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IDENTIFICATION AND EVALUATION OF OFF-TRACK TRAIN DETECTION SYSTEMS FOR GRADE CROSSING APPLICATIONS

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16. Abstract

The study focused on a detailed investigation of all potential train detection techniques which do not use the track. Both point sensing and continuous sensing system approaches were analyzed. It was found that the transmission line sensor and magnetic point sensor offer the greatest likelihood of yielding a practical off-track detection system. A comprehensive system analysis and evaluation of these concepts is made. The study included a limited field test of the transmission line concept, which was then selected as the most promising for follow-on development.

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PREFACE

The work described in this report was performed by GARD, INC., a subsidiary of GATX Corporation, under Contract No. DOT-TSC-1448 as part of an overall program at the Department of Transportation to provide a technical basis for the improvement of railroad-highway grade crossing safety. The program is jointly sponsored by the Federal Railroad Administration, Office of Rail and Safety Research and the Federal Highway Administration Office of Research.

The authors would like to express their appreciation for the contribution of John V. Mirabella, the FRA Technical Monitor; John B. Hopkins of the Transportation Systems Center; and Janet Coleman of the Federal Highway Administration. Also the authors wish to acknowledge Raj Mittra and Fred Ore of the University of Illinois for their technical advice in the transmission line area and James E. Moe, an independent Railroad Consultant, for his technical inputs in the railroad instrumentation field.

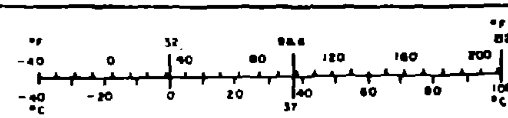
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

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

Approximate Conversions from Metric Measures

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



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EXECUTIVE SUMMARY

In the interest of safety and improved efficiency, the Department of Transportation has initiated several programs to study railroad-highway grade crossings. The objective of this program was to investigate and evaluate all potential off-track train detection techniques. Parameters were established whereby various candidate detection methods could be evaluated for pertinent performance advantages and disadvantages compared to a list of system constraints. Within the given constraints two approaches were deemed to be superior and these were evaluated in greater detail. One, the transmission line system, was studied in greater detail and a breadboard fielded unit was fabricated and tested. Results of the field test indicate that this system has merit as an off-track detection system. A variation of the standard transmission line was conceived by GARD which has promise of meeting the goals established for this study and could be cost competitive with the basic track type detector.

Train detection methods can be divided into two categories; continuous and point sensitive. The characteristics of the two methods are dissimilar, resulting in substantially different design and systems considerations. To meet the system requirements, the best transducer for the point sensor system is the magnetic sensor. The transmission line was best suited for the continuous sense technique. These two approaches were developed into off-track train detection systems for additional analysis and comparison to the present track system.

The point sensor system detects trains by sensors located at the ends of a track block. In order to determine train presence within a block, the following possibilities must be anticipated:

- o Change of train direction after entering block.
- o Turn out of part or all of the train onto a siding.
- o Coupling, leaving only a section of train in block.

For a system to be acceptable, it should not be fooled by the above situation.

If two presence detectors are employed at each end of a block, they are capable of detecting:

- The leading edge of a train and its direction of approach.
- The trailing edge, and its direction of departure.

This sensor system has a drawback. Consider the case in which a train enters a block, uncouples several cars and then moves out of the block, leaving the decoupled cars behind. The sensor system would detect the trailing edge of the departing train, and deactivate the warning signals. This potentially dangerous situation does not occur with the standard track circuit.

The limitation of the system arises from its inability to count cars. Had the system possessed this capability, it would have detected that fewer cars had left the block than had entered, indicating that the block was still occupied. Therefore, incorporated into any point sensor system must be the ability to count cars.

The present state of sensor technology limits the distance from which cars can be reliably counted. The task of counting rail cars entails the discrimination of fine features, such as wheels, wheel flanges or trucks. Because a sensor's resolution decreases with distance, there is a trade-off between distance and reliability. While it would be ideal to locate the sensor many feet away from the track, no presently available sensor has the resolution needed to reliably operate from that distance. Therefore it becomes necessary to place the sensor within inches of the object it is detecting. Of the candidate transducers identified, the one that best meets the above criterion is the magnetic sensor (Hall-Effect).

The transmission line system involves propagating a low frequency electromagnetic wave form down a properly terminated transmission line and detecting any reflected signal caused by a train perturbing the electromagnetic field sorrounding the line. The magnitude and phase of the reflected signal can be measured as a function of time to provide all the necessary data to (1) establish the presence of a vehicle in the detection zone; (2) the distance of the vehicle from the observation points; (3) the direction of travel of the train; and (4) the relative velocity with respect to the observation point. The method is somewhat similar to radar except, instead of transmitting the energy into free space by an antenna, it is impressed onto the transmission line which guides the waves along the desired path and keeps its extent within bounds.

Both of the above concepts offer the likelihood of a viable off-track train detection system. They operate in completely different sensing modes — point versus continuous. Both are feasible to use but both need additional engineering development in the detection (sensor) area. Point sensors cannot currently count cars with absolute reliability. Development is required to provide a sensor which can demonstrably perform such a task. While such a miscount may not create an unsafe failure, it can reduce system reliability and effectiveness. Current industry work is ongoing and the results should be monitored as inputs to this area.

The transmission line sensor requires two areas of development; geometry and constant warning time applicability. Geometry centers around the development of a configuration which does not interface with normal railroad operations. The development of a configuration with a low profile based on focused fields will minimize such interference. Constant warning time provision can be provided by use of TDR (Time-Domain Reflectometer) approach which uses pulsed excitation. Such an approach may have implementation problems in a high noise environment. A promising variation of the transmission line uses a standing wave "frequency partition" approach which was conceived by GARD for this application.

A trade-off analysis between these off-track sensing candidates and the basic track circuit indicates there is no obvious better choice. Each has the potential for providing the same function as the basic track circuit.

1. INTRODUCTION

Several thousand deaths and injuries occur each year due to accidents at rail-highway grade crossings. The severity of these accidents ranks second only to aircraft accidents, and it is this category that accounts for a large percentage of rail-associated accidental deaths. The protection of rail-highway intersections is made difficult by the wide variation of characteristics encountered, such as the type of traffic (rail and highway), the environment (rural, suburban, or urban), number of tracks, type of roadway, view of tracks, and the track configurations.[(1)]

If significant improvement is to be made in grade crossing safety, it will require improvements in a number of areas. For example, grade crossings need to be designed and installed so as to minimize visibility of approaching trains and at the same time minimize road hazards. Improvements are required in driver education. Stricter enforcement of laws for not obeying grade crossing signals is needed. Other areas requiring improvement are warning signals and train detection.

An overall program has been initiated by the Department of Transportation to provide a technical basis for the improvement of grade crossing safety.[(2)] This program is sponsored by the Federal Railroad Administration (FRA) which supports Government activities designed to promote greater safety in railroad passenger and freight service. The development of off-track train detection concepts for activating grade crossing warning systems is one such research effort.

The Highway Research Board (now called the Transportation Research Board) has suggested possibilities for the development of a more improved method of grade crossing protection. Future research is to include consideration of a method other than track circuitry to detect the train.[(3)] The track circuit, invented in 1872, is a direct means of achieving train detection in a fail-safe manner. This system is likely to remain the basis of railroad signaling for the near future, but it does have disadvantages which warrant examination of potential alternatives. The prospect of improving grade crossing safety through the application of modern technology was the impetus for the off-track train detection program described herein.

The project was a study of potential off-track train detection techniques including an extensive analysis of each technique. A cost trade-off analysis was performed for each train detection system so that a detailed comparison could be made among the potential concepts. This analysis included pertinent performance and operational parameters which define the advantages and disadvantages of each technique. A comprehensive evaluation of the selected concepts was performed to resolve any questionable areas concerning their implementation as a practical system. This evaluation included detailed analysis and conceptual design of a model system. A field test and demonstration was conducted for the most promising concept (transmission line system) to determine its feasibility.

2. TRAIN/TRACK PERTURBATION

When a train is in motion, its presence is indicated in a number of physically detectable ways. Whether a train is standing or moving, its presence on the track structure is evident by static and/or dynamic loading upon the track, the track supports, and the underlying soil. In motion, the train generates a variety of acoustic signatures of various intensities and frequency ranges depending on the acoustic generating mechanism of the train, the surrounding environment, and motion of the train. This section defines these perturbations and gives their magnitude.

2.1 MECHANICAL

PRESSURE

The presence of the train causes forces to be applied to the track, ties, ballast, and supporting soild due to the dead weight of the train. Figure 2.1 shows the vertical pressure distribution on the subgrade below a single tie.[5] Figure 2.2 shows the average vertical pressure distribution, while Figure 2.3 shows the ballast pressure under a tie.

NOISE

Wayside noise measurements were made next to the tracks of a New York-to-Washington Line in Plainsboro, New Jersey.[6] Trains traveled at high speed in this area on welded rails.

Microphones were set up a offset distances of 25, 50, and 100 feet from the centerline of southbound track No. 2 (measurement stations 1, 2, and 3, respectively) and were placed 5.5 feet above grade level and 3.3 feet above the level of the rails of track No. 2. The line at this location consists of four tracks numbered 1 through 4, west to east. The centerline of track No. 3 (northbound) was 38, 63, and 113 feet; and of track No 4 was 50, 77, and 125 feet, respectively, from the three microphone stations. Table 2-1 shows the results of this testing.

VIBRATION

Wayside ground vibration measurements were made utilizing an insulated triaxial arrangement of vibration transducers mounted on two brass rods (2 feet long and 7/8 inches in diameter).[6] The rods were driven into the ground at a point offset 25 and 50 feet from the centerline of track 2

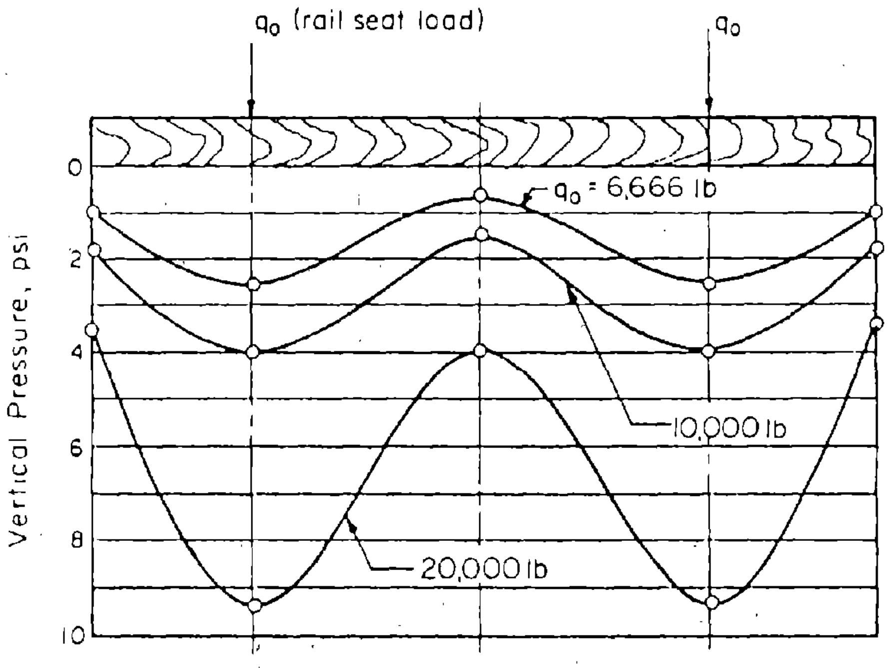


FIGURE 2.1 AVERAGE VERTICAL PRESSURE DISTRIBUTION ON THE SUBGRADE AT A DEPTH OF 18 INCHES OF BALLAST BELOW A SINGLE TIE.

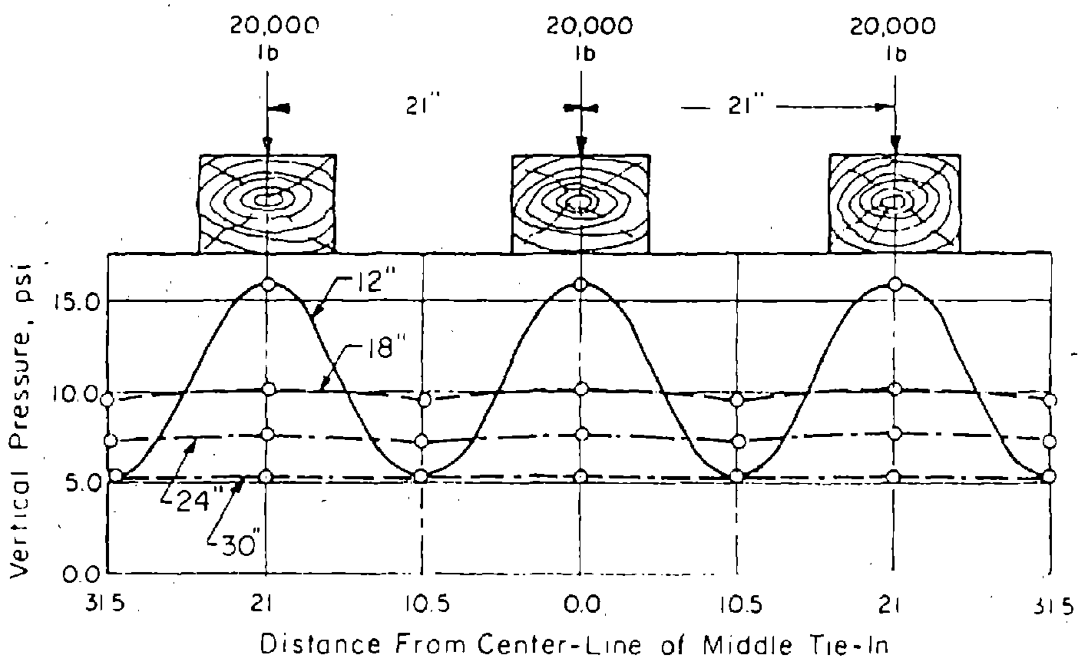


FIGURE 2.2 AVERAGE VERTICAL PRESSURE DISTRIBUTION ON THE SUBGRADE USING THE PRINCIPLE OF SUPERPOSITION FOR DIFFERENT BALLAST DEPTHS.

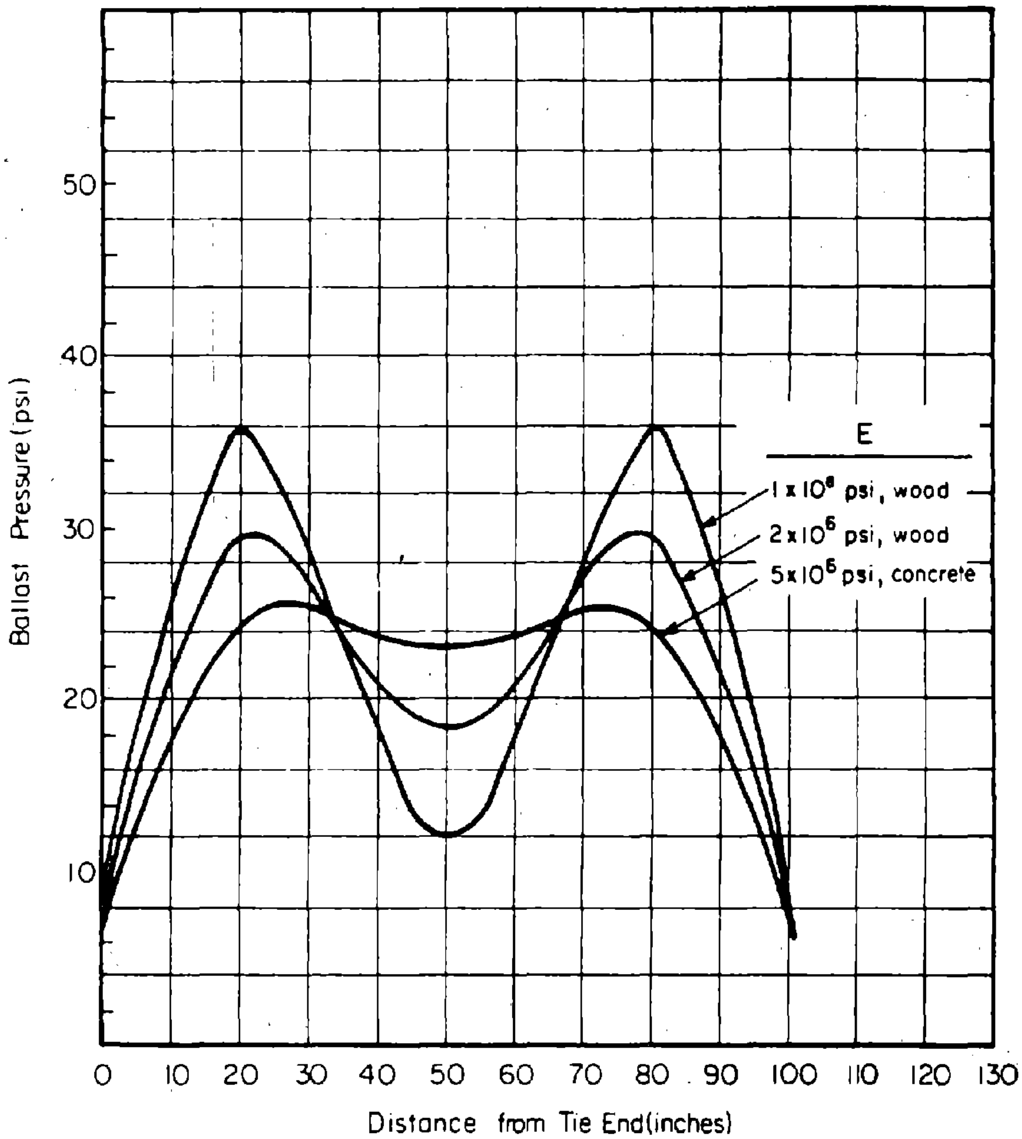


FIGURE 2.3 BALLAST PRESSURE UNDER 6" x 8" x 8' 6" WOOD AND CONCRETE TIES. BALLAST FOUNDATION MODULUS k_o = 5000 psi AND THE RAIL SEAT LOAD q_o= 17,500 LBS.

TABLE 2-1

COINCIDENT WAYSIDE NOISE AND GROUND VIBRATION LEVELS
CONVENTIONAL PASSENGER AND FREIGHT TRAINS
PENN CENTRAL RAILROAD, PLAINSBORO NJ
5/23/72

No. of Engine + Cars	Track No.	Direction	Time of Day	Speed mph	Peak RMS Noise Level(B) dBA re 20 μN/m² At Measurement Station(A)			Peak RMS Acceleration Levels(B) dB re 10^{-6}g At 25 ft			At 50 ft			See Note
					1	2	3	z-axis	x-axis	y-axis	z-axis	x-axis	y-axis	
Passenger Trains														
1 + 4	2	S	1121	72	100	94	90	87	83	87.5				
1 + 6	2	S	1323	84	99	96	90.5	88	86	88				
1 + 10	2	S	1515	82	103.5	98	91	85	86	87.5			84.5	
1 + 8	2	S	1632	86	103	97.5	91.5	88.5	90	92	86			
1 + 12	2	S	1643	40	103	98	94	84.5	86	87		78.5		D
1 + 8	4	N	1034	76	97.5	92	87.5				88.5	81	89.5	
1 + 5	4	N	1104	78	93	88.5	83				87.5	80.5	89	
1 + 11	4	N	1205	80	95	89	83.5				87	79.5	85	
1 + 2	4	N	1337	70	83	79.5	73.5				75.5	72.5	74	
1 + 4	4	N	1354	70	84.5	88.5	84				84.5	79.5	82	
1 + 5	4	N	1404	78	96	90.5	83.5				86	79	86.5	
1 + 12	4	N	1550	80	94	89.5	85				86	79.5	85	
1 + 2	4	N	1612	57	87	81.5	78.5				79.5	74	77	
1 + 15	4	N	1635	80	98	93.5	90				81	76	83	C,D
1 + 4	4	N	1709	46	93	89	83				79	77	80	
Freight Trains														
2 + 33	2	S	1136	34	92	87	82	80	87.5	87.5				E
2 + 48	2	S	1144	32	93.5	88	83	79.5	81.5	83				D
2 + 58	2	S	1223	66	103	96	92	85	85	87				E
2 + 95	2	S	1228	50	98	91.5	88.5	86	82	88				
2 + 63	2	S	1306	50	101.5	96.5	91	83	86	88				C,D
2 + 35	4	N	1040	84	98	93	88				87	80	86.5	
3 + 99	4	N	1154	48	92	88	85				84.5	82.5	85.5	
2 + 41	4	N	1309	35	90.5	86.5	82				80.5	80.5	85	C
3 + 71	4	N	1420	40	87.5	83	80				75	75	76	D

A) Measurement Stations 1, 2 and 3 located 25, 50 and 100 ft from centerline of Track 2; and 50, 75 and 125 ft from centerline of Track 4, respectively.

B) Peak levels occurred during passby of Engine except where noted.

C) Peak level occurred during passby of Passenger or Freight cars.

D) Vibration level tabulated is in time coincidence with peak noise level tabulated but is not the peak level generated during passby.

(measurement stations 1 and 2). Table 2.1 shows the results of this test also.

DEFLECTION

Rail absolute deflection is shown in Figure 2.4.[7]

FORCE

Typical rail car weights are shown in Table 2.2.[5]

FREQUENCY[7]

There are three major frequency bands that generate W/R loads through vehicle/track interaction. The first of these, from 0 to 15 Hz, includes static loads and the sprung-mass dynamics of the vehicle, such as car body bounce, pitch, roll or yaw, and the lower-frequency body bending modes, and truck frame resonances. A second frequency band, from about 15 to 150 Hz, includes the resonances of the vehicle unsprung (wheelset) masses on the track overall stiffness, typically 20 to 30 Hz, plus some resonant frequencies inehrent in the track structure. Finally, a third frequency band of interest, from 150 to 2000 Hz, covers the frequencies of the track and wheelset that are excited by transient impacts. These are characterized by the rail effective mass oscillating on the wheel/rail contact stiffness.

Because of ride quality considerations, rail passenger vehicles have sprung-mass resonant frequencies in the 0.7 to 1.5 Hz range. Typical freight car natural frequencies as measured by the Canadian Pacific Railway are listed in Table 2.3 for several common freight car configurations.

Measurements of track dynamic response to traffic, paricularly through tie plate vertical loads, rail vertical and lateral displacements, and subgrade pressures, have defined the more pronounced resonant frequencies due to track and unsprung mass dynamics. Important observed frequencies from measurements on the Northeast Corridor track (3-23, 3-24) of 140 lb/yd CWR included 25-30 Hz, 45-70 Hz, 100-130 Hz, and 150-170 Hz. Noticeable oscillations in subgrade pressure were recorded in the 45-50 Hz range.

2.2 ELECTROMAGNETIC

At Proviso Yards (C &NW), Melrose Park, magnetic signatures of railway cars provided limited electromagnetic information. Signatures were

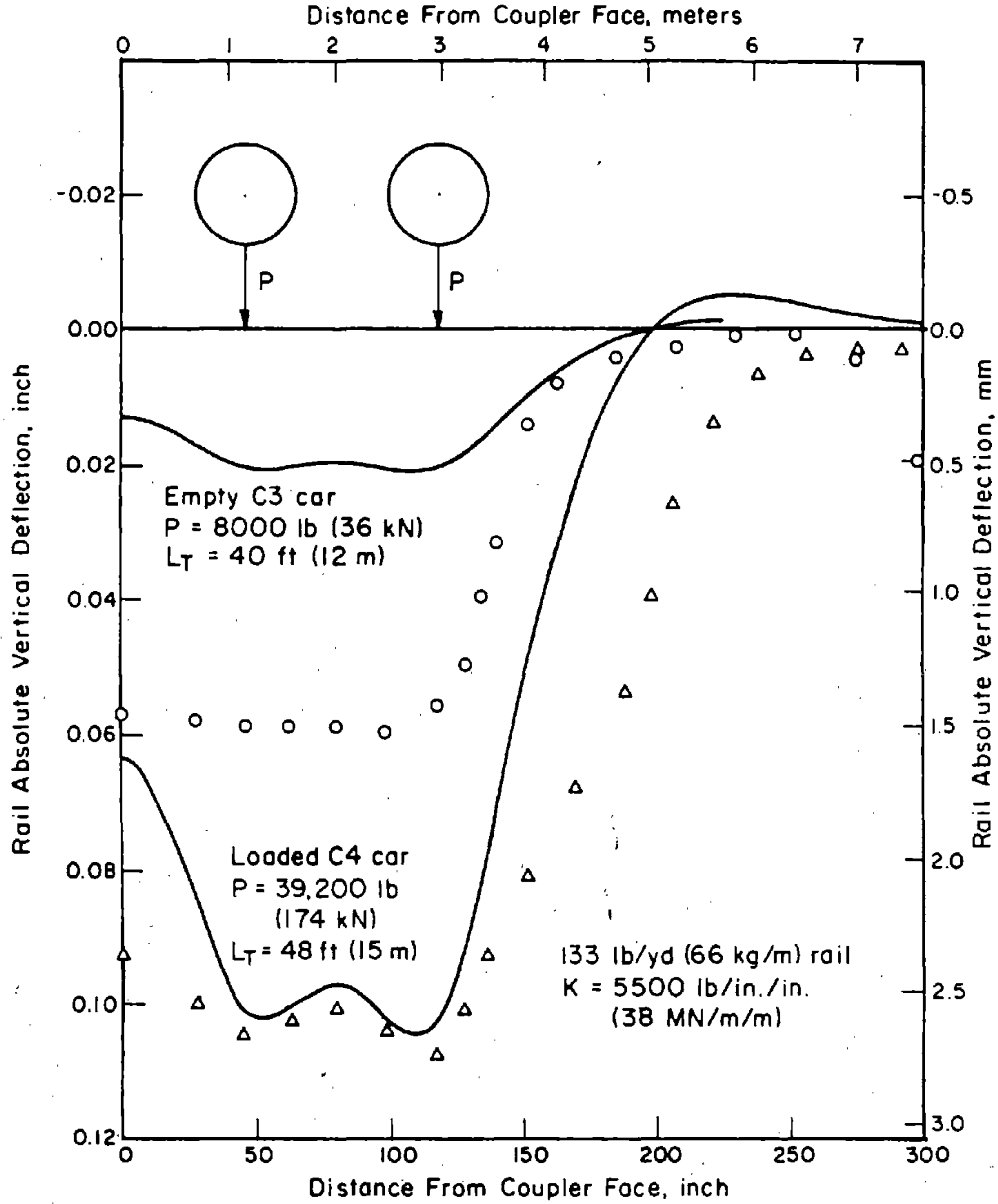


FIGURE 2.4 COMPARISON OF IDEALIZED (LINEAR BEAM ON ELASTIC FOUNDATION) AND MEASURED RAIL DEFLECTION SHAPES UNDER WHEEL LOADS OF COUPLED CARS.

