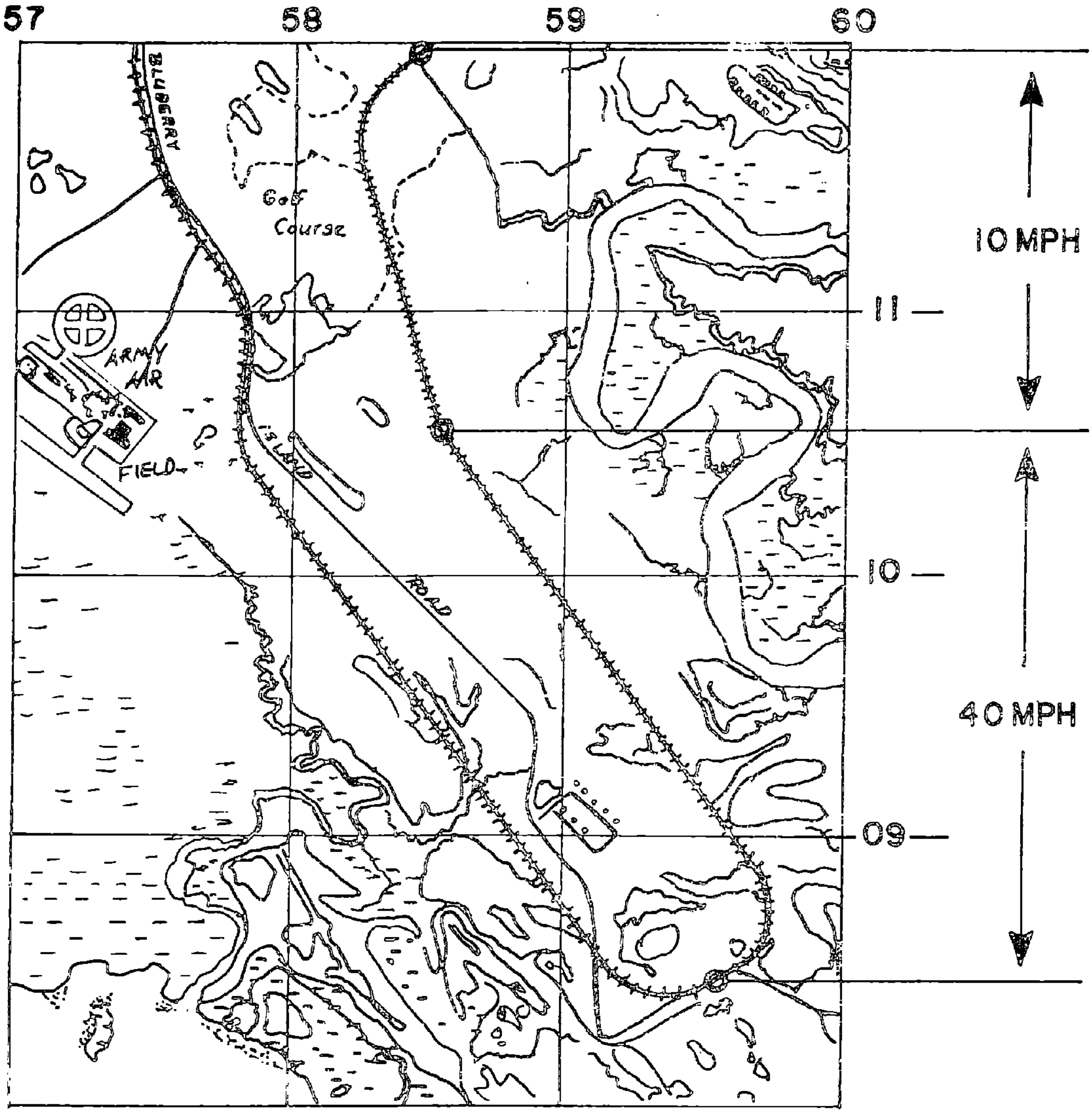

FIGURE 5-1. GRID MAP OF TEST AREA
FT. EUSTIS, VIRGINIA
(with track speed designations)

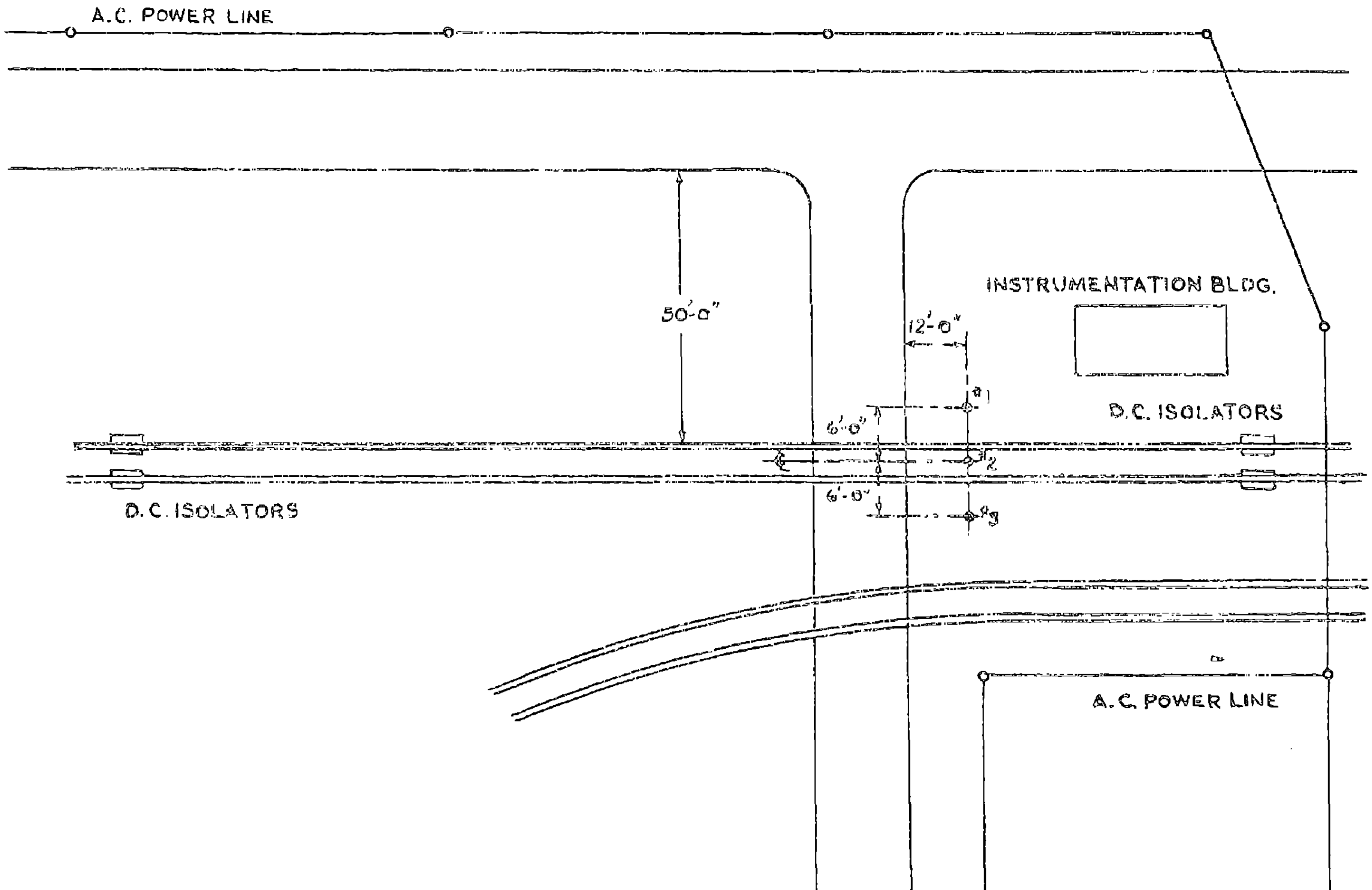

FIGURE 5-2. TEST AREA, FT. EUSTIS, VIRGINIA

the locomotive signature is the earliest portion of the data record for north runs and the last portion of the record for south runs. These facts must be kept in mind when interpreting the data records presented in the following sections. In addition to these dynamic tests, static tests were conducted in which the locomotive was positioned close to and, in some cases, directly above the sensors as shown in Figure 5-3. Sensor positions used in these tests are denoted by #1, #2 and #3 in the figure. Positions #1 and #3 are six (6) feet on either side of the track, with position #2 midway between the tracks.

A total of 25 test runs were carried out to evaluate the magnetic/seismic transducer package. In some of these tests, the transducer package was operated in its dual magnetic-seismic mode; however, in other, a single mode (magnetic or seismic alone) was used.

5.1.2 Test Descriptions

Tests #1 and #2

Train direction: #1 north, #2 south
Train velocity: 5 mph
Unit mode under test: magnetic-seismic
Unit under test location: position #1
Unit under test gain setting: 60 dB (maximum)
x-y plotter speed: 5 mm/second

The train, on both north and south runs, caused the amplifier contained within the transducer package to saturate. It was evident that the gain factor of 60 dB was too great. However, signature correlation between test #1 and #2 was realistic. The signatures were equal in magnitude, but reversed in time.

It was noted that interaction between the magnetic and seismic sensors caused a random algebraic subtraction of the output signal, rather than addition. Based upon this fact, design changes of the electronic package were made. The changes consisted of separate amplifiers and rectifiers for each sensor. This was done to insure that the combined signal output would at all times be additive.

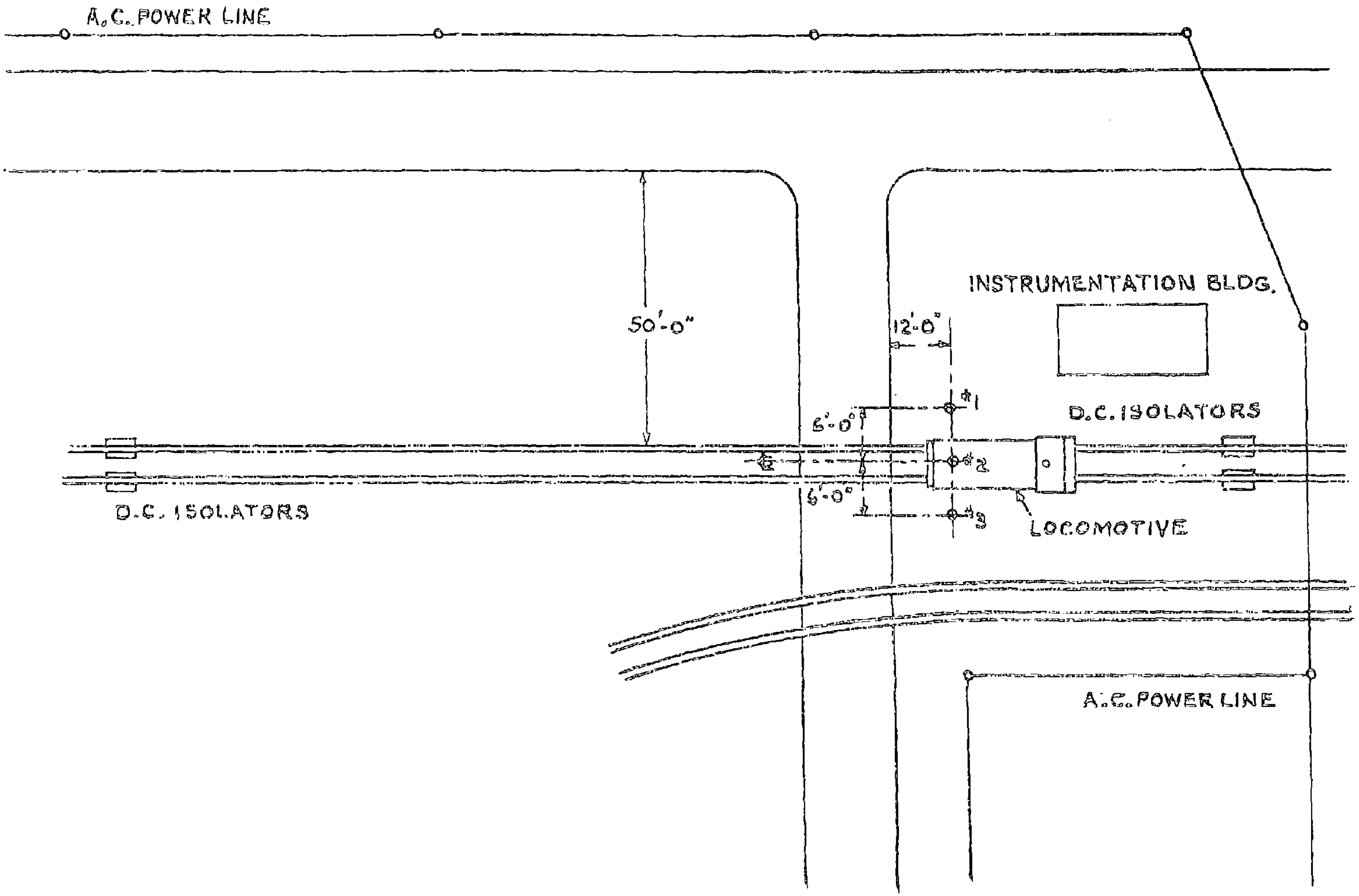

FIGURE 5-3. LOCOMOTIVE OVER TEST HOLES

Tests #3 and #4

Train direction : #3 and #4 south

Train velocity: 5 mph

Unit mode under test: magnetic

Unit under test location: position #1

Unit under test gain setting: 40 dB

x-y plotter speed: 5 mm/second

This test displayed a more stable output signature. The amplifier was not driven into saturation. The signature appeared to be reproduced each time the train passed the unit under test location.

Based on the results of tests #1 through #4, it was decided to reduce the unit under test gain setting to its lowest level.

Tests #5 and #6

Train direction: #5 north, #6 south

Train velocity: 5 mph

Unit mode under test: seismic

Unit under test location: position #1

Unit under test gain setting: 0 dB

x-y plotter speed: 5 mm/second

Results from these test indicated that repeatable train profiles were present and may possibly qualify as definite train signatures. However, the definition of this profile was not as distinctive as its magnetic counterpart due to background noise.

Tests #7, #8 and #9

Train direction: #7 north, #8 south, #9a north, #9b south

Train velocity: #7 - 5 mph; #8 - 10 mph; #9 - 20 mph

Unit mode under test: magnetic-seismic #7 and #8;
magnetic only #9

Unit under test location: position #1

Unit under test gain setting: 0dB

x-y plotter speed: 5 mm/second

Employing the combined package, a definite train signature was perceived; however, the problems associated with test # 1 and #2 were still present. Test #8 revealed a signal amplitude approximately twice that of test #7. Test #9 was an evaluation of the magnetic sensor exclusively. A significant increase in sensor output was noted due to the greater speed, and a repeatable magnetic profile was reproduced.

When each car in the train passed the location of the unit under test, the output profile tended to alter format. This alteration was probably due to train make-up, i.e., locomotive, coach, flat car, etc.

Tests #10, #11a, b, c and d

Train direction: stationary, locomotive adjacent to unit under test

Unit under test location: position #1

Unit mode under test: #10 magnetic; #11a seismic; #11b and c magnetic; #11d seismic

Unit under test gain setting: 0 dB

x-y plotter speed: 5 mm/second

The output signature from test # 10 was useless, indicating that it will be difficult to detect a stationary train with the magnetic sensor. Test #11a displayed a very distinctive signature. The movement of the pistons within the locomotive engine could be seen in the seismic signature. An increase in the engine idle speed created a proportional increase in the magnitude of the data. The operator of the locomotive was requested to place the locomotive in the forward-go position, lock the brakes, and increase engine speed to a setting approaching maximum where the brakes would begin to lose adhesion to the track. This resulted in slight forward movement of the mass being detected.

Tests #11b and c were a continuation of test #10. The signal to noise ratio was good, but would not provide for reliable train detection.

The unit under test was relocated to position #2 (between the rails) for further testing.

Tests #12, #13, #14 and #15

Train direction: #12 north, #13 south, #14 north, #15 south
Train velocity: 10 mph
Unit mode under test: magnetic-seismic
Unit under test location: position #2
x-y plotter speed: 5 mm/second
x-y plotter gain setting: 5 mv/inch

These were repetitions of tests #1, #2, #7 and #8 for the new sensor position. Analysis of this data disclosed train character and possible train velocity; however, environmental interference was present in the signature, largely through the seismic sensor.

Tests #15a and #15b

Train direction: #15a north, #15b south
Train velocity: 10 mph
Unit mode under test: magnetic
Unit under test location: position #2
x-y plotter speed: 10 mm/second and 20 mm/second
x-y plotter gain setting: 10 mv/inch

The output waveform was a duplication of that displayed in tests #12 through #15.

Tests #16 and #17

Train direction: #16 north, #17 south
Train velocity: 10 mph
Unit mode under test: seismic
Unit under test location: position #2
x-y plotter speed: 5 mm/second
x-y plotter gain setting: 100 mv/inch

With the x-y plotter gain attenuated, the seismic waveform was detectable. However, analysis of this waveform indicated that it was not reproducible.

During data accumulation, the pen rate of the x-y plotter was set to its maximum speed. Greater resolution of the output signature was accomplished with a Visicorder. It was possible to capture a larger spectrum of the output waveform.

From this test, it was concluded that:

1. The number of axles per railroad car was detectable.
2. Vehicular traffic present on the adjacent road affected the sensor.

Test #18

Train direction: north
Train velocity: 5 mph
Unit mode under test: magnetic
Unit under test location: position #2
x-y plotter speed: 5 mm/second
x-y plotter gain setting: 100 mv/inch

This test was conducted to establish gain limits of the unit under test. In essence, this test was a repetition of tests #3, #4, #15a and #15b; however, the signatures were larger and better defined than those observed from position #1.

Test #19

Train direction: stationary (immediately over sensor)
Unit mode under test: seismic
Unit under test location: position #2
x-y plotter speed: 5 mm/second
x-y plotter gain setting: 100 mv/inch

This test was analogous to tests #16 and #17. Piston movement within the locomotive engine was seen in the data record. Each drive motor was positioned directly over the unit under test.

Test #20, #21, #22, #23, #24

Train direction: #20 north; #21 south; #22 south;
#23 north; #24 south
Train speed: #20 5 mph; #21 5 mph; #22 10 mph;
Unit mode under test: magnetic
Unit under test location: position #2
Amplifier gain: 0 dB
x-y plotter speed: 5 mm/second
x-y plotter gain setting: 100 mV/inch

Tests #20, #21 and #22 were performed to determine what effect, if any, the train engine and electrical components had on the magnetic sensor. There was absolutely no change in the train magnetic profile as it coasted without power across the sensor at both 5 and 10 mph. The train was then brought forward in order to run the test at the same speed with the engine on. No difference in the magnetic signature was noted. Two additional tests were then run to determine the change in magnetic amplitude versus speed. A marked increase in amplitude was noted when the train speed increased.

Test #25 and #26
Train direction: #25 north; #26 south
Train speed: #25 20 mph; #26 20 mph
Unit mode under test: seismic
Unit under test location: position #2
Amplifier gain: 0 dB
x-y plotter speed: 5mm/second
x-y plotter gain setting: 100 mV/inch

Tests #25 and #26 were made as one last check of the seismic sensor and nothing could be noted as different from the earlier test other than the expected compression of the signal and the corresponding increase in its amplitude due to the trains increased speed.

This completed the transducer tests.

5.1.3 Transmission Demonstration

The underground transmitter was demonstrated by inserting the completely self-contained unit in position #3. (See Figure 5-3.) To simulate worst case conditions, the locomotive was pulled up beside the test hole and allowed to sit there at idle. Using an inexpensive Radio Shack DX300 receiver (after test it was discovered the unit was faulty), whose frequency of 30 MHz and its antenna input connected to a Citizens Band base loaded antenna mounted on the roof of a station wagon, the test was run. Then, the engineer was asked to move the locomotive away from the transmitter location to observe what effect, if any, it had. None was observed. At this point, the locomotive was moved once more to a position beside the buried transmitter, and the car with the receiver was driven away from the transmitter. Weather conditions (heavy rain) required the use of the electric windshield wiper on the van which created heavy static interference on the receiver as the van moved down the road parallel to the track. At a distance of 1.2 miles from the transmitter, the signal was still barely discernible (audio/visual).

NOTE: Since this test, a marked increase in antenna power output has been obtained with a new antenna design. This design yields positive operation up to 1.5 miles.

5.1.4 Test Data

Preliminary testing results show that a reliable and readily discernable magnetic signal is attainable using the magnetic sensor and RF transmitter. Moreover, testing revealed that the magnetic signature of a locomotive is a consistently recognizable waveform. This feature may be worthy of further investigation for providing a faster and more efficient method of velocity computation. The amplitudes of the output signature were also found to increase with increasing train speed.

Figure 5-4 is the x-y plot of the magnetic sensor output for Run #3. Since the train is moving backwards past the sensor in this run, the earlier section of the record is the sensor's response to the coaches and flat cars that make up the bulk of the consist. The signature of the locomotive is the very last section of the record. The most prominent feature of this signature is a nearly sinusoidal damped oscillation which includes the peak sensor response. Figure 5-5 shows the same feature for run #9a where it appears in the earliest section of the record since the locomotive is leading in this case. Here, it appears that the greater speed of the train (20 mi/hour) amplifies the locomotive signature relative to that of the coaches and flat cars as compared to Run #3 (5 mi/hour) where the peak due to the locomotive is only slightly larger than the coach and flat car response. Figure 5-6 shows the same effect observed in Run #9b where the train was moving in reverse at the same speed. Both of the figures were produced by the digital signal analyzer.