TABLE 2.2 WEIGHTS OF TYPICAL RAIL CARS

Light Rail Cars	Total Car Weight (lbs)		Average Wheel Load (lbs)	
	Empty	Maximum	Empty	Maximum
MBTA[1]	32,000	47,000	4,000	5,800
Shaker Heights	42,000	60,600	5,300	7,600
Rapid Transit Cars				
BART[2]	61,000	98,000	7,600	12,200
PATCO[3]	75,000	98,200	9,400	12,300
CTA[4]	84,000	106,000	10,500	13,300
NYCTA (R-42)[5]	74,500	116,500	9,300	14,500
NYCTA (R-44)	83,000	132,000	10,400	16,500
SOAC[6]	90,000	135,000	11,300	16,900
Railroad Cars				
Passenger (Typ.)	131,500	144,000	16,400	18,000
Metroliner	158,000	170,000	19,800	21,200
Freight (Large)	80,000	280,000	10,000	35,000
Cooper E72	-	-	-	36,000

(1) Massachusetts Bay Transportation Authority
(2) San Francisco Bay Area Rapid Transit
(3) Port Authority Transit Corporation
(4) Chicago Transit Authority Stress Analysis Loading
(5) New York City Transit Authority
(6) State-of-the-Art Car

TABLE 2.3 NATURAL FREQUENCIES OF SOME HEAVY FREIGHT CARS

Car Type	Gross Weight, lb.	Natural Frequency, Hz Bounce	Pitch	Roll	Twist
LPG Tank Car	86,320	4.4	5.8	0.8	-
	217,540	3.2	4.2	0.9	-
100T Covered Hopper Car	59,000	5.8	7.4	1.0	-
	262,500	3.3	5.7	0.7	-
	256,060	2.8	4.3	1.1	-
80T Open-Top Hopper Car	51,980	5.2	5.2	1.7	4.8
	204,700	3.0	3.9	1.3	4.0
89 ft. Container Car	62,540	8.0	12.5	2.2	9.5
100T "Bathtub" Coal Cars	54,700	5.7	5.7	0.9	4.0
	272,640	2.8	4.9	0.9	-
-With C-PEP-	271,580	3.1	4.9	1.3	-

taken with a Gauss meter capable of measuring the horizontal and vertical field. Typical readings (18 inches from target) will range between .2-1 gauss. High magnetic readings were observed around the wheels (4 gauss typical) with a range of .5-40 gauss. Data taken indicates a large variation in readings between cars. Local mangnetization of parts of the car caused the high readings. An extrapolation of field data would yield a magnetic field as shown in Figure 2.5 and 2.6.

2.3 TEMPERATURE/CHEMICAL PERTURBATIONS

Temperature and chemical perturbations are present during the passage of a train. Chemical and temperature signature information on trains was unavailable in the literature.

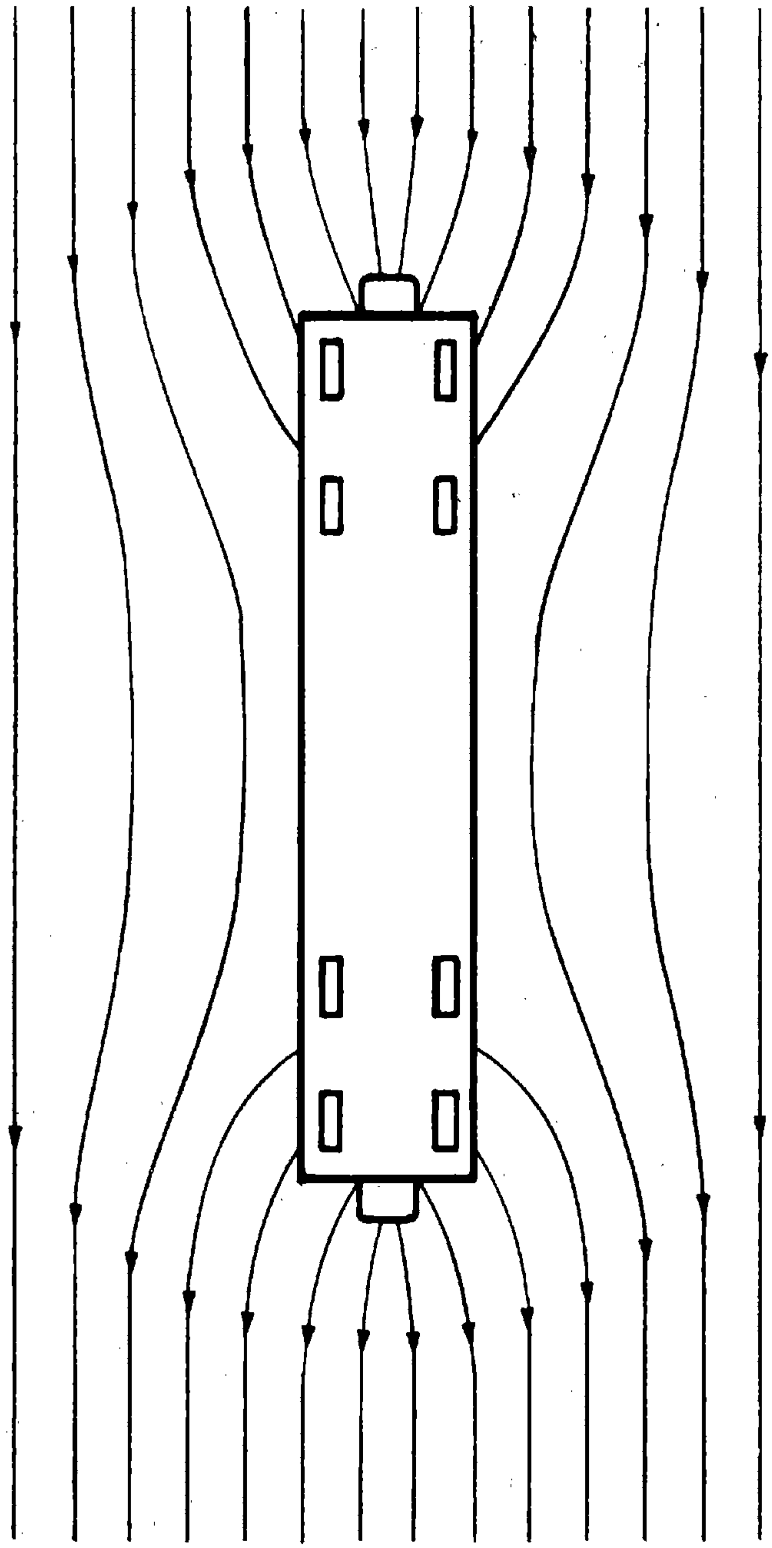


Figure 2.5 HORIZONTAL MAGNETIC FIELD

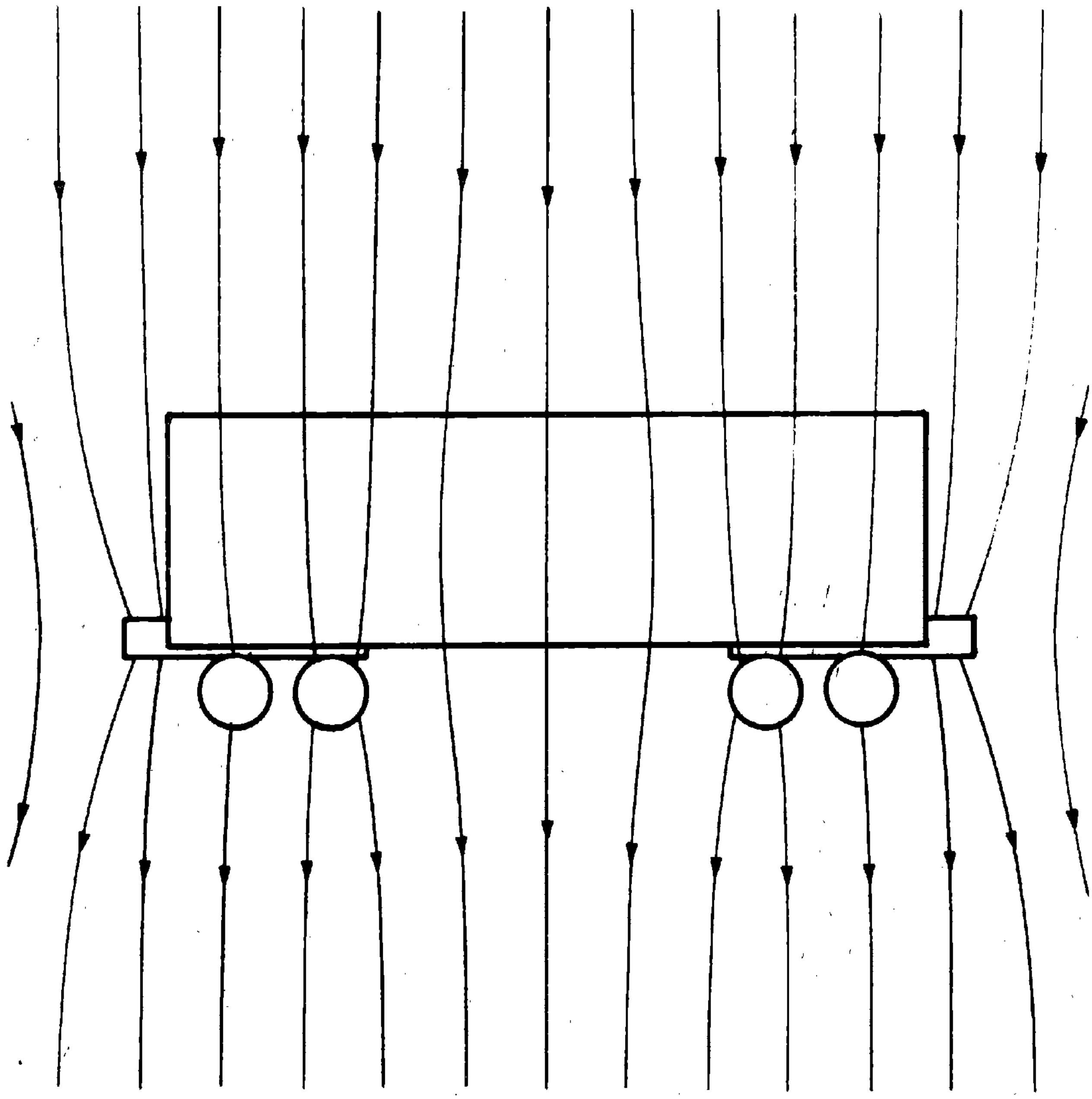


Figure 2.6 VERTICAL MAGNETIC FIELD

3. SELECTION CRITERIA

The first step on the development of a viable technique for off-track train detection is to generate system performance and operational requirements. These can then be used as a basis of comparison for the candidate techniques.

PUBLIC SAFETY

Train detection techniques must present no public safety hazard.

TRAIN SPEED RANGE

Train speed limit can range from 0 to 125 miles per hour. A system valid to 60-80 MPH would have very wide applicability.

ADAPTABILITY

Multiple track configurations are common; therefore, care must be taken to insure that a sensor does not falsely trigger due to a train traveling on tracks adjacent to the track for which the sensor was intended. In suburban areas, there are usually a number of crossings located in close proximity to one another and care must be taken in insuring that there is no interference between crossings due to the technique used for train detection/communication. Also, any technique used for detection or communication must be compatible with curved track sections.

RELIABILITY

The installation must be unattended and require virtually no maintenance while guarding a grade crossing to protect public life. This demands an extremely high reliability performance from the system. Although a malfunction in a safe failure mode does not necessarily expose the public to danger, this type of system failure will result in false alarms. Unless the system, including the sensor, is highly reliable, the frequency and duration of false alarms can lead to loss of credibility to the public, and this eventually leads to accidents caused by disregard for the grade crossing signals.

Reliability is the probability that a system or component will achieve a design goal under specified environmental condition for a prescribed period of time or number of cycles. Reliability is measured in term of mean time before failure (MTBF). An absolute constraint for the mean time between failures is 100,000 hours for a non redundant detector component. A higher reliability goal is obtainable at a higher cost factor in material purchase price and maintenance cost. For the purpose of absolute candidate evaluation 100,000 hours will be used, but keeping in mind this can be upgraded with a cost trade-off.

Electromechanical sensors are described more accurately with regard to reliability when rated in the total number of cycles of activation. This is due to the direct relationship of mechanical wear to the units reliability. Two factors must be considered in setting the minimum cycle rating; first and most important, the overall life in the field without unsafe failure, and second, the characteristics of the devices available. If the life rating is related to the number of train axles passing a detection point (4 axles/car), 1,000,000 cycles would occur in,

a) 100 days for 25 trains/day, 100 cars long.
b) 6.84 years for 1 train/day, 100 cars long.
c) 1.82 years for 25 trains/day, 15 cars long.

Therefore, 1,000,000 cycles at best is a minimum rating when compared to desired maintenance and reliability levels.

ENVIRONMENT

The environmental conditions to which a train detection system can be exposed will vary considerably depending upon site location. However, since each system will not be individually designed for a particular site, the design must consider all possible environmental conditions which can conceivably influence its performance. These conditions include (1) the natural environment, consisting of temperature, solar radiation, precipitation, wind, electrostatic discharge, sand, dust, and fungi; (2) the induced environment, consisting of the shock and vibration caused by the rolling locomotive and freight cars, the chemical sprays which inhibit vegetation growth, the soot and oil from the passing cars, the electrical fields produced by power lines and other electrical equipment, and salt spray from nearby roadways (or ocean spray); and (3) the abusive environment encountered by most railroad equipment. In addition, there are the topographical factors of hills, curves, trees, man-made obstructions, and multiple track configurations to consider.

The above factors can operate individually or in combination to affect performance of an off-track train detection system. It is necessary to know the extremes of these conditions in order to establish realistic design requirements. Knowledge and consideration of these factors at the early design stage can eliminate many problems that would otherwise become evident during the hardware and/or testing phase. The guideline for evaluation of the above environmental factors will be MIL-STD-810C.[5] This standard establishes uniform environmental test methods for determining the resistance of equipment to the effect of natural or induced envrionments. It provides test methods which generate reproducible results.

With regard to electrical surges, an absolute system constraint of 3000 volts will be used based on environmental characteristics developed during previous DOT studies.[6] According to a study on lightning and its effects on railroad signal circuits, 5000 volts might be an appropriate constraint but this figure is based on worst case conditions which are likely to occur in an area over an eight year span.[7] Since this specification might rule out otherwise favorable candidate devices, the more practical limit of 3000 volts was chosen for this program.

Attacks by vandals can range from simple stone throwing to bullet or dynamite attacks. The likelihood for vandalism can be reduced by making the system (1) extremely rugged or impenetrable in appearance and/or (2) unattractive, hidden, unnoticeable, or out of reach.

All of the above environmental conditions will be considered with regard to the design concepts under study. For example, with line of sight communication links, topography is an important factor while with other techniques it is not. Also, those concepts using optical techniques must anticipate dirt, soot, and dust, while those using sensitive solid-state devices must consider temperature, power surges, and electrical interference.

FAILURE MODE

The sensing techniques examined, together with the signal analysis system, must be designed to fail only in a safe mode. That is, loss of power or any vital portion of the system must activate the crossing warning system.

OFF-TRACK

The objective of this study is the development of firm conclusions concerning the technical and economic viability of off-track train detection. Off-track detection is defined as a means of train sensing that requires neither physical connection to nor dependency upon the rails nor the electrical continuity of any length of the rail.

COMMERCIAL AVAILABILITY

It is described that the sensor and associated hardware be available from at least two manufacturers. This reduces cost and development, but additional product development must be allowed in these areas if required.

SERVICE LIFE

Current rail crossing detection systems have an average service life of 30 years. Any concept selected in this program should, as a minimum, offer the same service life.

CONSTANT WARNING TIME

This means that the motorist warning signal is activated a fixed amount of time before the arrival of the train at the crossing. Generally, this warning time is between 20 and 30 seconds.[(2)] Constant warning time allows the motorist to clear the crossing safely while eliminating needless waiting for slow trains. This feature provides a far more precise, and thus, more credible warning; motor vehicle operators are more likely to obey signals which experience has shown to be truthful. Systems which provide constant warning time must have transducers which provide velocity and directional data, and signal processors capable of reducing this data to grade crossing signals.

RAIL VEHICLES DETECTABLE

The system developed must be able to detect any rail vehicle that the present track circuit can detect.

MALFUNCTION WARNING

In any system using self-check circuits, a separate warning may be displayed to indicate a malfunction. The malfunction warning signal would allow railroad personnel to report the failure. This feature would add credibility to the system.

MAINTENANCE REQUIREMENTS

In order to comply with some state regulations and AAR requirements, it will be necessary to inspect the grade crossing system at routine intervals to ensure that primary power as well as battery back-up power is available. This requirement may vary but it can be as short as seven days.

In addition to the seven day inspections, it may be necessary to inspect the entire system. At this time, a complete visual inspection can be made along with a functional check of the system. If the system is of the redundant self-checking design, no further inspection should be required. Any damaged or deteriorated components must be replaced or repaired at this time. If the system is not of the redundant self-checking design, it will be necessary to replace critical components at regular intervals in order to retain a highly reliable system. A detailed maintenance schedule such as this can only be developed after the specific candidate system has been chosen.

The mean-time-to-repair (MTTR) for the train sensing circuitry must be as short as possible. The circuitry must also be packaged in a modular fashion so that maintenance nontechnical personnel can quickly replace circuit modules. This reduces both system downtime and the technical requirements for the maintenance personnel. The defective module can be repaired at a maintenance shop by qualified personnel or discarded depending on the nature of the failure. A major factor in the MTTR will be the accessability of the system. If a portion or all of the sensing circuitry is underground, this might drastically increase the MTTR.

POWER REQUIREMENTS

A concept requiring low-power consumption allows complete battery operation at the down-track point. This can produce significant savings in installation costs. Even if line power is readily available, there will still be a significant reduction in the power supply and size of back-up battery needed.

COST

Although the current program pertains to the evaluation of sensing techniques for off-track train detection, the complete system cost must be considered. Ideally, the cost of the proposed complete system would be equal to or less than that of the current basic rail crossing, but based on investigations to date, an off-track detection system will cost 46 percent more than the present design.[9] However, as the complexity of the crossing increases this cost differential decreases.

The initial cost of the current basic system can be broken down as follows:

Installation labor	40%
Engineering design & layout	10%
Signal devices & hardware	5%
Sensor and associated hardware	45%

The last two items are variable depending on signal devices used in the system. The proposed system costs for engineering design and layout, and the signal devices and hardware, should be the same as the current basic system. The installation labor costs for the proposed system will vary depending on the type of detector, but the 40 percent figure will be used on this program as a guideline.

The sensor and associated hardware costs for the proposed system varies depending on the specific sensing scheme. The sensor reliability is a key cost factor; therefore, redundant sensors will most likely be required. The sensing device cost is typically 15 percent of the initial system cost, with the sensor hardware, control circuitry, and packaging comprising approximately 30 percent of the initial system cost. These estimates are guidelines, and they are not meant to be absolute constraints.

INSTALLATION REQUIREMENTS

The sensor installation may be broken down into three categories: above ground, below ground, and rail contact. The rail contact sensor is the least desirable, and will be considered only as a possible alternative to off-track techniques. Emphasis in this program is on noncontact techniques. A desirable sensing technique from an installation and maintenance standpoint is the above ground sensor. While the below ground sensor is protected and inconspicuous, and minimizes the effects of weather and vandals, it may be difficult to install. A sensor which can be used in more than one of the categories would be desirable. This would permit one type of sensor to be used under variable site conditions.

PACKAGE REQUIREMENTS

Enclosures must be designed to protect personnel against accidental contact with the enclosed electrical devices as well as to protect the system from the environment. For the purpose of comparison of candidate devices, a NEMA standard is used. In locations where equipment is located above ground, a Type 4 enclosure [10] is desirable. They are normally designed to protect against splashing, falling, or hose-directed water, seepage of water, and severe external condensation. If the condition exists where occasional submersion is encountered, a Type 6 enclosure is indicated. A package of the above types would also have a high rating against vandalism.

COMPATIBILITY/FLEXIBILITY

Sensors must be compatible with any possible communication links (buried cables, optical cables, carrier, or radio). Also, sensors, together with the signal analysis system and communications link, must be designed to fail in a safe mode.

APPLICATION AREAS

The choice of a sensor that has applications in other areas can increase the production volume; and thus, decrease the cost.

4. EVALUATION

Many technologies are relevant to the specific problem of detecting train presence at grade crossings. In the implementation of this program, the required investigations were conducted in an unbiased and thorough manner to the extent allowed within the constraints of the program. However, it is not sensible to spend excessive effort on approaches that give early and obvious indications of not being suitable for this application.

The evaluation scheme developed in this section allows for a broad-base investigation; but at the same time, allows the identification of a reasonable number of candidate detection techniques as rapidly as possible.

4.1 EVALUATION TECHNIQUES

The evaluation of the suitability of candidate techniques can be quite subjective. In this case, evaluation is somewhat simplified because a number of the parameters which define a candidate off-track detection system are absolute requirements and therefore must be intrinsic to any acceptable system. Examples of this type of requirement are the ability of a sensor to withstand the environment and the need of having an extremely long mean time between unsafe failures. Secondary requirements, such as initial cost, power consumption, and other items, which can be compared on a cost basis, will also be considered.

The applicable system constraints have been divided into two levels, as given in Figures 4.1 and 4.2. The absolute constraints of Figure 4.1 include those features that must be met by an acceptable technique. The desirable constraints of Figure 4.2 includes all trade-off items.

So as to be broad in technical scope, and yet eliminate from consideration all concepts which are trivial, an evaluation form, as shown in Figure 4.1, has been used for evaluation of absolute constraints. Shown in the form is the acceptable range of each parameter for an ideal train detection system. The acceptable range given for each parameter is based on Department of Transportation (DOT) Technical Reports, AAR, FRA, and FHWA standards, GARD's experience, and appropriate Military Specifications and Standards. All techniques under consideration during the program are evaluated and compared to

FIGURE 4.1

ABSOLUTE CANDIDATE EVALUATION SHEET

Candidate Device/Phenomena: ______________________________

ABSOLUTE SYSTEM CONSTRAINTS		
Parameters	System Goals	Candidate Device
Public Safety	Required	
Train Speed Range	0 – 125 MPH	
Adaptability		
Multiple Track	Required	
Multiple Crossing	Required	
Curved Track	Required	
Reliability		
MTBF - Detector	100,000 HR	
False Alarm	20,000 HR	
Cycle Life	1,000,000 Cycles	
Environment		
Temperature	-40°F to +185°F (14)	
Humidity	0 – 100% (2)	
Rainfall	5 In/Hour (2)	
Contaminants	MIL-STD-810C (13)	
Vandalism		
Electrical Surges	3,000 VAC (14)	
Electromagnetic	MIL-STD-461A (18)	
Shock & Vibration	AAR T48-75 (19) (a)	
Failure Mode	Fail-Safe	
Off-Track	Required	
Rail Vehicle Detectable	Same as Basic Track Ckt.	

Comments/Results: (a) Shock – 15g 11 msec. Vibration – 10g 70 - 2000 Hz

Prepared by ______________________ Date ______________

Figure 4.2

DESIRABLE CANDIDATE EVALUATION SHEET

Candidate Device/Phenomena: ______________________________

DESIRABLE SYSTEM CONSTRAINTS		
Parameters	Ideal System	Candidate Device
Commercial Availability	Yes	
Service Life	30 Years (20)	
Constant Warning Time	20-30 Sec (2)	
Malfunction Warning	Yes	
Maintenance RQMTS		
Schedule Interval	6 Months	
MTTR	2 Hours	
Accessible	Yes	
Personnel	Same As Basic Track CKT	
Power Requirements	1 Year Service	
Cost		
Initial	Same As Basic Track CKT	
Installation	40% of Initial (8)	
Maintenance	5% of Initial/Yr (20)	
Installation RQMTS		
Above	Yes	
Below	Yes	
Attached	Yes	
Package RQMTS	NEMA TYPE 4 (17)	
Compatibility/Flexibility	Yes	

Comments/Results:

Prepared by ______________________ Date ______________

these acceptance ranges. Primary emphasis is placed on determining if candidate concepts can provide off-track train detection.

After the first level of analysis is complete, the large number of candidate concepts is reduced by the selection of only the most promising. The number of candidate concepts in each category is reduced to one or two. This is accomplished by a trade-off analysis amongst the candidates of each category. Cost, availability, practicality, and anticipated reliability were the basis for selection. After this selection process is complete, the number of candidate concepts can be further reduced by choosing one from a group of candidates that have the same principle of operation. The final list of candidates will be evaluated on a system basis with respect to the desirable system constraints as part of the next phase of this program.

4.2 EVALUATION OF BASIC TRACK CIRCUIT

In this section, the parameters of the Basic Track Circuit (BTC) is measured against the absolute and desirable system constraints developed above. The results are given in Figure 4.3 and 4.4. Since any detection system developed must be, at a minimum, as good as the BTC, the results serve as minimum acceptable criteria for off-track sensors. The shortcomings of the BTC can be quickly identified by comparison to the system goals as can be those of any candidate system evaluated.

For completeness, a brief description of the Basic Track Circuit is included. The track circuit, invented for general railroad signal processes in 1872, was first applied to grade crossing in 1914. The basic concept is illustrated in Figure 4.5. The principle of operation is quite ingenuous. The battery at one end of a section of track is connected to a relay at the other end using electrically isolated rails as conductors. The relay, thus energized, is in an open contact position. When a train is between the battery and the relay, the tracks are short circuited and the relay, losing current, closes its contacts and activates a desired warning signal.

The basic crossing protection system requires a track circuit on both sides of the grade crossing ("approach circuits") with a third section covering the region where the tracks actually cross the highway ("island circuit"). The length of the approach circuits are sufficient to provide 20

FIGURE 4.3

ABSOLUTE CANDIDATE EVALUATION SHEET

Candidate Device/Phenomena: Basic Track Circuit

ABSOLUTE SYSTEM CONSTRAINTS

Parameters	System Goals	Candidate Device
Public Safety	Required	No Safety Hazard
Train Speed Range	0 – 125 MPH	0 – 125 MPH
Adaptability		
Multiple Track	Required	Need No Additional Effort[8]
Multiple Crossing	Required	Require Particular System Design[21]
Curved Track	Required	Need No Additional Effort[8]
Reliability		
MTBF - Detector	100,000 HR	
False Alarm	20,000 HR	Water, Ice, Brine Solution[1] Broken rail or bond, power failure
Cycle Life	1,000,000 Cycles	
Environment		
Temperature	-40°F to +185°F [14]	-40°F to -185°F[14]
Humidity	0 – 100% [2]	0 – 100%[2]
Rainfall	5 In/Hour [2]	5 Inches/Hour[2]
Contaminants	MIL-STD-810C [13]	Soot, Dirt, Oil Film,[2] & Rust[21]
Vandalism		Can Happen Easily
Electrical Surges	3,000 VAC [14]	3,000 VAC[14]
Electromagnetic	MIL-STD-461A [18]	Insensitive
Shock & Vibration	AAR T48-75 [19] [a]	Not Affected
Failure Mode	Fail-Safe	Fail-Safe[1][2]
Off-Track	Required	
Rail Vehicle Detectable	Same as Basic Track Ckt.	

Comments/Results: (a) Shock – 15g 11 msec. Vibration – 10g 70 - 2000 Hz

Prepared by ______________________ Date ______________

FIGURE 4.4

DESIRABLE CANDIDATE EVALUATION SHEET

Candidate Device/Phenomena: Basic Track Circuit

DESIRABLE SYSTEM CONSTRAINTS		
Parameters	Ideal System	Candidate Device
Commercial Availability	Yes	Multiple Sources
Service Life	30 Years (13)	30 Years (13)
Constant Warning Time	20-30 Sec (2)	
Malfunction Warning	Yes	Impossible (2)
Maintenance RQMTS		
Schedule Interval	6 Months	6 ~ 12 Months
MTTR	2 Hours	
Accessible	Yes	
Personnel	Same As Basic Track CKT	
Power Requirements	1 Year Service	Several Watts (Min) (2)
Cost		
Initial	Same As Basic Track CKT	
Installation	40% of Initial (9)	
Maintenance	5% of Initial/Yr (13)	
Installation RQMTS		
Above	Yes	
Below	Yes	
Attached	Yes	
Package RQMTS	NEMA TYPE 4 (10)	
Compatibility/Flexibility	Yes	

Comments/Results:

Prepared by ______________________ Date ______________________

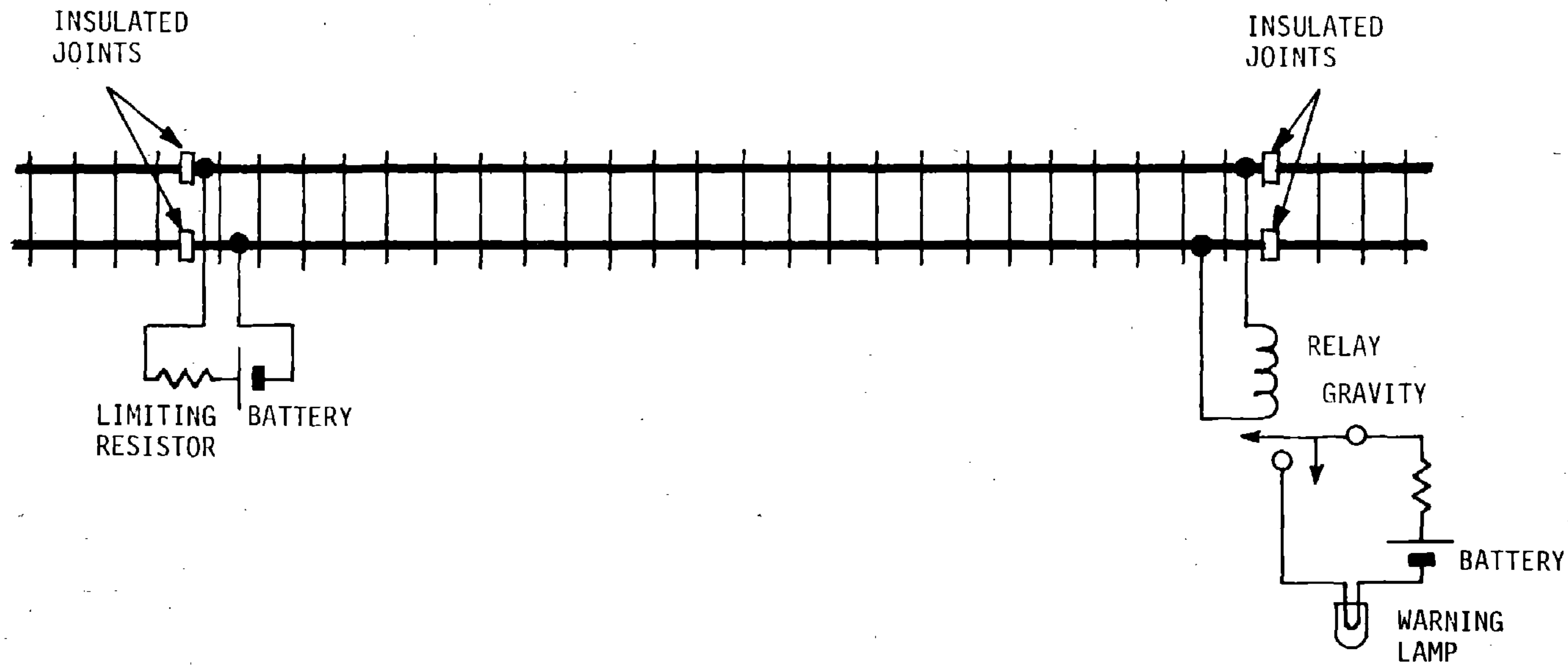


Figure 4.5 BASIC TRACK CIRCUIT

to 30 seconds warning for the fastest train speed allowed. Logic functions are also included to determine activation after the train has completed passage of the crossing and prior to its leaving the "approach" block on the departing side.

4.3 CANDIDATE EVALUATION

In Section 2, the environmental perturbations caused by trains were described. The purpose of this section is to identify and evaluate techniques that can be used to detect these perturbations using the criteria discussed in Section 3. Figure 4.6 lists all candidate sensors according to the phenomena they detect. Numbers following a technique indicate the reason for failing the absolute evaluation. Figure 4.7 shows the result of the evaluation of candidates. Detail evaluation and results are given below.

4.3.1 MECHANICAL SENSORS

DISPLACEMENT

Displacement is the vector representing a change in position of a body or point with respect to a reference point. Displacement of track, track support structures, and soil will occur due to the train load on the track. Displacement can indicate train presence at a particular position. Displacement will occur both vertically and horizontally due to the load induced deformation of the soil.

Candidate displacement transducers categorized by transduction principle include; capacitive, electromagnetic, inductive, potentiometric, reluctive, strain-gage, and photoconductive devices. Evaluation based on absolute system constraints eliminates the electromagnetic (failure mode and on track) and potentiometric (train speed range and adaptability) techniques.

In order to reduce the types of displacement transducers to a manageable number, a trade-off analysis was made (see Figure 4.8). The inductive type displacement transducers are eliminated because of the large power consumption and the low operating life. Photoconductive transducers are eliminated because of the low operating life and high cost. Reluctive transducers are eliminated because of power consumption and the poor rating in shock and vibration. Capacitive and strain gage displacement transducers are the best candidates in the displacement category. Strain gage type

FIGURE 4.6

CANDIDATE TRANSDUCERS

Mechanical
- Displacement
  - Capacitive
  - Electromagnetic 6,7
  - Inductive
  - Potentiometric 2,3
  - Reluctive
  - Strain
  - Photoconductive
- Force
  - Capacitive
  - Piezoelectric 2
  - Reluctive
  - Strain
  - Vibrating wire 5
- Pressure
  - Capacitive
  - Inductive 4,5
  - Piezoelectric 2
  - Potentiometric 4
  - Reluctive 5
  - Resistive
  - Strain
- Sound
  - Carbon 3
  - Capacitive 2,3,4,5
  - Dynamic 3
  - Inductive 2,3,4,5
  - Magnetostrictive 2,3
  - Piezoelectric 2,3

KEY
1: Public safety
2: Train speed range
3: Adaptability
4: Reliability
5: Environment
6: Failure mode
7: On track

Mechanical
- Acceleration
  - Capacitive
  - Piezoelectric 2
  - Photoconductive 4
  - Potentiometric 4
  - Reluctive
  - Strain
  - Servo
  - Vibrating element 5
- Flow 2,3
- Attitude
  - Inertial reference 7
  - Gravity sensing 5,7
  - Magnetic field 7
- Velocity

Electromagnetic
- Light 2,5
- Radio
- Magnetic field
  - Flux gate
  - Superconducting 5
  - Thin film
  - Resonance
  - Hall-effect
  - Magnetorestive
  - Magneto-optic
  - Induction
- Atomic radiation
  - Ionizing/transduction 1,5
  - Photoconductive 5
- Thermal 7
  - Thermal transduction
  - Thermocouple
  - Quartz
- Chemical
  - Gas vapor 2,3
  - Fine particle 2,3

FIGURE 4.7

EVALUATION RESULTS

Mechanical

- Displacement
  - Strain gage
- Force
  - Reluctive
  - Strain gage
- Pressure
  - Strain gage
  - Capacitive
- Acceleration
  - Capacitive
  - Strain

Electromagnetic

- Magnetic field
  - Hall-effect
  - Induction
- Radio

FIGURE 4.8

DISPLACEMENT TRANSDUCERS

TYPE	COST (DOLLARS)	POWER (mW)	CYCLE LIFE	OP LIFE (YEARS)	TEMP RANGE (F)	SHOCK & VIBRATION
Capacitive	100 - 1500	<100	Unlimited	10	-50 to +250	Good
Inductive	100 - 500	500	$10^6 - 10^9$	5	-70 to +300	Good
Photo-conductive	500 - 1500	300	Unlimited	4	0 to +170	Good
Reluctive	<100 - 500	<250	10^9	5-20	-30 to +200	Poor
Strain Gage	<100 - 1500	<100	10^7	>10	-65 to +200	Excellent

transducers were chosen over capacitive because of their excellent commercial availability. Strain gage displacement transducers are the only candidate for which an additional analysis, in this category, will be considered.

FORCE

The presence of a train will cause static forces to be applied to the track, ties, ballast, and supporting soil due to the dead weight of the train. This force will vary along the axis of the train according to the location of wheel supports and the stiffness of the track and supporting structure. Thus, the total force signature provides knowledge of train size as well as specified location.

A great many transducers are commercially available for monitoring force or torque. They accomplish the conversion of these phenomena to an electrical signal by making use of the basic laws to effect a change in a parameter of an electrical circuit. Candidate force transducers are the capacitive, piezoelectric, reluctive, strain and vibrating wire types.

The vibrating wire transducer was not considered because of the hostile environment and the piezoelectric type will not cover the speed range of the train. A trade-off analysis between candidates indicates that the best force transducer would be the strain gage type (Figure 4.9).

PRESSURE

Pressure is a force acting on a surface. It is measured as force per unit area. In the same manner as the force sensor, the presence of car will cause static forces to be applied to the track, ties, ballast, and supporting soil due to the dead weight of the train. Thus, the pressure signature provides knowledge of train size as well as specific location.

A great many transducers are commercially available for monitoring pressure. They accomplish the conversion from pressure to electrical energy signal by making use of the basic laws to effect a change in a parameter of an electrical circuit. Typical parameters which are changed due to these phenomena are resistance, inductance, capacitance, reluctance, strain, piezoelectric, and potentiometric. The strain and capacitive pressure transducers are the only types that meet the absolute

FIGURE 4.9

FORCE TRANSDUCERS

TRANSDUCER TYPE	COST (DOLLARS)	TEMPERATURE RANGE (F)	PRIMARY ADVANTAGES	DISADVANTAGES	POWER WATTS (MW)	OP LIFE (YEARS)	CYCLE LIFE
Strain Gage wire	100-1500	-65 to +250	Low output impedance can use AC or DC excitation	Low voltage output requires balanced circuit	30 - 250	1 - 10	10^6
Strain Gage solid-state	100-500	-65 to +250	DC response, low impedance (calibration capability)	Low sensitivity, can fracture crystal thermal sensitivity	30 - 60	1 - 10	10^6
Variable capacitance	100-500	-100 to +250	DC response, gas damping	Requires balance circuit & demodulator relatively large weight.	100	10	10^8
Variable reluctance (inductance)	100-500	-60 to +200	Low output impedance	Does not have high linear range, requires balanced circuit and demodulator	250	10	10^6

* These ranges are not for one instrument but for several in each category.

constraints. The inductive and potentiometric transducers would tend to have reliability problems while the piezoelectric pressure transducer would not be able to detect a very slow train.

SOUND

A sound receiver (microphone) is a type of pressure transducer. The sensing element is invariably a diaphragm. A variety of transduction elements are available. The range of pressures to be measured is normally small compared to ambient (atmospheric) pressure, even for the most intense sounds. Linearity over a wide range of amplitudes and frequencies is a desirable characteristic. Directional patterns must also be considered.

Sonic (10 Hz - 20 KHz) and Ultrasonic (greater than 20KHz) emissions can come from either the car or the track. The use of acoustic signals to identify car presence requires that the car is in motion.

In the case of multiple tracks or multiple crossings, it is difficult or impossible to determine which track the train is on for off-track sensing. Beam Breaker devices are available which can detect the trains presence. These devices consist of a transmitter and receiver, where the transmitted sound waves are interrupted by the train and not received at the receiver. The problem with these systems is that they are too susceptible to the environment. Heavy buildup of snow or ice will prevent operation and generate a false alarm.

ACCELERATION

The car, in motion, will generate dynamically varying forces due to the coupling of vertical and lateral oscillations of the car together with damping forces present in the car's shock-absorbing and spring suspension system. These dynamic signals will also contain signature information indicative of the car's linear velocity. Thus, strain, stress, vibration, velocity, and acceleration information are imposed on the track support structure.

The sensing element common to all acceleration transducers is the seismic mass (proof mass), which is restrained by a spring, and whose motion is usually damped in a spring-mass system. When an acceleration is applied to the transducer case, the mass moves relative to the case. When the acceleration stops, the spring returns the mass to its original position. If an acceleration was applied to the transducer case in the opposite direction, the spring would be compressed.

Photoconductive and potentiometric acceleration transducers will have limited reliability in this application. The vibrating-element, used for space applications, is difficult to manufacture, making it costly. In order to limit the number of acceleration candidates Figure 4.10 has been prepared. Using this analysis, candidate acceleration transducers are limited to those of the strain gage and capacitive type.

FLOW

One of the unique environmental perturbations caused by trains is the significant displacement of a volume of air leading to the turbulence and net mass transfer of an air column. Various anemometer sensor techniques exist for the detection of mass motion of gases. Some of the more common techniques are hot-wire bridges, thermistor sensors, and vane/lever arrangements coupled with electro-optical techniques. This approach requires the ability to positively distinguish a train-induced perturbation from background "noise" due to wind or passage of vehicles other than trains. Problems would also arise at multiple track locations. These problems can not be solved, therefore, this technique is not practical for train detection.

ATTITUDE

Attitude is the relative orientation of an object represented by its angles of inclination to three orthogonal reference axes. An attitude transducer measures angles of inclination with respect to such a reference system so that orientation can be determined. A train passing through a railroad crossing causes disturbances to the surroundings to a degree sufficient for sensing the trains presence with an attitude sensor. The tracks and ties are temporarily deflected or deformed under the train's weight so that an attitude sensor can be used to detect these changes. The rolling train also sets up vibrations in the earth which can be sensed by an attitude sensor.

There are several different reference coordinates that can be utilized in an attitude sensor. With respect to train detection, inertial-reference sensing, gravity-reference sensing and magnetic-reference sensing techniques

FIGURE 4.10

ACCELERATION TRANSDUCERS

TRANSDUCER TYPE	ACCELERATION RANGE (G)	USEFUL FREQUENCY RANGE*(Hz)	COST (DOLLARS)	TEMPERATURE RANGE (F)	PRIMARY ADVANTAGES	DISADVANTAGES	CYCLE LIFE
Strain Gauge	0.01 to 10000	0 (DC) to 1500	100-500	-65 to +350	Low output impedance can use AC or DC excitation	Low voltage output requires balanced circuit	10^6
Strain Gauge solid-state	5 to 1000	0 (DC) to 10,000	100-500	-65 to +250	DC response, low impedance (calibration capability)	Low sensitivity, can fracture crystal, thermal sensitivity	10^6
Variable capacitance	0.1 to 10,000	0 (DC) to 12,000	100-500	-100 to +250	DC response, gas damping	Requires balanced circuit & demodulator, relatively large weight	10^8
Variable reluctance (inductance)	0.1 to 75	0 (DC) to 300	100-500	-65 to +200	Low output impedance	Does not have high linear range, requires balanced circuit and demodulator	10^6
Servo accelerometer	0.0001 to 100	0 (DC) to 100	500-1500	-65 to +250	DC response, low impedance	Limited to G level	10^6

apply. The only practical location for these transducers to determine the deflection of the track or ties is to mount the sensor on the track or tie. This is not suitable for our application since off-track sensing techniques are to be employed. An attitude sensor can be mounted off track for vibration sensing but there are better suited transducers for this application, i.e., force, pressure, acceleration, velocity and displacement transducers.

VELOCITY

Although velocity transducers in general do not apply to train sensing, the secondary effect of vibration can be detected. The moving train causes vibrations and shock waves that propagate thru the earth. These vibrations can be detected by a linear-velocity type seismometer.

As in the case above, there are better suited transducers for this application which will provide the same information with a less complex device.

4.3.2 ELECTROMAGNETIC SENSORS

LIGHT

The use of light energy from ultraviolet (UV) to far infrared (IR) is a candidate sensing technique, but it is also sensitive to the environment. In the UV and visible wavelength regions, a variety of light sensor techniques and components are available. Solid state devices, both light-emitting and light-sensing junction diodes, exist in a wide variety of sizes, sensitivities, and packaging arrangements. Additionally, phototransistors are available with varying degrees of signal sensitivity and output signal power capabilities.

Both vacuum and gas-filled phototubes are manufactured including photomultipliers with many stages of secondary emission amplification of the primary photoelectrons emitted. Camera tubes of many types and varieties from vidicon to image isocons are available with sophisticated capabilities. They share the same disadvantages with regard to sensitivity to rain, snow, ice, and dirt. In the low sensitivity region, light dependent resistor (LDR) devices permit simple circuitry and exhibit usable sensitivity for moderate to high light levels in the lower end of the visible spectrum.

In the far infrared region, a variety of more exotic detectors exist. These sensor types include cooled indium antimonide and similar transducers capable of detecting infrared radiation wavelengths up to 10 microns or more. Similarly, bolometers made of extremely fine resistance wire bridges with radiation absorbing backing can detect far infrared radiation. Cooled germanium diodes are similarly used to detect long wave infrared radiation. The infrared spectrum (especially the far infrared region) is better capable of looking through precipitation and dirt than detectors operating in the visible and UV regions.

Light radiation includes passive and active sensor systems. Light beam interrupt sensors were not considered because of the train environment. Infrared sensors can detect the heat given off by the train, but generally these devices are also subject to the environment. In addition, except for the engine, the temperature range of the detectable phenomena is limited.

RADIO FREQUENCY

Another promising technique involves illumination (by locally generated radio frequency emission) and subsequent detection after absorption, reflection, or scattering. Frequencies of interest extend from VHF (Gigahertz) region to the VLF (Kilohertz) region. Radio frequency techniques also permit very sophisticated modulation and demodulation techniques to convey much more than simple on/off information. The size and design of transmission and receiving antennas depends on the frequency of transmission and upon the desired amount of directivity (antenna gain).

Another important attribute of an RF approach is that it cannot only sense car presence but also communicate the signal over long distances without a hard wire link. The many variations of using RF energy to detect a car all depend on illuminating the car appropriately with selected radio frequency energy with or without frequency, amplitude, or phase modulation in continuous or pulse form. The system then either detects signal strengh variations (inluding signal/no signal) and/or interpretable changes to the modulation information imposed on the carrier energy. Properly planned, the radio frequency techniques can not only detect car presence, but also can provide velocity and direction information.

Low frequency radio signals were not considered as candidates because of antenna size, vulnerability to extraneous signals, and limited frequency allocation. At microwave frequencies a stationary train will mask echo from adjacent trains. Also false targets are received from objects moving parallel to the tracks.

The above comments on RF sensing are based on a system where an emitter is part of the system and the sensor is detecting radiated or near field radiation. Radio frequency can also be used in detection methods which do not require the sensing of radiated energy. This involves the use of a transmission line, the field of which is perturbed by the presence of metal in the train as it passes.

MAGNETIC FIELD

The methods and devices used to detect and measure steady and alternating magnetic fields comprise the field of magnetometry.

Man-made noise is obviously most significant in populated areas and, by and large, consists of magnetic fields at the power line frequencies and its harmonics. In a conventional dwelling, the magnetic field intensity at power-line frequences (60 Hz in the U.S.) may be in the range of 10^{-5} to 10^{-3} (9) oersted. The earth's magnetic field is on the order of 0.5 oersted. The magnetic field at a distance of one meter from a conductor carrying a current of 1 ampere is about 10^{-3} oersted. This, however, does not apply to a conduit or a pair of conductors carrying such current, since the flow of current in the opposite direction in the conductors cancels the magnetic fields generated by each current. The higher frequency content of power line noise is mostly at the odd harminics, due to imbalance of the three-phase electric power distribution.

Fluctuations in the earth's magnetic field are found everywhere and are caused primarily by thunderstorm activities. The fluctuation intensities decreases with increasing latitude and vary inversely with the 3/2 power of the frequency in the range below 100 Hz. Magnetic field fluctuations below 100 Hz were found to exceed 10^{-6} oersted when measured in a bandwidth of one Hertz only.

A car's wheels, suspension structure, and body constitute a large ferromagnetic mass with some significant degree of semi-permanent magnetic polarization. Thus, its static or dynamic presence constitutes a perturbation to the earth's magnetic field or locally installed permanent magnetic field or electromagnetic field. Wheel detectors based on sensing disturbance of a locally generated magnetic field have been developed and are being used on some railroad systems.

Measurement of perturbation to the earth's magnetic field can be accomplished using the well developed fluxgate sensor designs or actual compass card techniques combined with electro-optics. The method of using the earth's field depends primarily on sensing a degree and rate of field vector change as being characteristic of a train. This technique could also provide velocity and direction information. Vulnerability to false targets would be a problem to be solved in the more sensitive earth's magnetic field perturbation sensors. The track mounted magnetic sensor type is less vulnerable to outside influence because of its proximity to the train wheel. The use of track mounted multiple magnetic sensors also provides information on velocity and direction of travel and it is more adaptable to multiple track installations than the earth's magnetic influence type.

Evaluation of this technique, with respect to the absolute system constraints, indicates the approach looks promising. The use of the superconducting magnetometer requires a cryogenic environment, therefore it will not be considered a candidate. Devices which passed the absolute constraints are listed in Figure 4.11. The figure provides a trade-off analysis which will limit candidates to hall-effect devices and the induction loop.

Temperature transducers will not pass the absolute constraints because of the limited amount of heat present and the need for contact with the devices being measured.

4.3.3 CHEMICAL

A train in passing causes a chemical perturbation of the environment. Diesel fuel combustion results in the addition of hydrocarbons to the ambient air. Diesel electric devices create ozone molecules which mix with the air. The moving train disturbs the surroundings, lifting dust and dirt particles, and temporarily suspending them in the air. There exist sensors capable of detecting concentrations of these gases or particles to a high degree of sensitivity.

FIGURE 4.11

MAGNETOMETERS

TYPE	SENSITIVITY (nT)	RANGE (T)	BANDWIDTH (Hz)	COMMENTS	COST (DOLLARS)
Fluxgate	± 0.1	$\pm 10^{-7}$	0 - 3	Three-axis, Space application Portable Long term stability	<100
Superconducting	10^{-4}	large	0 - 12	Space and bioengineering applications Gradiometer	>1500
Thin-Film	0.1	10^{-7}	DC only	Based on anisotrophy dispersion	<100
	10 - 100		10^{6}	Based on thin-film magnetoresistance	
Resonance	1	10^{-4}	only	Proton processing, rugged	100-500
	10^{-2}		0 - 1	Scalar, optically pumped	>1500
	10^{-1}	10^{-7}	0 - 1	Vector, optically pumped He4	>1500
	10^{-3}	10^{-8}	0 - 0.5	Vector, optically pumped He4	>1500
Hall-Effect	1	10^{-4}	$0.3\text{-}10^{-3}$	Flat with frequency	<100
	100	10^{-4}		Flat with frequency	
Induction				AC only	<100

Chemical phenomena associated with a trains diesel engine or electric drives can be detected within the current state-of-the-art of vapor sensors, but the train detection systems cannot be based on engine car detection alone, since the engine car can be the furthest car from the rail crossing as the train approaches. There is another problem with this technique. Sensing only the engine car does not indicate how long the signalling device should be activated, since the remaining rail cars are not being detected. Furthermore, both vapor and fine particle sensors cannot detect a stopped train with the engine off. In addition, the effectiveness of these sensors are extremely limited by adverse environmental conditions. Wind, rain, snow, and ice will severely reduce or eliminate the chemicals the sensors are to detect.