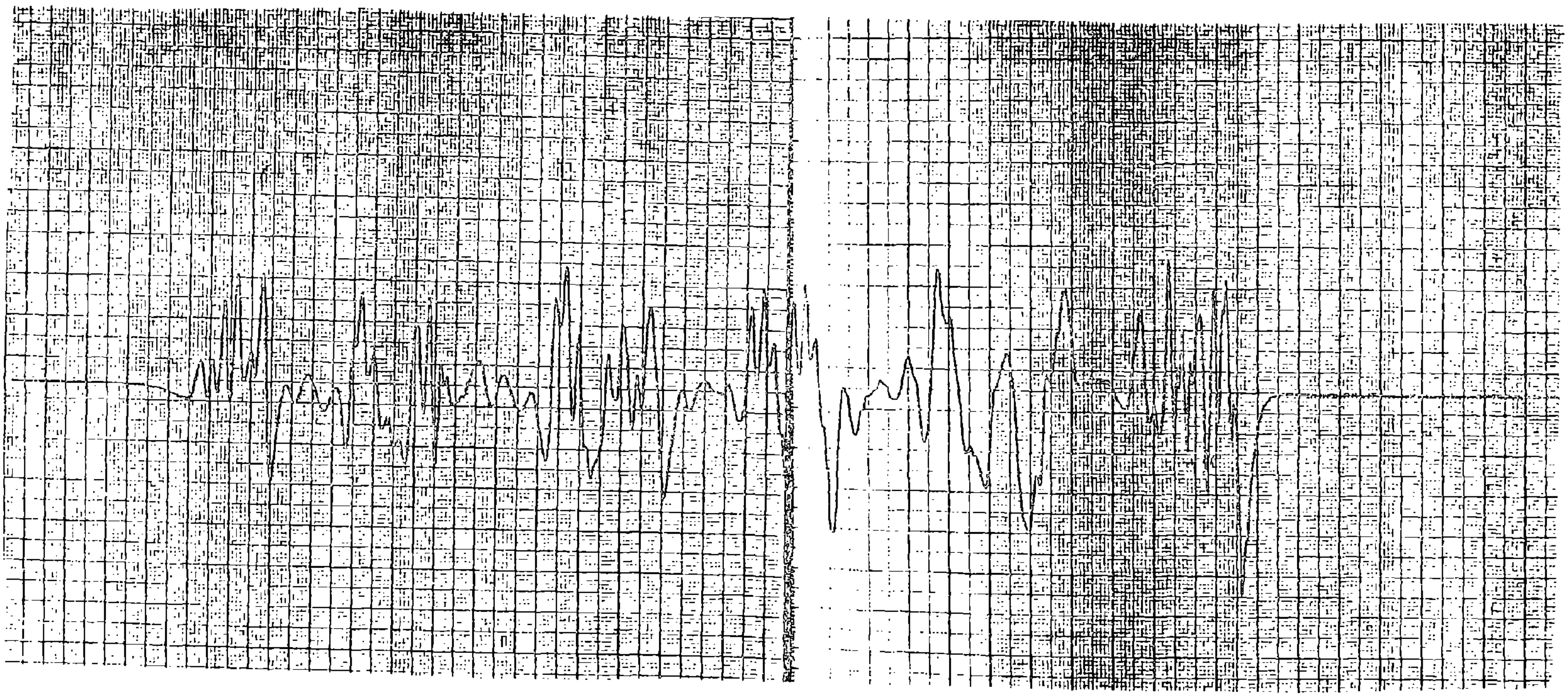

FIGURE 5-4. MAGNETIC SENSOR - TEST RUN #3

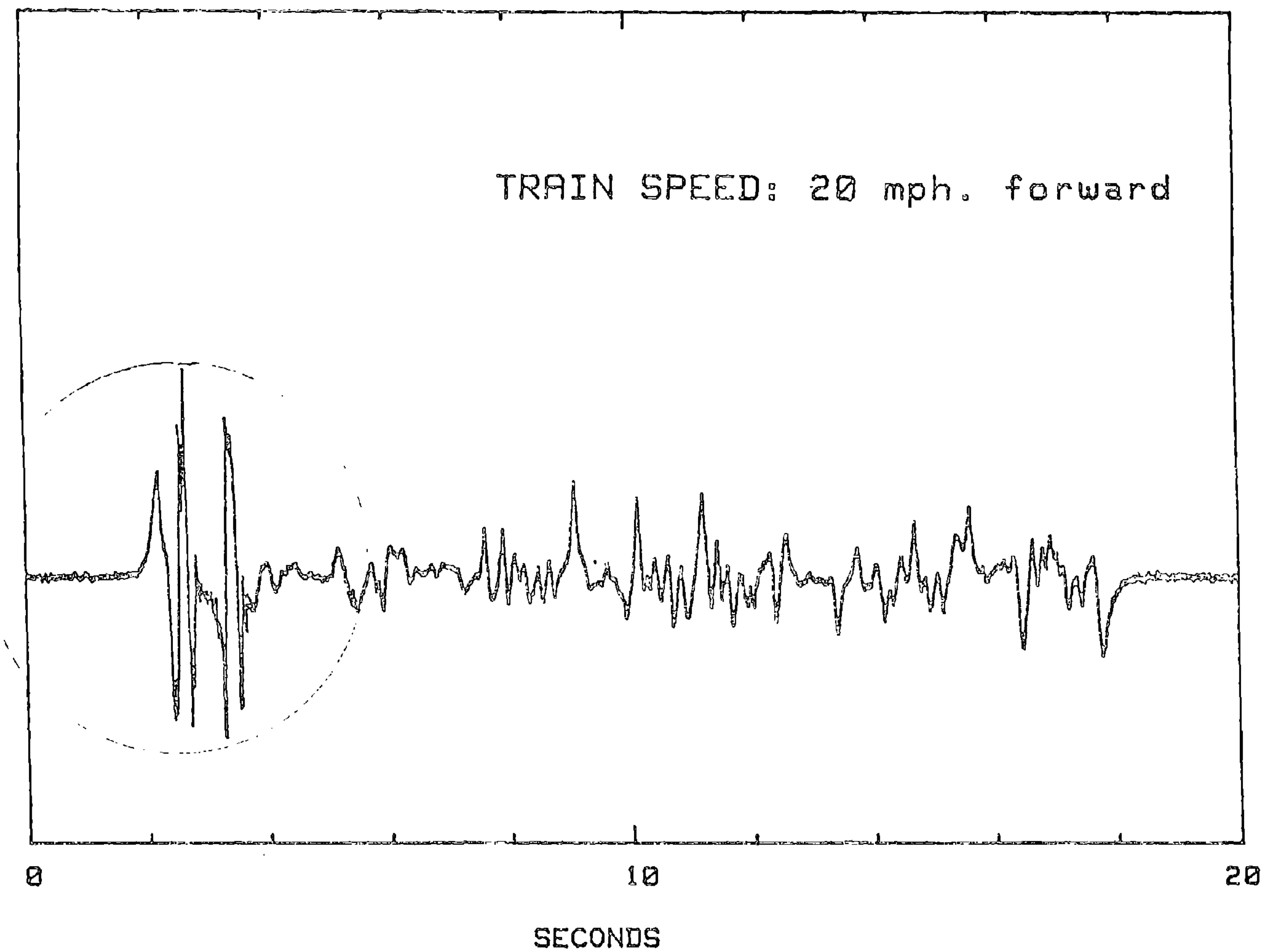

FIGURE 5-5. MAGNETIC SIGNAL VS. TIME

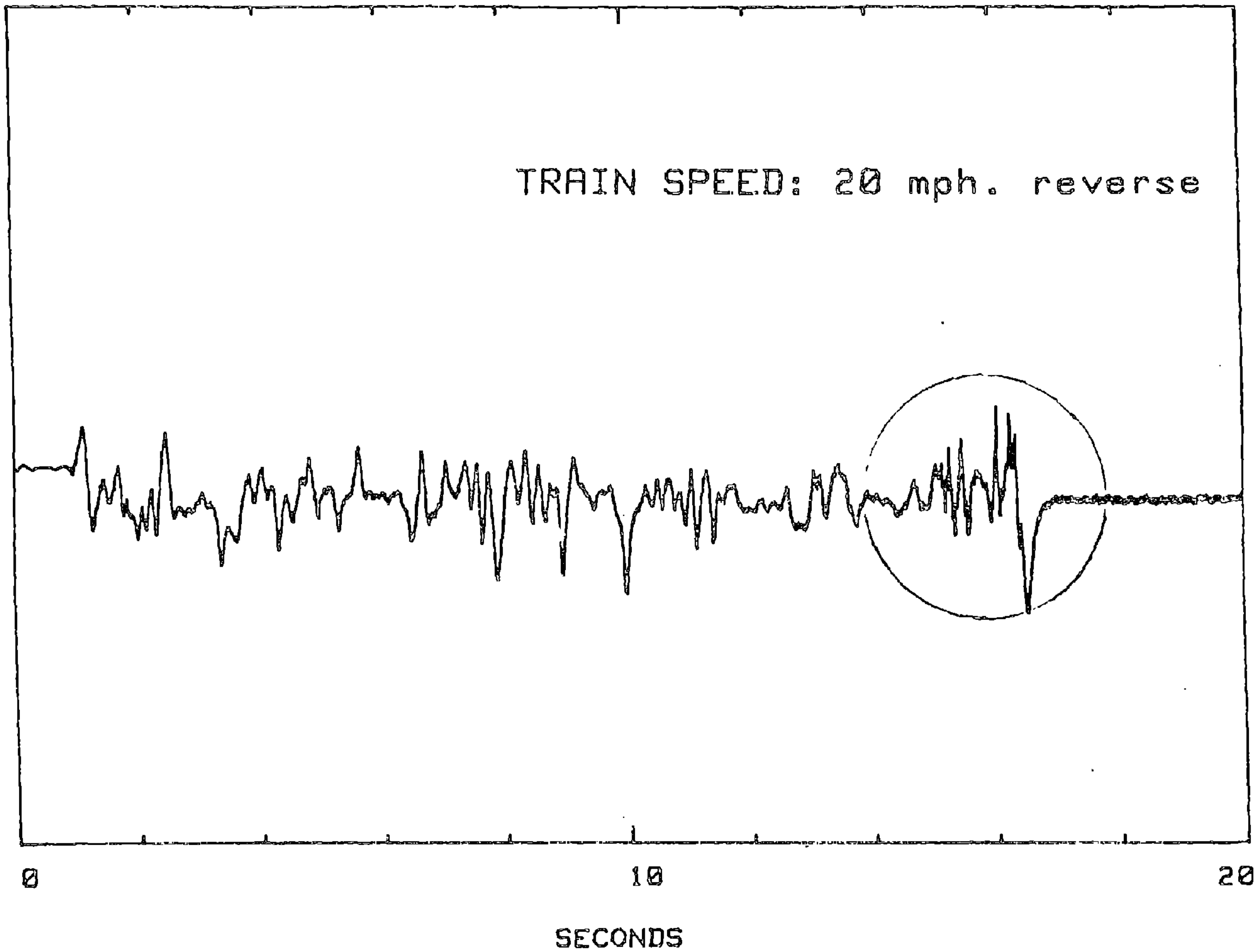

FIGURE 5-6. MAGNETIC SIGNAL VS. TIME

Excellent correlation between sensor response on forward and reverse runs was observed in all cases where runs were made at the same speed. This is illustrated by Figure 5-7 which is an overlay of Runs #9a and #9b.

Figure 5-8 is the linear spectrum obtained for Run #9a. This figure shows that the frequency spectrum of the magnetic sensor is within usable levels in the range from 0 to approximately 10 Hz. This is within very low frequency ranges, thus, the signals will not interfere with power lines' frequencies (60 Hz).

Finally, Figure 5-9 shows the interesting correlation between strain gage data (upper curve) and magnetic data that was observed on Run #7. This suggests that individual coaches and flat cars in the consist could be identified by a combination of magnetic sensors and strain gages.

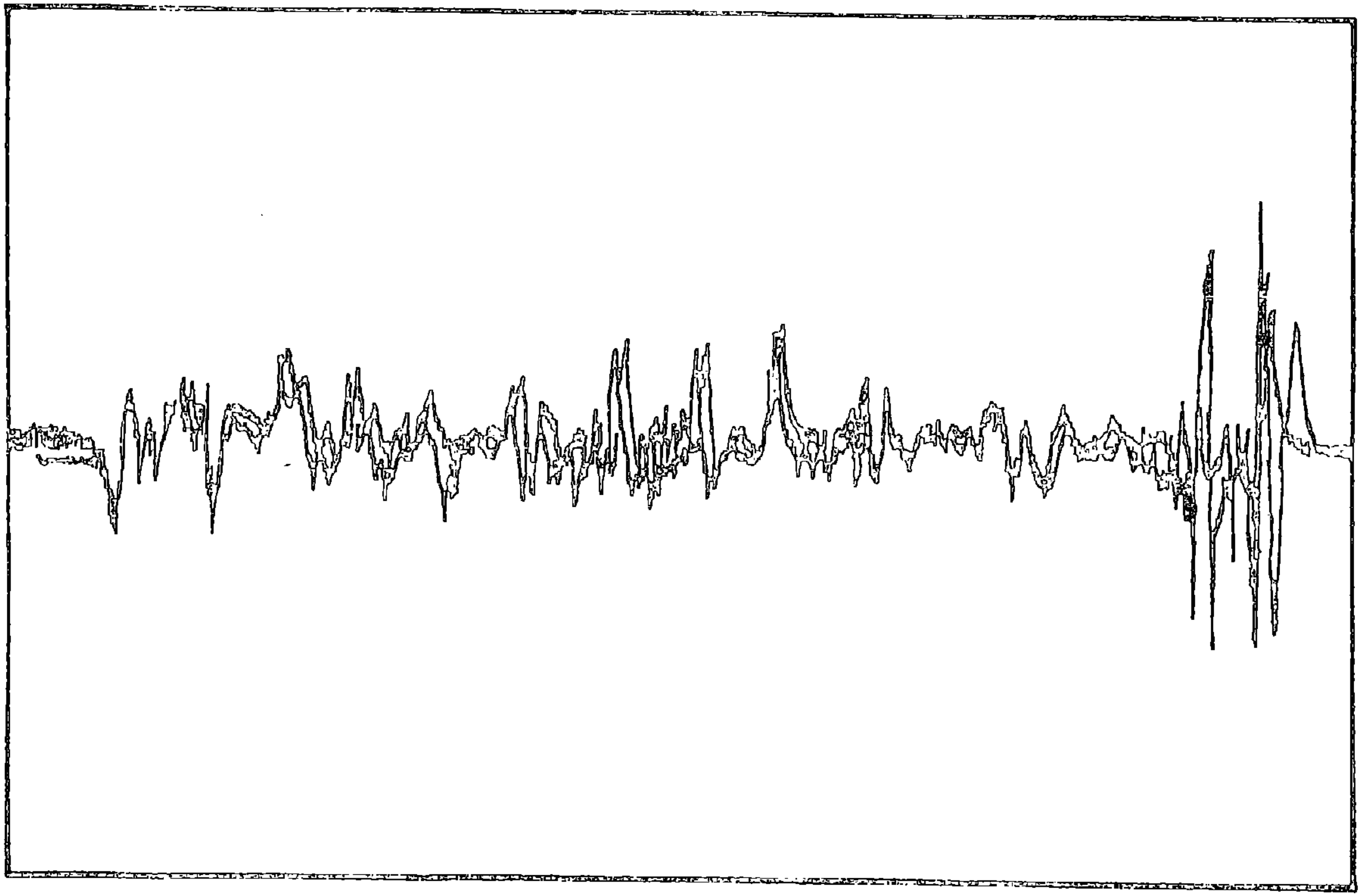

FIGURE 5-7. MAGNETIC SIGNAL VS. TIME
(Forward and Reverse Signature Overlay)
(Runs #9a and #9b)

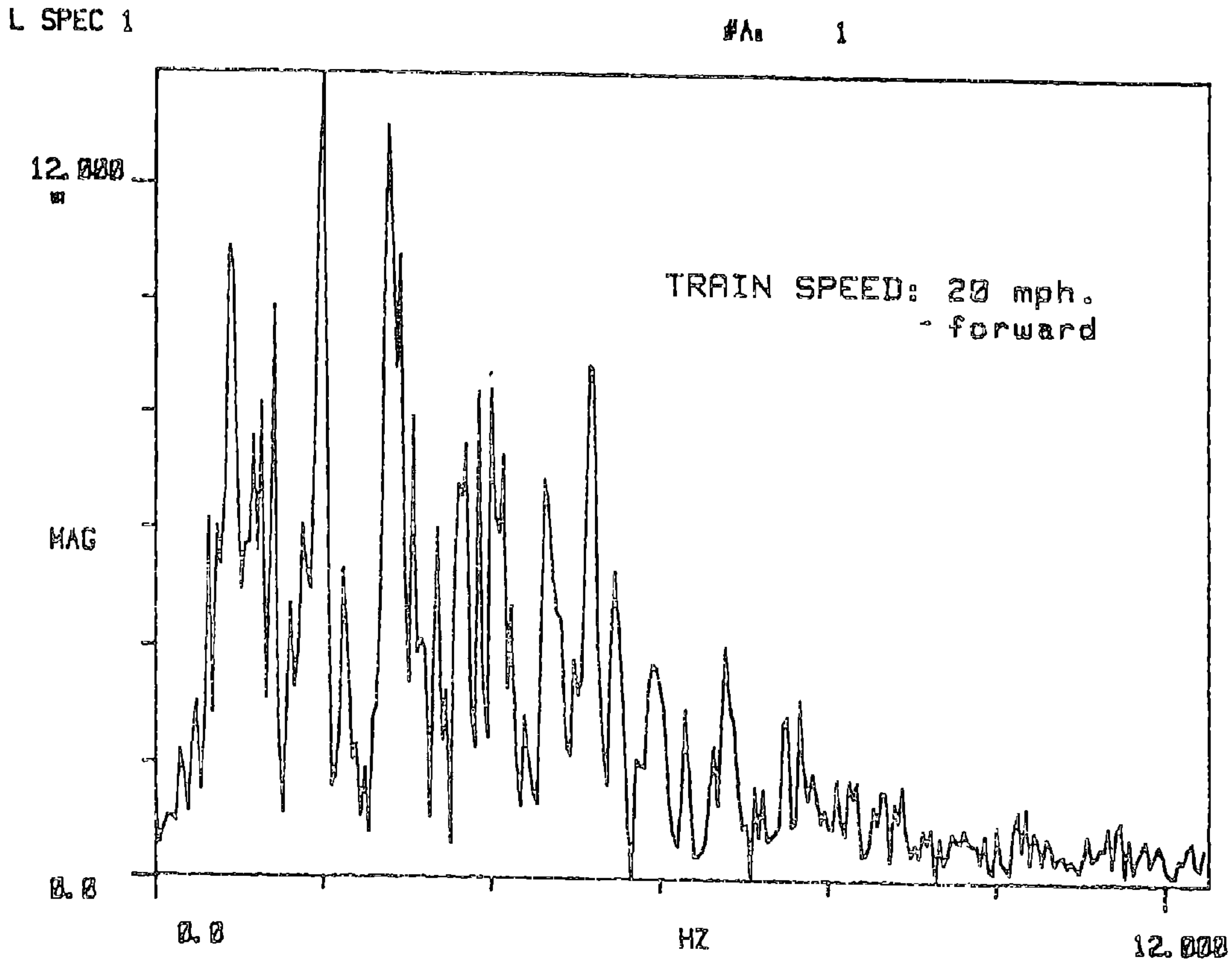

FIGURE 5-8. LINEAR SPECTRUM
MAGNETIC SIGNAL
(Run #9a)

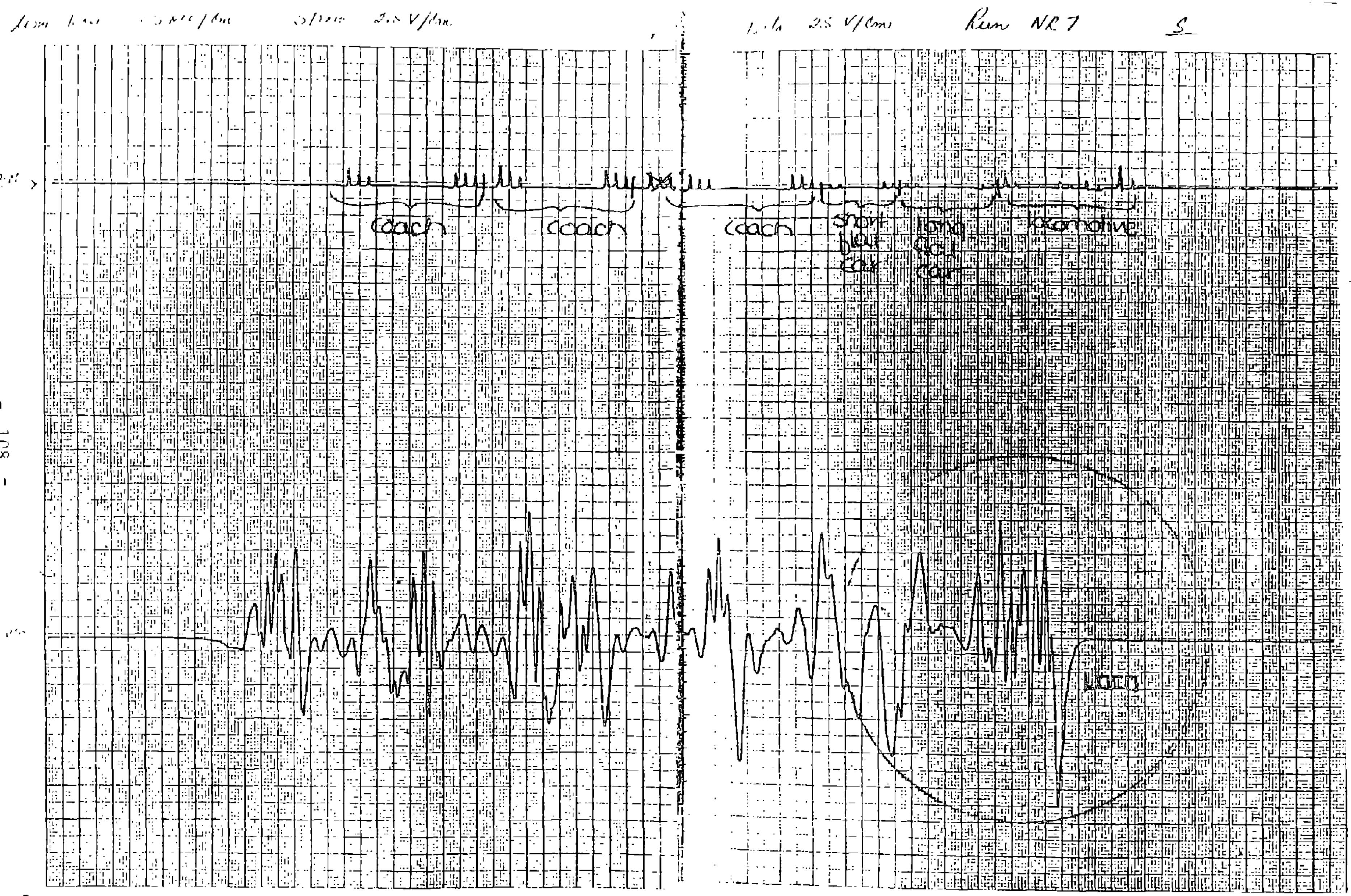

FIGURE 5-9 STRAIN GAUGE VS. MAGNETIC SIGNATURE

5.2 FIELD TESTS OF THE ACOUSTIC CONCEPT

The general acoustic CWT concept as described in section 4.2 is an active system in that it involves a piezoelectric generator to provide for signal input. Initial testing of the concept investigated both active (Phase I) and passive (Phase II) methods of deriving signal outputs. Phase I of the testing involved an impulse noise generator on the track and then recording of the acoustic time traces. Phase II tests entailed passive monitoring of acoustic signals through the rails induced by an approaching train.

These tests were only the necessary first steps towards understanding the overall acoustic concept potential. Results from these preliminary phases demonstrated that a discernable acoustic signal can certainly be obtained. Future testing, however, will be required to develop the system concept further.

5.2.1 Phase I Testing (Impulse Noise Generator)

Tests were conducted using an impulse noise generator on the track, in this case an 8-lb. sledge hammer dropped from 36" above the rail. Each test run consisted of three (3) hammer blows. Table 5-1 shows distances from the transducer that the sledge hammer was dropped. Figures 5-10 through 5-24 illustrate the acoustic frequency spectrum determined in each test run.

5.2.2 Phase II Acoustic Testing (Passive Monitoring)

During the month of December 1979, a test series was run to evaluate a track mounted acoustic receiver used in conjuction with a track mounted impulse producing device (IPD) as a basis for a constant warning time system. Since the IPD experienced mechanical failure early on,it meant the testing focused on monitoring the passage of acoustic ways through the rails due to the locomotive itself (i.e. passive mode.)

Test Plan

The overall test plan required the real-time data recording of wide band information using the track mounted acoustic receiver

TABLE 5-1. ACOUSTIC SLEDGE HAMMER TESTS

Test Run.	Distance From Transducer (ft)	
1	300	
2	600	
3	900	
4	1200	
5	1500	
6	1800	
7	2100	
8	2400	
9	2700	
10	3000	
11	3500	
12	3600	
13	3900	
14	4200	
15	4500	
16	4800	Insufficient magnitude to read data
17	5100	Insufficient magnitude to read data
18	5400	Insufficient magnitude to read data
19	5700	Insufficient magnitude to read data

This test was conducted prior to the recording of train data in an effort to determine the magnitude of any shunting effect caused by the train.

TABLE 5-2. ACOUSTIC SLEDGE HAMMER TESTS
FREQUENCY ANALYSIS OF ACOUSTIC DATA

SETUP STATE

MEASUREMENT : LINEAR SPECTRUM

AVERAGE : 3 , STABLE

SIGNAL : TRANSIENT

TRIGGER : INTERNAL , CHNL 1

CENT FREQ : 0.0 HZ

BANDWIDTH : 12.8000 KHZ

TIME LENGTH : 20.0000 mS

ΔF : 50.0000 HZ ΔT : 19.5312 µS

ADC CHNL	RANGE	AC/DC	DELAY	CAL (C1/C2)
* 1	10 V	DC	0.0 S	1.00000
2	10 V	DC	0.0 S	1.00000

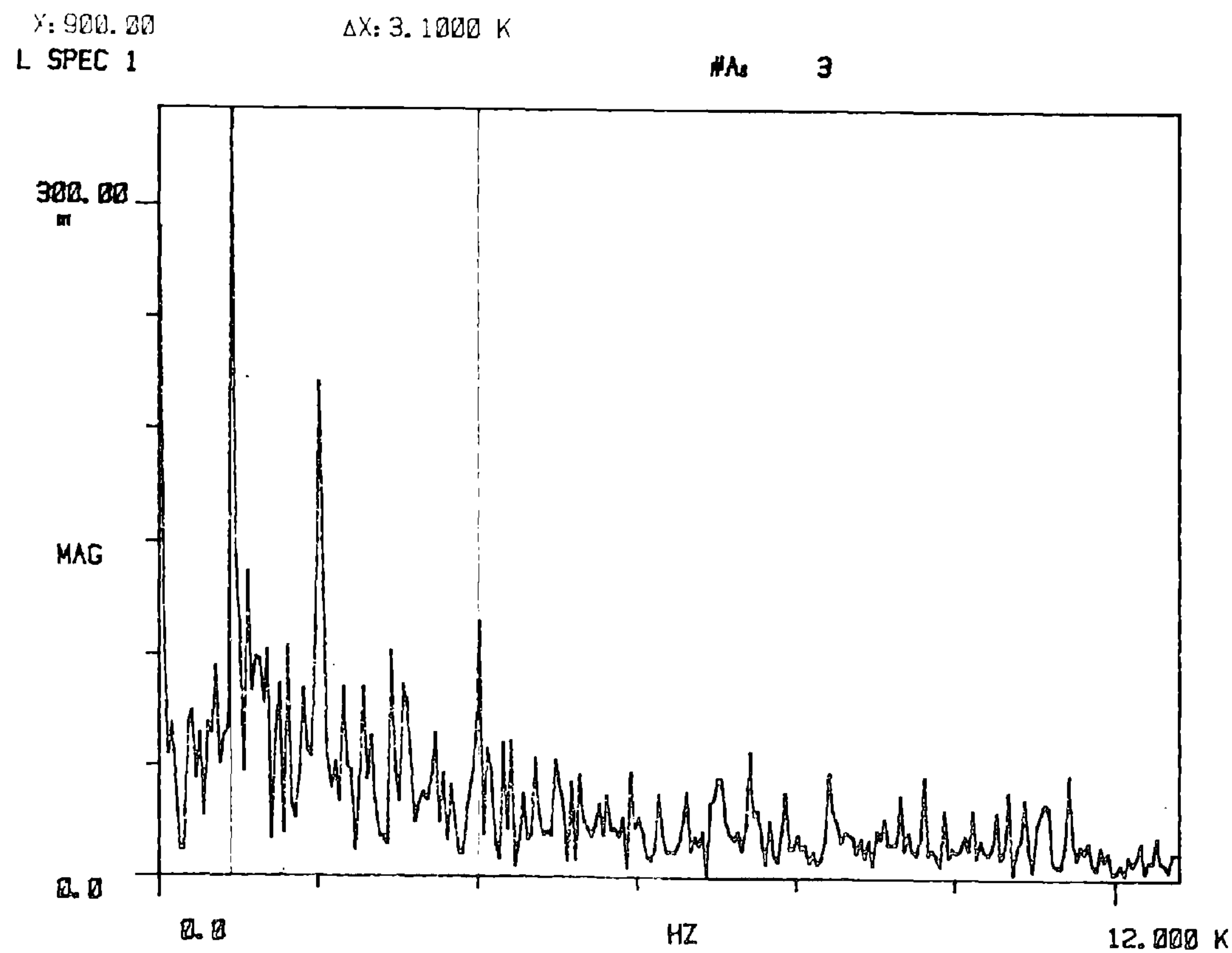

FIGURE 5-10. ACOUSTIC TEST RUN #1

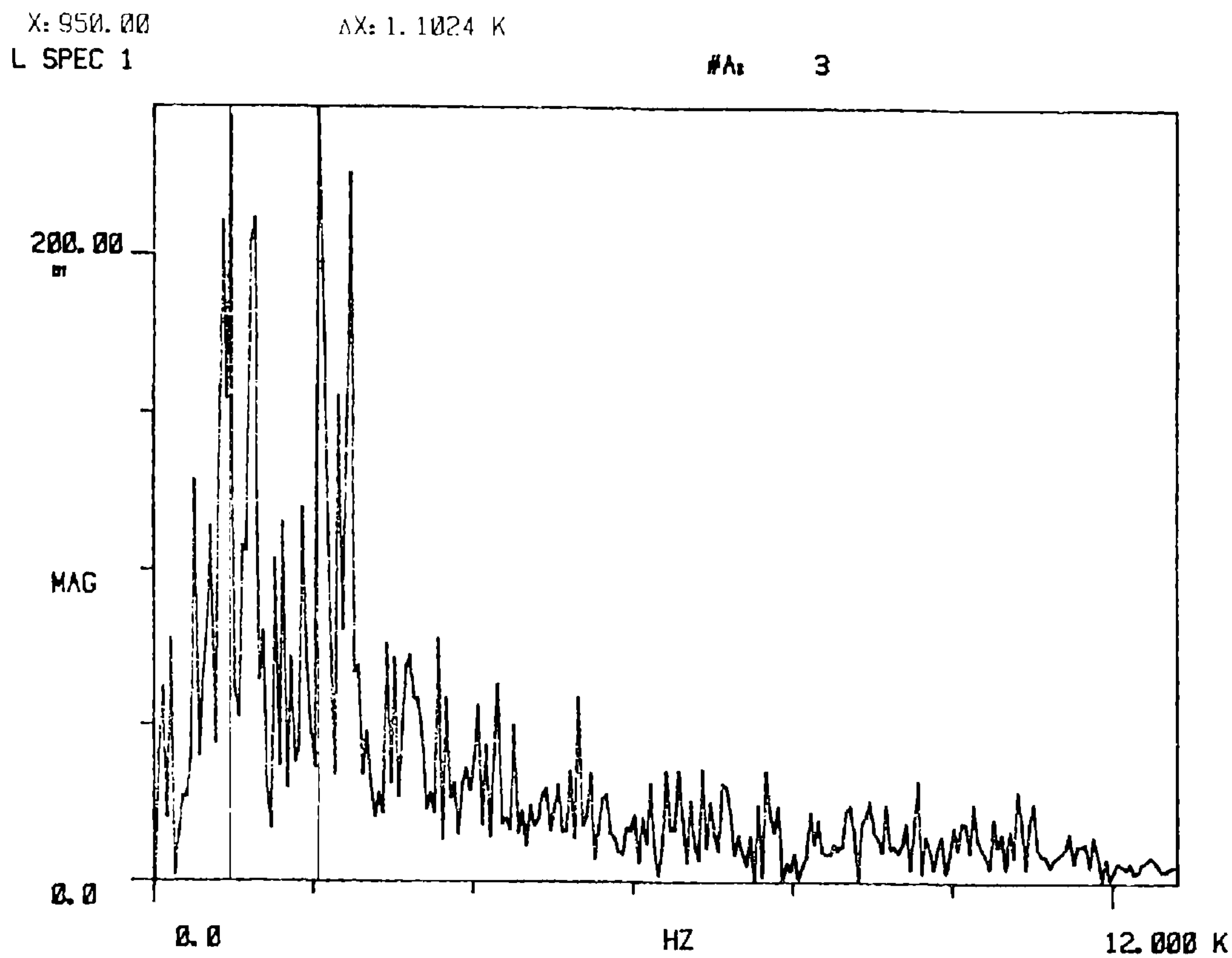

FIGURE 5-11. ACOUSTIC TEST RUN #2

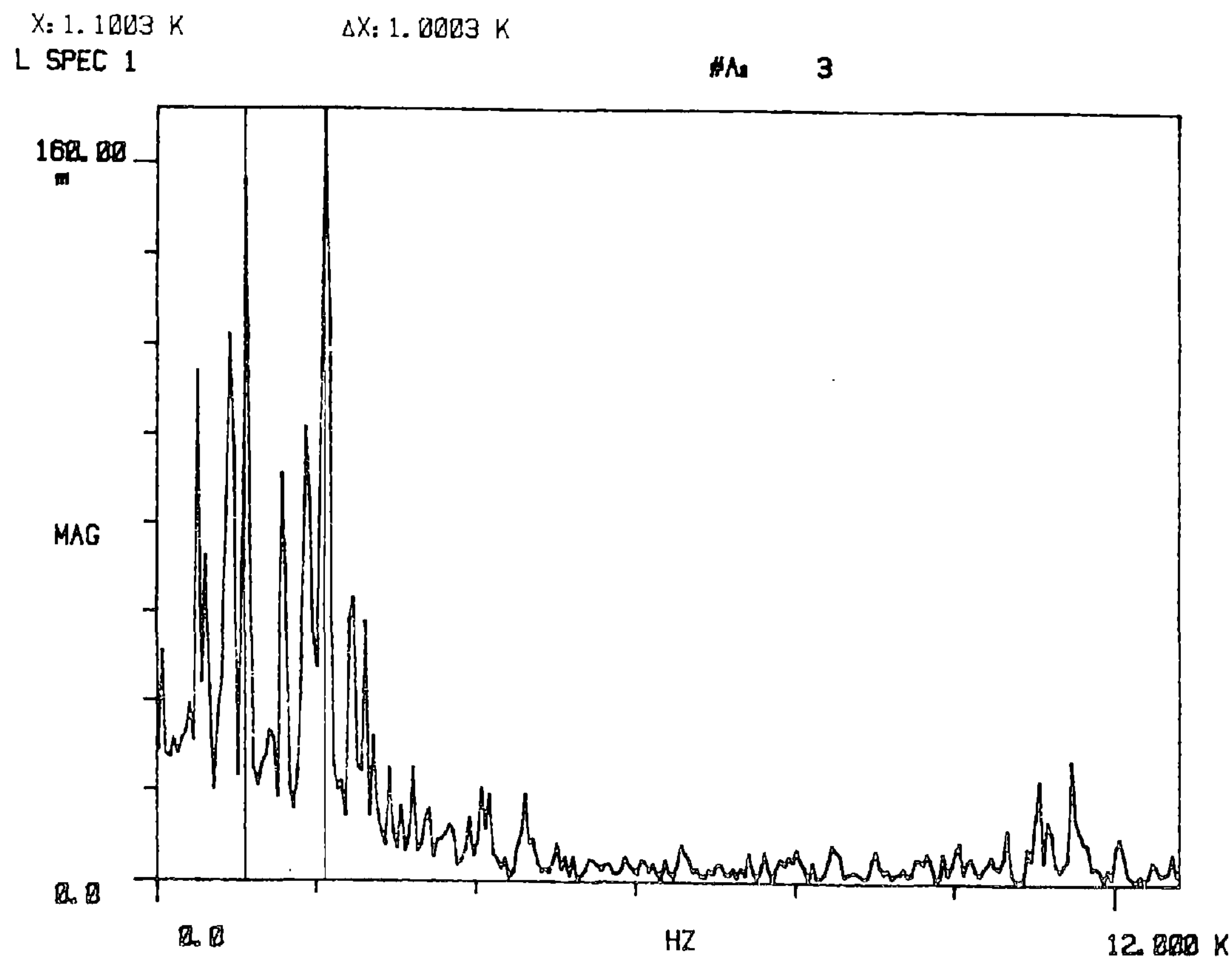

FIGURE 5-12. ACOUSTIC TEST RUN #3

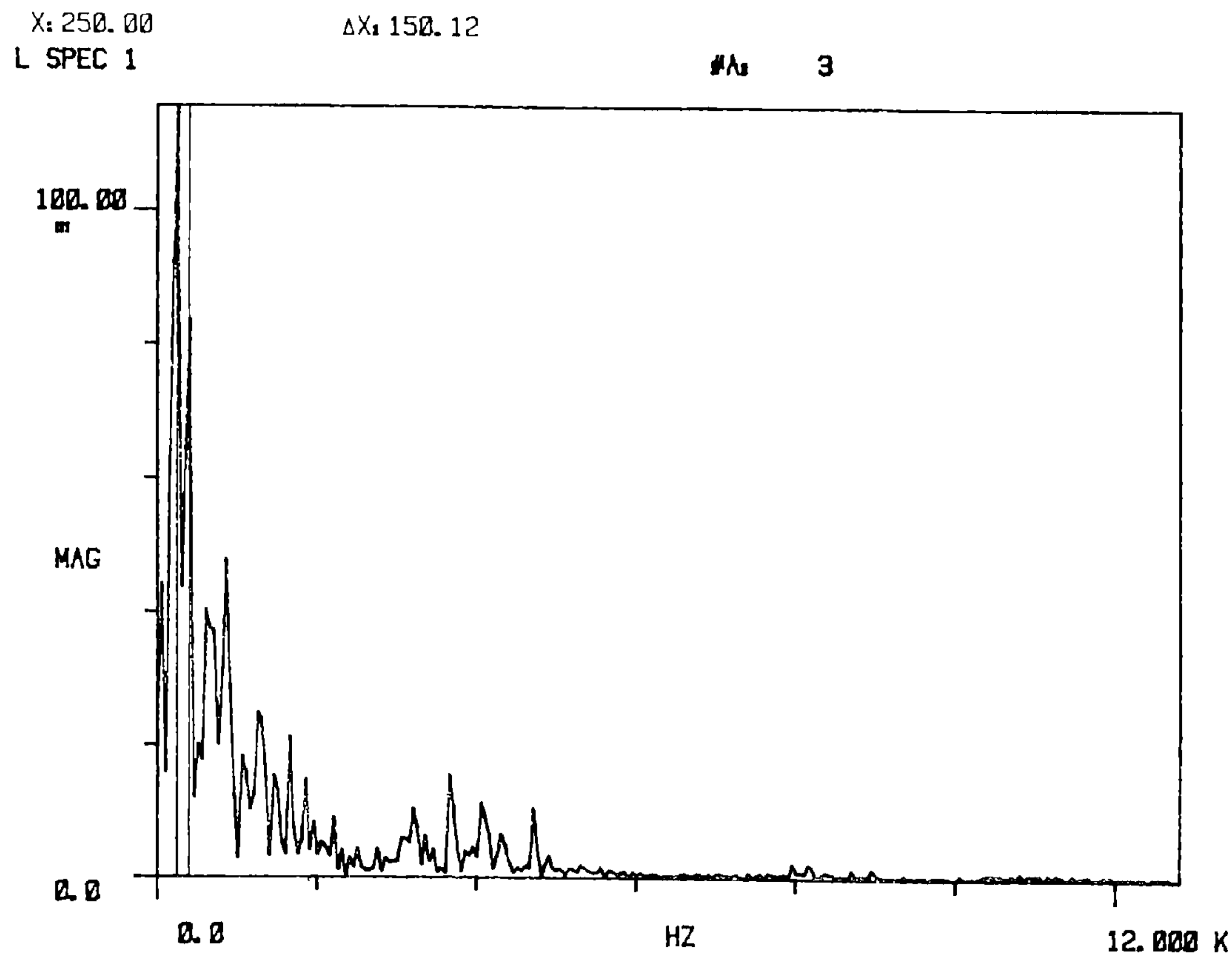

FIGURE 5-13. ACOUSTIC TEST RUN #4

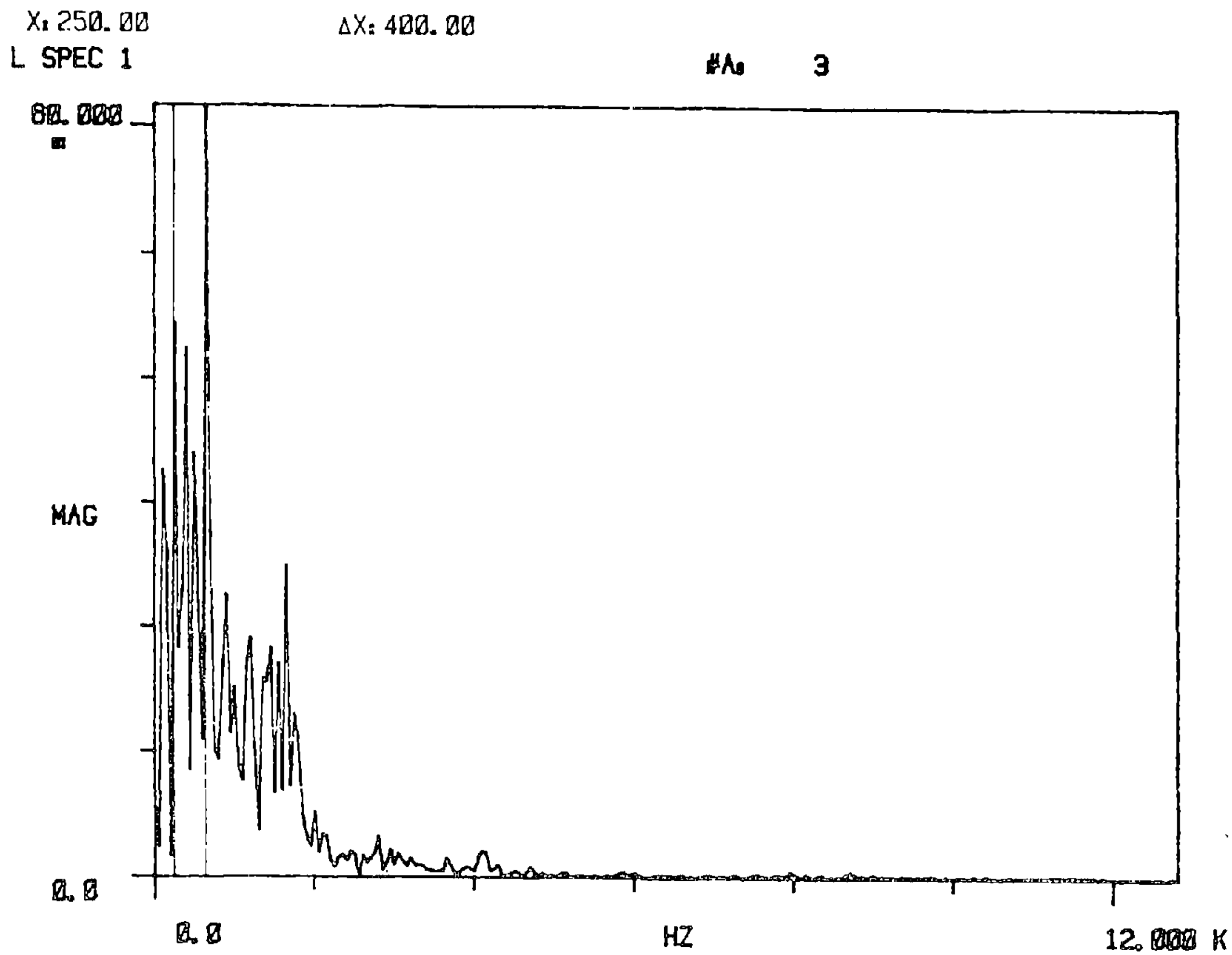

FIGURE 5-14. ACOUSTIC TEST RUN #5

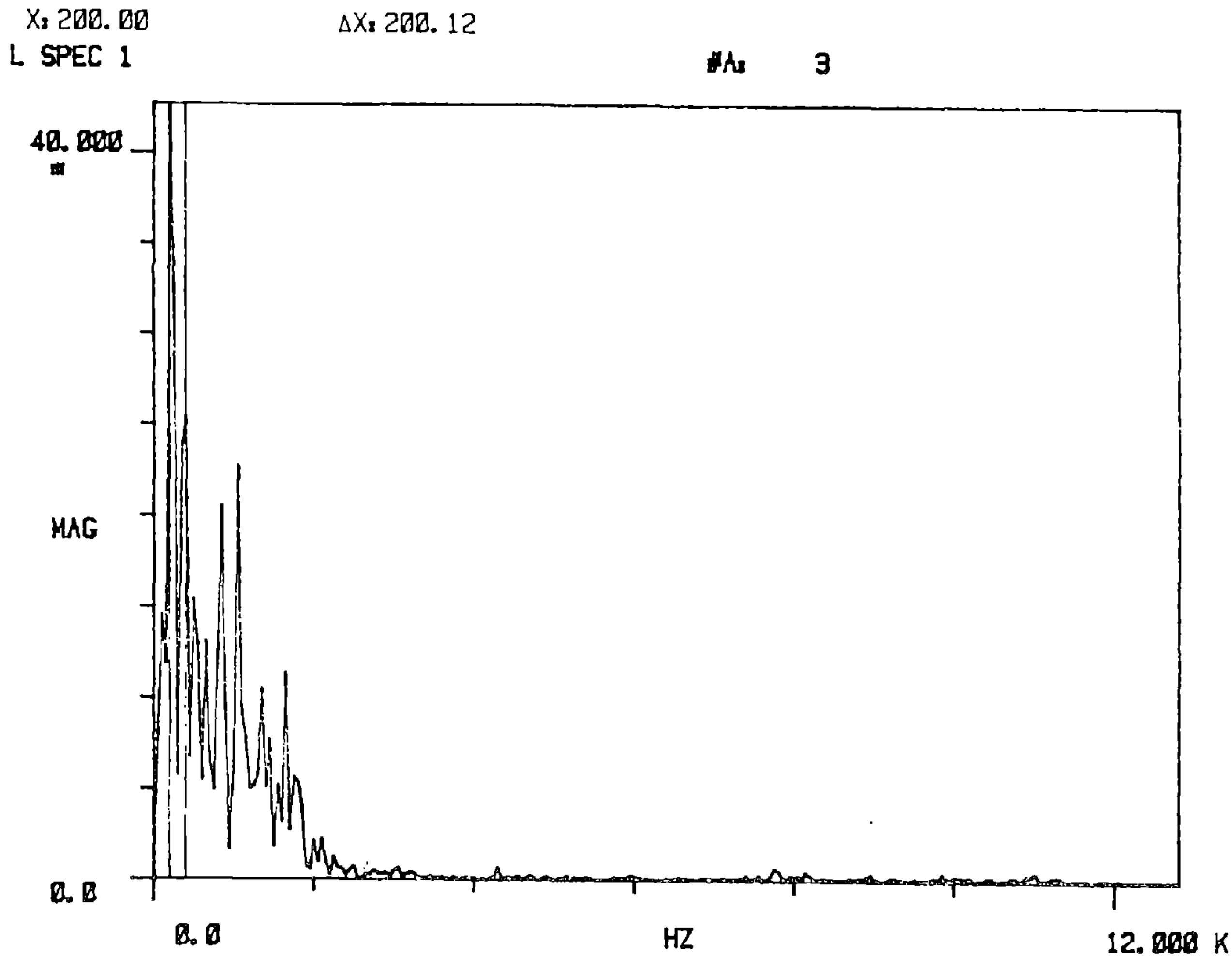

FIGURE 5-15. ACOUSTIC TEST RUN #6

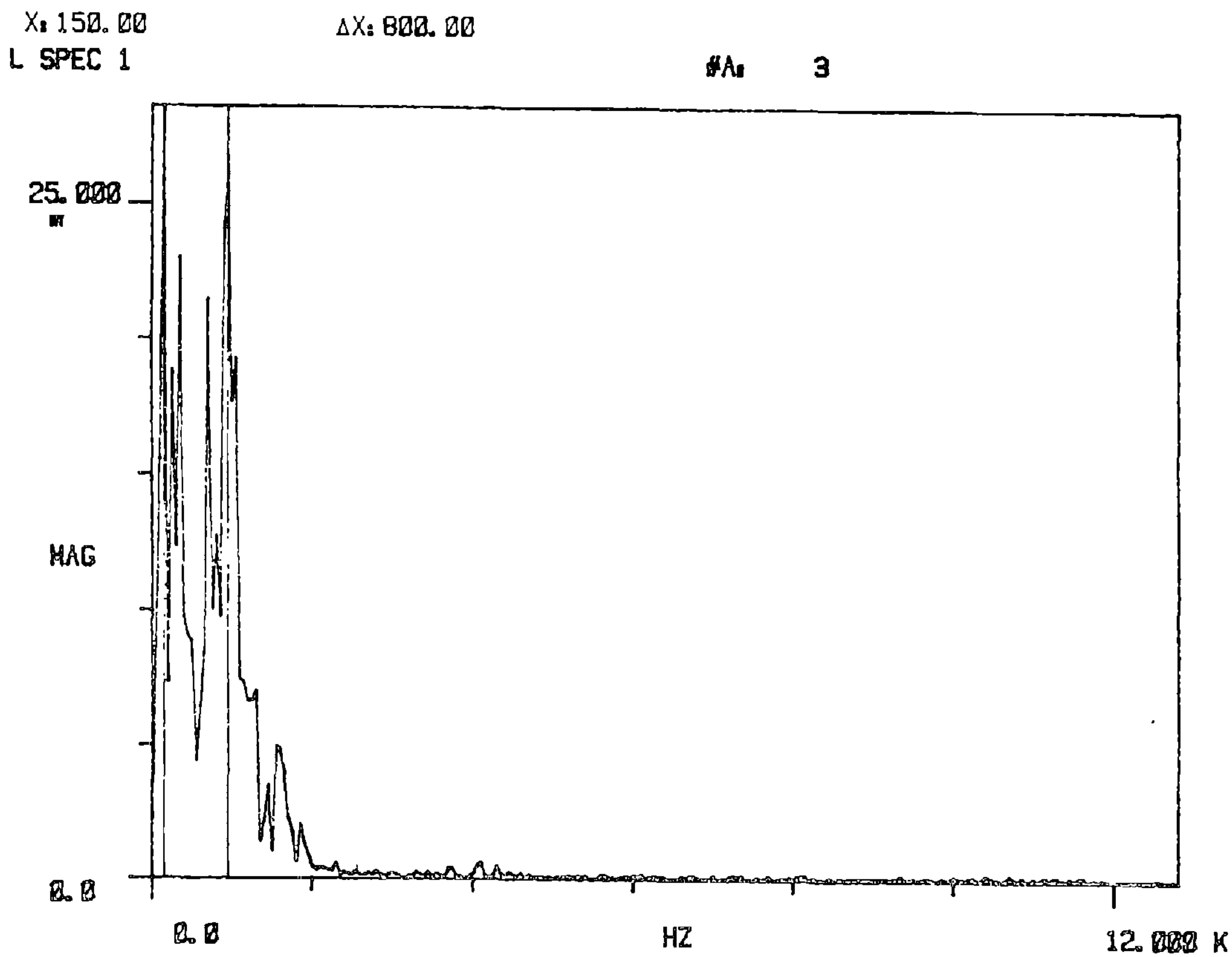

FIGURE 5-16. ACOUSTIC TEST RUN #7

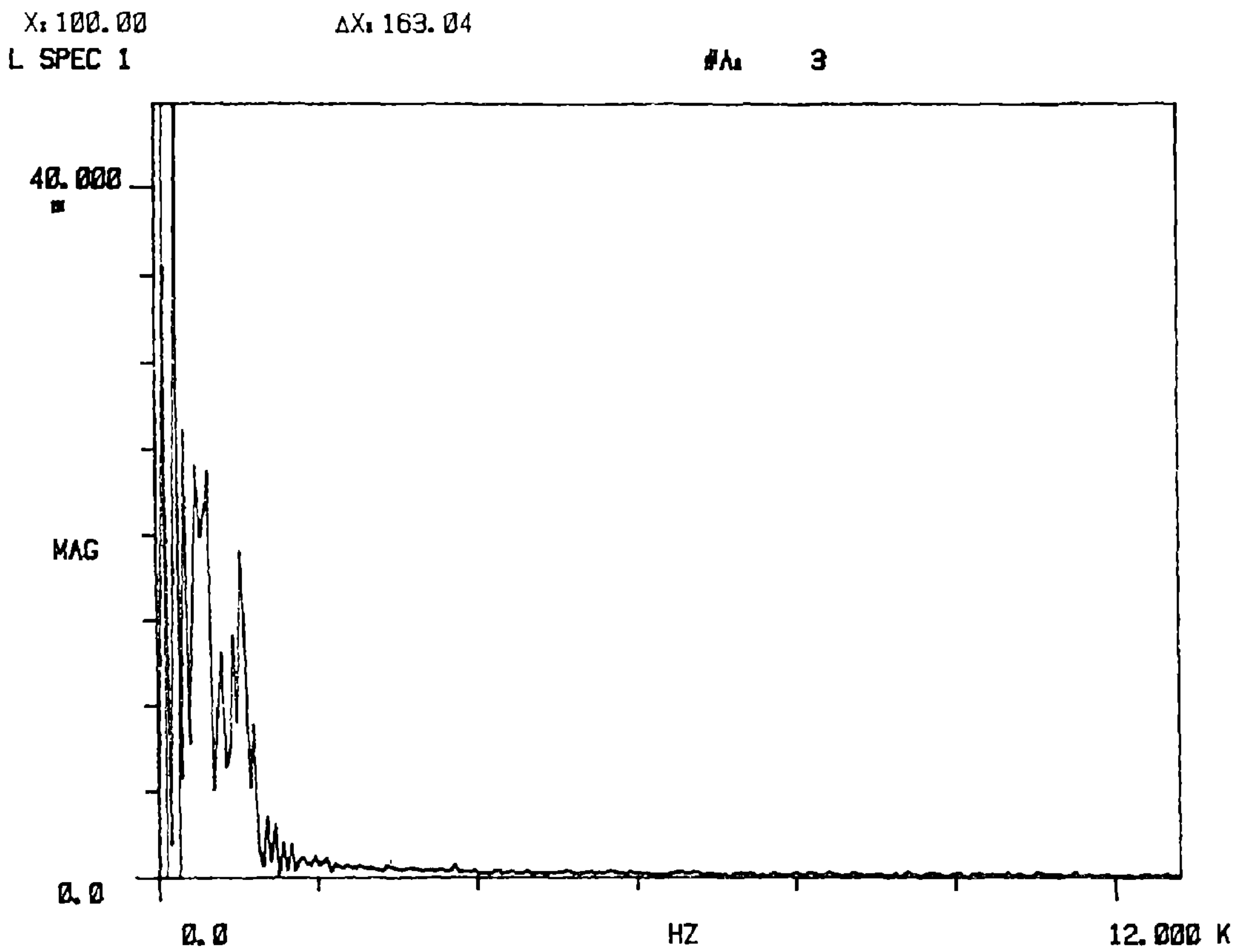

FIGURE 5-17. ACOUSTIC TEST RUN #8

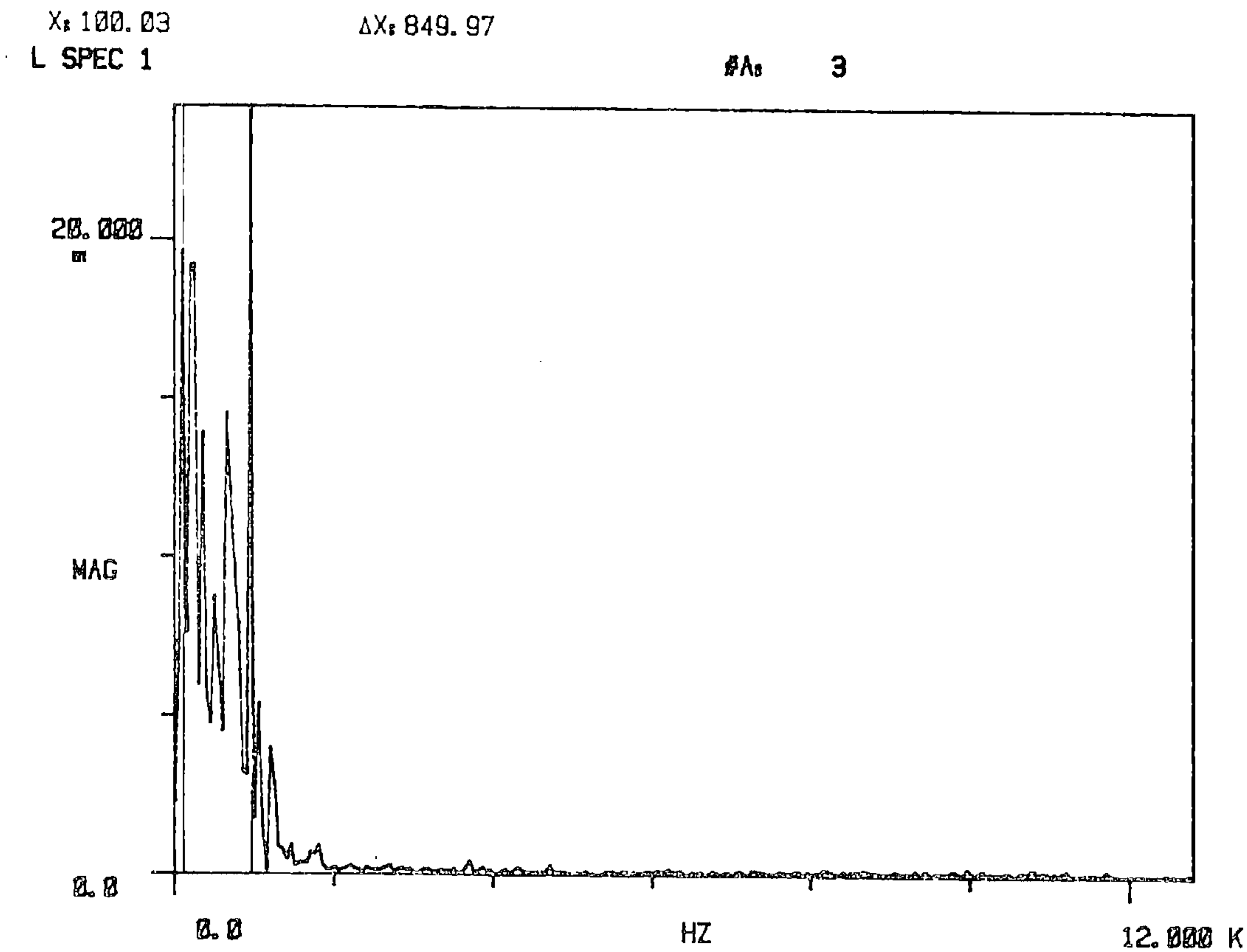

FIGURE 5-18. ACOUSTIC TEST RUN #9

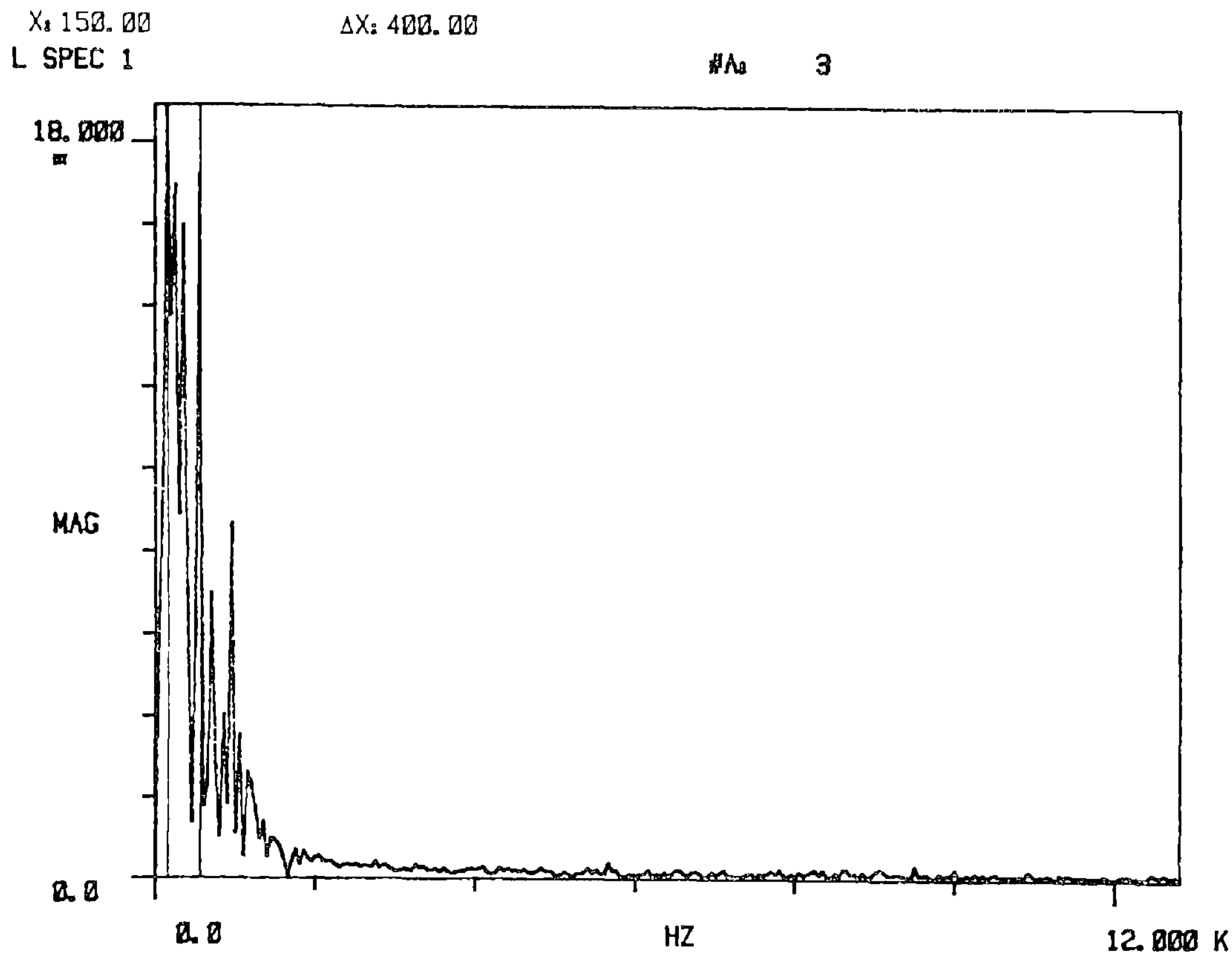

FIGURE 5-19. ACOUSTIC TEST RUN #10

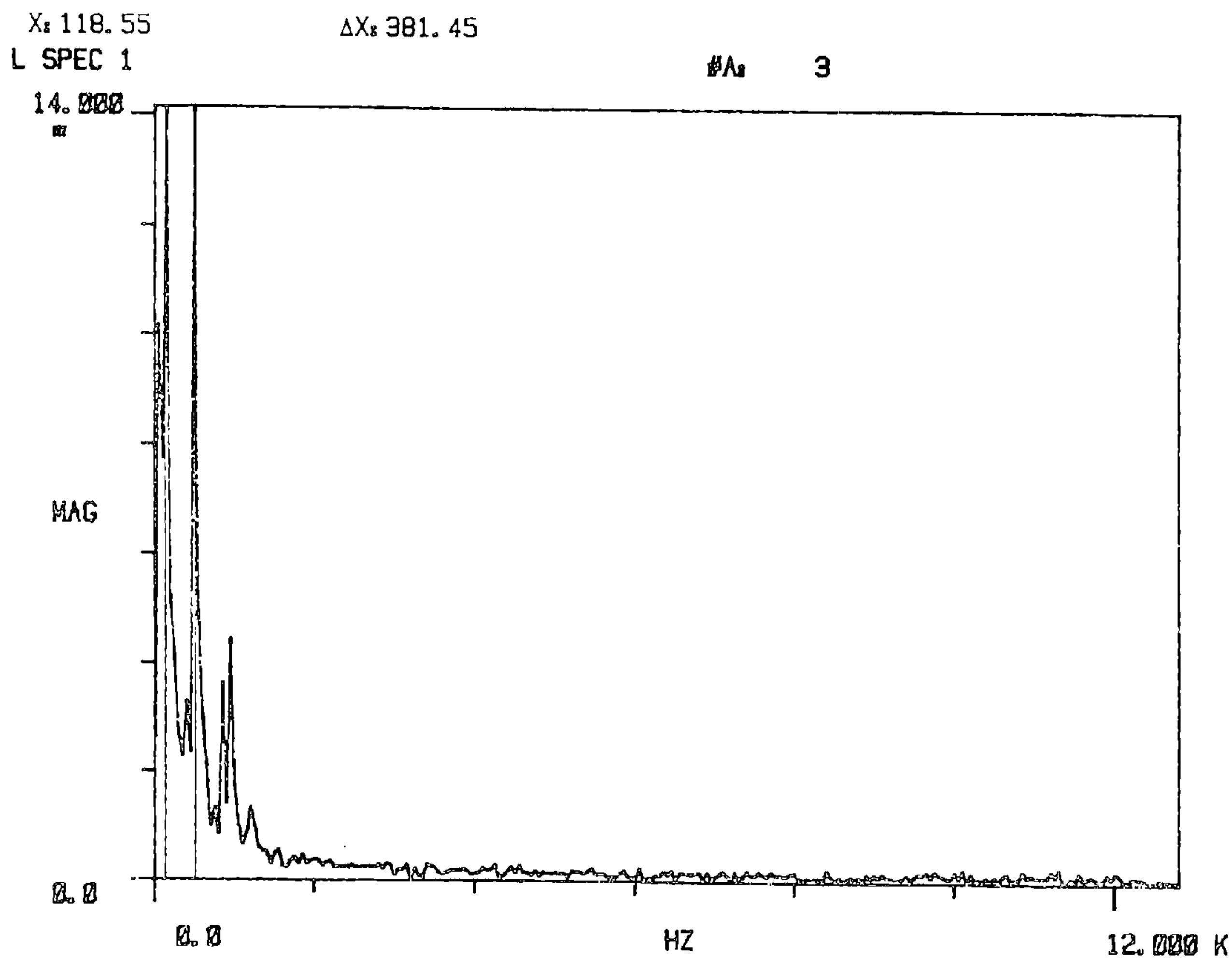