The evaluation of this phenomena with respect to the absolute system constraints indicates the technique is not practical for train detection.

NUCLEAR

A train approaching a railroad crossing can be detected using a nuclear source and a radiation detector. A gamma radiation source, due to its strong penetration capability, is well suited for the severe environmental conditions associated with train detection. Therefore, accurate train detection is within the state-of-the-art utilizing a gamma source and appropriate detector. Unfortunately this strong penetrating capability is also a major drawback for this technique. The gamma rays present a severe safety hazard thereby eliminating the possibility of using a gamma source technique.

Alpha and Beta particles do not have the strong penetration capability of gamma rays, therefore a technique utilizing such a source would not be functional in severe environmental conditions (rain, snow, mud, etc), furthermore even these sources present a potential health hazard if not properly contained.

The evaluation of this phenomena with respect to the absolute system constraints indicates the technique is not practical for train detection.

4.3.4 THERMAL SENSORS

Temperature is defined as the thermal state of a body and is a function of the mean kinetic energy of the molecules of a substance. Heat is a form of energy and can be transferred from one body to a second when the temperature of the first is greater than that of the second. This process is commonly called heat flow. Heat can be transferred by conduction, convection or radiation. The term thermal conductivity expresses the relative ability of a substance to transfer heat by conduction.

If one wishes to measure the heat flow, or to measure the thermal conductivity by measuring the temperature change caused by a known heat flow, one must immediately plan to measure the temperature. The temperature information is used in conjunction with known heat flow and dimensions to find thermal conductivity, or with dimensions and known thermal conductivity to find heat flow.

A thermal detector can be used to measure temperature changes caused by the train. The engine obviously provides a temperature variation but so do the other cars. A source of temperature variation is the friction developed between the track and the rolling train. The problem with sensing this phenomena is the long rise and fall time for the temperature change in the track. Another approach would be to sense the heat radiated by the roller bearings of the wheels as the train passes.

5. SYSTEMS CONSIDERATIONS

In the development of all off-track train detection systems, the existing track circuit serves as a standard of performance. The new system must be capable of duplicating the activities and maintaining the high level of reliability of the standard track circuit.

Train detection methods fall into two categories: continuous and point sensitive. The characteristics of the two systems are essentially dissimilar, resulting in substantially different design and systems considerations. Incorporated into these systems will be the transducers selected in Section 4 of this report. The best transducer for the point sensor system is the magnetic sensor for it can provide the resolution and reliability required by the system. The transmision line was best suited for the continuous sense technique. The two systems will be separately discussed in the following sections.

5.1 THE POINT SENSOR SYSTEM

The point sensor system is shown in Figure 5.1. Trains are detected by sensors located at the ends of a track block. In order to determine train presence within a block, the following possibilities must be anticipated:

- o Change of train direction after entering block.
- o Turn out of part or all of the train onto a siding
- o Decoupling, leaving only a section of train in block.

For a system to be acceptable, it cannot be fooled by the above situation. Furthermore, it must be failsafe under these circumstances, and it must be comparable in cost to the existing track circuit. The point sensor system consists of three general functional areas as shown in Figure 5.2. These functional areas will be discussed below.

5.1.1 SENSOR REQUIREMENTS AND SPECIFICATIONS

There are two types of point sensors. One type is capable only of detecting the presence of a broad target. It senses over a large area and cannot resolve fine features. Examples of this type are loop sensors and buried pressure transducers.

If two presence detectors are placed at each end of a block, they are capable of detecting:

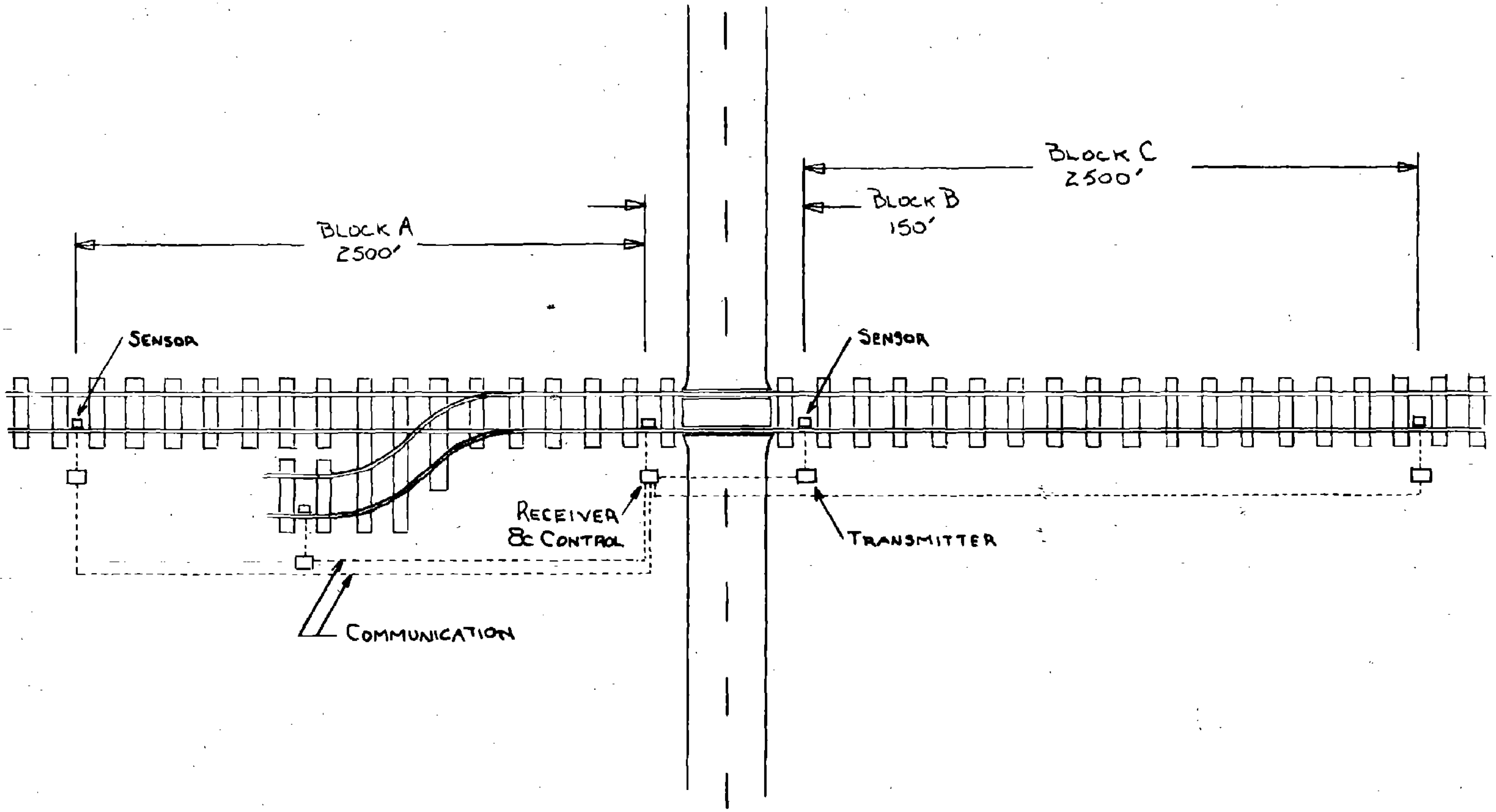


Figure 5.1 POINT SENSOR SYSTEM CONFIGURATION

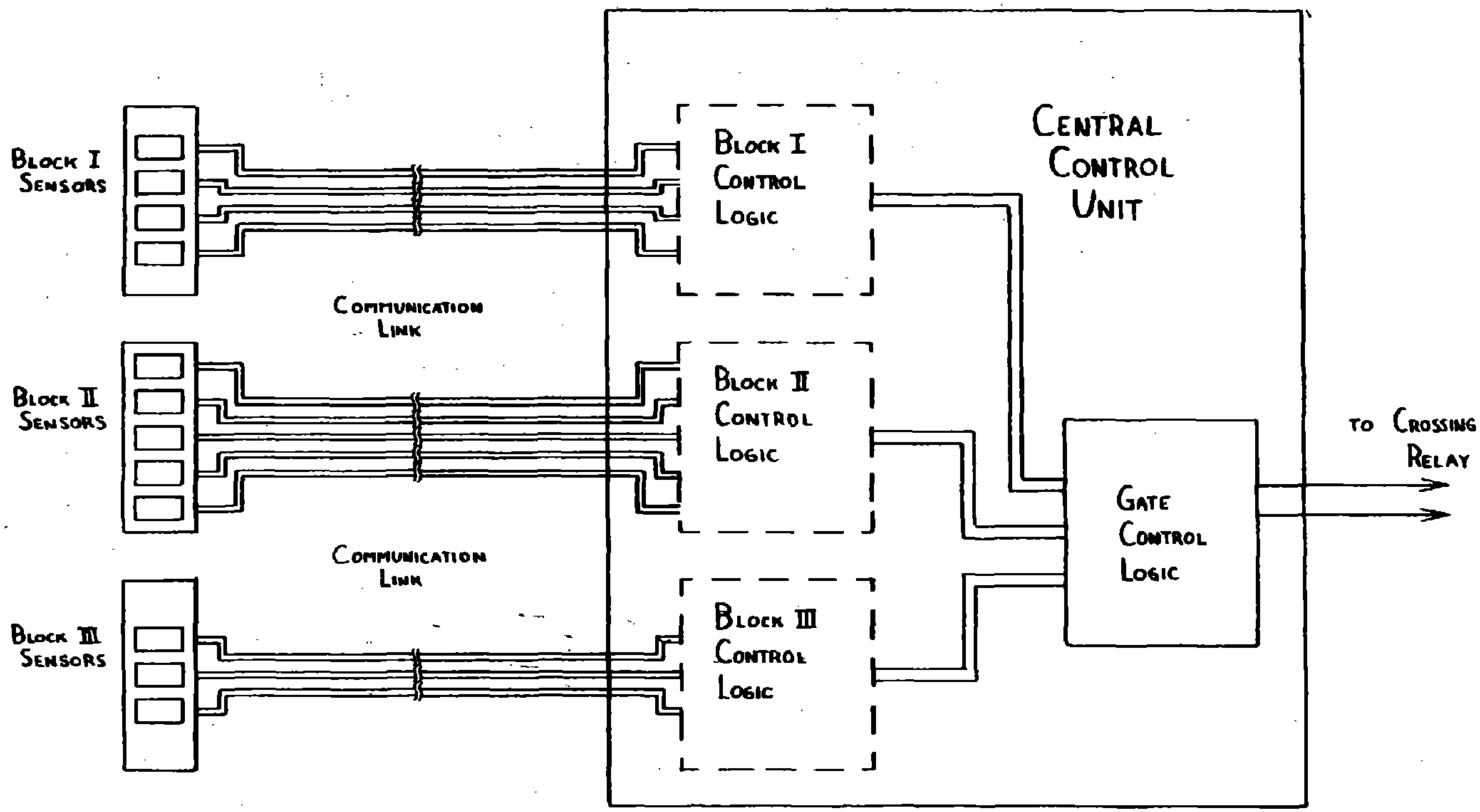


Figure 5.2 THE POINT SENSOR SYSTEM BLOCK DIAGRAM

- o The leading edge of a train and its direction of approach.
- o The trailing edge, and its direction of departure.

This sensor system has one severe drawback. Consider the case in which a train enters a block, uncouples several cars and then moves out of the block, leaving the decoupled cars behind. The sensor system would detect the trailing edge of the departing train, and deactivate the warning signals. This potentially dangerous situation would not have occurred with the standard track circuit.

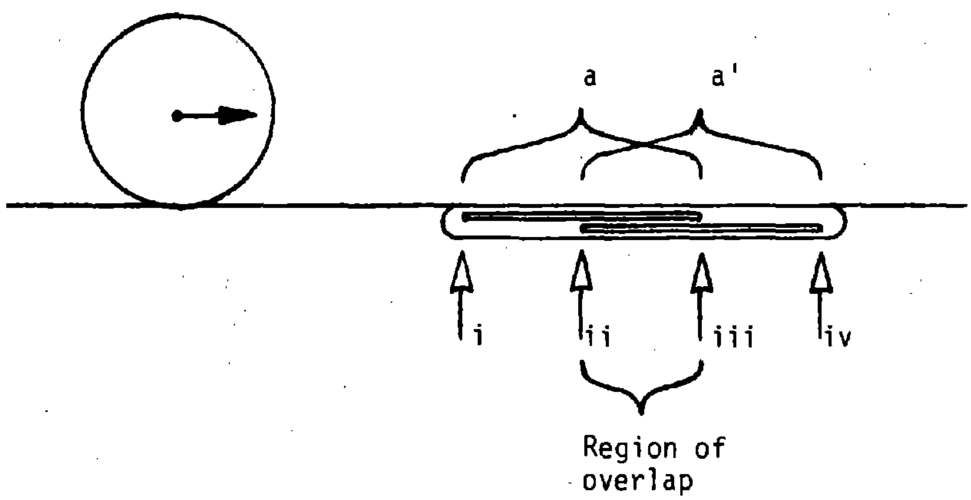
The fault in the system arises from its inability to count cars. Had the system possessed this capability, it would have detected that fewer cars had left the block then had entered, indicating that the block was still occupied. Therefore, incorporated into any point sensor system must be the ability to count cars.

The present state of sensor technology limits the distance from which cars can be reliably counted. The task of counting rail cars entails the discrimination of fine features, such as wheels, wheel flanges or trucks. Because a sensor's resolution decreases with distance, there is a trade-off between distance and reliability. While it would be ideal to locate the sensor many feet away from the track, no presently available sensor has the resolution needed to reliably operate from that distance. It therefore becomes necessary to replace the sensor within inches of the object it is detecting.

Of the candiate transducers identified in Section 4, the one that best meets the above criterion is the magnetic sensor (Hall-Effect). Further reference to a point sensor in the text will now imply the magnetic type.

Given that the sensor can count reliably, one must then configure the system to detect change of train direction. Obviously, this cannot be done by a single point sensor. Two sensors, arranged so that they have a region of overlap, can account for all situations. The operation of a pair of dual overlapping sensors is depicted in Figure 5.3. The presence of an axle between points I and II turns on sensor A. An axle present between points III and IV activates sensors A'. Observe that in the region between points II and III (the region of overlap), both sensors are activated. Figure 5.4 shows the signal generated as a wheel passes over a sensor pair. Observe that, in order for the system to resolve individual wheels, the total region encompassed by the sensor pair must be no greater than minimum distance between axles.

Figure 5.3 DUAL OVERLAPPING SENSOR



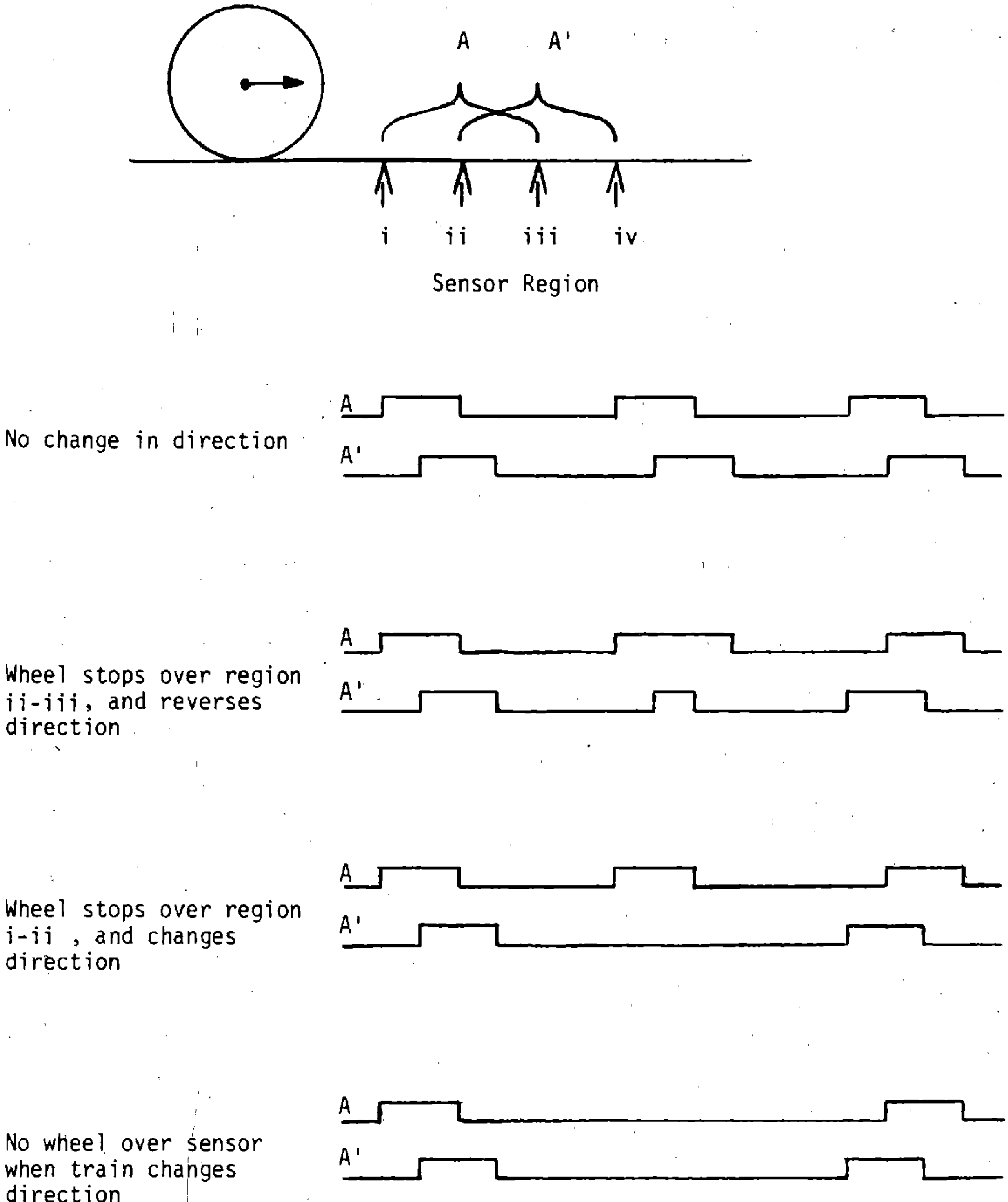


Figure 5.4 SIGNAL GENERATED BY DUAL OVERLAPPING SENSORS

Figure 5.5 demonstrates that an overlapping pair can unequivocally determine change of train direction. The decoding and recognition of these signal combinations can be effected by hardware logic or microprocessor. An example of hardware logic which can perform this function is shown in Figure 5.10. The system shown in the square labelled DECODE LOGIC-SENSOR A provides the decoding of the signal combinations shown in Figure 5.5. The same decoding could be performed by a microprocessor.

5.1.2 COMMUNICATION LINK

The communication link forms a subsystem of the overall point sensor system. The subsystem must be immune from environmental phenomena, such as rain, heat, EMI and lightning. It must be fail safe, yet have minimal maintenance requirements. It need transmit information a distance of a half mile with data rates up to 10 KHz. It is desirable that the system be battery operable, i.e., low power. Three different methods of transmission are discussed below.

BURIED CABLE

The most direct method of communication is that employing a buried cable. Such a system is demonstrated in Figure 5.6. The design philosophy is best understood in terms of the problems which befall such a system.

A half mile length of cable is very receptive to electromagnetic noise. Interference problems are often compounded by the presence of high power lines which share the rail road right of way. This problem can be circumvented by transmitting in the differential mode over a shielded twisted pair. This will also allay problems associated with grounding, since the transmitter and receiver are electrically isolated from one another.

Another major design consideration is the vulnerability of cable to lightning induced surges. A surge of a few milliamps can destroy semiconductors. To protect the sensitive electronics, elaborate surge suppression system is required. Power semiconductor (TransZorbs) need precede the line driver/ receiver. Only they are fast enough to divert surges before the electronic are damaged. Because TransZorbs are very limited in their power handling capacities, they must be precede by spark gap arrestors which are capable of diverting the brunt of a high power surge. But because these are slow to react, they are interfaced to the TransZorbs via medium power medium speed

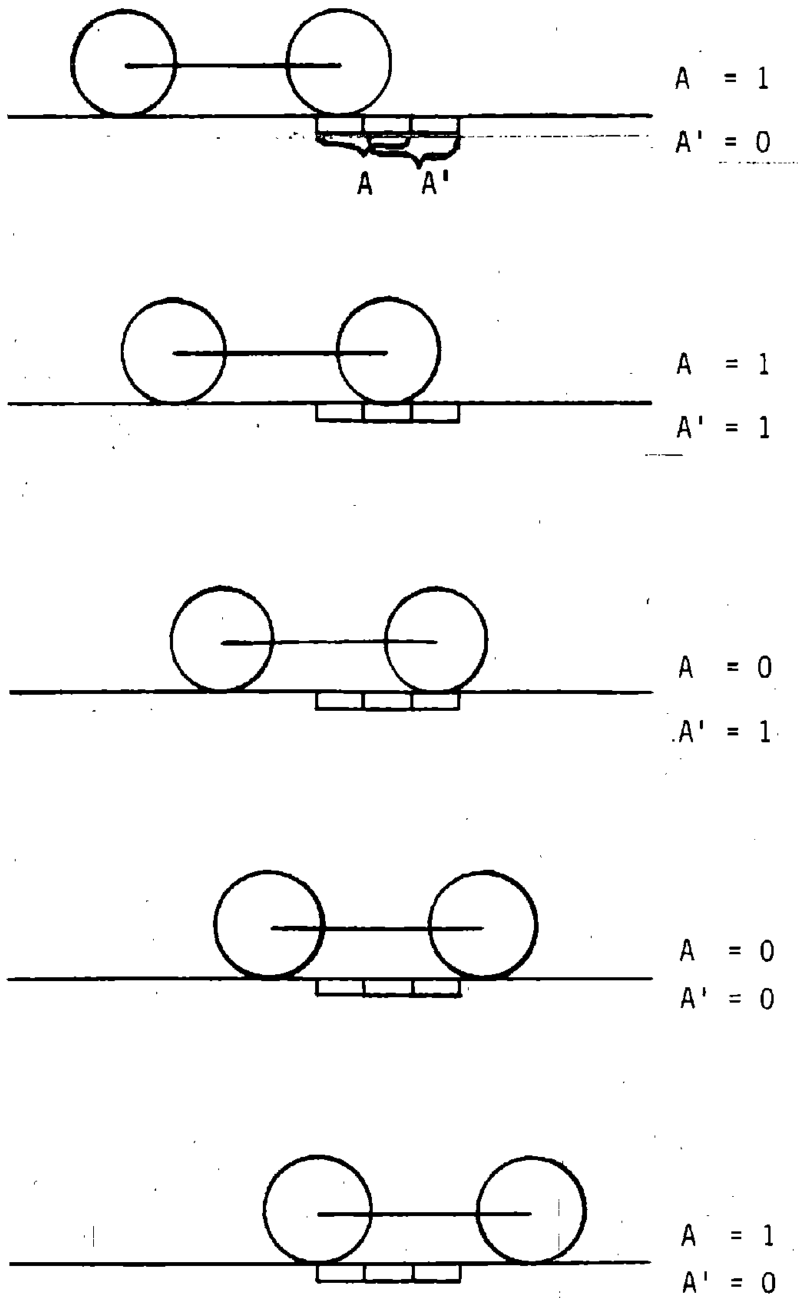


Figure 5.5 GENERATED SENSOR SIGNAL VS. WHEEL POSITION

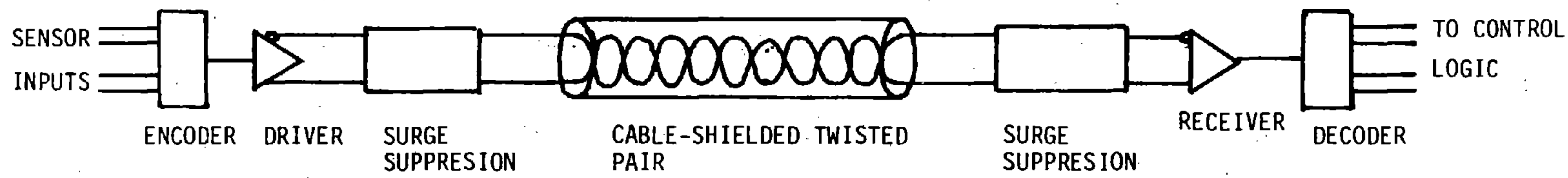


Figure 5.6 BURIED CABLE

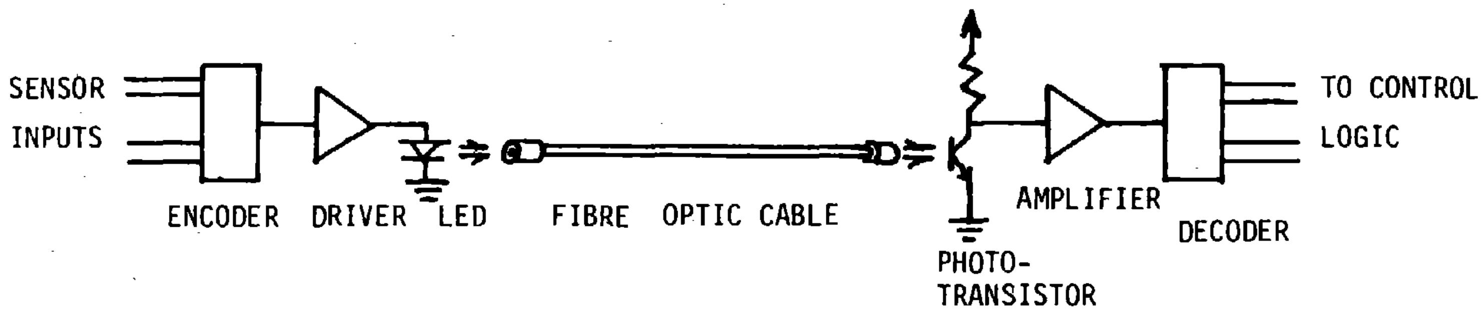


Figure 5.7 OPTICAL TRANSMISSION LINE

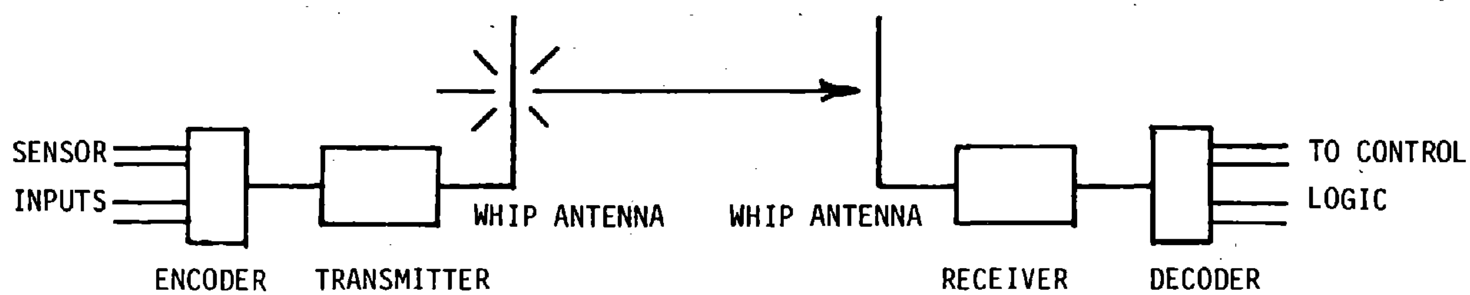


Figure 5.8 WIRELESS TRANSMISSION

varistor units. Thus, three different types of suppression device are required to reduce the very large surges induced by lightning to the very small levels tolerable by semiconductors.