FIGURE 5-20. ACOUSTIC TEST RUN #11

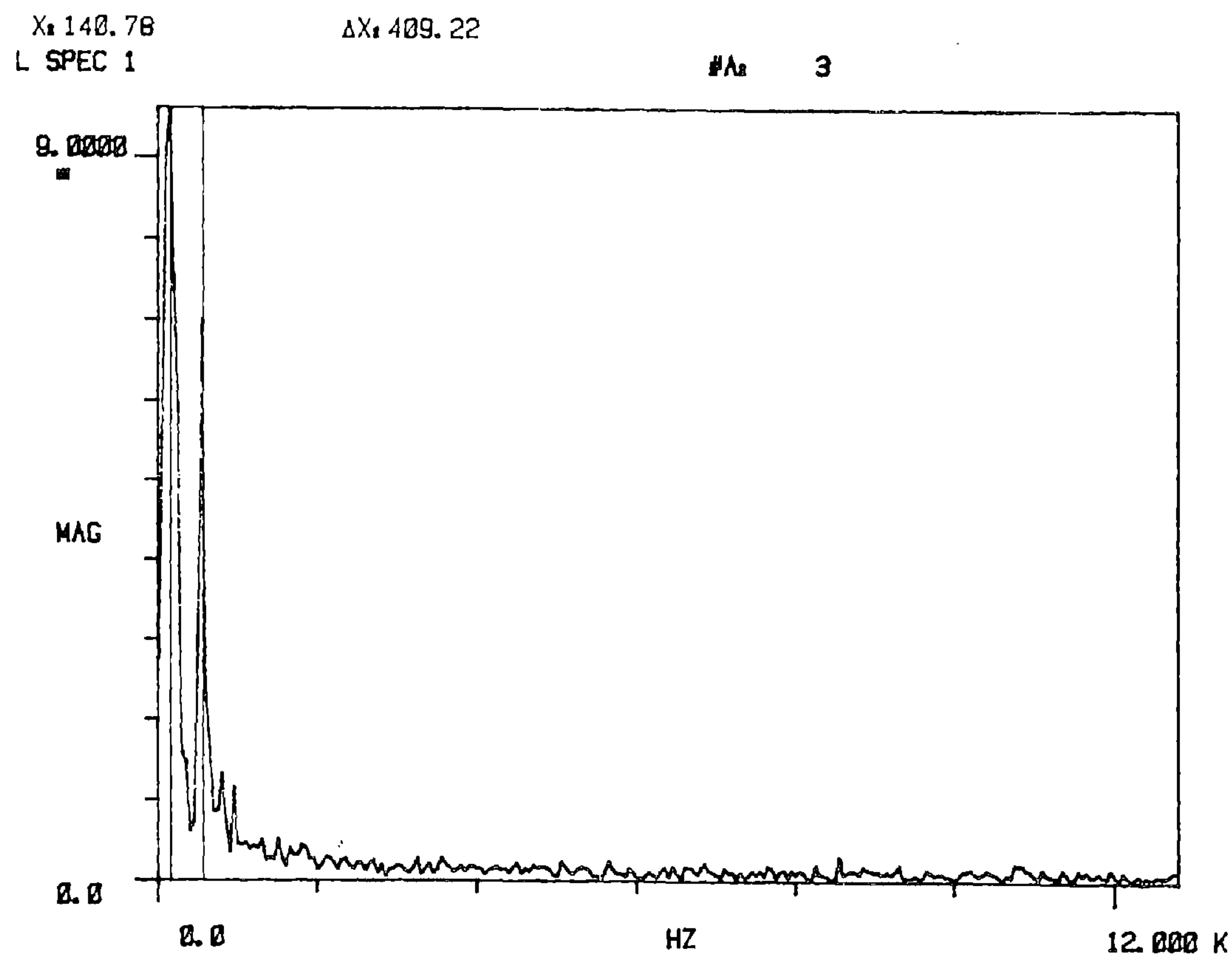

FIGURE 5-21. ACOUSTIC TEST RUN #12

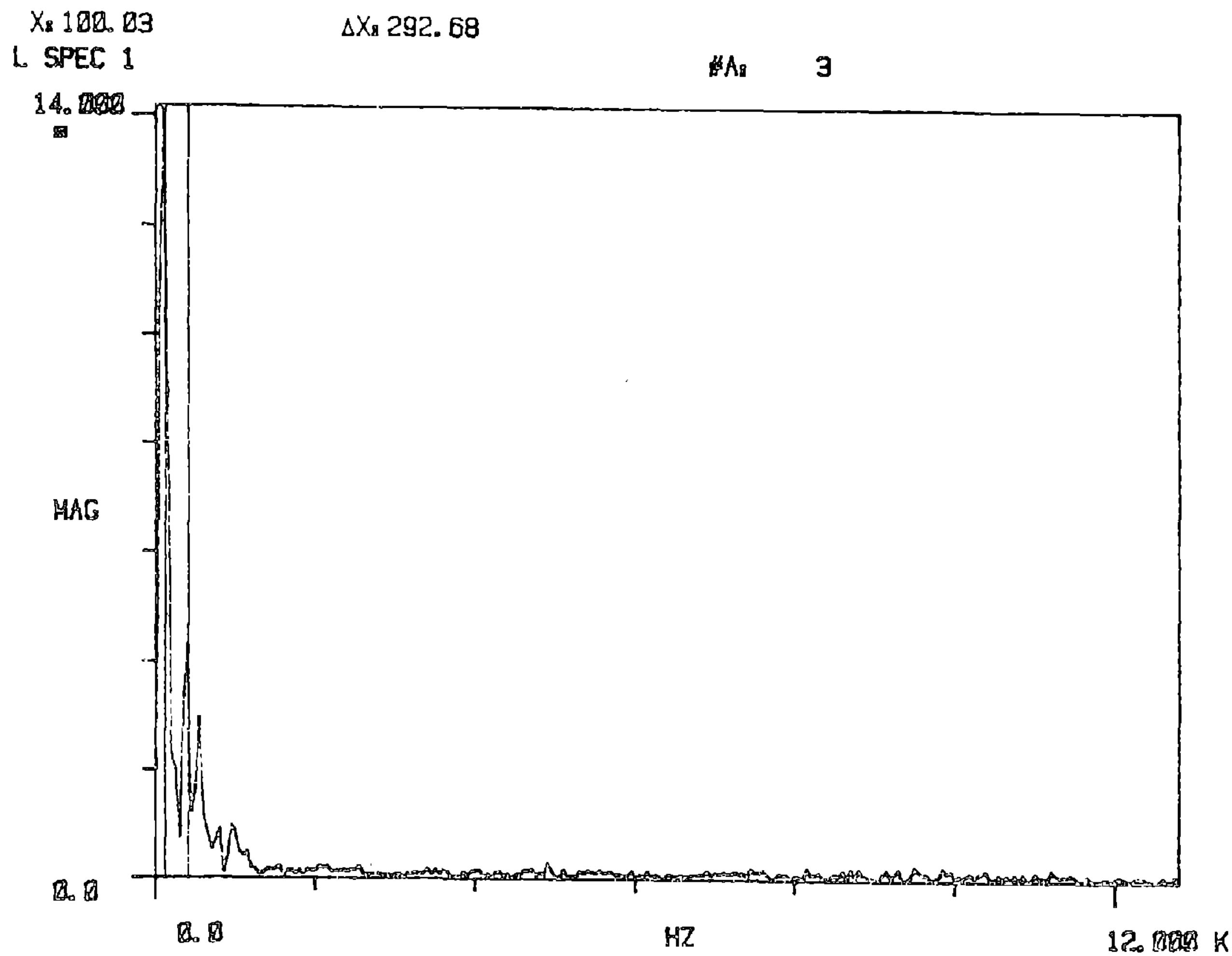

FIGURE 5-22. ACOUSTIC TEST RUN #13

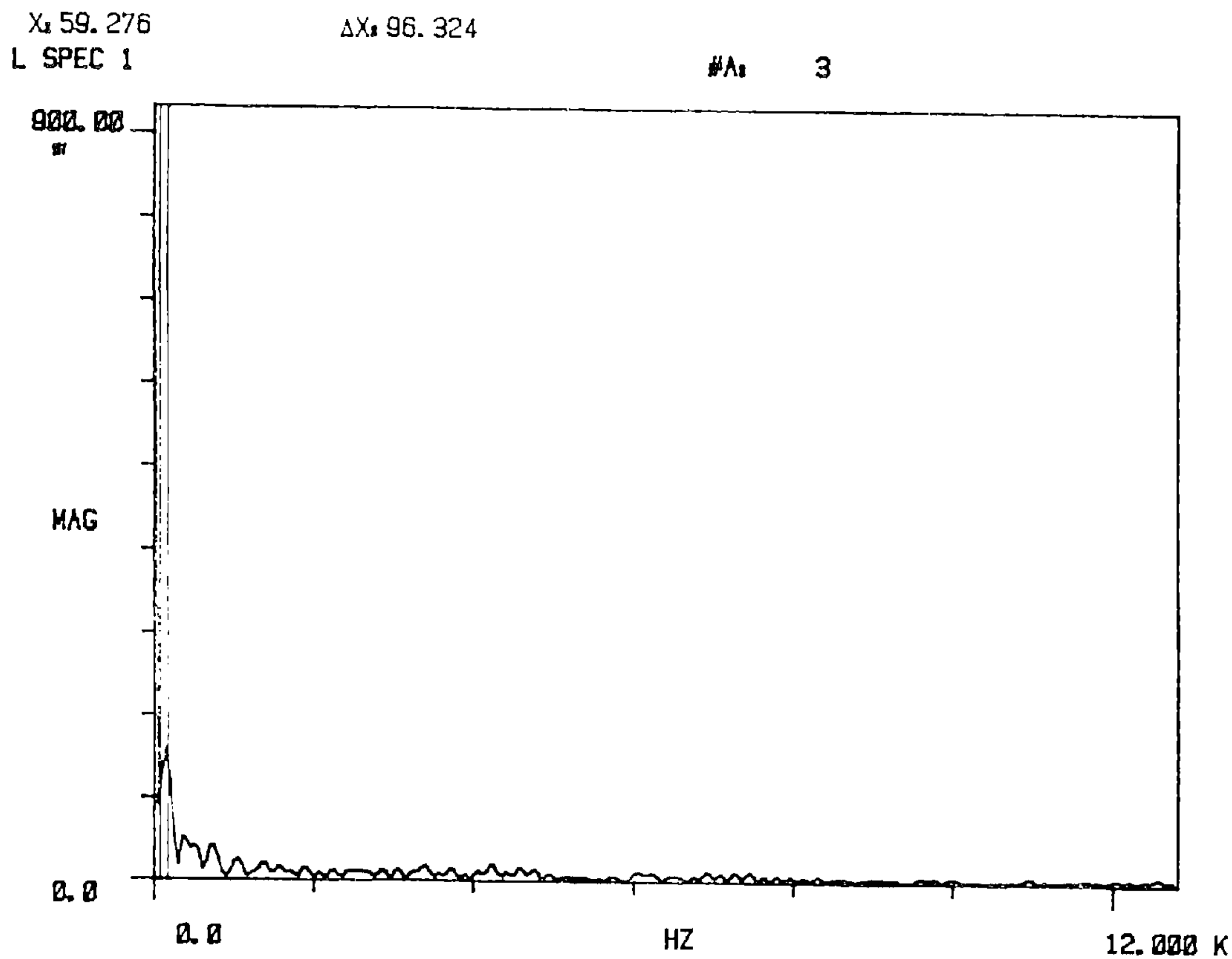

FIGURE 5-23. ACOUSTIC TEST RUN # 14

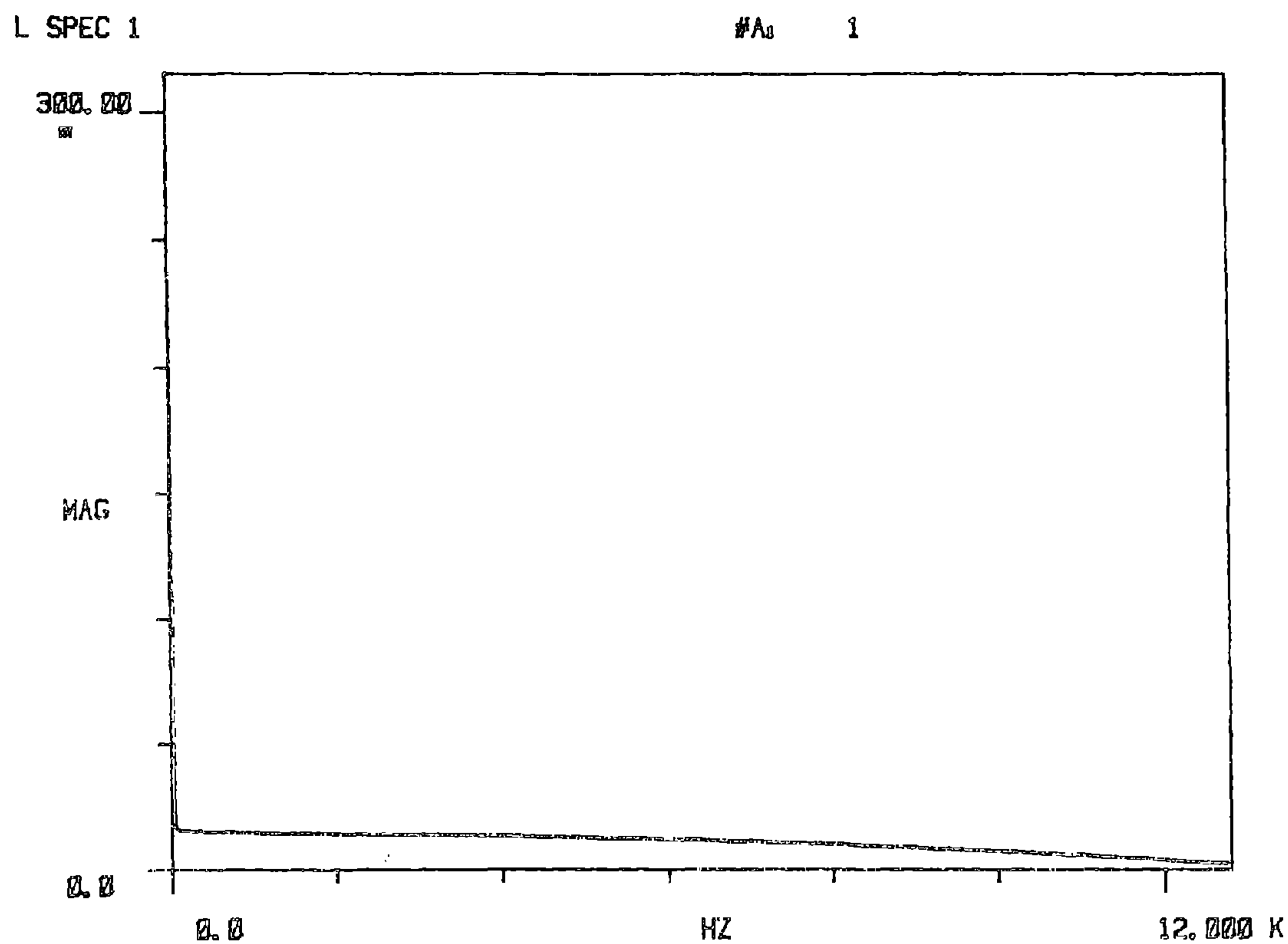

FIGURE 5-24. ACOUSTIC TEST RUN #15

on different types of ties and tracks, such as 70-lb. to 132-lb. rail. Additional testing will need to be performed in welded rail as well as testing made in inclement weather.

Instrumentation

The test plan required the fabrication of a wide band amplifier covering the dynamic range of 30 to 150 db.

To accomplish this task and reduce spurious resonances, the acoustic accelerometer was rigidly mounted to the track at a rail joint by means of a mechanical steel block. The accelerometer block was affixed to the track with the active mode of the device oriented in the horizontal (longitudinal) direction. It was then attached through a defined -30db to 150db wide band, dynamic range preamplifier to the input of a General Radio model 1933 sound level meter, with a second preamplifier output being fed directly to a wide band instrumentation tape recorder (See Figure 5-25).

Acoustic data was recorded from the DC meter and AC signal outputs of the sound level meter and the integrated AC signal were also coupled to an additional channel of the magnetic tape recorder (a Honeywell Model 5600-E, Group I, IRIG specification).

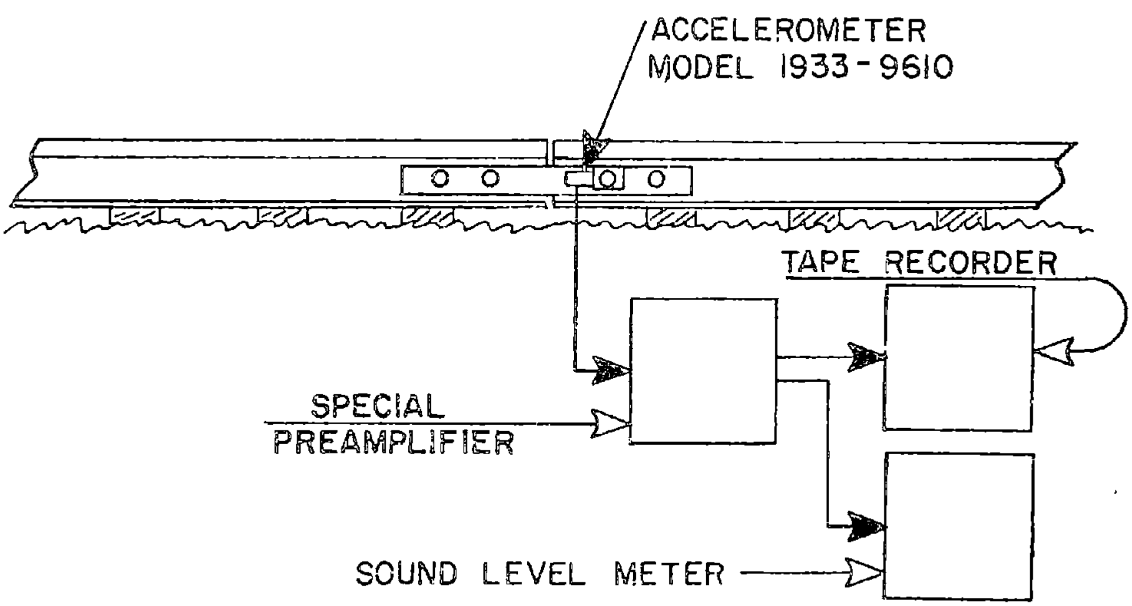

FIGURE 5-25. ACOUSTIC PICK-UP CONFIGURATION

Equipment Used

This consisted of:

(1) STL-designed wide band, constant amplitude dynamic range amplifier (-30 to 150 db)

(2) General Radio Corporation Model 1933-9610 Vibration/Integration Systems

(3) General Radio Corporation Model 1933-9610 Sound level and filter system

(4) Dual trace oscilloscope (supplied by DOT)

(5) IRIG wide band tape recorder, model 5600-E Honeywell Group I (supplied by DOT)

(6) Radar gun for confirming train velocity

(7) Analogue and Digital VTVM; assorted tools, cables and connecters

Data Acquisition

The acoustic signal data were collected through an accelerometer attached to a model 1933 General Radio precision sound level meter and analyzer. The accelerometer was a model 1933-9610 vibration integration system. To insure maximum results, all data in the analysis was recorded in wide band mode, with the 1933-9610 vibration intgration system adjusted to the acceleration readout parameter.

To reduce resonances, the accelerometer was, in all cases, rigidly mounted to the track at a rail joint by means of a 2½ x 3¼" thick angle iron. The angle iron had a 1¼" hole in the 3" side on center. The accelerometer was affixed to the 2¼" side and this assembly was attached to the track with the active mode of the device oriented in the horizontal direction. It was then electrically connected via an 8' cable to the input of the 1933 sound level meter. Data were taken from the DC meter and AC signal. Outputs of the sound level meter with the AC signal being fed to a wide band magnetic tape recorder and the DC meter output being fed into a visicorder.*

*Due to technical difficulties with the visicorder, the unit was not operated during the test runs.

The equipment was calibrated and longitudinal ambient noise levels of the track were read over a period of time. Once the ambient noise level was referenced (approximately 30 to 32 db), the tests were begun.

Test Data

Numerous measurement readings were taken with the locomotive idling at 8' from the accelerometer in an effort to determine the effects of electrical, mechanical or magnetic interference to the instrumentation. Initial tests were run at distances of one half-mile and subsequent tests at distances of one mile; speeds varied from 5 to 35 mph (refer to Table 5-3). Levels measured at one-half mile ranged from ambient background levels of 30 db to over 140 db the maximum reading available from the equipment) as the locomotive passed over the accelerometer. When heavy helicopters were over the area, levels went as high as 40 db or about the same as an approaching train 1700 ft. from the accelerometer. All these tests were run with two (2) sixty-ton EMD locomotives placed in tandem to approximate a 120-ton locomotive.

Although readings were taken at one mile distances, the one-half mile tests were selected for data analysis as the frequency response of the General Radio 1933 Sound Level Meter had to be limited to 2000 Hz in order to get usable signal to noise (s/n) ratios. Then, with the exception of distances being 2 to 1, the s/n ratio remained approximately the same in all test cases.

A typical data trace is shown in Figure 5-26 where it has time averaged to smooth out spurious noises.

Data Analysis

At the conclusion of the track tests, the wide band electromagnetic taped data were subjected to A/D conversion (See Section 4.4) using an effective trigger reference level of zero volts. Then, a linear spectrum was conducted to analyze frequency content. A typical spectrum (for the important range of 400-600 Hz) is shown in Figure 5-27.

TABLE 5-3. SIGNAL LEVELS IN db VERSUS VELOCITY IN MPH AS A FUNCTION OF DISTANCE FROM THE SENSOR*

Distance in ft.	5mph	10mph	15mph	20mph	25mph	30mph	35mph
2,600	32db	32db	30db	30db	30db	30db	30db
1,700	40db	35db	35db	35db	35db	35db	35db
1,400	50db	40db	40db	40db	40db	40db	*
1,112	60db	50db	45db	50db	50db	45db	70db
824	70db	65db	60db	70db	60db	70db	80db
536	80db	70db	75db	90db	*	80db	*
248	90db	80db	90db	120db	*	90db	*
0	100db	110db	130db	130db	130db	130db	130db

Frequency = 2000 Hz

*In some cases, data taken manually could not be recorded rapidly enough due to requirements of manual instrumentation switching. The missing data was, however, recorded magnetically and remains part of the final test data.

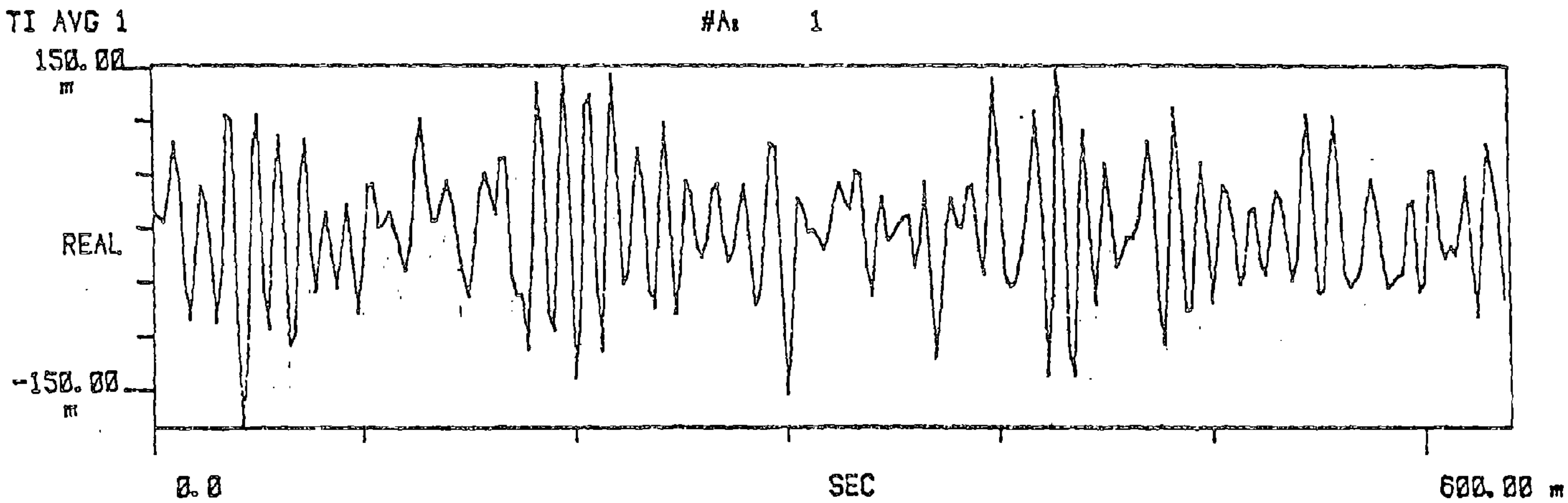

FIGURE 5-26. TIME AVERAGING ANALYSIS OF ACOUSTIC DATA

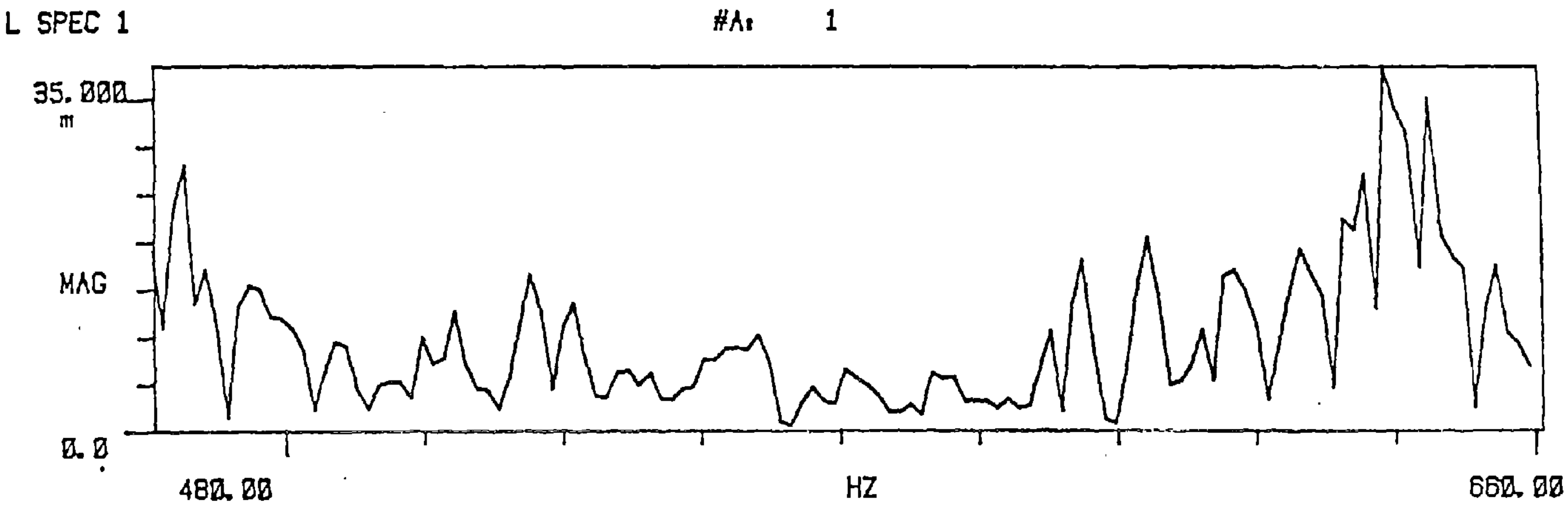

FIGURE 5-27. LINEAR SPECTRUM ANALYSIS OF ACOUSTIC DATA

It can be seen that the acoustic signal has substantial energy in the 400 Hz range and again in the 600 Hz range. Autocorrelation analysis indicated that the energy in the 600 Hz range is centered around 610 Hz which could be associated with resonance of the accelerometer mounting device and not necessarily related to the acoustic waves being generated in the rail. Nevertheless, these tests gave an initial indication that acoustic energy can be transmitted in the rails at usable amplitude levels. Further tests will be required for determining the optimum frequency at which to monitor the acoustic signal for maximizing the acoustic detection capability.

6. CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

The investigation of existing grade crossing predictor systems which have the potential for providing constant warning time information revealed that their accuracy is considerably degraded by commonly occurring variations in the track ballast conditions. Consequently, CWT system concepts need to be identified which do not directly or indirectly involve those parts of the track system susceptible to variations in ballast conditions.

Several potentially promising sensor/transducer concepts were evaluated for their applicability to CWT signalling control system requirements. These concepts included seismic, magnetic and acoustic transducers; doppler, guided and two-dimensional radars; video sensors; beam interruption sensors; strain gages; proximity switches; and track impedance methods. Of the candidate concepts, the magnetic and acoustic concepts best met the established performance criteria.

Key aspects of both the magnetic and acoustic concepts were field tested to ascertain that practical, field-implementable CWT systems could eventually be developed. The acoustic concept has the greatest flexibility in that it can detect trains standing still, moving in either direction as well as at varying speeds. However, further research is required to determine an optimum operational frequency bandwidth for the concept. The magnetic concept is also flexible in that it can provide a unique characteristic signature of the locomotive running in either direction or coasting. This system additionally offers a system that is impervious to the environment and vandalism. However, for accommodating trains that are stopped, this magnetic concept should be supplemented with a motion sensing circuit.

6.2 RECOMMENDATIONS

STL recommends that further research be conducted on the acoustic concept to establish its operational performance and operating frequency bandwidth. At the conclusion of this research, an assessment and comparison of the acoustic versus magnetic sensor concepts should be made with respect to the performance criteria discussed in Section 2. This will provide the necessary background for the industry to select an optimum CWT system for development and implementation.

7. LIST OF REFERENCES

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2 J. G. Frayne, *Theory and Operation of Grade Crossing Predictor is Explained,* Railway Signalling and Communications, Vol. 56, No. 11, November 1963.

3 J. B. Hopkins, R. Abbott, F. R. Holmstrom, E. F. White, and A. T. Newfell, *A Communication-Link Approach to Actuation of Grade-Crossing Motorist-Warning Systems*, U. S. Department of Transportation, Transportation Systems Center, Cambridge, MA., July 1975.

4 A. J. Carey, *Basic Track Circuit Limitations*, Bulletin 261 Westinghouse Air Brake Co. Union Switch and Signal Division, Pittsburgh, PA.

5 F. V. Blazek, *Track Circuit Characteristics Associated with Motion Monitor,* Westinghouse Air Brake Co., Union Switch and Signal Division, Pittsburgh, PA, 1975.

6 R. L. Monroe, *A Survey of EMI Problems Generated by Traction Control Systems Employing Thyristors*, prepared under FRA Contract No. DOT-FRA-8042, Systems Technology Laboratory, Inc., Arlington, VA, July 1979.

APPENDIX A

STATE OF THE ART ASSESSMENT

A.1. INTRODUCTION

As part of developing concepts for constant warning time systems, a thorough review of the state-of-the-art in grade crossing warning systems was carried out. A large body of references derived from both government research projects and industry products were reviewed to provide the most current information on grade crossing warning systems. (A selected bibliography of the more pertinent references are given in Section A4 of this Appendix.) Since many grade crossing warning systems currently based in North America rely entirely upon the occupancy information developed from track circuits, these are discussed in some detail in Section A.2. Following this, a historical development of the various grade crossing warning systems are given, including aspects of serviceability, maintenance, credibility, installation requirements, etc.

A.2. TRACK CIRCUITS

There are several types of track circuits in general use today. While they all perform the same basic function of providing occupancy information, some of them serve as circuits for transfer of information from one point to another. Other track circuits have the capability of providing position and motion information, as well as occupancy information. One common characteristic of track circuits is that they utilize the rails as electrical conductors. The most commonly used track circuit systems are as follows:

A.2.1. <u>DC-Battery/Relay Track Circuit System</u>

The DC-Battery/Relay Track System is the original basic track circuit, and relies upon a battery to supply load current to one end of the track circuit which is isolated at both ends by insulated joints. A series resistance is utilized to protect the battery by limiting current when the track circuit is shunted. At the opposite end of this track circuit, a relay is connected across the rails. This is normally energized when no train is present. Occupancy of the track circuit at any point will "short circuit" the rails and cause the relay to function. The functioning of the relay provides the occupancy information for the track circuit (See Figure A-1 and A-2.) In addition to providing the basic occupancy information, when it is shunted by a pair of rail vehicle wheels, it is also a "fail-safe" system. The opening or short circuiting of any of the conductors associated with the track circuit results in the relay dropping. Many of the other track circuits utilized in signalling, as well as control circuitry utilized for all forms of railroad signalling employ this closed circuit principle. The DC source may be a primary or rechargeable battery. The latter is used increasingly as availability of alternating current (AC) for recharging has become almost universal. Either source provides continued operation in the event of a power interruption.

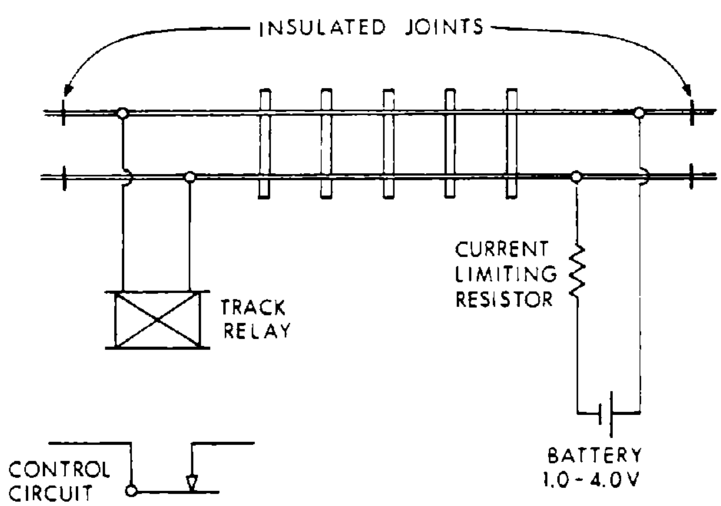


FIGURE A-1. DIRECT CURRENT BATTERY/RELAY TRACK SYSTEM

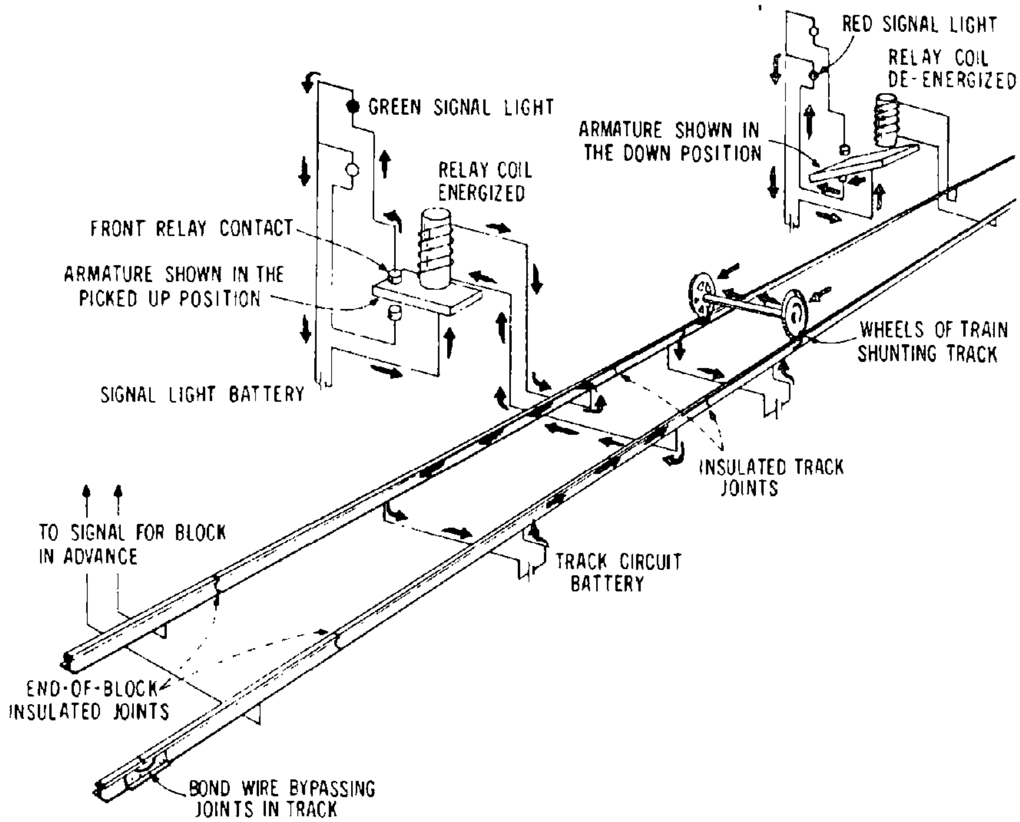


FIGURE A-2. TRAIN SHUNT PROVIDES OCCUPANCY INFORMATION

A.2.2. AC-Transformer/Relay Track Circuit System

This circuit is a variation of the DC-battery/relay track circuit and substitutes a transformer-derived AC for the battery. Normally, this type of track circuit is utilized where traction current or other forms of spurious or foreign currents are present. The system uses phase-sensitive relays to positively detect the presence of a train. This technique assures that the signal received from the track is unique to that provided at the feed end of the specific track circuit. A wire line circuit is utilized along the track and provides both the power and phase reference for this track circuit. Two prevalent frequencies used for AC track circuits in this country are 60 HZ and 100 HZ. The latter frequency is generally used when there is a significant 60 HZ interfering signal, as in the case of 60 HZ AC traction , or foreign current present due to the power distribution grid. As with the DC track circuit, the AC track circuit requires insulated joints at each end to electrically isolate it from the rest of the system (See Figure A-3.)

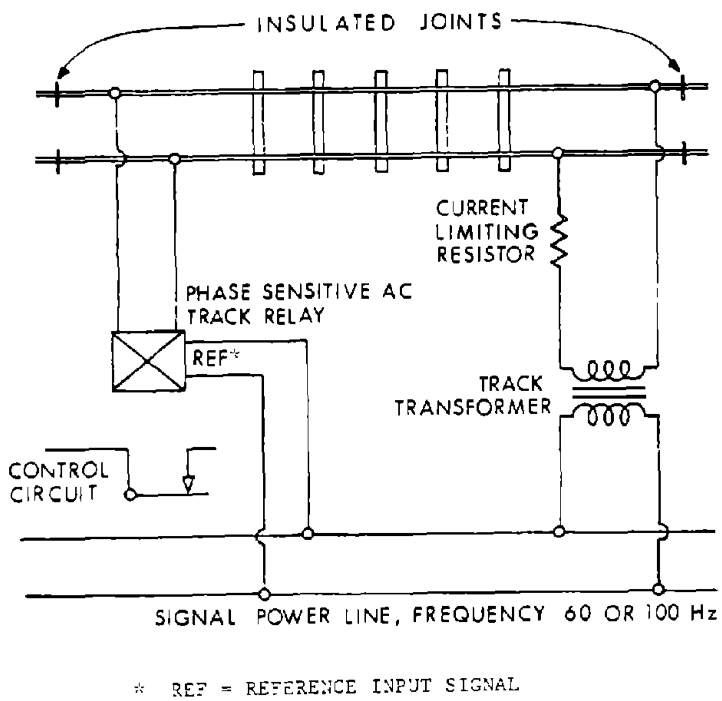


FIGURE A-3. AC-TRANSFORMER/PHASE SENSITIVE RELAY TRACK CIRCUIT

A.2.3. Coded Track Circuit System

In this system, the energy feed to either the DC or AC track circuit is periodically interrupted, whereby the output relay located at the opposite end of the track circuit is energized and de-energized in time with the energizing and de-energizing of the track circuit. This operation has a dual advantage. First of all, the output relay is constantly cycled from an energized to a de-energized position and provides positive operation particularly over long track circuits. It avoids operational problems associated with aging of the relays where hysteresis between pick-up and drop away values starts to increase. The second advantage of the Coded Track Circuit is that it provides information in the form of variable period and variable pulse width modulation. This provides the capability of transmitting information from one end of the track circuit to the other. This is utilized for signal aspect control without the need for line wires parallel to the track. In the case of the AC track circuit, the information can be inductively coupled to the locomotive and provide on-board signal information. As with the previous track circuits, the Coded Track Circuit requires insulated joints to isolate the individual track circuits. This system is a variation of the AC Transformer/Relay and DC/Battery Relay track circuit systems.

Coded track circuits have traditionally used mechanical relays for timing pulse width and spacing. Other systems can be designed to provide encoding and decoding signals utilizing solid state electronic circuitry to facilitate for presence detection and signal aspect control. This was previously done with the coding/decoding relays. A block diagram for a Coded Track Circuit is shown in Figure A-4.

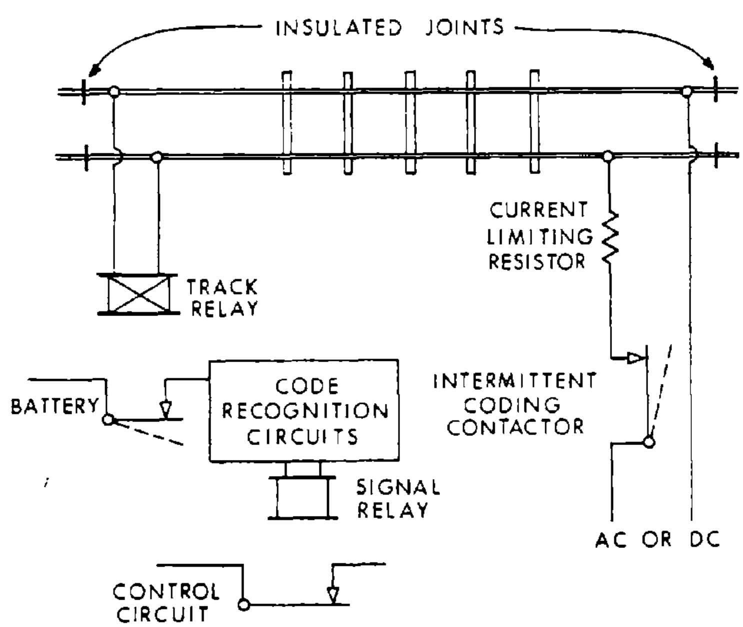


FIGURE A-4. AC OR DC CODED TRACK CIRCUIT

A.2.4. Audio Frequency Track Circuits

An audio frequency signal applied to the rails can be detected at some remote point along the rails (see Figure A-5.) There are several useful properties associated with Audio Frequency Track Circuits not be found in the systems previously mentioned. The fundamental advantage of the Audio Frequency Track Circuit is that it can operate without insulated joints.