Another consideration associated with lightning protectors is the diameter of the cable conductors. Calculations based on a triangular current-vs-time wave form (with peak current of 100,000 amps occurring at t=10μsec. diminishing lineraly to Zero current at t=100μsec.) indicate that 12 gage wire is required to prevent melting the wire insulation ($\Delta T = 60^oC$).[15]

Due to the great length of the transmission line, it is possible for the transmitted signal to be reflected, resulting in bit error. This problem can be averted by properly terminating the line. The terminal resistor, R_L should ten times the characteristic impedance of the transmission line (Ro). The series source impedance (Rs) should be 2/3 Ro. These proportions ensure that signal attenuation and ringing are minimized.[27]

Cost can be reduced by transmitting both sensor signals over the same wire. This necessitates encode and decode logic thereby raising the required transfer rate of the transmission line from 100 to 5000 Hz.

FIBRE OPTIC TRANSMISSION

In recent years, the availability of fibre optical equipment has steadily increased. To date, there are many successfully operating optical data links. The cost advantage of optical transmission as it pertains to this application is derived from its complete immunity from stray electromagnetic and lightning induced interference, eliminating the need for such protection circuitry. An optical data system is shown in Figure 5.7.

For the system to be feasible, the transmitter must be battery powered, because the cost of laying a power cable is prohibitive. To achieve this low power requirement, one optical cable is used to carry encoded information from both sensors. The transmitter is only used when a train is passing. To maintain fail safety, a periodic check pulse need be relayed to the receiver when no train is present. An edge emitting LED is chosen as transmitter because its power requirements are lower than other light emitting devices. However, it would still be run at considerably below recommeded current rating (i.e., at 40 mA). Although this has the effect of limiting the system bandwidth, it will still operate satisfactorily at the low frequencies (less than 10 KHz) required in this application. Using these power saving techniques one can approximate the life expectancy of a 12V 90 A.H. power supply to be four years (excluding the power requirements of the sensor).

The total signal attenuation between the LED and the receiver is expected to be less than 30 db. Using moderate loss (10 db/Km) single fibre cable, optical coupling losses can be maintained below 10 db per termination.

The receiver is not hampered by power restrictions because photo transistors draw little current. The silicon P-I-N photo transistor is followed by a gain stage to recover the line losses. A decoder is then used to reconstruct the original sensor signal.

WIRELESS COMMUNICATION

Studies have been performed on the feasibility of using wireless communication links in grade crossing systems. The results are stated below so that comparisons can be made between transmission systems. Figure 5.8 depicts a wireless system.

The first step in designing a wireless data link is to chose the optimal transmission frequency. VHF seems to be the best. Lower frequencies suffer greatly from skip interference, whereby stray signals propagating over great distance are received and confused with intended signals. High frequencies (UHF and microwave) are less efficient than VHF (can be partially compensated by use of high-gain antennas); and their wide bandwidths (corresponding to high data rates) would make it difficult to get an assignment in this low data rate application.

VHF is less prone to skip interference because higher frequency signals attenuate more rapidly. To overcome what interference is found in this band, it is necessary to tune transmitter/receiver pairs to different frequencies.

It is desirable to power wireless systems from batteries because of the high cost of running power cables. VHF systems are compatible with low power consumption. A transmitter with an output of 100 mw will reliably span a distance of a half mile.[8] As with optical transmission, a VHF system will operate only when a train is present. Otherwise, it sends a periodic check pulse to ensure that the system is functioning properly.

Since dual sensor signals are communicated via the same transmitter, an encoder/decoder is required. Also, transmitters associated with the same crossing system must use different carrier frequencies because a single antenna must receive signals from several transmitters. Field studies of wireless transmission (microwave specifically) have shown them to be completely weather-proof. It was found that perhaps the most serious problems result from multipath interference. When two out-of-phase signals appear at an antenna simultaneously, they cancel each other. This can happen when signals are reflected from the ground or the side of a truck or rail road car. It should be possible to solve this problem by using two or more antennas spaced at half wave length intervals.

Though more field work is indicated in the area of multipath interference, wireless transmission is already established as a feasible method of communication. Component cost is low, and expertise is readily available.

5.1.3 BLOCK CONTROL LOGIC

The block control logic functions to determine block occupancy. Its inputs come directly from the sensors, and its output is received by the gate control logic.

Figure 5.9 is the flow diagram of the block control logic. Sensor pairs (e.g., A & A', B' & B, etc.) are placed at the ends of the track block, and at every turn out from the track block. A wheel entering the block increments the counter, and decrements the counter upon leaving. When the number of wheels entered is equal to that having left, the block is empty. To demonstrate the simplicity with which such a system might be implemented, the logic system in Figure 5.10 has been generated. The basic elements of the system are the up/down counter, the multiphase clock, and the sensor selector. This system could alternatively be built around a microprocessor.

5.1.4 RELIABILITY & FAIL SAFETY

The reliability of a sensor system depends as much upon the sensor configuration as on the transducer. The transducer establishes the minimum level of reliability. By anticipating the failure modes of the system, and compensating for them by good design, reliability can be made arbitrarily high. The goals in this case are to provide fail safety and to hold maintenance requirements to a minimum.

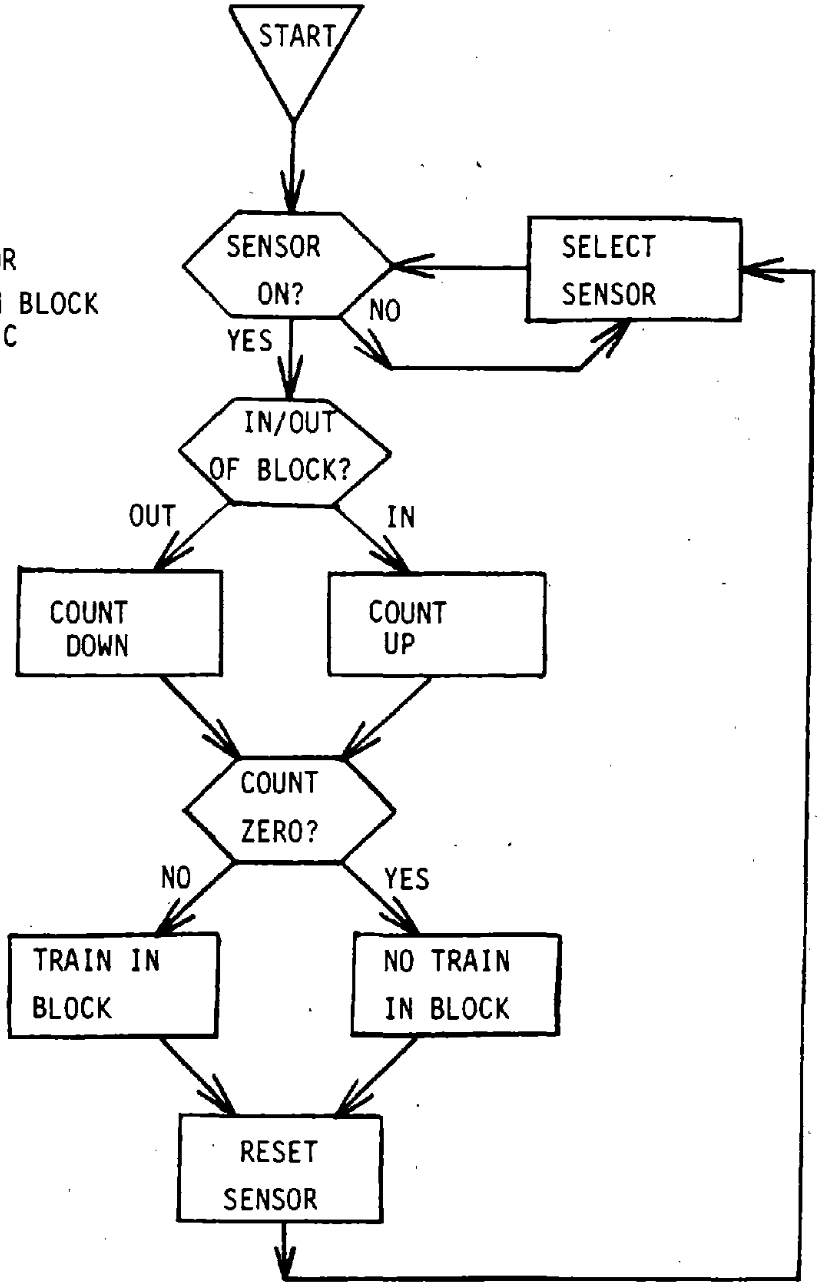
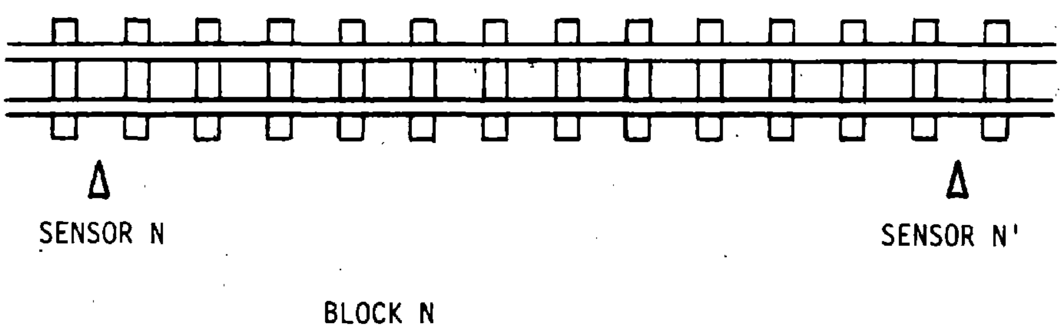


Figure 5.9 POINT SENSOR FLOW DIAGRAM BLOCK CONTROL LOGIC



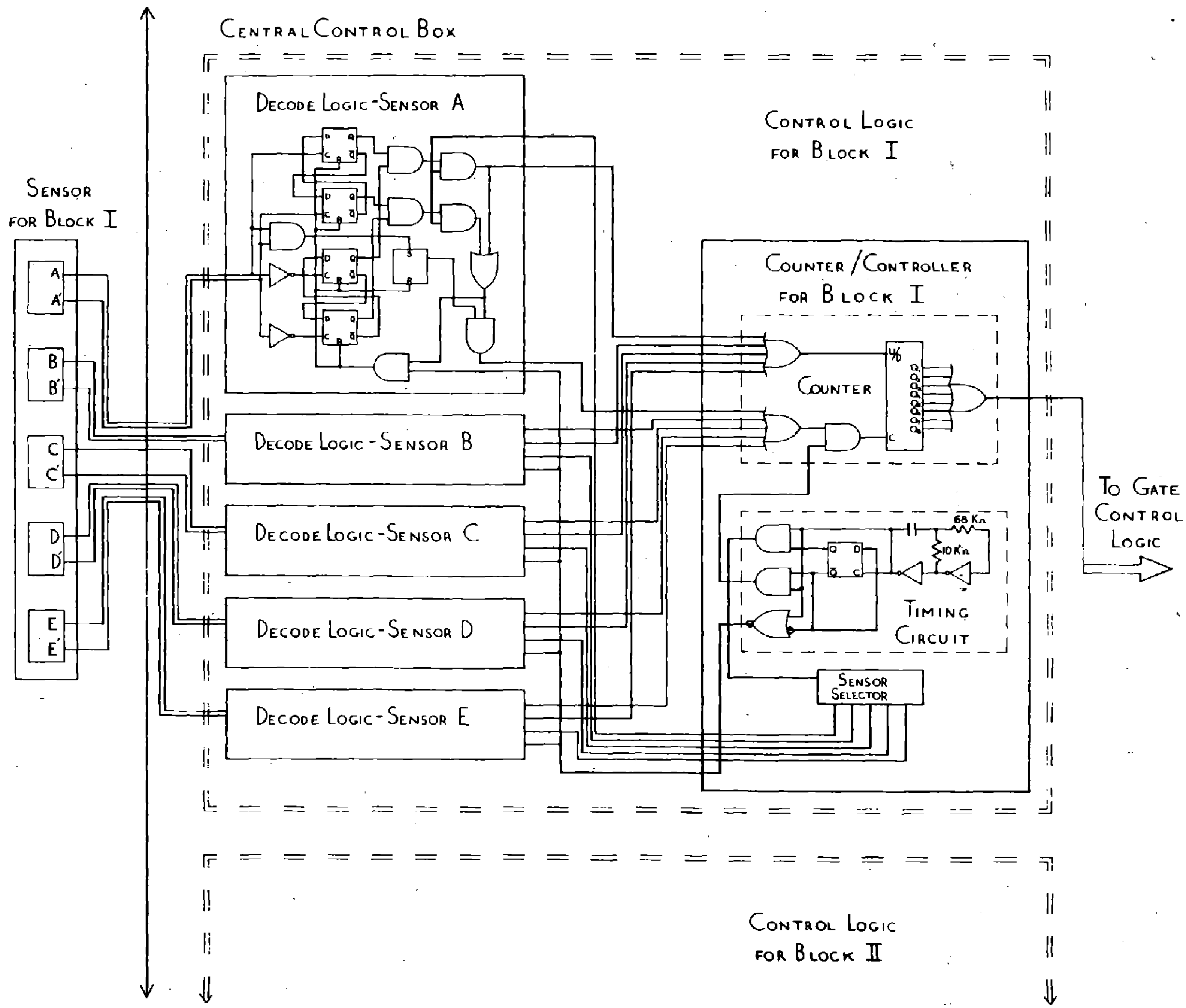


Figure 5.10 BLOCK CONTROL LOGIC

FAILURE MODES OF POINT SENSORS

A point sensor can fail in two ways. It can miss a count, ie., occasionally allow a wheel to pass by undectected; or the sensor can become permanently defunct.

Counting errors made by point sensors do not precipitate unsafe failures. The system can correct itself if only one or two errors are made; for there is a minimum of four axles per car. If more than two errors are made, the counter will not be zero when the train has left the block, and the motorist warning system will remain activated. Though this is a safe condition, it is a serious problem. because it requires that someone manually reset the system. These errors must be kept to a minimum if the system is to remain feasible.

The other type of failure occurs when the sensor becomes physically damaged, or when internal component fail.

SYSTEM RELIABILITY ANALYSIS

The following analysis demonstrates the techniques by which the MTBF of the system can be made sufficiently great so as to ensure safety at railroad highway grade crossings.

The reliability of a system, i.e., the probability that it will not fail unsafely in a given time period, is given by the equation,

$$R = e^{-\lambda t}$$

where λ is the failure rate ($\lambda = \frac{1}{MTBF}$), and t is the interval of operation. The probability of failure (P) is given by

$$P = 1 - R = (1 - e^{-\lambda t}).$$

The probability of failure for the basic system (Figure 5.11) in a six month interval, assuming an MTBF of 100,000 hours,

$$p = 1 - e^{-(10^{-5}\text{hrs.})\ (4380\text{ hrs.})} = .0429.$$

This means that there is approximately a 4% chance of failure for this system in a 6 month period. If this system were utilized on 50,000 railroad crossings, there would be a probability of 2,145 failures during the 6 month intervals. This is an awesome figure and the situation must obviously be improved.

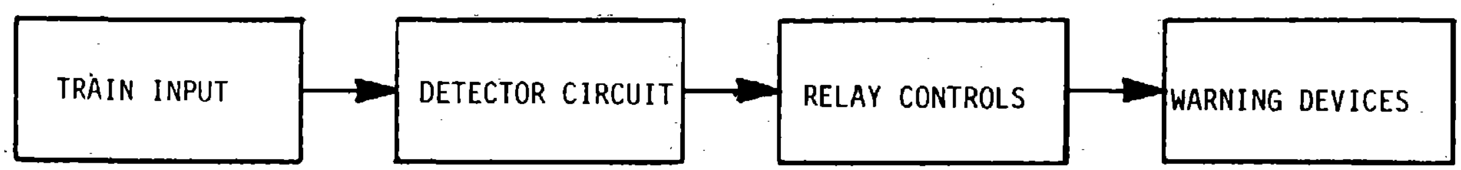


Figure 11 BASIC DETECTOR SYSTEM

One improvement would be to increase the MTBF of the basic system. If one could design or choose a system with a MTBF of 10^7 hours, the probability of failure over a 6 month interval for the basic system would be,

$$P = 1 - e^{-(10^{-7}\text{hrs.})\ (4380\ \text{hrs.})}$$

$$P = 0.000438$$

This means that there is apprximately a .04% chance of failure for this system in a 6 month period. If this system were employed on the 50,000 railroad crossings, there is a probability of 22 failures in a 6 month interval.

The MTBF of 10^7 hours is equal to a mean time between failures of 1,140 years for this basic system. It is unrealistic to think that a basic system utilizing the mechanical or magnetic sensors which we have chosen to evaluate further, can operate without a failure for this period of time. A more practical solution is necessary.

An alternative to increasing the MTBF is an approach utilizing double redundant detector circuitry, such as the system illustrated in Figure 5.12. The probability of failure of a double redundant circuit is

$$P = (1 - e^{-\lambda t})^2.$$

Based on a maintenance interval of 6 months and a MTBF of 100,000 hours

$$P = 1 - e^{-(10^{-5}\text{hrs.})\ (4380\ \text{hrs.})^2}$$

$$P = .001836$$

This means that there is a 0.18% chance of failure for this system in a 6 month period. If this system were employed on the existing 50,000 active railroad crossings, there is a probability of 91.8 failures in a 6 month interval. Redundant circuitry is only effective if the systems are truly independent and not subject to common failure (eg., a common power supply.

It can be shown for a triple redundant detection circuit the P = .0000787 using a MTBF = 10^5 and interval of 6 months. For 50,000 railroad crossings this is 4 failures for a 6 month interval. Thus with triple redundancy in the detector circuitry, the probability of a failure, between the 6 month interval, is much less than that for the basic system in Figure 5.11 with a MTBF of 10^7 (1,140 years).

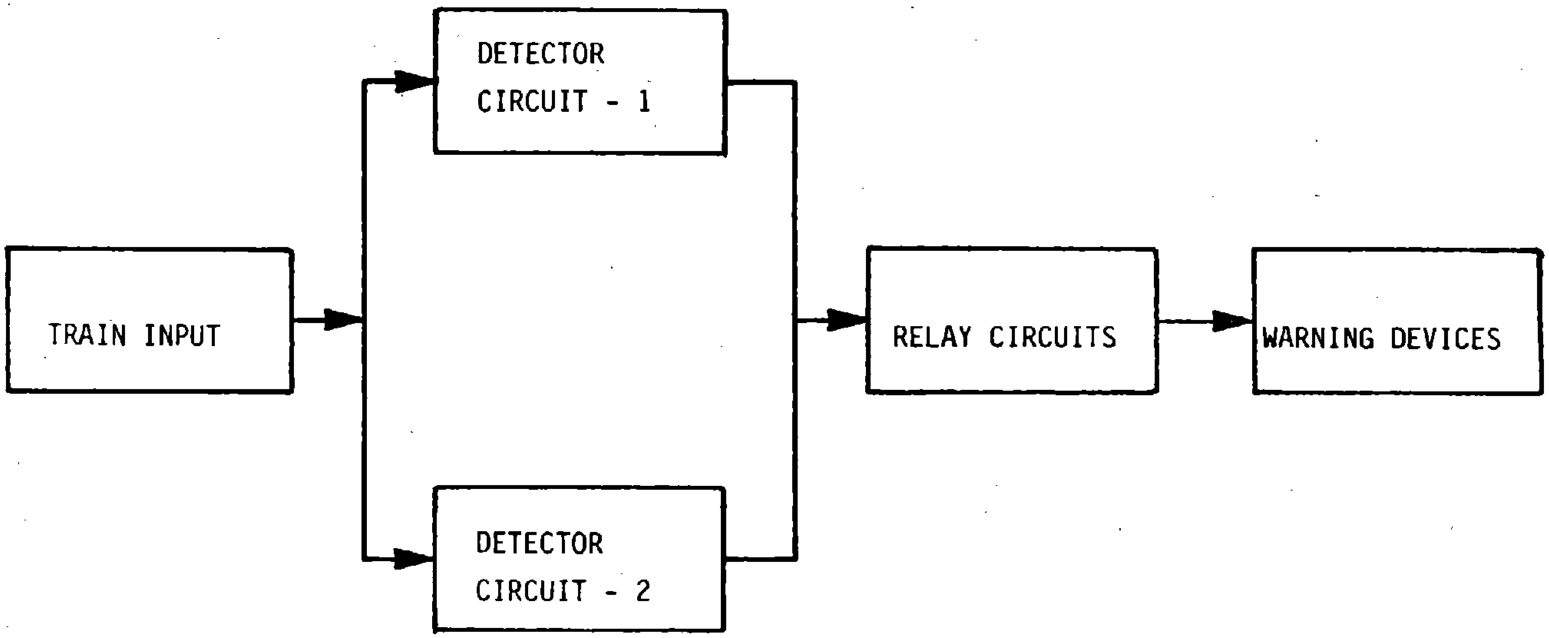


Figure 12 DOUBLE DETECTOR REDUNDANCY

There is one more potent method of eliminating failures. Failure mode analysis is the determination of all possible failure modes of a system. Given such information, corrective measures to reduce the likelihood of failure can be built into the system. Such efforts can markedly increase system reliability.

RESOLUTION

The design of a feasible point sensor system must incorporate all of the above methods of increasing reliability. The use of redundent components can convert the costly problem of occasionally missing axles. Failure mode elimination techniques combined with redundent design can enable levels of reliability comparable to any existing system.

5.1.5 SYSTEM COST COMPARISON

Estimates of the approximate current cost of the point sensor detection system is shown in Figure 5.13. The prices cover all aspects of materials, construction and installation necessary to produce signals indicating the state of occupancy of the track block at a "typical" crossing.

This section is meant to provide a means of cost comparison between systems. Accurate long range preduction of the cost of all fail safe system is made difficult by seemingly small details that demand expensive solutions. However, to the extent that the proposed costs reflect system simplicity and reliability, the final system costs will be proportional to those give here.

The magnetic sensor system configuration is shown in Figure 5.1. It consists of five sensor pairs linked by one of three different transmission schemes. A control box for signal conditioning and transmission accompanies each of the sensor pairs. The box is mounted on a concrete slab.

Not included in this estimate is the cost of motorist warning signal itself and the cost of the relay logic that controls these signals. This exclusion will not affect the relative cost between system since it is common to them all.

Figure 5.13 POINT SENSOR SYSTEM COST

	COMMUNICATIONS LINKS		
	WIRELESS	OPTICAL	CABLE
TRANSMITTER			
o Enclosure	900	900	900
o Electronics	1800	1500	950
o Antenna	1570	—	—
o Protection CKT	—	—	1800
o Hardware	680	450	650
o Battery	1350	1350	1300
TOTAL	6300	4200	5600
RECEIVER			
o Electronics	600	650	700
o Enclosure	250	250	250
o Protection CKT	—	—	1800
o Antenna	550	—	—
o Hardware	200	200	250
o Battery	300	300	300
TOTAL	1900	1400	3300
CABLE (1 mile)			
TOTAL	—	3000	5000
TRANSDUCER			
TOTAL	1400	1400	1400
INSTALLATION			
TOTAL	3,000	5,000	5,000
TOTAL	12,800	18,000	20,000

5.2 CONTINUOUS SENSOR SYSTEM

Continuous sensor approaches identified in Section 4 are limited to the radio frequency (electromagnetic) area. We have limited our analysis in this area to the study of transmission lines because of their inherent fail safe and proximity detection characteristics. Other (antenna-type) radio frequency techniques have, in previous studies, been shown to be subject to spurious reflections and environmental conditions.

The transmission line system consists of propagating a low frequency electromagnetic wave form down a properly terminated transmission line and detecting any reflected signal caused by a vehicle perturbing the electromagnetic field surrounding the line.[26] The magnitude and phase of the reflected signal can be measured as a function of time to provide all the necessary data to (1) establish the presence of vehicle in the detection range; (2) the distance of the vehicle from the observation point; (3) the direction of travel of the vehicle; and (4) the relative velocity of the vehicle with respect to the observation point. This method is somewhat similar to radar except instead of transmitting the energy into free space by an antenna, it is impressed onto the transmission line which guides the waves along the desired path and keeps its extent within bounds.