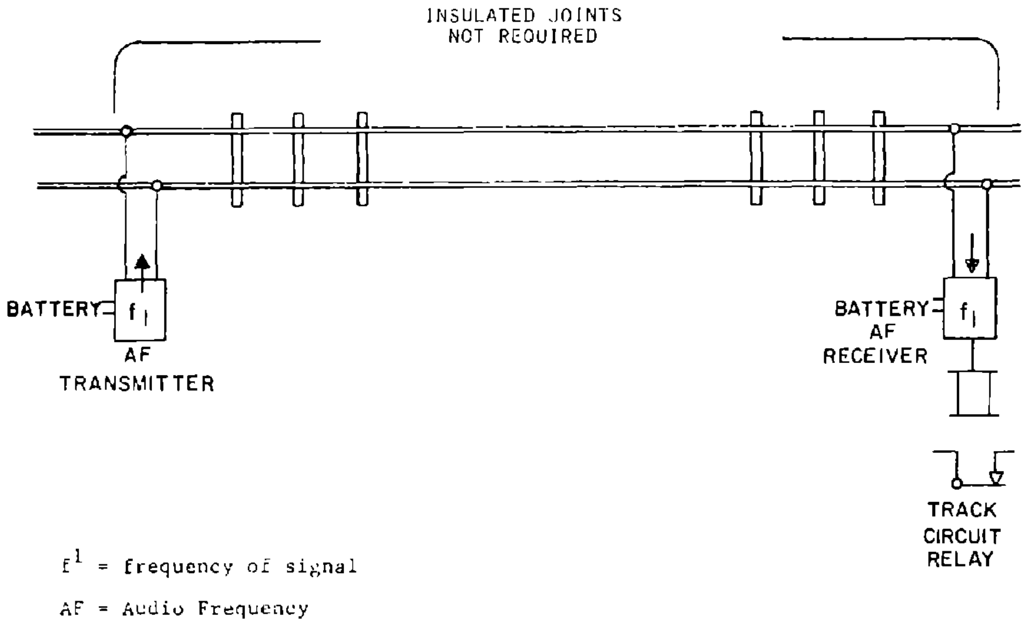


FIGURE A-5. BASIC AUDIO FREQUENCY TRACK CIRCUIT

A train which is near but outside the input connection points of the Audio Frequency Track Circuit, may attenuate the received signal, but because of the inductive property of the rail it will not provide a sufficient shunt to remove energy from the track connection at the receiving end,and drop the relay. However, when the shunt is at the feed wire point, or any point between the input and output feed wires, energy will be removed from the receiver providing positive occupancy information. It is possible with the Audio Frequency Track Circuit to apply a fixed signal frequency at the transmitter and sharply tune the circuit from another. With this capability, it is possible to overlap track circuits so that each operates independently. This independent operation holds for shunts and occupancy between the track circuit limits as defined by the placement points of the transmitter and receiver (see Figure A-6.)

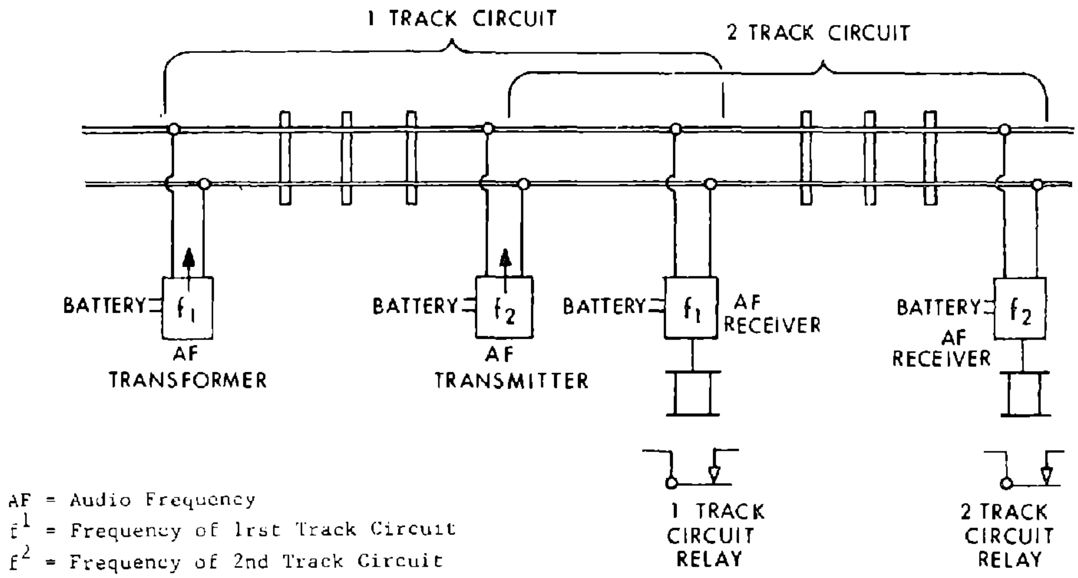


FIGURE A-6. OVERLAPPING AUDIO FREQUENCY TRACK CIRCUITS

The lack of insulated joints in the Audio Frequency Track Circuit has another advantage. It is independent from a conventional DC or AC track circuit sharing the same rails. This allows Audio Frequency Overlay grade crossing approach start circuits to be applied without intervention in the DC or AC wayside signalling circuits. With the recent dramatic increase in the number of crossings having active warning devices, the use of separate track circuit systems for grade crossing warning has become mandatory. When an Audio Frequency Track Circuit extends through insulated joints, large value capacitors are used to pass the audio frequency while blocking the DC (see Fig. A-7.)

Some of the early Audio Frequency Overlay equipment built between 1956 and 1972 utilized an unmodulated continuous wave to provide the track circuit with voltage. The receiver was dependent upon a selective filter and a specific detection threshold

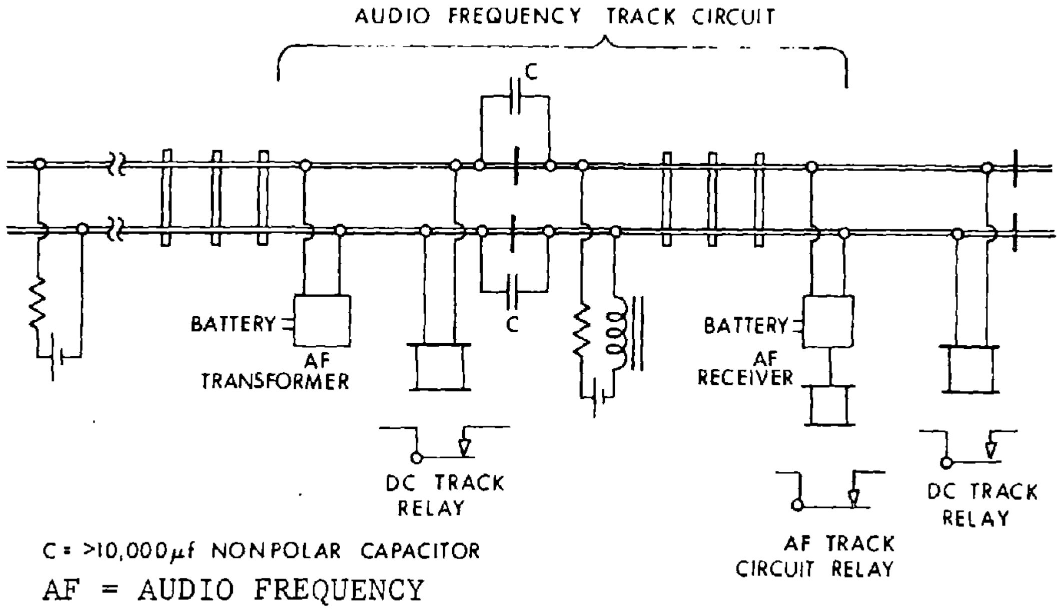


FIGURE A-7. AUDIO FREQUENCY TRACK CIRCUIT SPANNING INSULATED JOINTS

which was necessary to provide security against spurious "foreign" signals. As the use of audio frequency equipment proliferated with the railroads and industry, the need for greater security became apparent. To achieve this, a modulated system was designed and introduced in the early 1960's. By the late 1960's, this system accounted for the majority of the systems sold. Amplitude, frequency and phase modulation systems are currently used by several manufacturers.

A.2.4.1. Audio Frequency Track Circuit System for Position Determination

Another characteristic of Audio Frequency Track Circuits based on the natural self-inductance of the rails is the ability to determine the distance of the train shunt from the transmitter feed point. In this configuration, the transmitter and receiver are both connected at the feed point, and a constant current is impressed upon the track circuit by the transmitter. As the train shunt moves toward the transmitter/receiver connection, the impedance of the track circuit to the shunt decreases. This decrease causes a corresponding decrease in voltage across the transmitter/receiver wires. It is possible to determine the distance and motion of the train shunt from the track connection.

This feature of Audio Frequency Track circuits is utilized in one of the grade crossing predictor systems and several of the motion sensing systems now in use for grade crossing warning applications (see Figure A-8.)

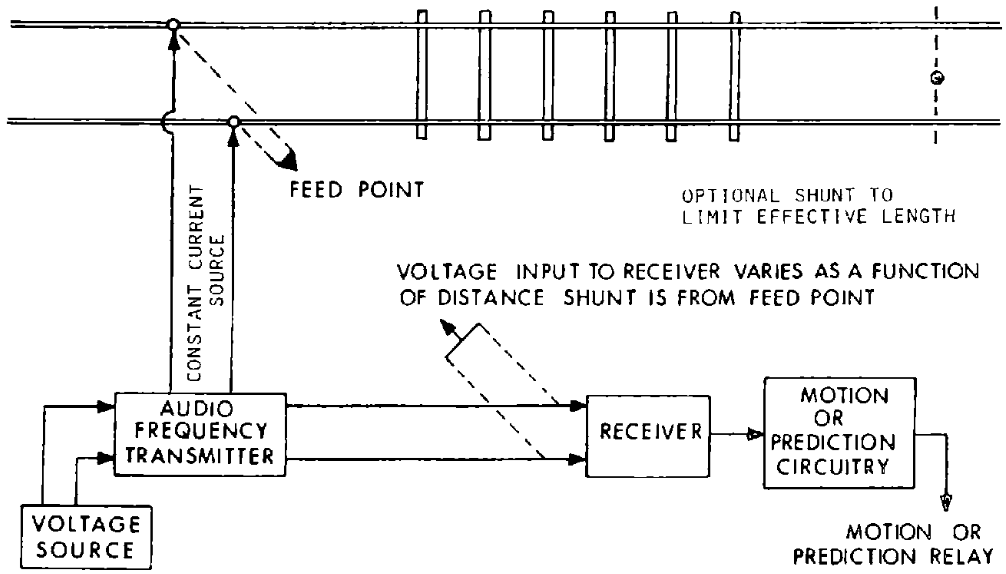


FIGURE A-8. MOTION SENSITIVE AUDIO FREQUENCY TRACK CIRCUIT

One of the currently available motion devices utilizes the variation in inductance of the track circuit due to the train shunt in another manner. The track circuit from the feed wire attachment point to the termination shunt, which defines the end of the track circuit, is used as the inductance in a parallel resonance "tank" circuit of an audio oscillator. The train shunt moving toward the track feed wires from the terminated end, reduces the inductance of the track circuit and increases the frequency of the oscillator. A variable compensating capacitor is utilized within the unit to keep the frequency constant. The rate at which the capacitor changes value provides distance and motion information for the rail vehicle occupying the track circuit. (see Figure A-9.)

PARALLEL RESONANT AUDIO FREQUENCY TRACK CIRCUIT

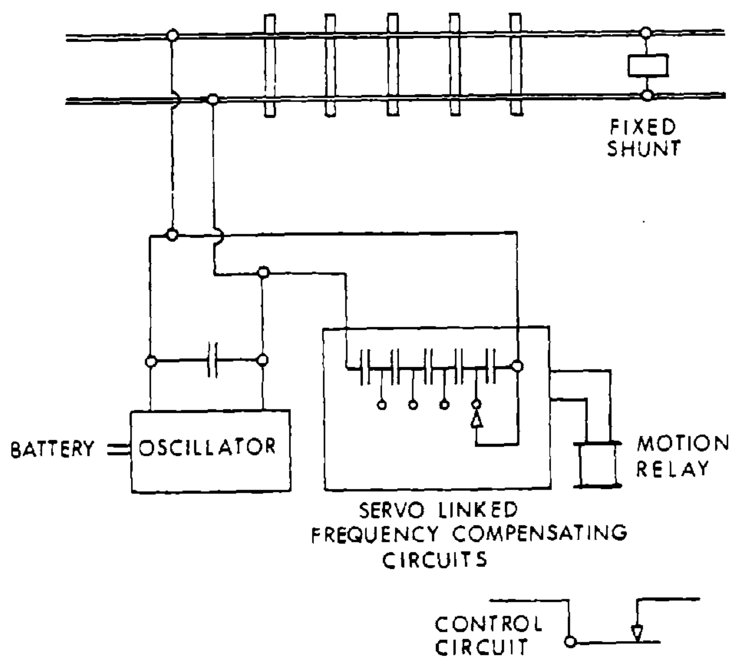


FIGURE A-9. PARALLEL AUDIO FREQUENCY TRACK CIRCUIT

A.2.4.2 Characteristics of the Audio Frequency Track System

The frequency range utilized for both the presence detection and the distance/motion sensing devices range from 25 Hz to 20 KHz. Due to the inductance of the tracks and the low ballast resistance often encountered, usable track circuit length ranges from 1000 ft. to 5000 ft. The distance.motion sensing system must react to the presence and motion of a track shunt at its outer extremities. The allowable lengths are substantially less than for those presence detection circuits which utilize a transmitter and receiver. DC track circuits are not affected by rail inductance, and the low DC resistance of the rails allows very long track circuits. DC track circuits of 10,000 - 12,000 feet are found in wayside signal control circuits.

A.2.5 Application of Track Circuit to Wayside Signaling and Grade Crossing Warning Systems

The above described track circuits are utilized for two specifically different functions: wayside signalling, and grade crossing warning information. DC Track Circuits, AC Track Circuits and DC or AC coded Track Circuits are utilized for wayside signalling and for grade crossing warning systems. Although Audio Frequency Track Circuits are utilized to a limited extent for wayside signalling, their use today is predominantly for grade crossing warning information.

As noted above, there is a distinct advantage in keeping the wayside signalling and grade crossing warning track circuits separate and mutually exclusive. The functions required of each are distinct and separate. Shared use or mutual interference usually results in greater cost and complexity. In most cases, an Audio Frequency Circuit can be overlaid on a wayside signalling circuit without mutual interference by use of the DC and AC Track Circuits for wayside signalling and Audio Frequency Track Circuits for grade crossing warning approaches. Additionally, the Audio Frequency Track Circuit Concept is the only presently used means of obtaining motion sensitive and constant warning time control for grade crossing warning devices.

A.3. GRADE CROSSING WARNING SYSTEMS

A.3.1. Historical Development

Grade Crossing warning systems initially consisted of a flagman utilizing a flag by day and lantern at night to warn road traffic and pedestrians upon the approach of a train. With the advent of track circuits and reliable electric track circuit data, information became available that provided more accurate advanced warning of the impending arrival of a train at the crossing. Crossing gates, controlled by the crossing guard, also were provided in heavily traveled areas to serve as an adjunct to other means of warning road users of impending train occupancy.

As both highway traffic and technology increased, dedicated track circuits were utilized to provide the flagman with information on when to start warning. With the train approach information the flagman normally added his own judgment, in the case of slow and intermittent train moves, to provide the minimum delay to the roadway traffic while maintaining safe warning time. Consequently, in the earlier flagman-controlled crossing warning systems, both the motion sensitive warning operation and, to some extent, the constant warning time capability were realized.

The automatic crossing warning system sought to replace the flagman's lantern with a wig-way and subsequently a pair of alternate flashing lamps to visually reproduce the oscillating, swinging lantern. Automatic, motor driven gates were also introduced to replace the manual or motor operated gates controlled by the flagman. Dedicated track circuits for operation of the crossing warning devices were provided and the crossing warning then operated independently of the wayside signalling system with the approach start track circuit lengths determining the warning time for the fastest train. A relay logic system was incorporated to determine train direction and to prevent the unnecessary operation of the warning devices after the train had passed the crossing, although it was occupying the approach track circuit opposite to that which it had entered (see Figure A-10.) This automatic crossing warning system did not rely on the sometimes questionable alternative of the crossing flagman and consequently, it was more dependable in providing required warning device operation due to its failsafe circuitry and construction. However, any train, or even a single rail car continuing to occupy the approach would keep the warning activated even though there was not train approaching the crossing. Consequently, minimizing operation of the warning devices, which was previously accomplished by the crossing watchman's judgment of train motion and velocity, was lost.

The approach starts for automatic crossing warning systems were initially DC Track Circuits or, if the wayside signals were controlled by AC Track Circuits, the crossing start circuits were generally AC. In the mid-1960's, Audio Frequency Track circuitry had become the preferred method of providing grade crossing approach information. The Audio Frequency Track Cir-

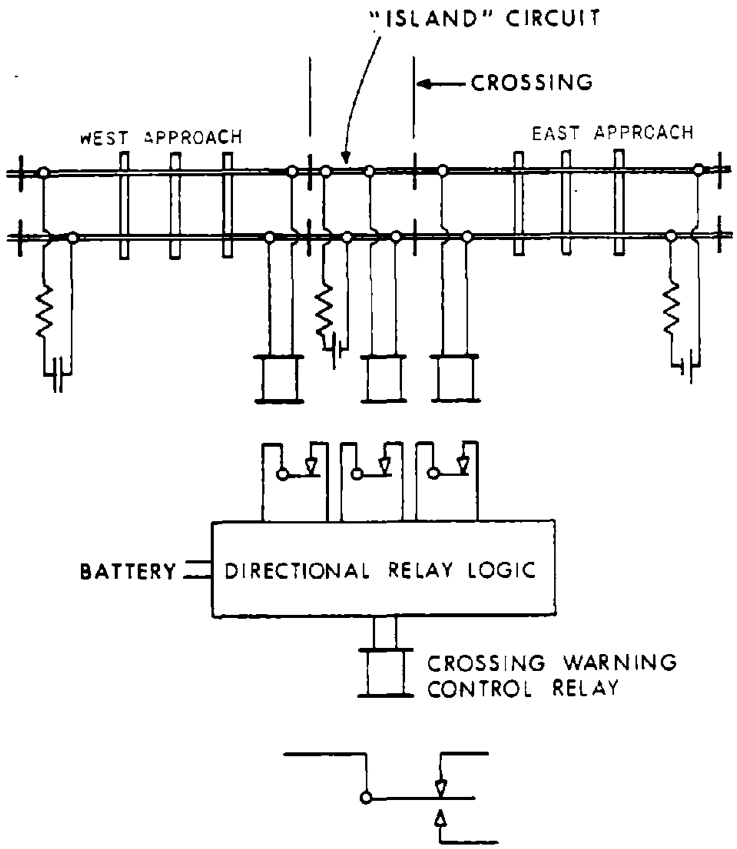
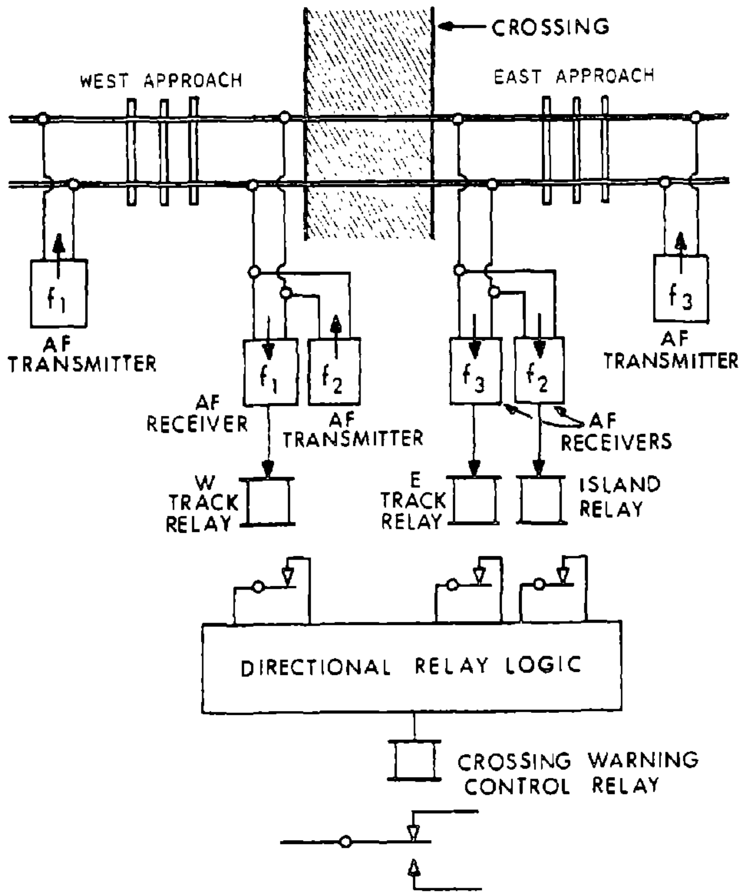


FIGURE A-10. AUTOMATIC BIDIRECTIONAL GRADE CROSSING WARNING SYSTEM EMPLOYING DC TRACK CIRCUITS

cuits were arranged in the same manner as the conventional DC Track Circuit and utilized the same relay directional logic (see Figure A-11).

During the same time period, the AC/DC or "type C" Track Circuit was developed and was generally accepted in nonsignalled territory. This track circuit utilizes an alternating current feed at one end of the track and a diode at the opposite end. This track circuit requires insulated joints. When the AC from the feed transformer is impressed across the diode, it is rectified and provides a DC level superimposed upon the AC originally impressed upon the track circuit. The DC level is utilized to energize a conventional DC track circuit relay. The relay will not respond to the low level of AC used and consequently will become energized only when the diode is "visable" to the transmit/receive end of the track circuit. A train shunt anywhere within the track circuit will both shunt the AC and DC and prevent the impressed AC from appearing across and being



f^1, f^2, f^3 = TRANSMITTER FREQUENCIES
AF = AUDIO FREQUENCY

FIGURE A-11. AUTOMATIC BIDIRECTIONAL WARNING SYSTEMS EMPLOYING AUDIO FREQUENCY OVERLAP

rectified by the diode. The advantage of this track circuit is that it is fed from one end, and requires only the diode at the opposite end of the track circuit. This eliminates the expense of providing power to the opposite end of the track circuit and/or providing power to the AC/DC circuit is identical to that utilized for the DC Track Circuit or Audio Frequency overlay circuit (see Figure A-12.) This AC/DC track circuit is not, however, compatible with any other track circuits so its use is restricted to nonsignalled territory without overlapping crossing approach circuits.

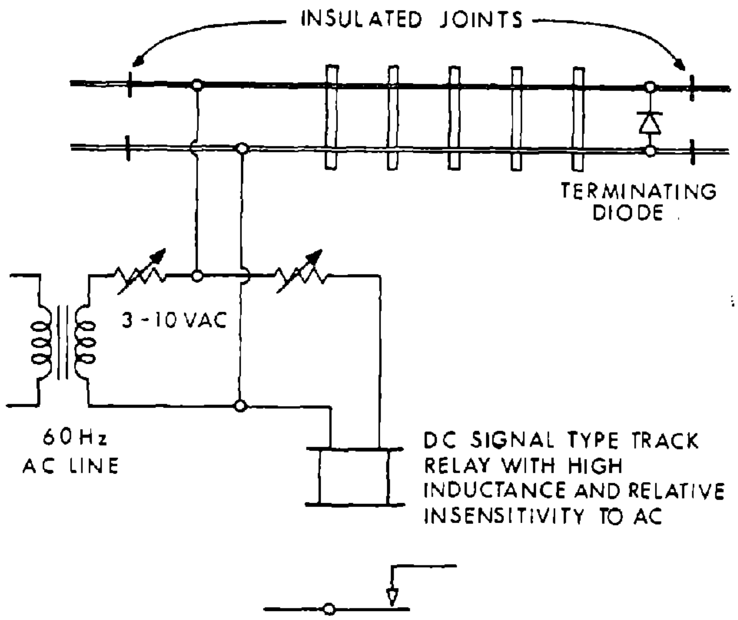


FIGURE A-12. AC/DC (TYPE-C) TRACK CIRCUIT (USED AT GRADE CROSSINGS IN NON-SIGNAL TERRITORY)

A.3.2. Early Attempts at Providing Constant Warning Time

During the period 1958-1960, the Southern Pacific Railroad became involved in a widespread program of installing crossing gates as an adjunct to the standard crossing warning lamps. Unfortunately, in areas where train speeds varied considerably, needless traffic delays were experienced due to slow or stopped trains keeping the gates down unnecessarily. Traditionally, to overcome the problem of unnecessary warning system operation, a type of constant warning time system had been utilized in many locations. This consisted of breaking the approaches into several shorter DC Track Circuits. These individual circuits were then utilized in conjunction with circuit timers to provide a crossing start only if the speed of the train was sufficient enough to allow it to reach the next track circuit before the timer which was started upon entry of the first circuit had run out. This also eliminated unnecessary gate operation if a train were to stop in one of the outer approach circuits (see Figure A-13.) While these time out approach sections were fairly effective in reducing unnecessary crossing warning operation, the complex circuitry and expense of intervention in the wayside signaling systems were unacceptable.