5.2.1 SYSTEM REQUIREMENTS/CONFIGURATION

The transmission line configuration is shown in Figure 5.14. The optimum configuration/location of the transmission line will have to be determined with field testing. The best location is between 1.5 feet to 3 feet away from the truck of the car in order to prevent interference with multiple track operations. Also, the transmission line can determine train speed and acceleration. With these parameters it may not be necessary to have an island circuit if one can assure that no portion of a train is on the highway using these parameters.

The transmission line detection system (Figure 5.15) consists of two functional areas, the tranmission line and the excitation and measuring system. Paragraphs 5.2.2 and 5.2.3 will discuss these in detail.

5.2.2 EXCITATION/MEASURING SYSTEM

The excitation and measuring system is very similar to the type of system which is used in the modern laboratory to measure unknown impedance.

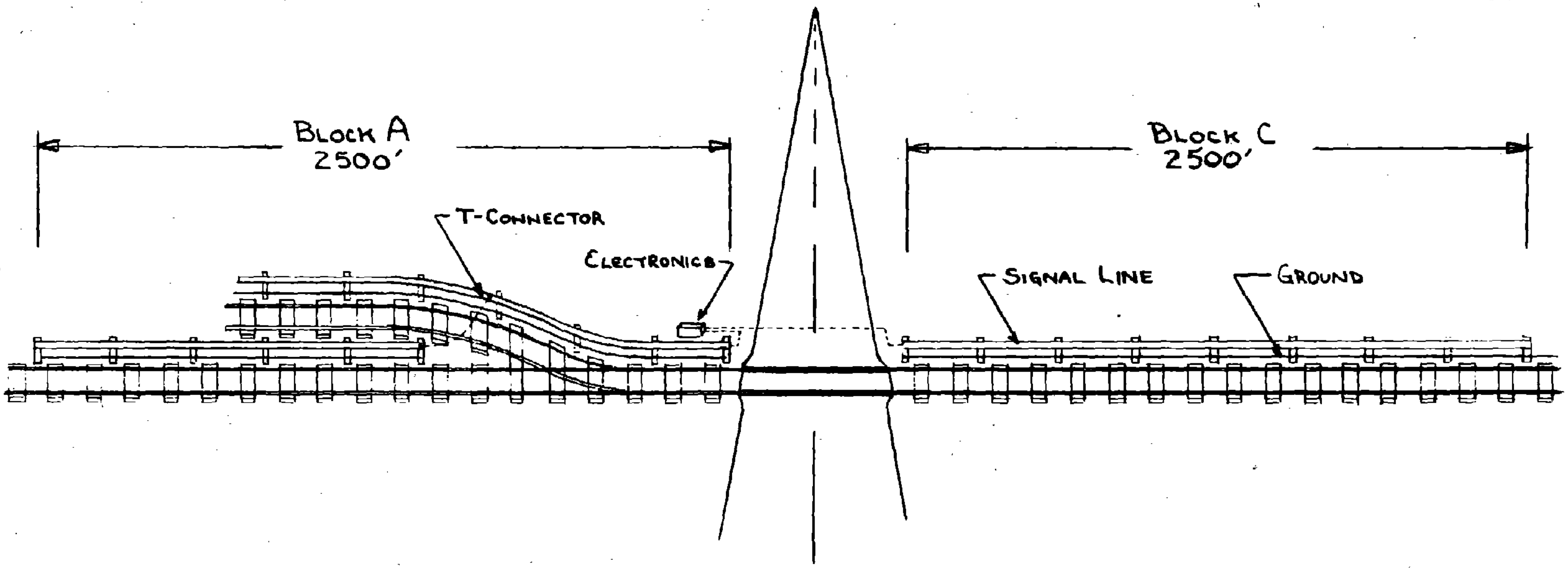


Figure 5.14 TRANSMISSION LINE SENSOR CONFIGURATION

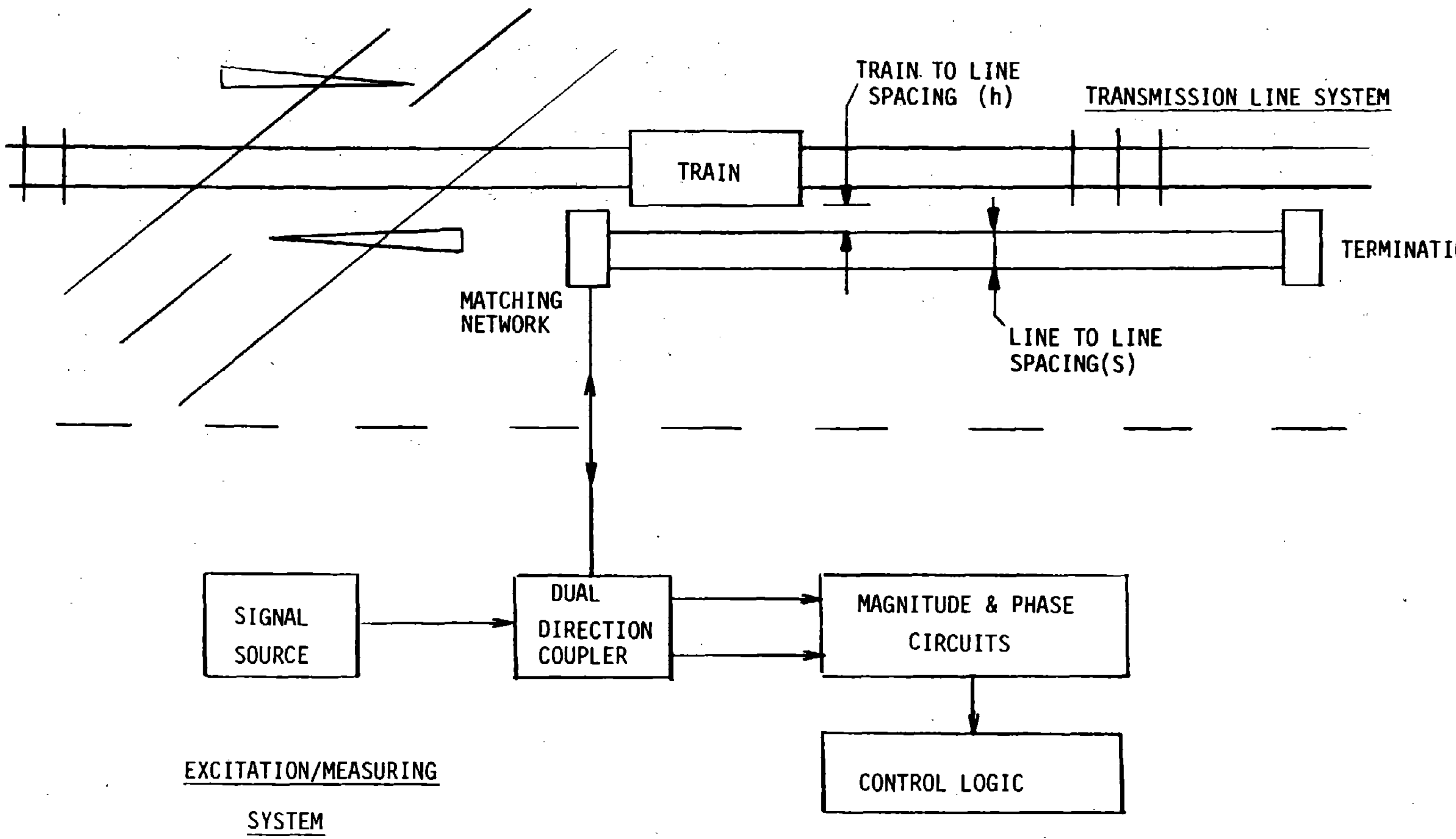


Figure 5.15 TRANSMISSION LINE BLOCK DIAGRAM

It consists of a low-powered signal source feeding power to an unknown impedance through a dual direction coupler. The dual direction coupler has two outputs. The signal from output-1 is proportional to the power being fed to the unknown impedance (incident signal). The signal from output-2 is proportional to the power being reflected from the unknown impedance (reflected signal). The network analyzer is a device which measures the relative phase and magnitude of the reflected signal with reference to the incident signal (reflection coefficient). The reflection coefficient information can be presented in polar form (Smith Chart or Reflection Coefficient Display) or in magnitude and angle form (metered output) and at the same time be converted to digital form for ease of computer interfacing.

Because the open-wire transmission line is properly terminated, the impedance, Z_o, of the transmission line is matched to the 50 ohm impedance of the measuring system, and when no vehicle is in close proximity to the transmission line, the reflection coefficient is zero.

As soon as a vehicle enters the detection zone, the system is no longer matched and a reflected signal is detected. The magnitude of the detected signal with respect to some set reference can be used to alert the computer that a vehicle is present in the detection zone. The phase of the reflected signal (delay) is related to the location of the vehicle in detection zone. The change in phase ($\Delta\theta = \theta_2 - \theta_1$) with respect to the change in time ($\Delta t = t_2 - t_1$) between measurement is related to the vehicle velocity within the detection zone. As the phase changes, the direction of change is an indication of the direction the vehicle is moving through detection zone.[26]

5.2.3 TRANSMISSION LINE REQUIREMENTS

Figure 5.16 shows a rough sketch of a typical truck with a possible arrangement of a transmission line in close proximity to the truck. Also shown is the maximum car dimentions with recommended clearance for structures.

Figure 5.17 shows the transmission line arrangement. Steel galvanized pipes are used for the transmission line.

This model is used to calculate Z_o of the line.

$$Z_o = \frac{276 \log\frac{s}{r} \log\frac{4h^2}{sr}}{\log\frac{4h^2}{r^2}} = 256 \text{ ohms}$$

where
$h = 60''$
$2r = 1''$
$s = 9''$

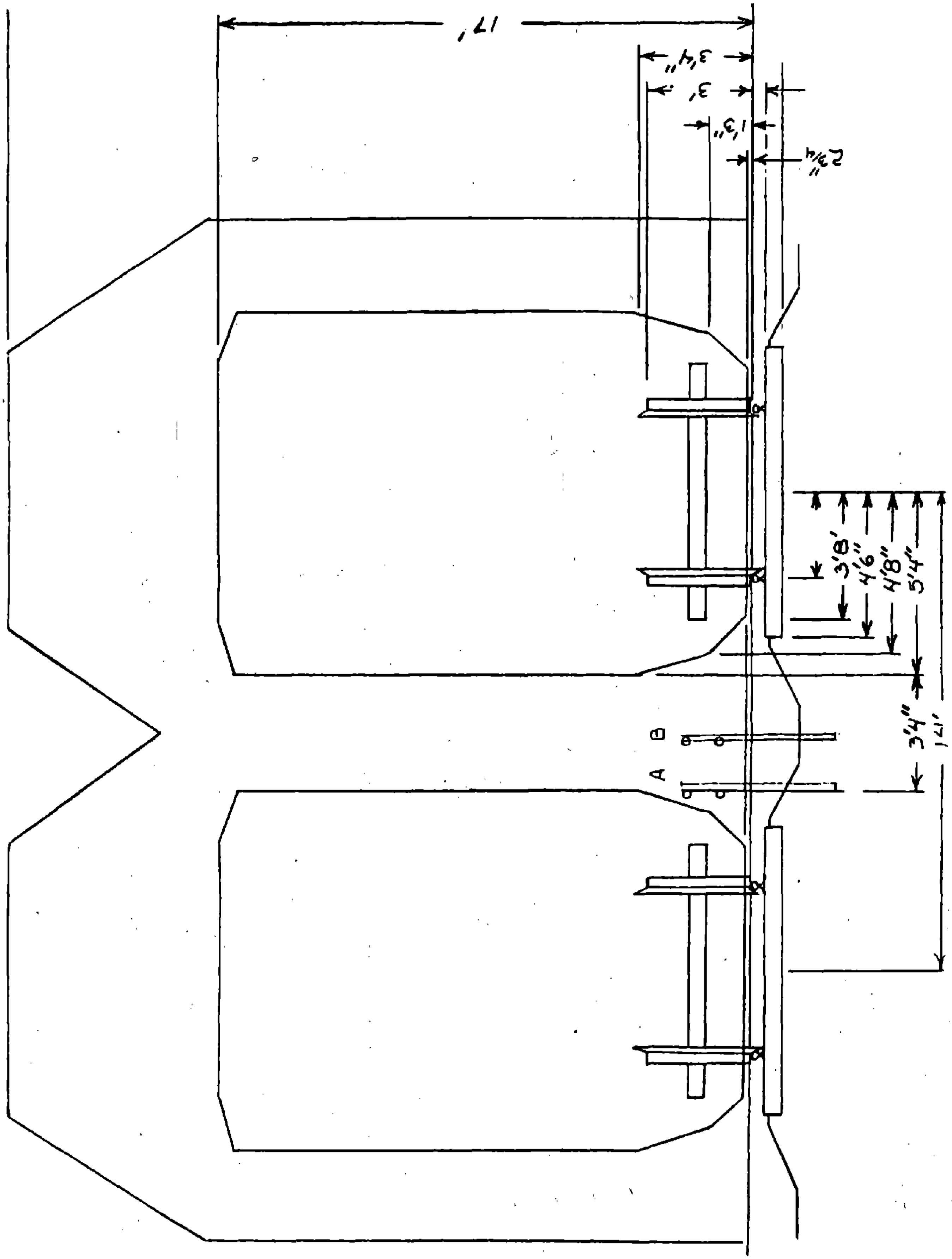


Figure 5.16 TRANSMISSION LINE CONFIGURATION

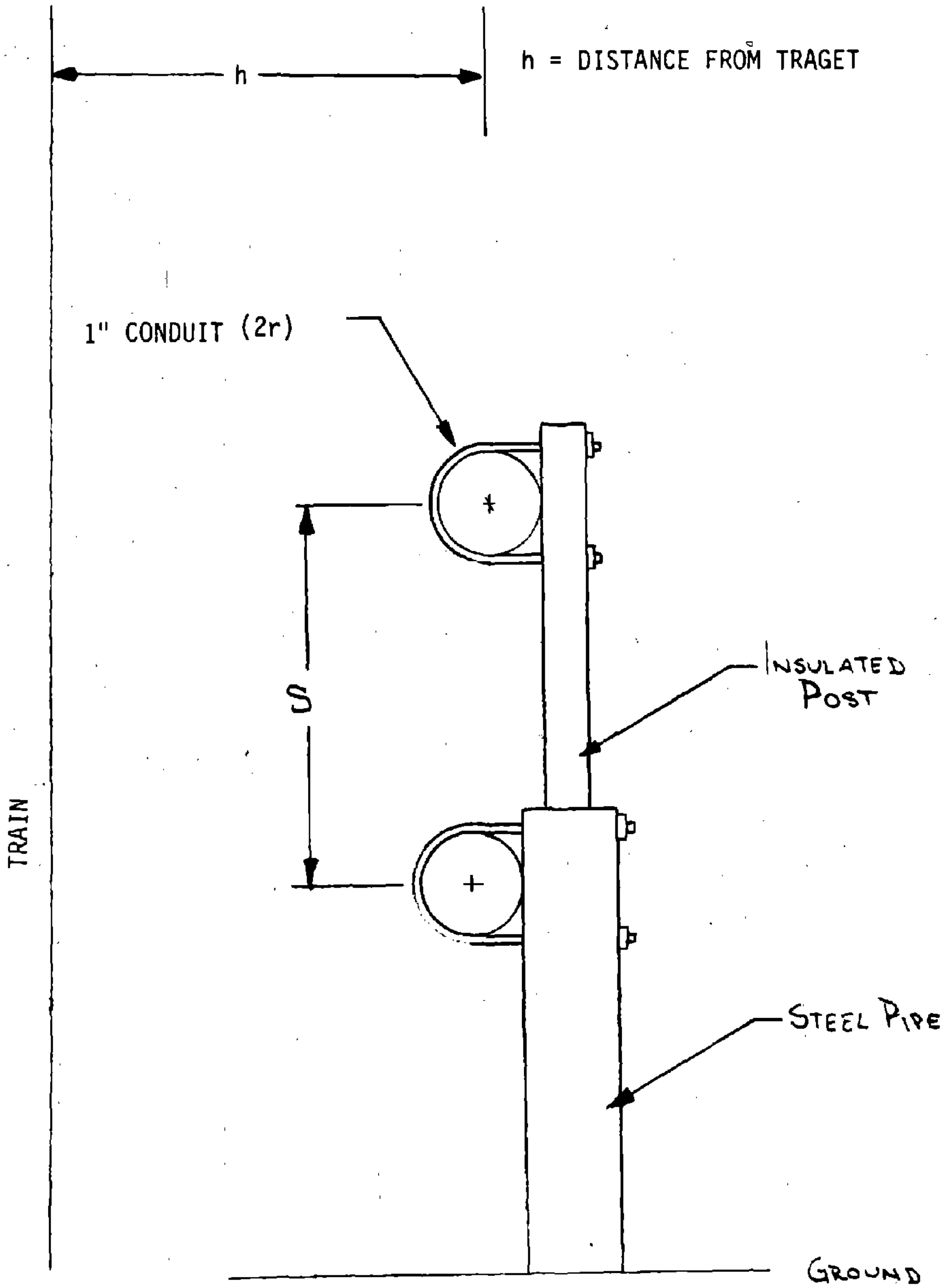


Figure 5.17 TRANSMISSION LINE SUPPORT

A resonable length detection zone would be approximately 1/2 mile or about 2500 feet. A frequency should be selected such that no distance uncertainties exist. Depending on the instrument used to measure the phase delay, the range of measurement is usually ±90 or ±180 electrical degrees. With a 90^0 or 180^0 off-set, the total measurement range is either 180 or 360^0. If one requires the phase delay of the reflected signal to be at most 180 electrical degrees, the length of the transmission line must be $\lambda/4$ in length.

Therefore if $L=2500$ ft$=\lambda/4$, then $\lambda=10{,}000$ ft.

The frequency must then be

$$f = \frac{V_i}{\lambda} = \frac{9.842 \times 10^8}{10^4} = 9.842 \times 10^4 \text{Hz}$$

$$f = 98.42 \text{ KHz}$$

For a phase delay of 360^0 the frequency would be $f = 196.84$ KHz.[26]

5.2.4 FAILSAFE/RELIABILITY CONSIDERATIONS

The reliability of a transmission line sensor system depends on the reliability of the entire system, which include the transmission line and excitation/measurement sub systems. Failure mode techniques and redundent design as discussed in paragraph 5.1.4 still hold true for the transmission line sensor system.

The transmission line consists of a minimum number of electrical parts, as shown in Figure 5.18 therefore it has a high potential of having a high reliability. Any failure in this circuit (open or short) will cause a reflection of the transmitted signal which in turn give a train present indication to the grade crossing. Such a circuit is analogous to the fail-safe basic track circuit.

5.2.5 TRANSMISSION LINE SYSTEM COST

The approximate cost of the transmission line system is shown in Figure 5.19. This is based on current prices of materials shown in Figure 5.17. The prices cover all aspects of materials, construction and installation necessary to produce signals indicating the state of occupancy of the track blocks. Not included in this estimate is the cost of highway warning signals nor the cost of relay logic that controls these signals.

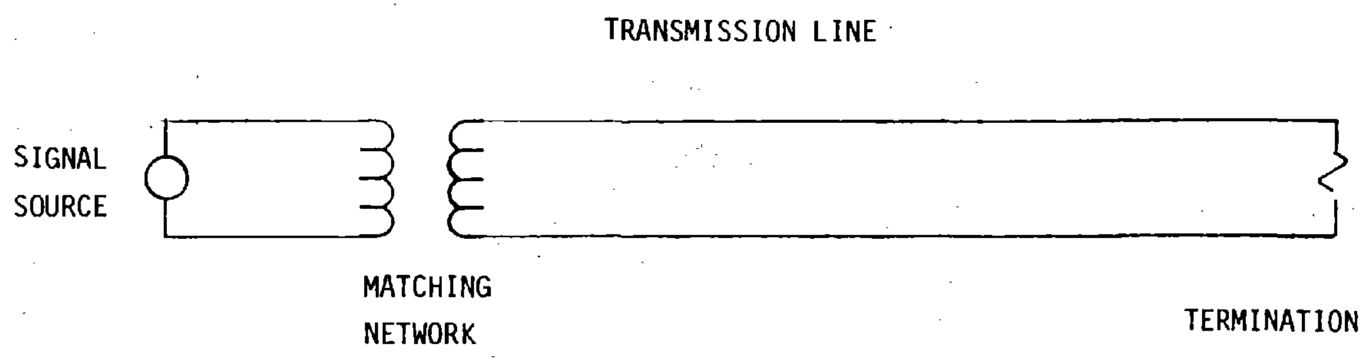


Figure 5.18 TRANSMISSION LINE

Figure 5.19 TRANSMISSION LINE SYSTEM COST

TRANSMISSION LINE (1 Mile)		
o Termination	$100	
o Matching Network	$100	
o Transmission Line	1.22/ft.	
Total		$ 8,000
EXCITATION/MEASUREMENT		
o Direction Coupler	$200	
o Analog Circuit	$1,000	
o Data Processor (μp)	($1,000)	
o Lighting Protection	$500	
o Package	$400	
o Cable	$600	
o Power Supply (Batteries)	$300	
Total		4,000
INSTALLATION		7,900
TOTAL		$19,900

5.3 GATE CONTROL LOGIC

The logic required to implement the gate control logic circuit is shown in Figure 5.20. This circuit will generate the train present signal when a train enters block A or block C (approaches blocks). Also it cancels the train present signal after the train leaves block B (island circuit). This circuit will duplicate the present stick relay circuit. One gate control circuit is required for each track (Figure 5.21). Figures 5.22 to 5.24 shows circuit operation for various train combinations and lengths.

5.4 TRADE-OFF ANALYSIS

In the previous sections, system considerations for both the magnetic point sensor and the transmission line sensor have been discussed. Figure 5.25 is a trade-off analysis between these off-track sensing candidates and the basic track circuit. There is no "obvious" better choice. Eash has the potential for replacing the basic track circuit. However questions remain for both.

The point sensor system has been developed to the limits of current technology. Information indicates that reliability (fail-safe) problems could occur. Presently available point sensors do not count with total reliability. Any grade crossing system implemented using such sensors must consider this problem in depth. The type of sensor needed is described in Section 5.1.1. Transmission line systems have not been developed to date for this application.

In order to help make a more informed selection between these two sensing approaches for follow-on development, transmission line feasibility demonstration is required. The next section will address this problem. It describes a field test run to determine transmission line sensing feasibility.