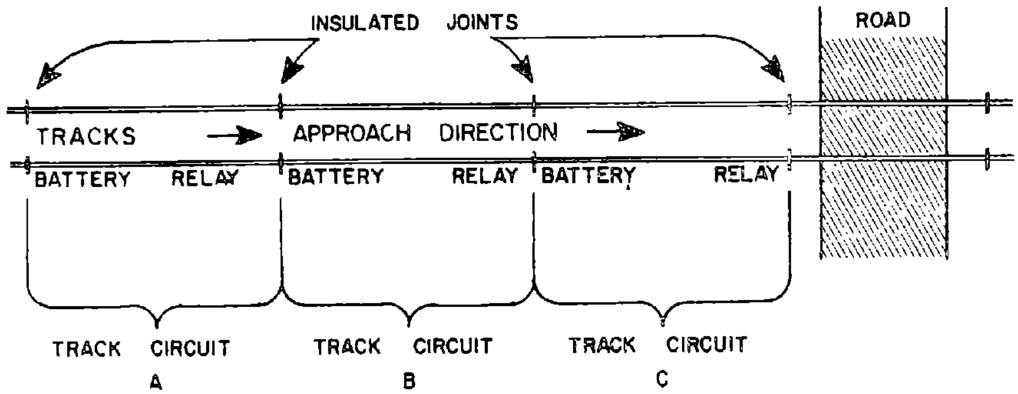


FIGURE A-13. "CONSTANT" WARNING TIME SYSTEM EMPLOYING TIME OUT APPROACH SECTIONS

A.3.3 Grade Crossing Predictor (GCP) Systems*

The Southern Pacific Railroad perceived that it should be possible to utilize the change in track circuit impedance as the train approached the crossing to provide a "constant" warning time system without the attendant problems of the time out track circuit approach sections. Stanford Research Institute (now SRI-International) was retained to develop a system which would utilize an audio frequency signal impressed on the track independent of the signal track circuit. Development was completed by SRI with field testing and additional technical input provided by the Southern Pacific Railroad. A functional system which provided a nearly constant warning time was developed.**

This system, named "Grade Crossing Predictor" was placed in service in 1963. It utilized a constant current feed to the track circuit and development of a voltage representing the total inductance of the track circuit out to the point of the train shunt. This voltage, then, was representative of the distance of the train from the crossing. By use of an ana-

*This study of the GCP is based upon the Model 300 series. It must be noted that updated models have been developed since this study was performed.

** *Theory and Operation of Grade Crossing Predictor*, is explained by John G. Frayne, Railway Signalling and Communications, Vol. 56, November 11, 1963.

log computer, the anticipated time of arrival of the train at the crossing was projected, assuming its velocity remained constant. This basic principle was utilized in the first commercial constant warning time "predictor" system and has continued to be used in subsequently developed systems. Manufacturing rights for the system developed by SRI were sold to by Marquardt Corporation and this equipment is currently manufactured by Safetran Systems Corporation. At present, this is the only constant warning time system being manufactured which has the potential for providing constant warning time. However, as is shown in Figure A-14, these systems do have a limitation in terms of range. It may be noted that the practical range (based on a figure of not less than 200 Hz) for main/GCP sensors goes up to 2000 ft. and for audio frequency overlay systems goes up to 5000 ft. D.C. Track Circuits have an effective range up to 12,000 ft.

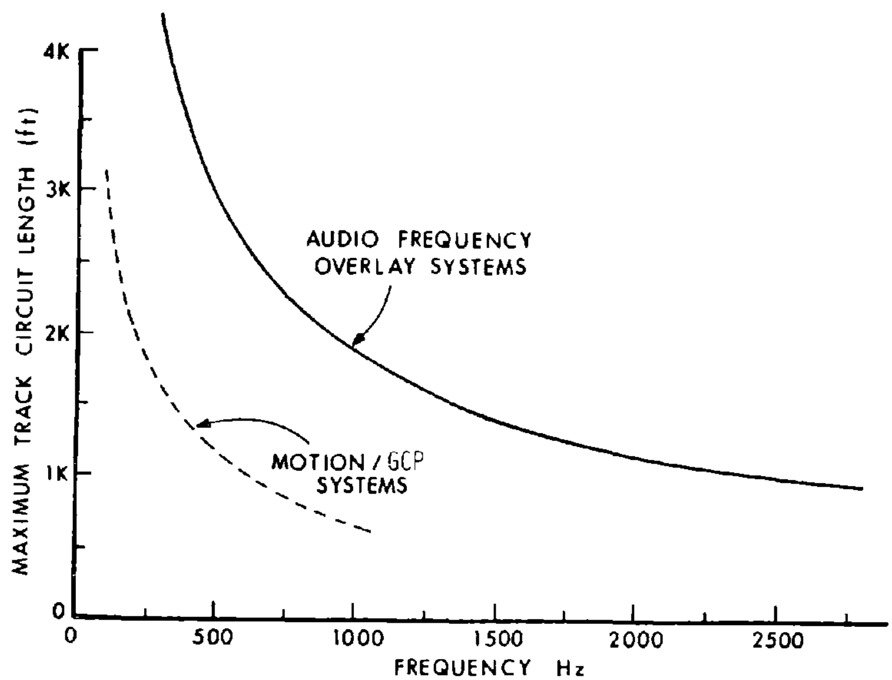


FIGURE A-14. RANGE VERSUS FREQUENCY FOR MOTION/GCP AND AUDIO FREQUENCY OVERLAY SYSTEMS

A.3.4 Recent Developments

During 1968-1970, Harmon Electronics developed their "Motion Detector" system and Marquardt Industrial Products Corporation* developed their "Motion Sensor" system. The Motion Detector and the Motion Sensor are both similiar to the Grade Crossing Predictor in that they initiate crossing warning operation as long as the train moves toward the crossing and clear the crossing when the train stops or moves away from the crossing. However, unlike the Grade Crossing Predictor Systems, they have no time base and cannot be used for predicting time of arrival of the train and providing constant warning time.

Subsequent to these initial motion devices, several others have been developed as follows:

- Motion Sensor Model 350
  Safetran Systems Corporation
- Motion Sensor Model 500
  Safetran Systems Corporation
- Motion Sensor/GCP Model 600
  Safetran Systems Corporation
- Digital Motion Detector
  SAB Harmon Industries
- Electromagnetic Movement Detector
  SAB Harmon Industries
- Motion Monitor
  Union Switch and Signal - WABCO

In terms of predictor systems which potentially can be used to provide constant warning time, the original Grade Crossing Predictor manufactured by the Marquardt Corporation was designated Model 200. This was supplemented by the Model 300 Grade Crossing Predictor. The Model 300 GCP utilized the reactive portion of the voltage developed across the track circuit to originate a voltage which represented a more accurate

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* Harmon Electronics is now SAB Harmon Industries Corporation and the Marquardt Industrial Products Corporation is now Safetran.

measure of distance of the shunt from the track feed wires. It also introduced the concept of a dynamic self-check circuit. This self-check operation consists of a periodic modulation of the constant current fed into the track circuit. As this results in a decrease of the track circuit voltage, it appears to the sensing circuits within the predictor as a train approaching at high speed each time the downward modulation occurs. If the operation of the prediction relay does not occur, the unit is declared inoperative and the crossing warning is started and operates continuously until the self-check cycle spontaneously resumes or maintenance is performed on the unit correcting the malfunction.

The Model 400 GCP (see Figure A-15) was introduced in 1968 to handle situations involving poor track ballast conditions

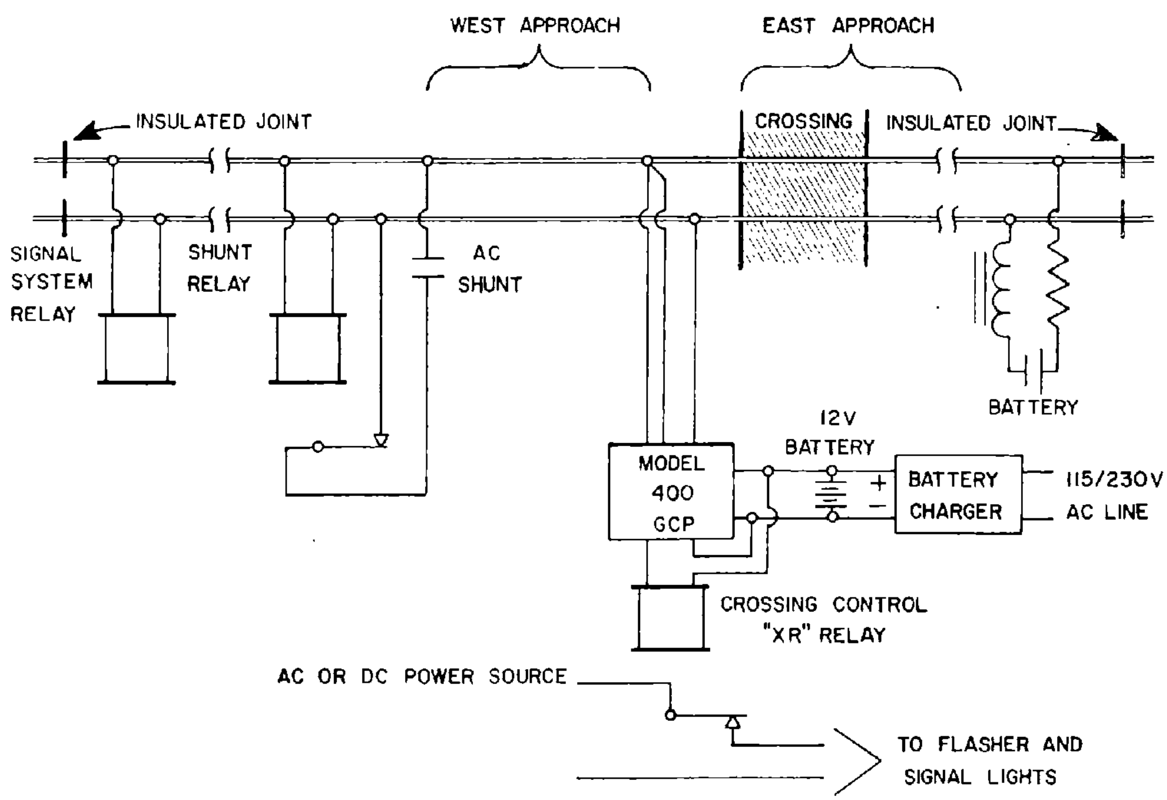

FIGURE A-15. SAFETRAN MODEL 400 GRADE CROSSING PREDICTOR

and to allow the use of a single unit for monitoring in both directions from the crossing (see Figure A-16.) Safetran Sys-

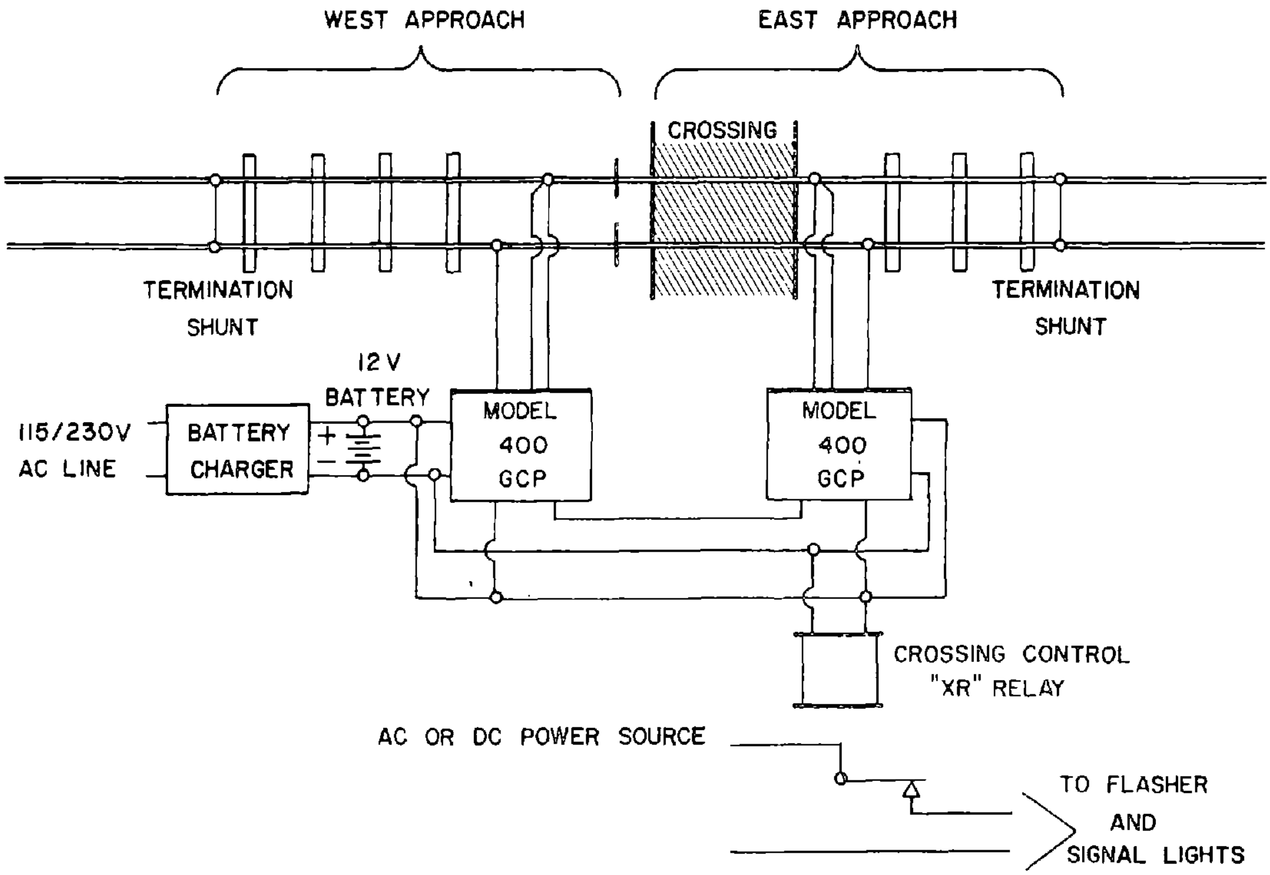

FIGURE A-16. SAFETRAN MODEL 400 GRADE CROSSING PREDICTORS USED IN A BIDIRECTIONAL MODE

tems Corporation has recently marketed the Model 600 motion sensor/grade crossing predictor. This system utilizes the basic concept of the Model 300 and Model 400 grade crossing predictor and is the interface between the two systems. In this unit a motion sensitive system can be installed and according to the manufacturer, by changing circuit modules, it can be employed as a predictor or constant warning time system.

Power consumption has been reduced for motion type systems and grade crossing predictions by the use of miniature relays which contribute both lower power requirements and increased reliability. Servicing aids have been introduced and troubleshooting procedures have been improved. Electromagnetic surge protection has been enhanced considerably.

A.4. SPECIFIC FACTORS TO CONSIDER WITH GRADE CROSSING WARNING SYSTEMS

A.4.1. Effect of Ballast Resistance on Grade Crossing Prediction Accuracy

Considerable effort has been expended by the manufacturers over the last 10 years to reduce errors in the prediction of time to reach the crossing caused by the variation of ballast resistance. The errors that are generated can be understood by referring to Figure A-17. The audio frequency concept which is normally the basis for determining the distance of the train shunt from the feed point (this is subsequently differentiated and a time base added to determine motion and time of arrival, respectively) is derived from the impedence (Z) of the track to a constant current source applied at the feed point. Since V = IZ and I is held constant it means the voltage across the feed point is directly proportional to the impedence. Provided the impedence of the rail varies linearly with distance, as it does in an ideal transmission line, then the voltage gives a direct measure of distance of the train from the feed point. Unfortunately, variations in the ballast resistance cause this ideal transmission line situation not to hold, and the impedence becomes a nonlinear function resulting in the curve shown in the lower half of Figure A-17. This means when a distance voltage V, is recorded the train is perceived to be at a distance d_1 based on the ideal transmission line characteristic, but in reality the train is at a much closer distance d_2.

The nonlinear characteristic (actual curve Figure A-17) arises from the effect of the ballast resistance and its shunting of the rail transmission line. In the case when the ballast has very high resistance minimal shunting takes place and the straight line characteristic is very closely followed. On the other hand when the ballast has deteriorated due to poor maintenance and particularly when it becomes damp the resistance drops and shunting takes place causing the nonlinear behavior displayed in the actual curve. One manufacturer has developed a system which looks at the reactive portion (X) of the track impedence* which is less affected by changes in ballast properties. The characteristics based on this concept is shown in the lower portion of Figure A-17.

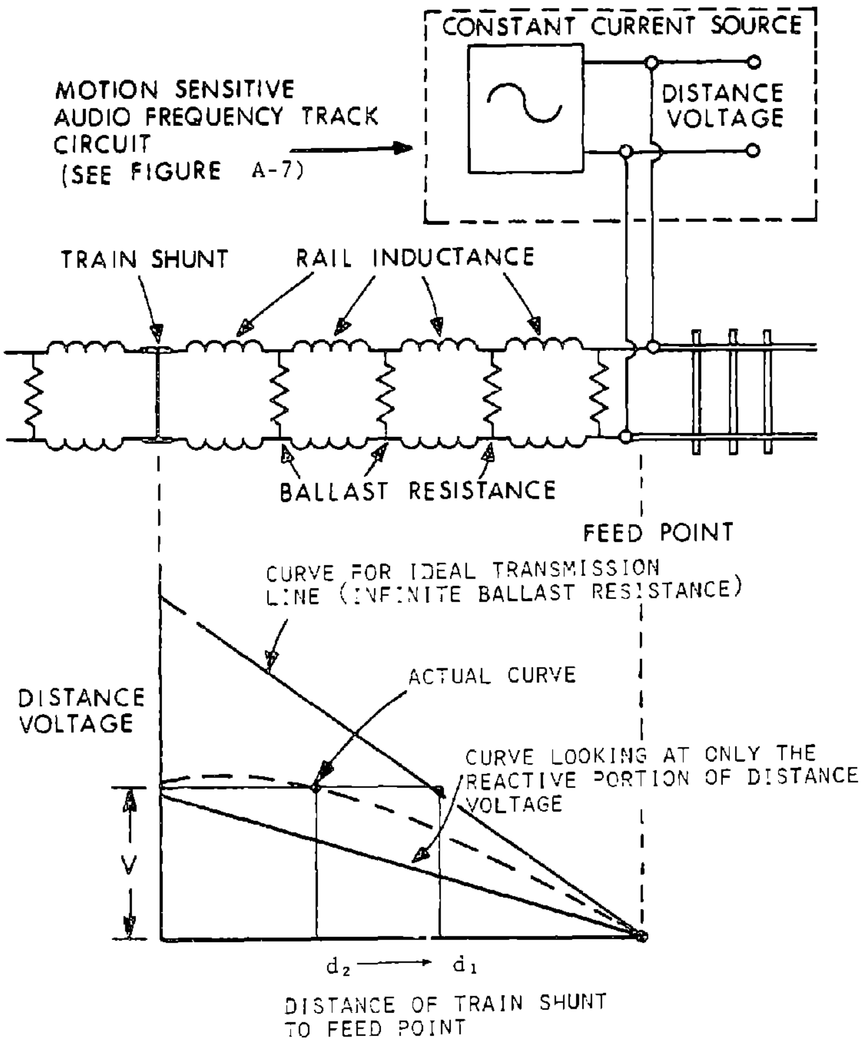

FIGURE A-17. EFFECT OF BALLAST RESISTANCE ON ACCURACY OF MOTION/GCP SYSTEMS

A.4.2 Motion/GCP System Reliability

The reliability of the conventional DC track circuit used in a grade crossing warning start is relatively high and has served as the model of reliability of all subsequent track circuits. The mean time before failure (MTBF) of a DC track circuit of this type might be as much as ten years although no data has

* Recall Z = R + X where R is resistive portion and X is reactive portion.

been compiled to accurately reflect this. This reliability is achieved with rechargeable track circuit batteries kept constantly on a low charge, or with a high degree of maintenance of primary cell track batteries. With increasing complexity in the track circuit equipment and use of audio frequency track circuits, information capability is enhanced but the trend has been for reliability to suffer somewhat.

No data are currently available for the MTBF of the motion sensors or GCP systems. In many instances, especially where a system is installed in a rural area away from major sources of electromagnetic interference, reliability has been quite high with the MTBF approaching that of the conventional DC track circuit. However, in many locations where severe electromagnetic interference exists and where severe electrical storms are frequent, the MTBF may be as short as one year or less.

Maintenance of the track circuit is another major consideration in the reliability of the system. In all of the motion sensitive and grade crossing predictor systems the track circuit forms an integral part of the entire crossing approach. Where ballast resistance is allowed to drop because of poor ballast drainage, or when electrical continuity of the track circuit is not properly maintained, reliability of the system will suffer more severely than for conventional track circuits. In the case of motion sensitive systems which are designed as "stand alone" systems in that they do not require additional track circuits to provide crossing warning control, sensitivity to low ballast resistance is the single most common operating limitation. The failure mode of these systems, when ballast resistance becomes too low to provide adequate warning, is to operate the crossing warning continuously. This type of failure, which is not directly unsafe, does contribute significantly to the lack of credibility of the crossing warning devices and places a heavy burden upon maintenance by railroad personnel.

Grade Crossing Predictor systems are also designed to fail in a similar manner when track circuit conditions are beyond the accommodating capability of the unit. The philosophy of design of all the track circuited equipment from DC track circuits to the Grade Crossing Predictor systems, is to provide failsafe operations of the crossing warning devices in the event of any malfunction within the system. This results in a very high ratio of safe to unsafe failures but adds considerably to the nuisance operation of the crossing warning with no train present.

Electromagnetic surges, introduced both through the rails and the power input, have been a major source of system failures (see Appendix B). With the introduction of solid state equipment connected to the rails and operating in a railroad environment, it became apparent that the conventional arrester type surge protection provided for earlier relay type circuits was not satisfactory. With the development of solid state surge protection it has been possible to provide suitable operating reliability and uniformity, providing adequate credibility of the crossing warning devices and to keep maintenance requirements in line with acceptable railroad practice.

A.4.3 Serviceability and Maintenance

Another consideration of the Grade Crossing Predictor and motion sensitive systems is their relatively high degreee of complexity and additional technical requirements for installation and maintenance personnel. The present systems all utilize printed circuit modules which are individually replaceable within the units, necessary to perform field servicing operations. It is necessary to perform trouble shooting routines in order to isolate the trouble in the track circuit or the unit itself and, if the trouble is located within the unit, to determine which of the modules is defective.

In the case of electrical surge damage, it is often possible for several failure modes to be present simultaneously. This imposes a substantial burden on the signal maintenance engineer who traditionally does not have detailed training in electronics or servicing and whose task has previously been confined only to mechanical and basic electrical circuit trouble shooting. Field servicing consists of replacing modules with the actual repair of the module being completed at a qualified service facility maintained by the railroad or, optionally, back at the manufacturer's facility. Installation and initial set up of the motion sensitive and grade crossing predictor systems require specific procedures to assure that the unit itself and the track circuit are properly adjusted and working together as a system. This procedure has been simplified by the various equipment manufacturers and the railroads, but still requires that the system designer and installer have a good knowledge of the system and its limitations.

Training of maintenance personnel remains one of the major problems of the railroads in adopting the present motion sensitive and grade crossing predictor systems. Further developments in constant warning time systems must be concerned with this limitation on technically skilled installers and maintainers.

A.4.4 Credibility of Crossing Warning Systems

The credibility of the crossing warning devices to the motorist is a major contributor to their effectiveness. The motion sensitive systems and grade crossing predictor system dramatically improve this credibility where the rail traffic and speed vary considerably and switching moves are prevalent. While the flashing lights alone at a grade crossing represent a warning to the motorist which places the decision in the hands of the motorist to determine if the track is clear,the presence of gates at the crossing while improving the effectiveness of the warning equipment,imposes a much more stringent requirements of creditability upon the warning system. The use of gates continues to create one of the major requirements for a motion sensitive or grade crossing predictor system. While the use of the grade crossing predictor and motion sensitive systems have been widely adopted in the industry and promoted by regulatory agencies, very little in actual or probable quantitative effectiveness of the devices has been compiled by railroads, equipment manufacturers or industry sources.

Installation Costs

The cost of installation is an important consideration with grade crossing warning systems. The conventional relay type system represents the lowest specific equipment cost with the AC/DC "type C" track circuit providing the very lowest equipment cost. A major item in the installation, however, is the track circuit itself and the requirement of insulated joints in those systems which utilize them. These are relatively high expense items and require additional expense in wayside signal system modifications where their use is required in wayside signal territory. Another major concern in the cost of the installation is the requirement to provide line wires or power out to the approach starts which may be as much as 3500 feet from the crossing itself. Generally, cost minimizing factors are: lack of requirement for insulated joints, minimum intervention in the existing wayside signal circuits, and lack of requirements for line wire to the approach start limits to perform as a system. In this regard, the motion sensitive system tends to result in the lowest installed cost because of the centralization of equipment at the crossing, the mutual compatibility with most wayside systems, and lack of requirement for insulated joints. This is true although the cost of the unit itself exceeds the cost of the basic components of the simpler systems. The initial cost of the grade crossing predictor systems, while considerably higher than the motion sensitive systems, are again installed with equipment only at the crossing and do not require active equipment at the approach starts. As a result, the overall installed cost of the grade crossing predictor systems tends to be moderate.

While the initial total systems cost of the more complex electronic systems is reasonable for the grade crosssing predictor and motion sensitive units, the maintenance requirements and costs for these systems are considerably higher. The cost of the modules tends to be higher and the periodic maintenance required both in preventive maintenance and in trouble shooting, is also higher. Maintenance is generally performed on a modular basis and it is necessary to field stock modules to provide the required back-up for the normal working system. Also, the MTBF of the motion sensitive and grade crossing predictor systems is lower than conventional track circuits and results in additional maintenance time. Quantification of the maintenance costs does not appear readily available from the industry due to the lack of specific records.

A.4.5 Crossing Warning Systems Selection Factors

There are no current guidelines by either the industry or regulatory agencies to select a specific type of approach track circuit for a particular configuration of railway and highway crossing. The trend is strongly away from the AC or DC track circuited approaches. Audio frequency overlay, motion sensitive and grade crossing predictor systems today account for as high as 80 to 90% of all grade crossing warning start systems installed. Also, the widespread use of motion sensitive devices has increased with these now representing perhaps the single largest group of systems selected. The grade crossing predictor system has only been adopted as a preferred track circuit for grade crossing warning starts by the Southern Pacific Railroad. In most other situations the grade crossing predictor systems are only utilized where there is a wide mix of train velocities in a given crossing situation. The additional complexity, requirement for training and cost of the system has proven to be a deterrent for more widespread use. This is, to a lesser extent, the case with the motion sensitive systems.

A.4.6 Summary and Conclusions

This state of the art assessment has included a detailed review of track circuit currently used in wayside signalling with particular emphasis on the use of these circuits to provide grade crossing warning information. A historical preview of the development of various types of grade crossing warning systems is included which involves an in-depth evaluation of the more recent motion sensing and grade crossing predictor system which have the potential for providing constant warning time. A major drawback of these audio frequency based systems is that the variations of ballast properties (due to deterioration and varying weather conditions) can lead to serious errors in distance and time of arrival predictions.

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APPENDIX B

VULNERABILITY OF ACOUSTIC AND MAGNETIC DETECTION TECHNIQUES TO EMI GENERATED BY TRACTION CONTROL SYSTEMS

B.1 INTRODUCTION

Of the final candidates (acoustic, and magnetic) that were evaluated for possible use as detection techniques in the constant warning time concept, it was determined that while they will be affected by currents and fields associated with locomotive control systems, it will only be significant on electrical railroads. It is shown that currents and fields generated by diesel-electric locomotives are too small to interefere seriously with any of the proposed techniques.

The vulnerability analysis given in the following section applies to the whole family of acoustic and magnetic detection devices of which the two specific concepts evaluated in section 4 are part

B.2 VULNERABILITY ANALYSIS

B.2.1 Acoustic Detection

Electric Traction: Some problems should be anticipated when the acoustic concept is applied to electrified railways. These can occur when the acoustic sensor is attached directly to a rail that normally carries several hundred amperes of return traction current generated by locomotives which may or may not be in the vicinity of the sensor. In such a situation it is an electromechanical device) will pick up and transmit enough energy from the traction current fundamental and its harmonics to effectively mask any local acoustic energy that may also be present at these frequencies. For 60 Hz traction such as is planned for the improved NEC (North-East Corridor), this would mean that the acoustic concept must be able to cope with severe background interference at 60 Hz, 120 Hz, 180Hz, 240 Hz, etc., up to frequencies of at least 1KHz.

Diesel-Electric Traction: A similar, though much less severe, problem may exist for the acoustic concept when it is applied in diesel territory where ac track circuits are employed. Ac track circuits also generate currents in the rail at low audio frequencies which may interfere with an acoustic sensor. However, track circuit currents are normally very much smaller than traction currents (1 amp versus 300-600 amps), and harmonics need not be considered except possibly those associated with the opening and closing of relays.

Currents generated on the rails by diesel-electric traction are in the 300-400 milliamp range at worse,[1] and will be confined to the vicinity of the locomotive. Therefore, these currents should be no problem for the acoustic concept and, in fact, might aid detection when present.

B.2.3 Magnetic Detection

Electric Traction: Since the magnetic technique is based on measurement of perturbations in an ambient magnetic field produced by the moving ferromagnetic mass of a consist, serious problems should be expected when it is applied to an electrified railway where large, fluctuating magnetic fields are always present due to traction currents in the catenary and rails. This will be true whether the geomagnetic field is used to record train perturbations as was the case in our field measurements using an RFL Model 101 Magnetometer[2] and a buried prototype fluxmeter, or whether the sensor itself generates the ambient field as is the case with magnetic wheel detectors.[3] There is little information available

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[1]Monroe, Richard L., *A Survey of EMI Problems Generated by Traction Control Systems Employing Thyristors*, prepared under FRA Contract No. DOT-FRA-8042 by Systems Technology Laboratory, Inc., Arlington, Virginia, July 1979.

[2]Anonymous. *Manual of Instructions, Model 101 Magnetometer*. RFL Industries, Inc., Boonton, New Jersey, 1969.

[3]Speh, P.E. and Griffin, S., *Railroad Electromagnetic Compatibility, Vol. II, Assessment for Classification Yards and Electrification*, FRA/ORD, 77/77,11, Electromagnetic Compatibility Analysis Center, Annapolis, Maryland: September 1978.

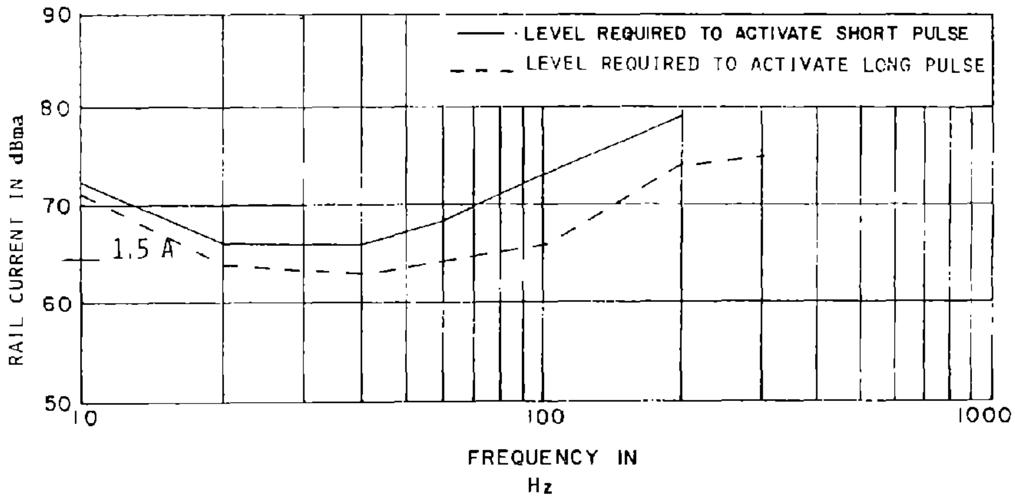

FIGURE 1. SINUSOIDAL RAIL CURRENT REQUIRED TO ACTIVATE WHEEL DETECTOR (10-1000 Hz)[3]

concerning the susceptibility of the RFL instrument in the 0 to 1KHz frequency range usually associated with traction currents. There is only a bare statement in the specification of the RFL device[4] that it has a frequency response from 0 to 8Hz. This probably means that it has a flat response from 0 to 8Hz, but there is no clue as to what its response at 25 or 60Hz might be beyond a few warnings[5] to avoid "large power transformers, motors or similar devices" when making precise measurements. Since large power transformers, motors and similar devices including traction control systems are always associated with electrified railroads, it is obvious that the RFL instrument would be unsuitable for use as a train detecting device in this type of environment without extensive modification. The prototype fluxmeter is much less sensitive than the magnetometer, and with filtering, it was able to cope with 60Hz interference from power lines in the vicinity of our field tests. Considerable additional filtering and accurate sensor placement will be required for dependable operation under these circumstances.

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[3] *Railroad Electromagnetic Compatibility.*

[4] Anonymous, *Manual of Instructions, Model 101*, 1969.

[5] Anonymous, *Using the RFL Model 101 Magnetometer for Testing Air Shipment Packages per DOT/FAA Advisory Circular AC 121-23*, RFL Industries, Inc., Boonton, New Jersey, 1969.

There are some data available on the susceptibility of magnetic wheel detectors. This is contained in Fig. 1, which is reproduced from reference 3. It shows that a rail current as low as 1.5A in the frequency range between 20 and 60Hz will activate the detector, that is, generate a false alarm. Since worst case currents on the present 25Hz NEC system are at the 300 A level and since worst case currents on the improved 60Hz system will be twice this amount, it is clear that a high degree of isolation from rail currents (at least 46 db in the case of the present system and 52 db for the improved system) would be required to make the magnetic wheel detector compatible with present and future electric traction. Part of this isolation could be obtained by increasing the threshold of the sensor; however, the amount that could be achieved by this approach is limited by inevitable losses in sensitivity. Part could be obtained by filtering; however, filtering at these frequencies and power levels is likely to be difficult. Finally, part could be obtained by orienting the sensor in such a way as to minimize magnetic field pick-up from traction currents. The latter is probably the simplest and most effective approach, but it requires accurate alignment of the sensor to be effective. Furthermore, in the process of minimizing pick-up from traction currents, there is also an excellent chance that the desired ferromagnetic pick-up will be reduced; that is, a loss of sensitivity will occur.

The magnetic field with the greatest potential for producing interference with magnetic detectors is that generated by return traction currents on the rails. A pair of rails, each carrying a traction current I in the same direction will produce a magnetic field H that is nearly vertical at a point P near the ground and close to the rails as shown in Fig. 2.

The magnitude of $\overline{H}$ is given to a good approximation by

$$H = \frac{1}{2\pi} \left(\frac{1}{r_1} + \frac{1}{r_1 + r_2} \right) I \qquad (1)$$

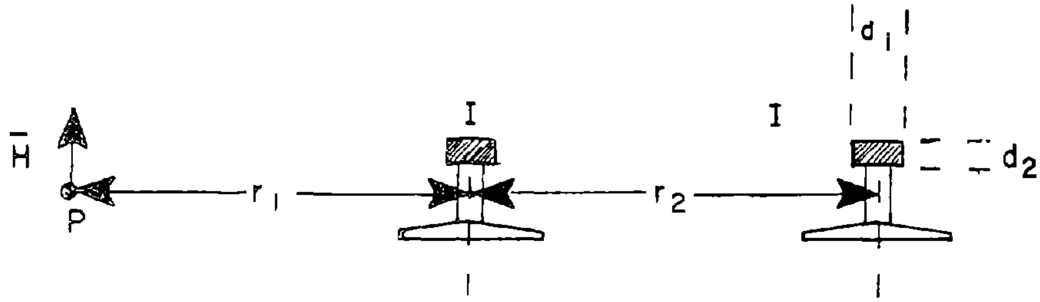

FIGURE 2. MAGNETIC FIELDS GENERATED BY RAIL CURRENTS

where r_1 is the horizontal distance between P and the center of the nearest rail and r_2 is the distance between rail centers.[6] This calculation ignores the effect of catenary currents which will tend to reduce H in magnitude and alter its direction. However, there will be little error in using equation (1) to calculate H at ground level within a few meters of the rail. Equation (1) will always give a slightly conservative estimate (larger than the true value) that is useful for calculating worst case values of the interference field.

To obtain worst case estimates of the interference field near the rails in present and future electric traction systems, we will use equation (1) to calculate H at a distance, r_1 of 1 meter for the worst case rail currents cited previously, that is, for 300 Amps per rail on the present NEC system and 600 Amps per rail on the improved NEC system.

For $I_{max} = 600$ A, $r_1 = 1$m, and $r_2 = 1$m, we obtain

$$H_{max} = 143 \text{ ampere turns/m},$$

which corresponds to a peak flux density of

$$B_{max} = \mu_o H_{max} = 4 \pi \times 10^{-7} H_{max} \text{ (Webbers/m}^2\text{)}$$

$$= 18 \times 10^{-5} \text{ (W/m}^2\text{)}.$$

[6]Ramo, S. and Whinnery, J., *Fields and Waves in Modern Radio*, John Wiley and Sons (New York: 1964), p. 94.

In cgs units, these are

$$H_{max} = 1.26 \times 10^2 \times 143 = 174 \times 10^2 \text{ (Oersteds)},$$

and

$$\begin{aligned} B_{max} &= 18 \times 10^{-5} \times 10^4 \text{ (Gausses)} \\ &= 1.8 \text{ (Gausses)} \\ &= 1.8 \times 10^5 \text{ (Gammas)}. \end{aligned}$$

Magnetic fields and flux densities generated by peak rail currents of 300 A will be one half of the preceding values.

Comparing these flux densities with a representative vertical component of the geomagnetic field in the United States ($.5 \times 10^5$ (Gammas) in northern New Jersey),[4] we find that in both cases the former is significantly larger than the latter. Of course, fields associated with rail currents are rms values corresponding to 60 and 25 Hz respectively, plus harmonics, while the geomagnetic field is close to dc. Thus these ac fields are not directly comparable to the geomagnetic field and the interfering effect which they would produce depends on the frequency response of the magnetic sensor among other factors. Nevertheless, it must be expected that fields of this magnitude subject to large and rapid fluctuations typical of traction currents will seriously interfere with any attempt to detect the presence of a locomotive on the basis of its perturbing effect on the local geomagnetic field unless great care is taken. Since the traction current field is inversely proportional to the distance to the rail (Equation 1), the easiest way to minimize its effect is simply to move the sensor farther away. For example, moving the sensor 10 meters away from the rail will reduce the flux densities computed previously by a factor of 10 and reduce both below that of the geomagnetic field. However in doing this, one also reduces the desired response of the train which may, and probably will, fall off more rapidly than $\frac{1}{r}$. A more effective approach is to orient the sensor perpendicular to the predominantly vertical traction current field and attempt to detect the train by its effect on the horizontal component of the

[4] *Manual of Instructions.*

geomagnetic field. This requires steady, accurate alignment because small errors in orientation will expose the sensor to relatively large effects from the traction field. For example, an error of 5^{o} in alignment will subject the sensor to 8.7% of the traction field. This would be a flux density of $.16 \times 10^5$ gammas in the case of 600 A rail currents and $.08 \times 10^5$ gammas for 300 A rail currents with the sensor 1 meter from the rail. Both of these flux levels are significant fractions of typical horizontal components of the geomagnetic ($.21 \times 10^5$ gammas)[4] and are capable of causing serious interference. Clearly it may be necessary to align the sensor with an accuracy of less than 1^{o} to effectively eliminate interference from this source.

Magnetic sensors which use self generated magnetic fields rather than the geomagnetic field to record the disturbing effects of ferromagnetic material associated with the train are normally located closer to the rail than the 1 meter distance we have considered appropriate for passive sensors. Indeed, the wheel detector system mentioned previously uses a sensor attached directly to the rail. Obviously, these sensors will be subjected to much larger traction current fields than we have considered up to this point, and they may require even more precise alignment than the magnetometer to avoid intolerable interference levels. A rigorous calculation of magnetic fields near a rail surface is greatly complicated by the relatively complex geometry of the rail. Such a calculation will not be attempted here; however, we will obtain a much simpler approximation which should be sufficiently accurate for our purposes. This approximation is based on the not unreasonable assumption that most of the rail current will be concentrated in the rail heads (shaded areas in Fig. 2) and that the latter can be replaced for purposes of computation by circular cylinders of equal cross sectional area. With the rail heads replaced by equivalent circular cylinders, we can apply a standard method[6] to calculate the near field. In this way, we obtain the

[4] *Manual of Instructions.*

[6] *Fields and Waves in Modern Radio.*

following approximate expression for the magnetic field on the rail surface:

$$H = \frac{1}{2\pi} \left(\frac{1}{r_e} + \frac{1}{r_e + r_2} \right) I \qquad (2)$$

where, in addition to previously defined quantities,

$$r_e = \sqrt{d_1 d_2 / \Pi} \qquad (3)$$

and d_1 and d_2 are the rail head dimensions (Fig. 2). Magnetic field lines in this case will follow the surface of the rail and be oriented perpendicular to the long axis of the rail. For a rail head with $d_1 = 2''$ and $d_2 = 1''$, we obtain $r_e = .8'' = 2 \times 10^{-2}$m from equation (3). Substituting $r_e = 2 \times 10^{-2}$m and $r_2 = 1$m into (2) gives the following relationship between rail current I and surface magnetic field H:

$$H = 51\ (I) 2\pi \qquad (\text{Amps/m}) \qquad (4)$$

Accordingly, a 600 A rail current will produce a surface magnetic field of approximately 4800 Amps/m and a flux density of 6.1×10^{-3} webbers/m^2. In cgs units, these figures convert to 6.24 Oersteds and 61 gauss. The latter is equal to a flux density of 6.1×10^6 gammas which is approximately 34 times the flux density 1 meter from the rail. A flux density of 6.1×10^6 gammas is also 400 times the level produced on the rail by a current of 1.5A which according to Fig. 1 is sufficient to generate a false alarm by the wheel detector. Therefore, to reduce interference from rail currents below this detection threshold, it would be necessary to align the sensor perpendicular to the magnetic field with an accuracy of .25°. For 300 A rail currents, an accuracy of .5° would be required. Since accuracies of this order would be difficult to obtain and maintain on the rail, additional measures such as an increase in threshold level would certainly be required to make this type of detection compatible with electric traction.

The preceding calculations document the very harsh electromagnetic environment faced by magnetic sensors as a result of return traction currents in the rails. This environment may well preclude the use under any circumstances of sensors attached directly to the rail. It will certainly limit the usefulness of any sensor which must be placed outside the rails. However, for a sensor which can be buried, such as the prototype fluxmeter, the quality of the environment can be mitigated somewhat by proper placement between the rails. In fact, the magnetic field seen by a sensor S can be minimized by placing the sensor on a vertical line bisecting the distance between the rails as shown in Fig. 3. Along this line (X,-X in the figure) the vertical component of the magnetic field produced by two rail currents of equal magnitude

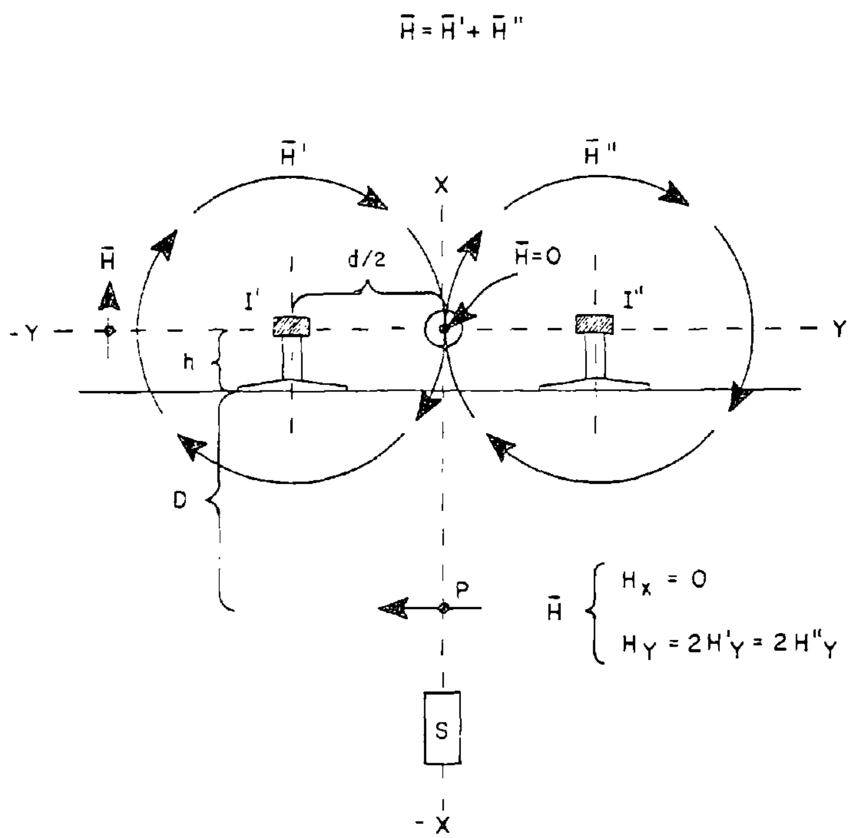

FIGURE 3. MAGNETIC FIELDS GENERATED BY RAIL CURRENTS I' AND I" SHOWING THE NULL POINT ◉

flowing in the <u>same</u> direction is zero. This is easily seen because the net magnetic field $\bar{H}$ at any point is equal to the vector sum of the magnetic fields generated by each rail separately. For example, a current I' flowing on the left rail will generate a magnetic field $\bar{H}'$ with field lines that are concentric circles centered on the left railhead as shown in the figure.

If current is flowing into the plane of the paper, the magnetic field is in the clockwise direction indicated by the arrows. Similarly a current I" on the right rail also flowing into the plane of the paper will generate a magnetic field $\bar{H}''$ with clockwise concentric field lines centered on the right railhead as shown. If the current I" on the right rail equals the current I' on the left rail, then the magnitude of the magnetic field $\bar{H}''$ at the point midway between the rails on the line -Y, Y will equal the magnitude of $\bar{H}'$ at that point. However, it is clear from the figure that the direction of $\bar{H}'$ at $\odot$ is opposite that of $\bar{H}''$. The sum of two equal but opposed vectors is the null vector; hence the net magnetic field at $\odot$ is zero, that is, $\bar{H}=\bar{H}' + \bar{H}'' = \bar{H}' - \bar{H}' = 0$ at $\odot$. At other points on (X, -X), $\bar{H}'$ and $\bar{H}''$ remain equal in magnitude, but complete cancellation does not occur because $\bar{H}'$ and $\bar{H}''$ are not directly opposed. Nevertheless, a consideration of the vector sum of $\bar{H}'$ and $\bar{H}''$ at any other point P on (X, -X) shows that H'_X, the vertical component of $\bar{H}'$, is equal in magnitude but opposite in sign to H''_X, the vertical component of $\bar{H}''$. That is, $H'_X = -H''_X$. Hence, the net vertical component H_X at P is zero since $H_X = H'_X + H''_X = H'_X - H'_X = 0$. The same consideration shows that H'_Y, the horizontal component of $\bar{H}'$, is equal in both magnitude and sign to H''_Y, the horizontal component of $\bar{H}''$ at P. That is, $H'_Y = H''_Y$. Hence, the net horizontal component H_Y at P is equal to twice the horizontal component of either $\bar{H}'$ or $\bar{H}''$ since $H_Y = H'_Y + H''_Y = 2H'_Y = 2H''_Y$. With P located a distance of h + D from $\odot$, where h is the height of the rail head above ground and D is the depth of P below ground level, it is a simple matter to compute H'_Y and H''_Y in terms of the rail currents. The result is:

$$H'_Y = H''_Y = \frac{I\,(D + h)}{2\pi\left[\left(\frac{d}{2}\right)^2 + (D+h)^2\right]} \qquad (5)$$

where, in addition to previously defined quantities, d is the distance between the rails and $I \equiv I' = I''$ is the current on each rail. With equation (5), the magnetic field $\bar{H}$ at any point P on (X, -X) is completely determined:

$$\bar{H} \begin{cases} H_X = 0 \\ H_Y = 2H'_Y = 2H''_Y = \dfrac{I\ (D+h)}{\pi \left[(d/2)^2 + (D+h)^2 \right]} \end{cases} \tag{6}$$

Equation (6) indicates that the interference field at points near the vertical plane bisecting the distance between the rails will be predominately horizontal. This is in contrast to the interference field at points outside the rails near the plane of the ground which is predominately vertical (Figure 2, Equation 1). Equation (6) also shows that, as far as buried sensors are concerned, the minimum interference field will occur when the sensor is located just at ground level where D = 0.* The field is then given by

$$\bar{H} \begin{cases} H_X = 0 \\ H_Y = \dfrac{Ih}{\pi (d^2/4 + h^2)} \end{cases} \tag{7}$$

Using the same values of traction current and rail separation employed in previous calculations (I=600A, d=1m) and assuming h=5" = .125 m, we obtain H_Y=88.4 A/m from (7). This can be compared with a figure of 138 A/m which we obtained at a point on the ground 1 meter from the rail using (1).

Although a 36% reduction is not spectacular, it could be quite significant. Furthermore, equation (6) shows that much larger reductions could be achieved by decreasing h, that is, by decreasing the distance between the sensor and the point of zero field ⊙ . This could be done either by decreasing the height of the rail or by raising the sensor slightly above ground level. Of course, operational considerations (train clearance requirements, exposure of the sensor to damage, etc.) will probably limit what can be achieved in this way.

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*Since $\bar{H} \to 0$ as $D \to \infty$ according to equation (6), one could in theory reduce the interfering field to any desired level by burying the sensor at a sufficiently great depth. However, as a practical matter, this is not likely to improve the situation since the desired response of the locomotive will also decrease with increasing depth. In other words, the signal to noise ratio will not improve with depth.

Diesel-Electric Traction: As previously mentioned, the largest, measured rail currents produced by diesel-electric locomotives are in the 300-400 milliampere range.[1] These currents are well below the threshold of magnetic wheel detectors (Fig. 1), and therefore, they should not affect these devices. They could affect magnetometer readings since according to equation (1), rail currents of 300-400 milliamperes will produce 900-1200 gammas at a distance of 1 meter from the rail (well within the measuring capability of the RFL instrument). However, these flux densities are 1500 to 2000 times smaller than those associated with worst case rail currents on the improved NEC, and their effects could be virtually eliminated through filtering and proper sensor orientation.

Therefore, currents and fields associated with diesel-electric locomotives should cause no serious problems for the magnetic concept. A limited experimental verification of this conclusion was obtained in field tests using a fluxmeter and a 60-ton diesel-electric test locomotive[7]. In these tests, with the sensor buried between the rails, measurements were made when the locomotive was coasted over the sensor with the diesel engine running in idle and power to all traction motors turned off. The sensors response obtained under these conditions was then compared with the response when the locomotive was driven over the sensor at approximately the same speed with traction motors engaged. No significant difference in magnetic signatures between the two cases was observed.

B3. CONCLUSIONS

In the preceeding section, the effects on acoustic, and magnetic detection techniques of currents and fields produced by traction control systems on diesel-electric and all electric railroads were considered. Currents and fields associated with diesel-electric control systems are likely to be too small to cause serious EMI problems for any of these techniques.

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[1] *A Survey of EMI.*

[7] De Backer, T. Albert, *Progress Report for May 1979 Contract-DOT-FRA-8042*, Systems Technology Laboratory, Inc., Arlington, Virginia, June 1979.

On the other hand, we found that control systems on electric trains acting through return traction currents on the rail can, and probably will, be a source of serious interference for acoustic and magnetic detection techniques.

Especially severe EMI problems can be expected with acoustic sensors and magnetic wheel detectors, both of which attach directly to the rail. These devices will be subject to the maximum effect of return traction currents in the rail which may reach peaks of 300A under present conditions and 600A in the future. Magnetic sensors placed off the rails face less severe conditions, but will still experience strong interference from magnetic fields generated by rail currents. This interference can be mitigated somewhat by proper orientation and placement of the sensors. Thus, sensors placed outside of the rails should be oriented horizontally to minimize pick up from the interference field which will be predominately vertical at ground level within a few meters of the rail. Sensors placed between rails should be oriented vertically to minimize pick-up from the interference field which in this case will be predominately horizontal near the vertical plane equidistant from the rails. In the latter case, further advantage can be taken of the fact that the net magnetic field generated by rail currents flowing in the same direction will be zero at one point between the rails. For balanced rail currents (current on one rail equal to current on the other), the null point, or point of zero interference, will occur approximately at the midpoint on a line joining the centers of the railheads. By placing the sensor sufficiently close to this point, it should be possible to reduce interference from rail currents to any desired level. However, operational considerations will limit what can be achieved by this means, and further measures such as filtering will probably be required to permit the use of magnetic detection on electrified lines.