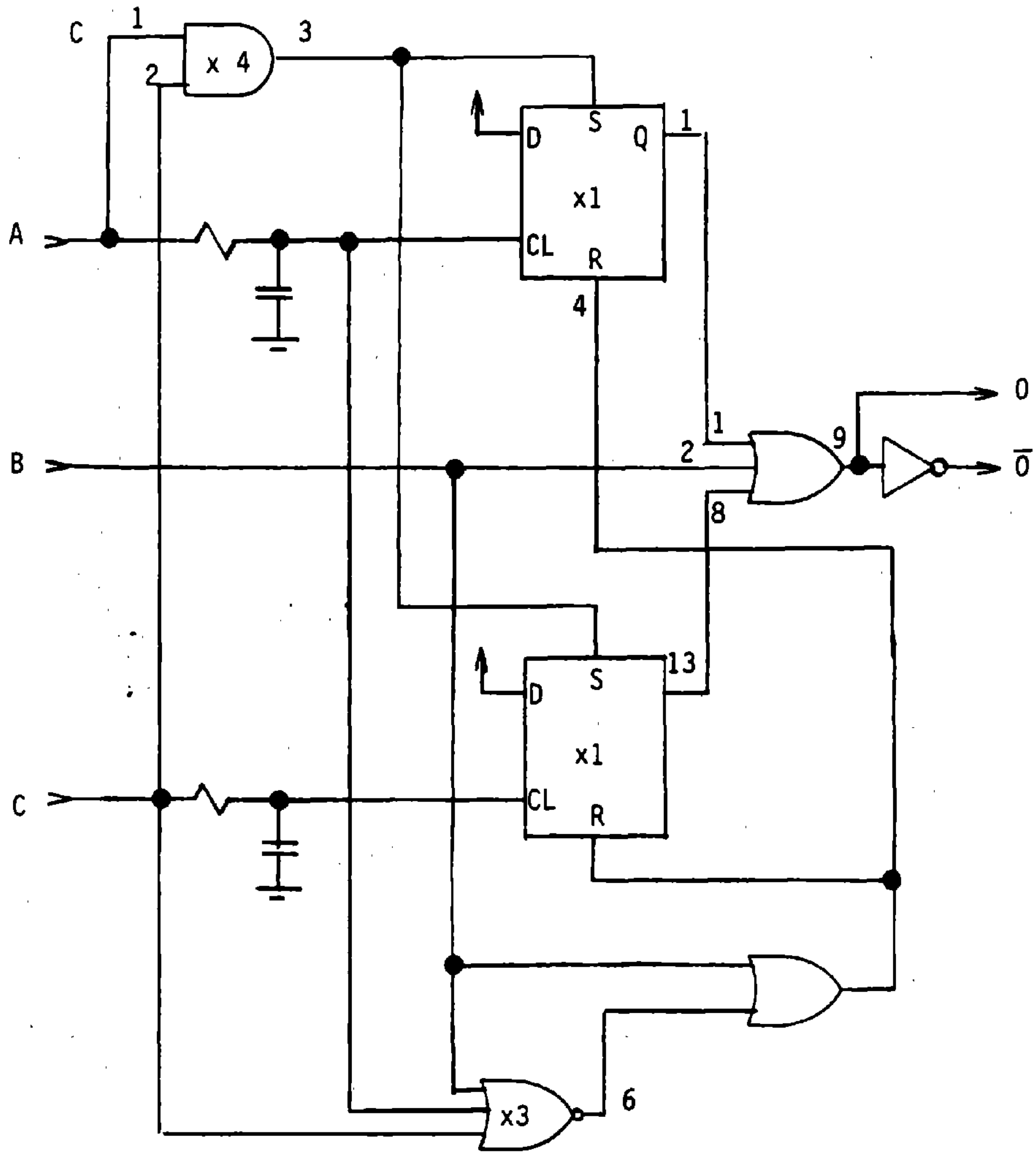


Figure 5.20 GATE LOGIC

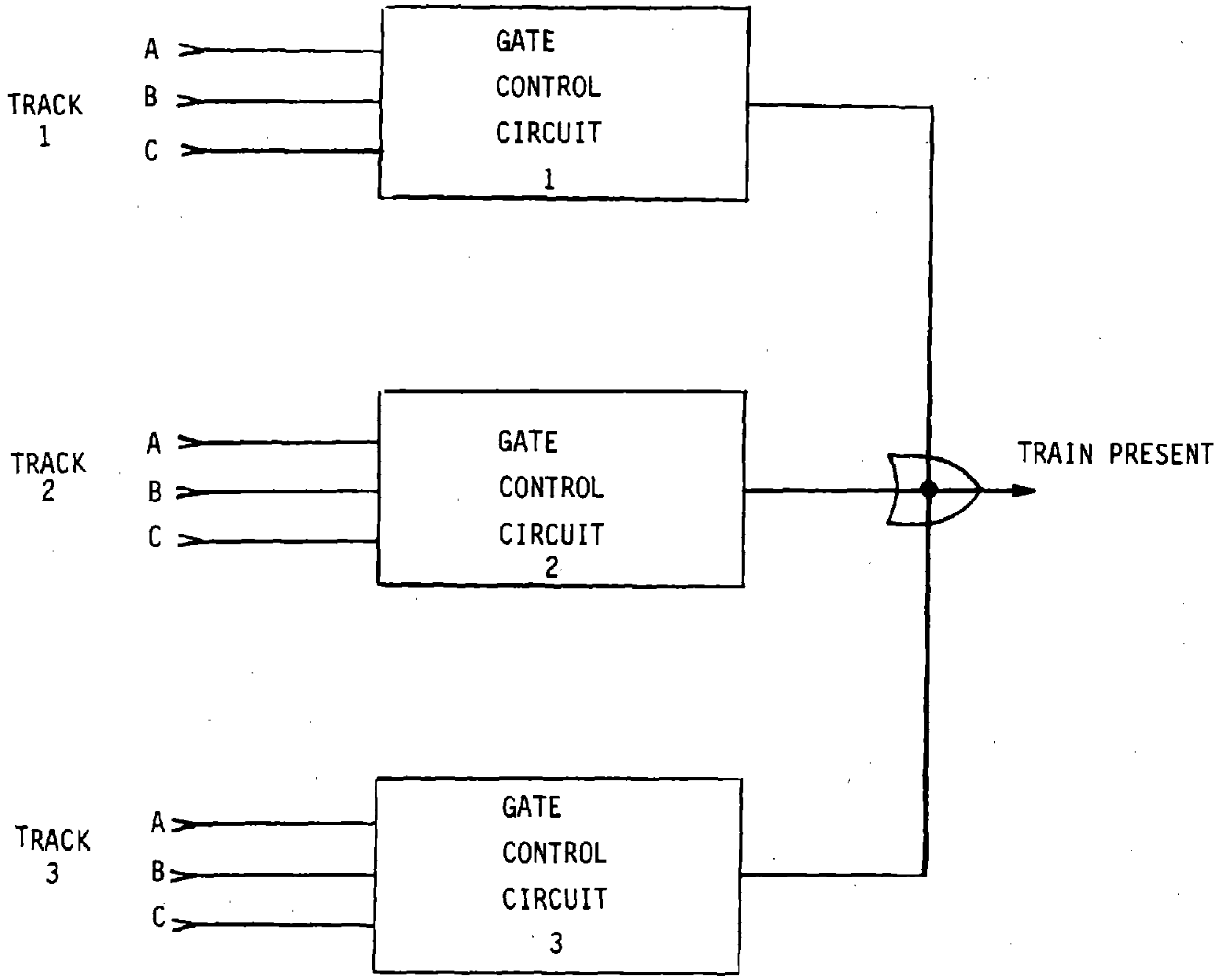


Figure 5.21 MULTIPLE TRACK OPERATION

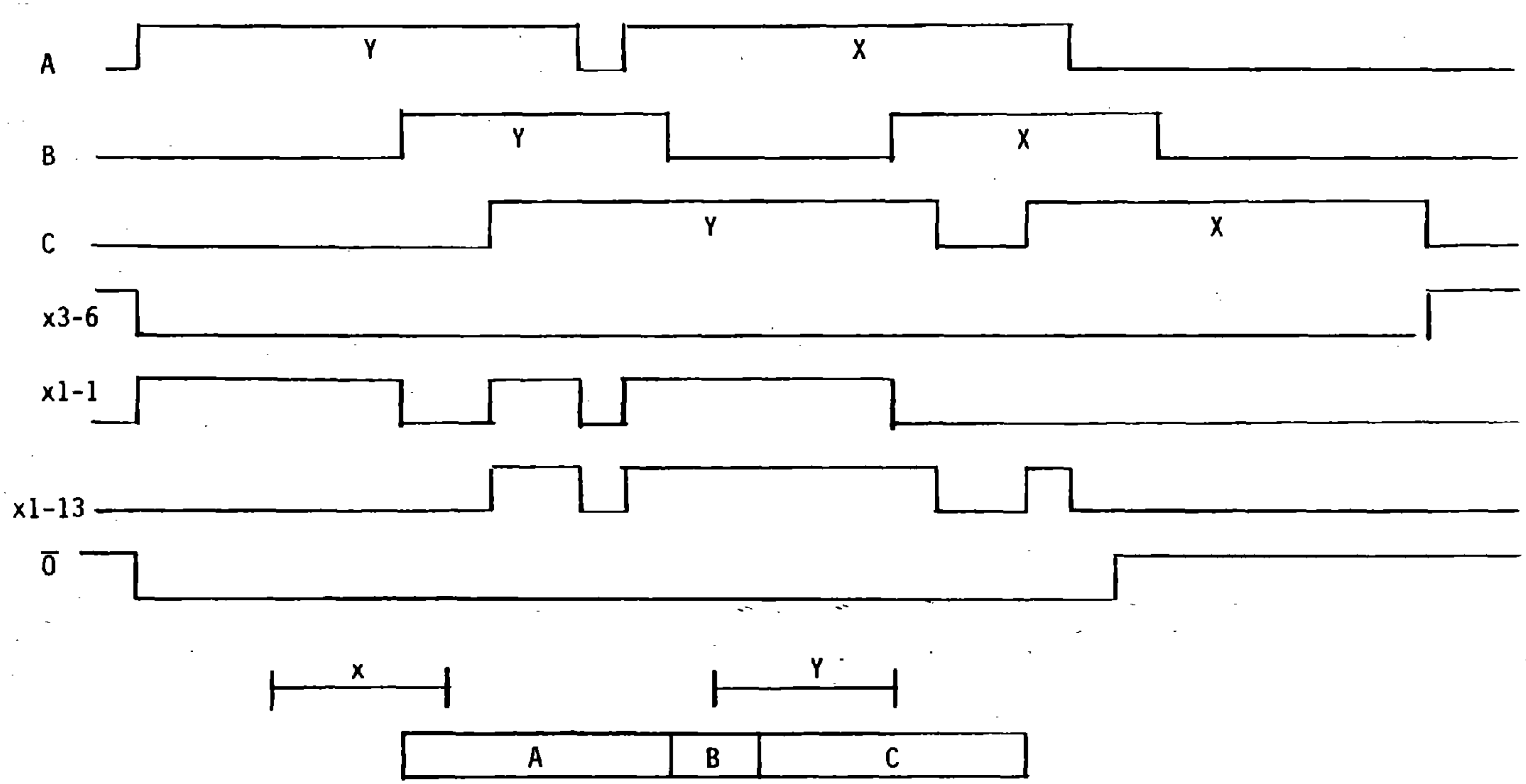


Figure 5.22 TRAINS X & Y

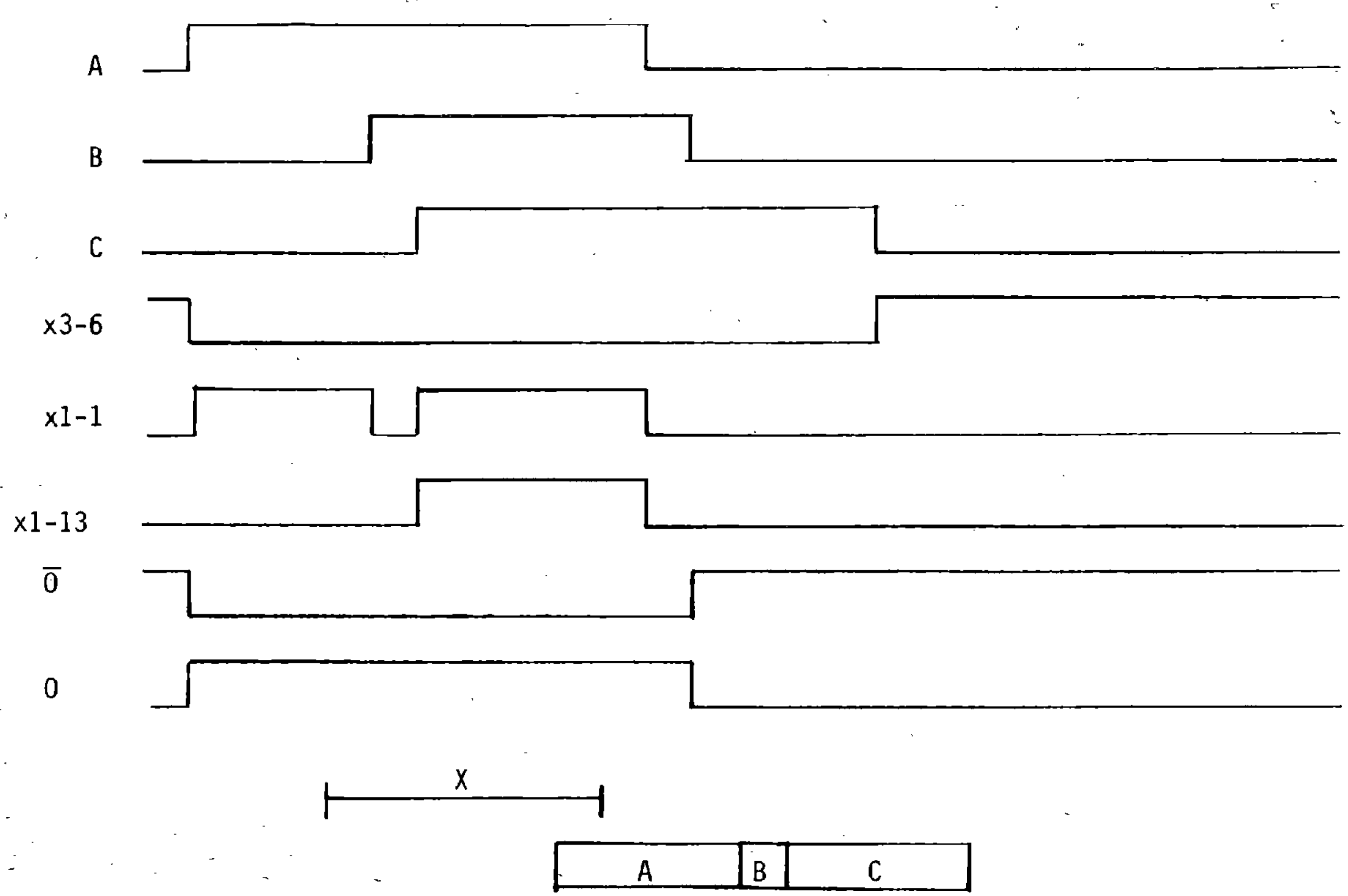


Figure 5.23 TRAIN X LONGER THAN BLOCK A

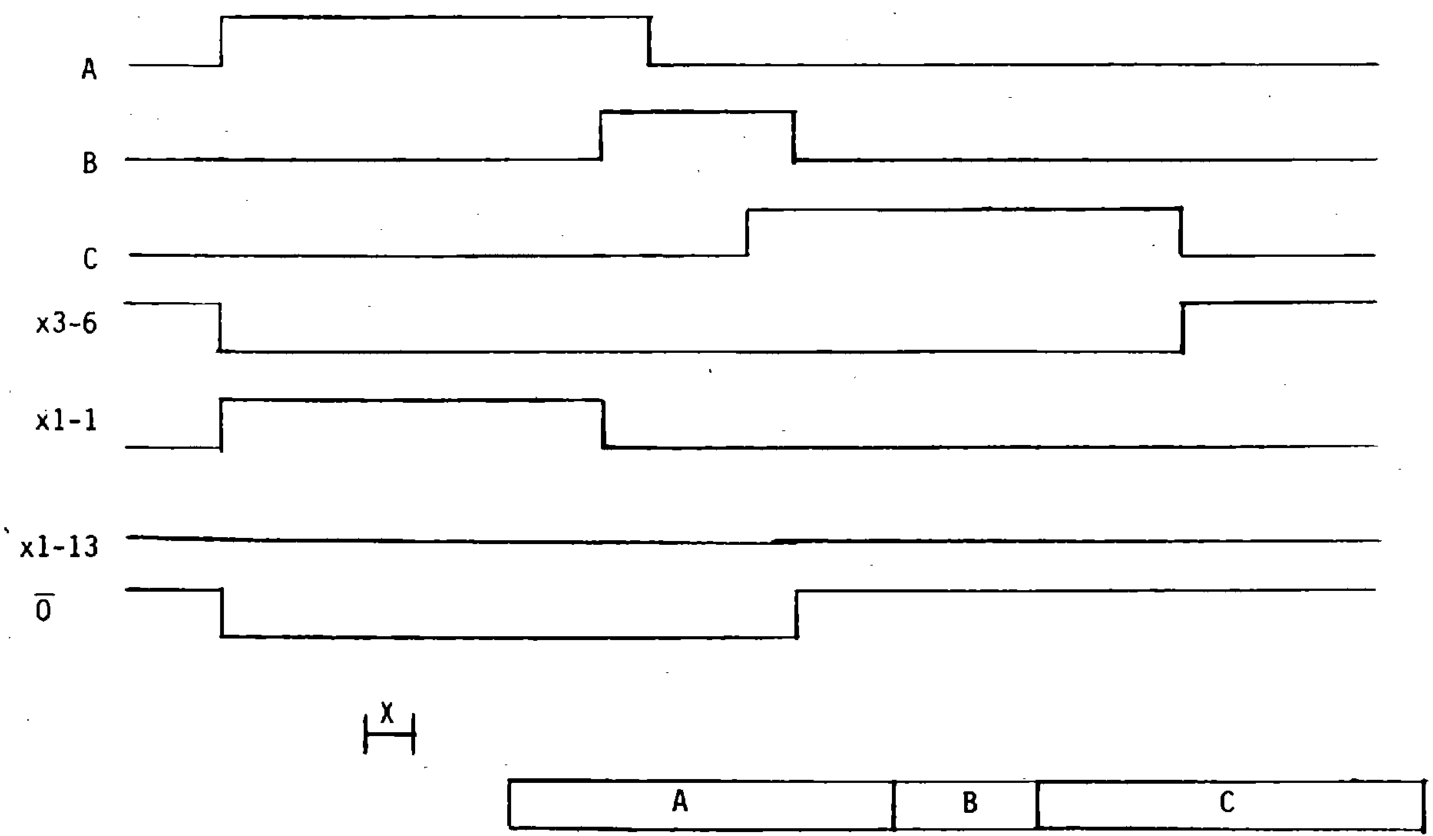


Figure 5.24 TRAIN X

Figure 5.25

MAGNETIC POINT SENSOR/TRANSMISSION LINE TRADE-OFF ANALYSIS

Parameters	Basic Track Circuit	Point Sensors	Transmission Line
Commercial Availability	Yes	Yes	Yes
Service Life	30 years(13)	*	*
Constant Warning Time		Yes	Yes
Malfunction Warning	No	Yes	Yes
Maintenance Rqmts.			
Schedule Interval	6 Months	**	**
MTTR			
Accessible	Yes	Yes	Yes
Personnel			
Power Requirements	Several Watts Min	Low	Low
Cost			
Initial	10K	10K	12K
Installation	9K	5K	8K
Maintenance	500	**	**
Installation Rqmts.			
Above	Yes	Yes	Yes
Below	No	No	No
Attached	No	Yes	No
Package Rqmts.			
Compatibility/Flexibility	Yes	Yes	(See 6.2.3)
Public Safety	No Safety Hazard	No Safety Hazard	No Safety Hazard
Train Speed Range	0 - 125 MPH	0 - 125	0 - 125
Adaptability			
Multiple Track	Yes	Yes	Yes
Curved	Yes	Yes	Yes
Reliability			
MTBF - Detector	High	High	High
False Alarm	Water, Ice or Brine	High, Magnetic Field	Low
Environment			
Temperature	$-40^{o}F$ to $+185^{o}F$(14)	*	*
Humidity	0 - 100% (2)	*	*
Rainfall	5 In/Hour (2)	*	*
Electrical Surges	3,000 VAC(14)	*	*
Electromagnetic	Insensitive	**	**
Shock & Vibration	Not Affected	Not Affected	Not Affected
Failure Mode	Fail-Safe	Fail-Safe by Design **	Fail-Safe,**
Off-Track Rail Vehicle Detectable	No	Yes	Yes

* Same as BTC or Better

** Remains to be Demonstrated

6. FIELD TEST

The objective of the field test was to determine the feasibility of detecting trains with a transmission line sensor. The test addressed the following areas:

- o Location of transmission line
- o Transmission line configuration
- o Magnitude of detected signal (gives indication of train presence)
- o Phase of detected signal (gives location of train in detection zone)
- o Change of phase with respect to time (related to train velocity in detection zone)
- o False alarms
- o Failsafety
- o Interference with railroad operation
- o Installation requirements

6.1 TEST PROCEDURE

6.1.1 TEST SETUP

Figure 6.1 shows the transmission line used for field testing. The total transmission line length is 250 ft. A phase delay of 180° provides maximum sensitivity to the train. Since 180^0 is a half of a wave length, and the length of the line is 250 feet, the frequency of transmission is,

$$f = \tfrac{1}{2} \times \frac{V}{250} = \frac{9.8 \times 10^4}{500} = 2 \times 10^6 \text{ Hz},$$

where V is the speed of light.

For a 2500 ft length transmission line, the frequency would be

$$f = \tfrac{1}{2} \times \frac{V}{2500} = 2 \times 10^5 \text{ Hz}.$$

Figure 6.2 shows the test setup in a block diagram form. Inter connections required between test equipment is shown. A detailed functional description is given in Section 5.2. Figure 6.3 shows the matching network used in the field. An impedance matching transformer was used for this application. At the other end of the line is located the line termination (Figure 6.4). The wide metal plates connecting the termination resistor to the line are used to minimize the effect of inductance, likewise with the parallel resistor combination.

Figure 6.1 THE TRANSMISSION LINE

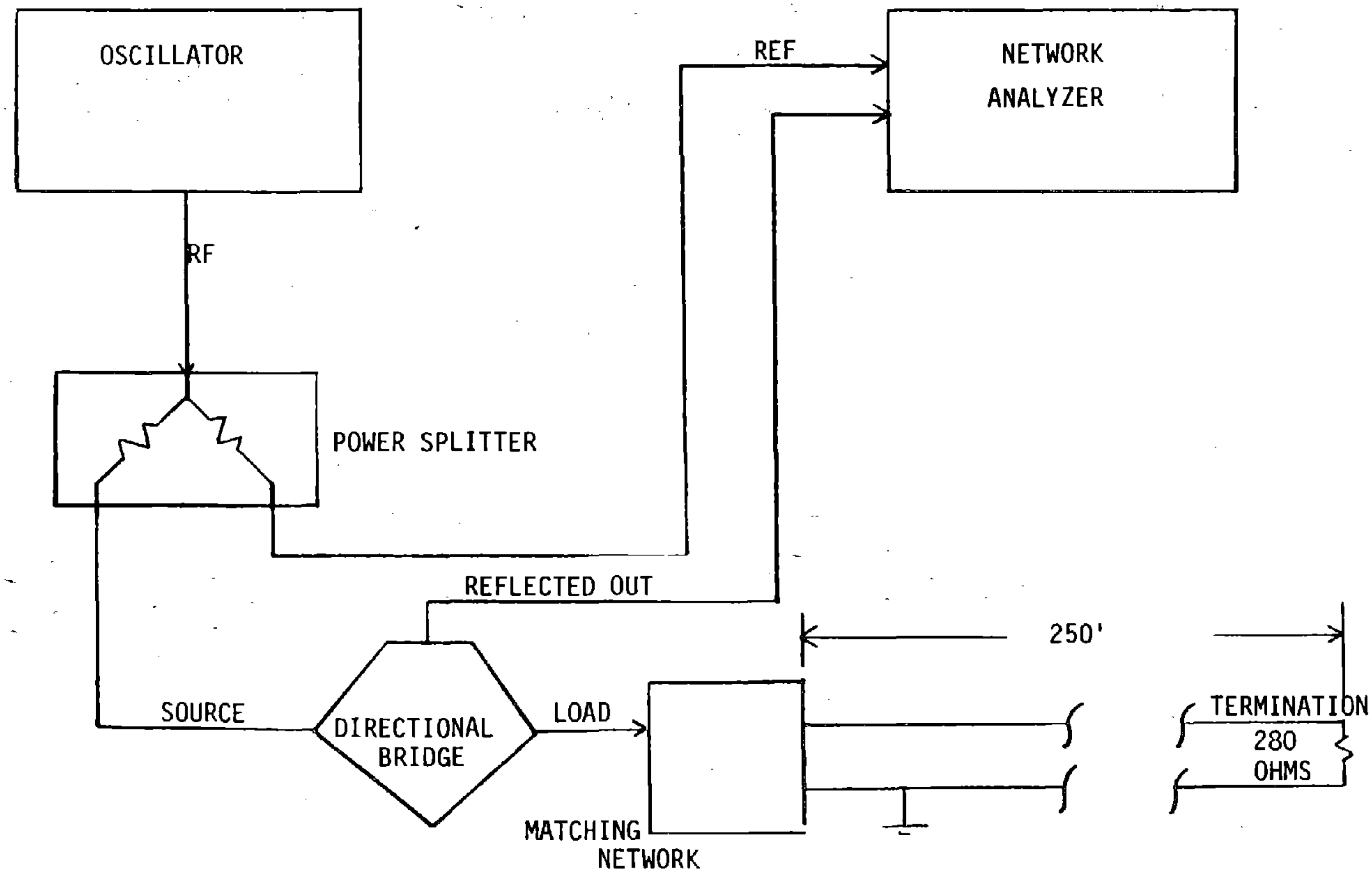


Figure 6.2 SYSTEM BLOCK DIAGRAM

Figure 6.3 MATCHING TRANSFORMER

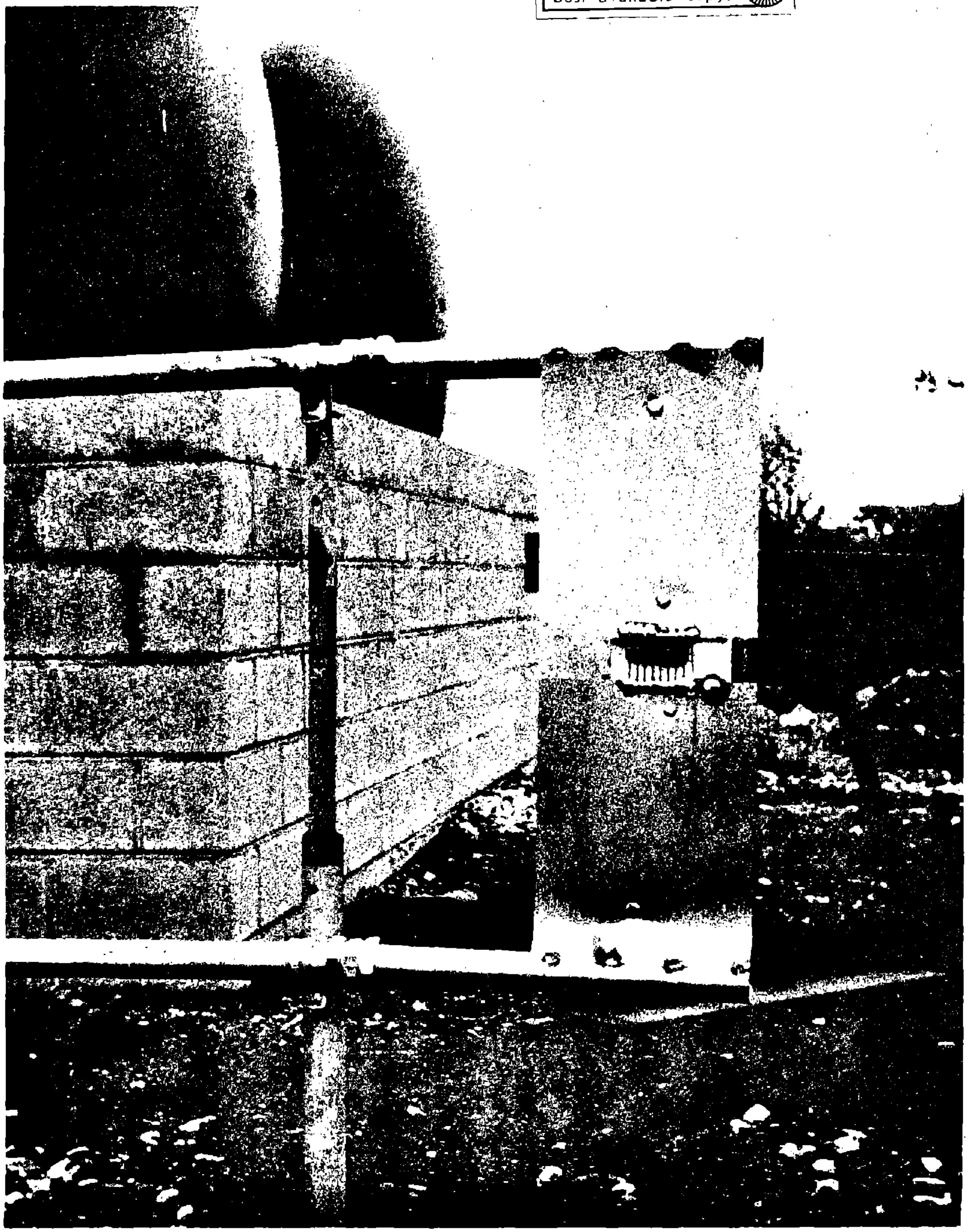


Figure 6.4 TERMINATION

6.1.2 TEST EQUIPMENT REQUIRED

Equipment to be used for testing the transmission line includes:

- o Dual directional coupler (HP8721 A)
- o Signal source (Wavetek 164)
- o Network analyzer (HP8407)
- o Matching network
- o Transmission line
- o Termination

GARD provided all required test equipment and personnel. The tank car repair shop (GATX) located in East Chicago, Indiana provided a track area for testing.

6.1.3 TEST PROCEDURES

Data obtained during testing was recorded on a form such as shown in Figure 6.5. Records were taken for each transmission line configuration (for example, line space at 12", ground plane at 12". Transmission line power at X1.) For this position, phase and magnitude data was recorded at intervals of 0, 62.5', 125'. 187.5', and 250' with the length of train noted on the form. Also conditions such as rain, snow, and electromagnetic interference (EMI) were noted on the form.

Data was taken for all transmission line configurations, except in cases where testing indicated that it was of little value. Also data was taken under various environmental conditions, as shown on the form, however all these conditions did not occur in the testing time period.

6.2 TEST RESULTS

Testing was done in two steps. First, it was determined if the transmission line works and functions as a low-loss transmission line. Next, amplitude and phase data was taken as trains passed.

6.2.1 LINE CONFIGURATION

Field testing indicates that the configuration shown in Figure 6.6 is a good low-loss transmission line. An important measurable quantity of a transmission line is the voltage standing-wave ratio (VSWR).

Figure 6.5 TRANSMISSION LINE DATA

DATE: TEST POSITION*: A B MEASURED PARAMETERS TRANSMISSION LINE CONFIGURATION	PHASE (ft. from source)	0 ft	62.5 ft	125 ft	187.5 ft	250 ft		MAGNITUDE (ft. from source)	0 ft	62.5 ft	125 ft	187.5 ft	250 ft	
LINE SPACE* 12 IN 9 IN 6 IN														
GROUND PLANE* 12 IN 24 IN														
TRANSMISSION LINE POWER* x 1 x 10 x 100														
NUMBER OF CARS														

CONDITIONS*:

FALSE ALARMS

RAIN
SNOW
DRY
EMI
ADJACENT TRAIN
AUTOMOBILE

FAIL SAFE

BREAK IN TRANSMISSION LINE
SHORT IN TRANSMISSION LINE

* Check all that apply

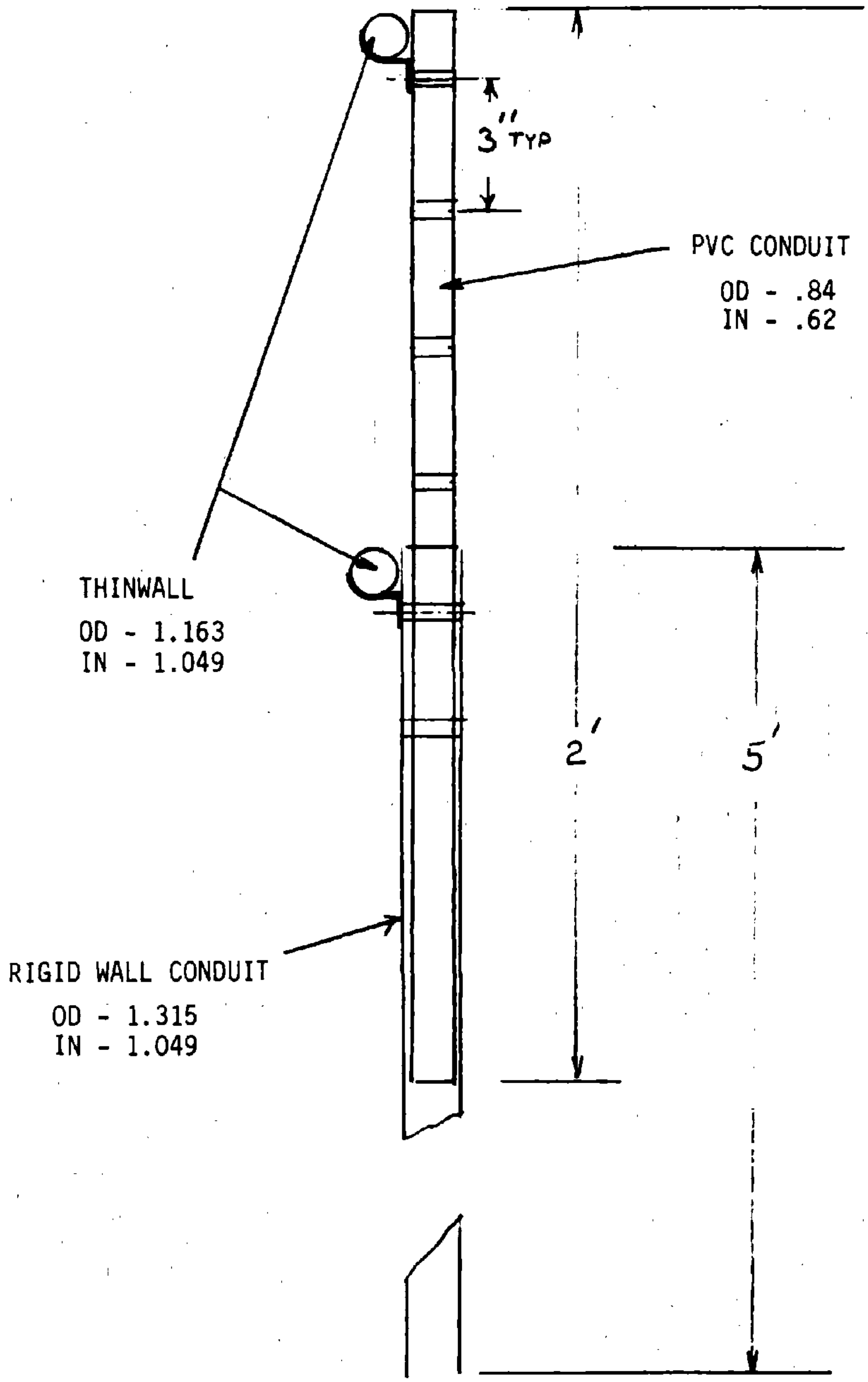


Figure 6.6 TRANSMISSION LINE STRUCTURE

Under the conditions when the terminating impedance Zr is equal to ∞, the VSWR is equal to Vmax/Vmin. For the conditions $\lambda/2$ the minimum voltage will occur at the midpoint of the tranmission line while the maximum voltage will occur at the end (See Figure 6.7). Field testing indicates a VSWR greater than 20. Another important measurable quantity is the transmission line loss. Under the conditions that a transmission line is terminated in its characteristic impedance, it will have equal amplitude of voltage along the line. That is, there is no standing waves on the line. Field testing indicates that the characteristic impedance for the transmission line in Figure 6.7 is 228 ohms. Also, field testing indicates that voltage of equal amplitudes were found along the transmission line (See Figure 6.8).

6.2.2 MAGNITUDE/PHASE DATA

The reflected signal amplitude is a function of the separation distance between the train and the transmission line. This distance does not change much from train to train, so large changes in amplitudes are not seen.

Data taken with a 9-inch (Zo=230 ohms) line space indicates that amount of perturbation to the line impedance is not large enough to give any desirable phase change. When the line space is increased to 18 inches (Zo=280 ohms), the change in line impedance is sufficient enough to give the results shown in Figure 6.9. As the length of the train increased in the detection zone, the amount of phase change is smaller. This is due to the effective change in the transmission line length as seen by the generator. When a small train, with respect to the length of the transmission line, passes the detection zone the generator sees a large impedance change (short) at a point. As the length of the train increases the generator sees an average impedance change over the length of the train. Therefore, some point past the leading edge of the train is seen as the leading edge. The data shows this is loosly related to the center of the length of the train within the sensing block.

Because of large changes in phase and magnitude, the presence of the train can be easily detected by the transmission line. In order to obtain accurate velocity measurements (required for constant warning time) the phase reading must be consistent from train to train regardless of length. The transmission line configuration evaluated in this program did not do this. A technique is shown in the Appendix which will provide a constant warning time.

6.2.3 COMPATIBILITY WITH RAILROAD OPERATIONS

The test location at East Chicago presented several operational problems. There were a large number of turnouts present. Daily operation

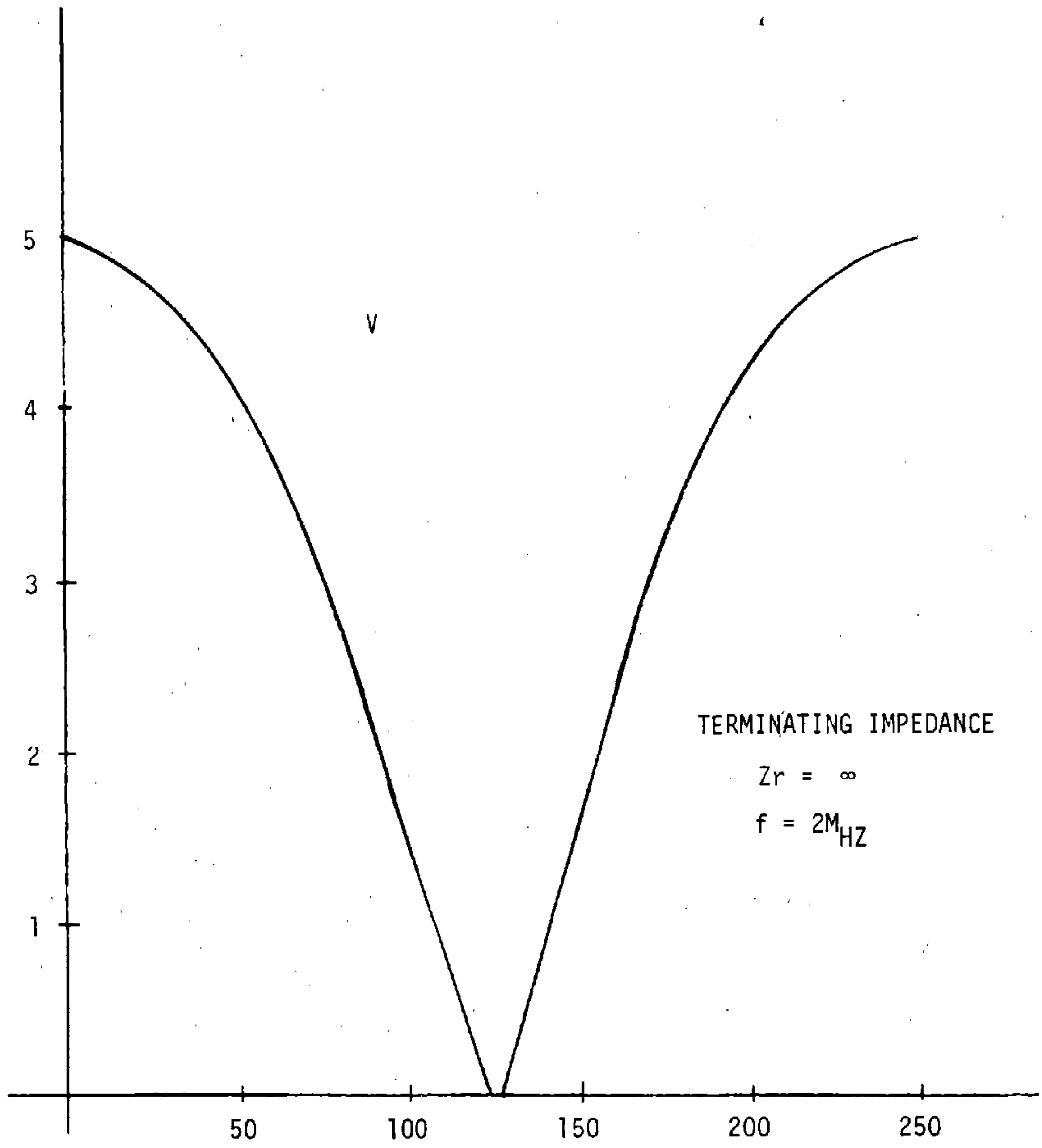


Figure 6.7 VOLTAGE DISTRIBUTION

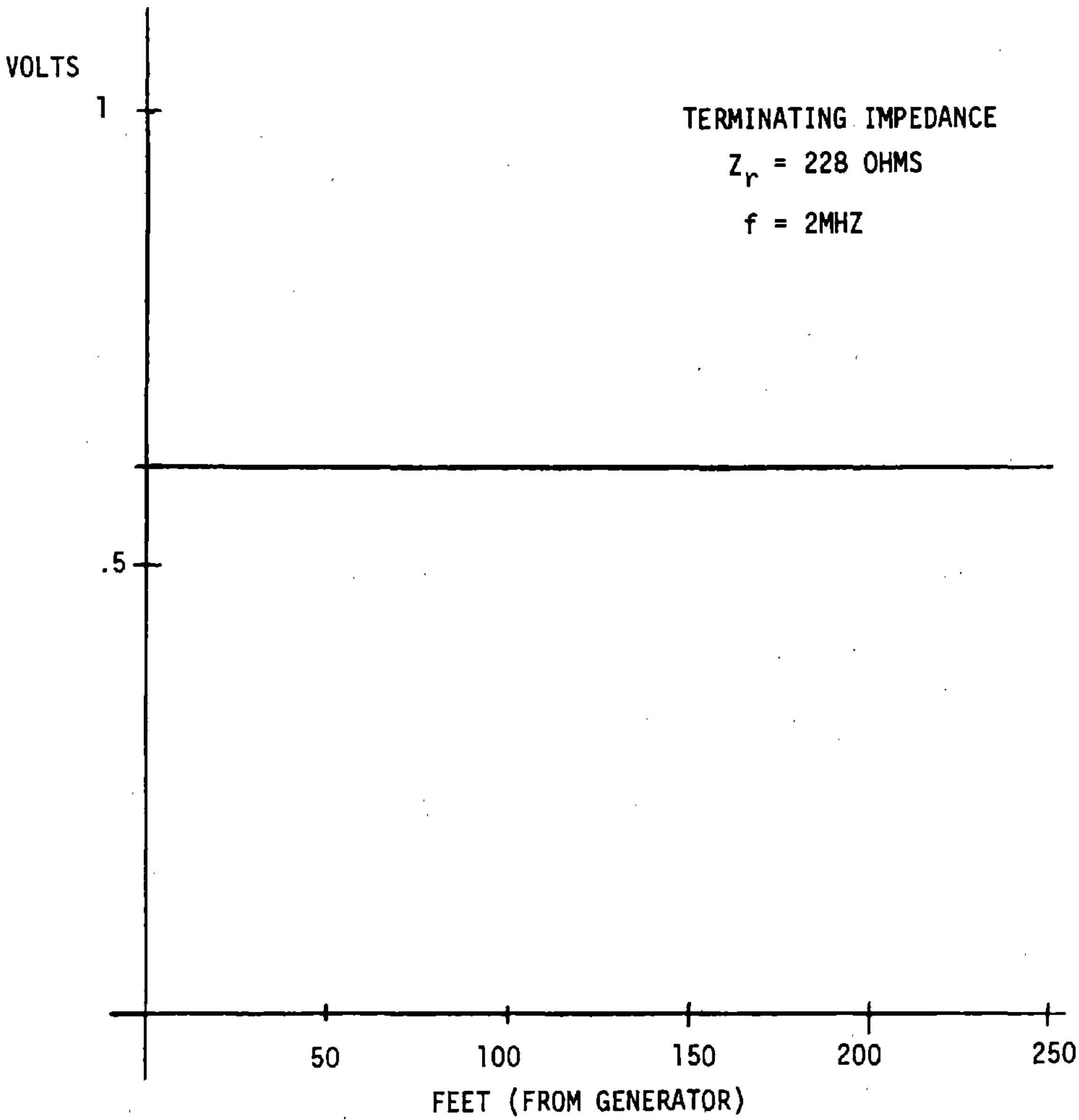


Figure 6.8 VOLTAGE DISTRIBUTION

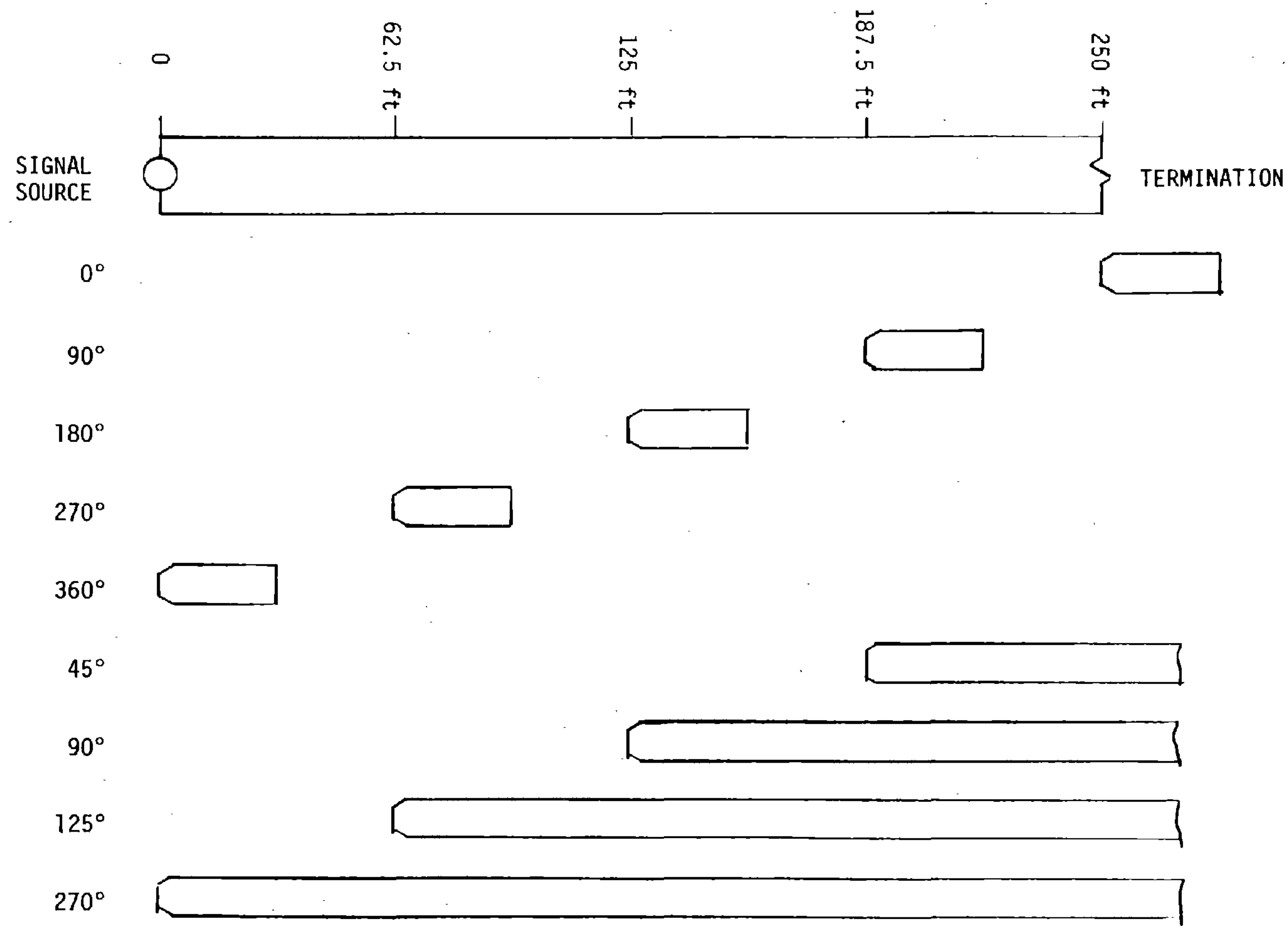


Figure 6.9 PHASE CHANGES

required continual switching operations. Also at this location an oversized crane was used in daily operation, which made it impossible to place the transmission line close to the track. Switching problems were eliminated by keeping the transmission line a sufficient distance away from the turnout. In the second case, signal levels obtained were large enough making it unnecessary to place the transmission line in close proximity to the track.

6.2.4 EMI

Radiation from power lines were detected on the transmission line. Noise levels were not of sufficient amplitude to create problems. In environments with high noise levels, a band pass filter could be used to extract the designed signal from the noise.

7. CONCLUSIONS AND RECOMMENDATIONS

7.1 CONCLUSIONS

Concepts which offer the greatest likelihood of off-track train detection are the magnetic point sensing system and the transmission line system. They operate in completely different sensing modes – point versus continuous. Both are feasible to use but both need additional engineering development in the sensor area. The amount of development required for each system will determine which is a better choice for this application.

Point sensors cannot currently count cars with absolute reliability. A development program is required to provide a sensor which can demonstrably perform such a task. While such a miscount may not create an unsafe failure, it can reduce system reliability and effectiveness. Current industry work is ongoing and the results should be monitored as inputs to this area.

The transmission line sensor, as tested, requires two areas of development: geometry and constant warning time applicability. Geometry centers around the development of a configuration which does not interfere with normal railroad operations. The development of a configuration with a low profile based on focused fields using plate type lines will minimize such interference. Constant warning time provision can be provided by use of a TDR (Time-Domain Reflectometer) approach which uses pulsed excitation. Such an approach may have implementation problems in a high noise environment. Another means is a possible standing wave "frequency partition" approach developed by GARD for this application. It is discussed in detail in the Appendix.

7.2 RECOMMENDATIONS

The transmission line sensing approach is intrinsically failsafe, reliable, and simple. Development of a simple geometry and constant warning time applicability will provide an inherently simpler and more straightforward approach to off-track train detection than the multi-sensor wheel counting scheme using magnetic point sensors. Thus, GARD recommends it for further development. A program approach which carries this concept through to final development and full scale test is presented here per requirement of the contract. The initial task in this effort is considered critical, and successful completion of this program is dependent upon successful results of this task.

The program is divided into five (5) tasks. Each task should be performed in the sequence given below:

TRANSMISSION LINE CONFIGURATION

An optimum transmission line configuration should be developed based on the results of the field test. The design must provide for optimum coupling with the train, maintain good low-loss transmission line features while keeping the interference with railroad operation to a minimum. Consideration must be given to adaptability to multiple track configurations. Also, the configuration must consider installation requirements and minimize the effects of weather and vandals. It should be designed with constant warning time applicability in mind. This selected configuration should be field tested before starting the next task.

SYSTEM DESIGN

A complete transmission line system should be developed. This includes the integration of the above transmission line into a functional system, complete with interface circuits, lighting protection, and all required control circuits. Having established the transmission line, consideration must be given to transmitting and receiving methods. A failure mode effect analysis is made at this time. This provides a means of evaluating the potential unreliable aspects of design by considering component failures and their result on the system. The following questions must be answered:

- How can each part fail?
- What mechanisms might produce these modes of failure?
- What would be the effects if the failure did occur?
- Is it a safe or unsafe failure?
- How is the failure detected?
- Means for reducing or eliminating possibility of failure?

Since the system has inherent requirements for safe applications, the reliability with respect to non-failsafe failure modes is of the highest significance.

DESIGN/DEVELOPMENT

A breadboard model should be constructed and tested. Performance of the subsystems must be checked. At this point, all circuits should be optimized.

PROTOTYPE TEST PROGRAM

The first step is to develop an overall test plan. The plan will present a test program, including hardware description, test schedules, test duration, test objectives and procedure for the evaluation of a transmission line sensor. The next step, based on the test plan, is to construct and test a complete transmission line system.

HARDWARE SPECIFICATION

A specification is required to state the complete performance requirements of intended hardware and the necessary interface and interchangeability characteristics. Performance requirements include all limits and tolerances under the specified environment. Requirements for specification include:

1. Item Definition
2. Function Description
3. Interface Definition
4. Functional Characteristics
5. Physical Characteristics
6. Reliability/Maintainability
7. Environmental Conditions
8. Design & Construction Standards
9. Materials, Processes and Parts
10. Electromagnetic Radiation
11. Workmanship
12. Interchangeability
13. Safety
14. Human Engineering Requirements
15. Standards of Manufacture
16. Quality Assurance Provisions

APPENDIX

FREQUENCY PARTITIONED TRANSMISSION LINE

SYSTEM OPERATION

Presented in Section 6.2 are the results of an experimental investigation of train detection by observing the energy coupling in the near field of a transmission line. As indicated in the experimental results, there is a reflected signal caused by the disturbance of the transmission line matching impedance resulting from the coupling of energy in the near field by the train metal mass. A measurement of the amplitude and phase of the reflected wave carries information as to the train's position and motion which can loosely be related to the approximate center of the total train length in the sensing block. This phenomena is complicated by the number of variables which can affect the parameter of the reflected wave through the point where it becomes difficult to reliably relate the phase and amplitude information to the location and motion of the entering end of the train. In the interest of providing constant warning time using the detection of coupled transmission line effects, the following approach is proposed.

A frequency partitioned transmission line system is represented in the block diagram of Figure A1. A signal generator (Vs) generates a group of linearly summed single frequency signals into the input end of a transmission line system matched to the natural impedance R_n of the system. The transmission line system consists of N segments of transmission line separated by N-1 high pass filters HPF1 through HPF N-1. The last section of transmission line is matched with its resistive natural impedance. The filters are designed with cut-off frequencies which are progressively higher toward the terminal end. The N signal frequencies are chosen as follows.

Signal frequency F5 is chosen to be higher than the cut-off frequency of HPF4 and thus passes unattenuated through all 4 filters and appears at signal strength in transmission line segment S5. Similarly each lower signal frequency is chosen to pass through all preceeding filters and be stopped by the next succeeding filter. Thus, all signal frequencies are present in transmission line segment S1 with frequencies dropping out one by one from the subsequent sections. As shown in Figure A1, a broadband preamplifier presents the linear combination of all signals seen at the input terminals of the first segment of transmission line to the inputs of 5 individually tuned narrow band amplifiers centered on each of the 5 signal frequencies selected in this example. These single frequency components represent the resultant transmitted and reflected continuous wave amplitudes

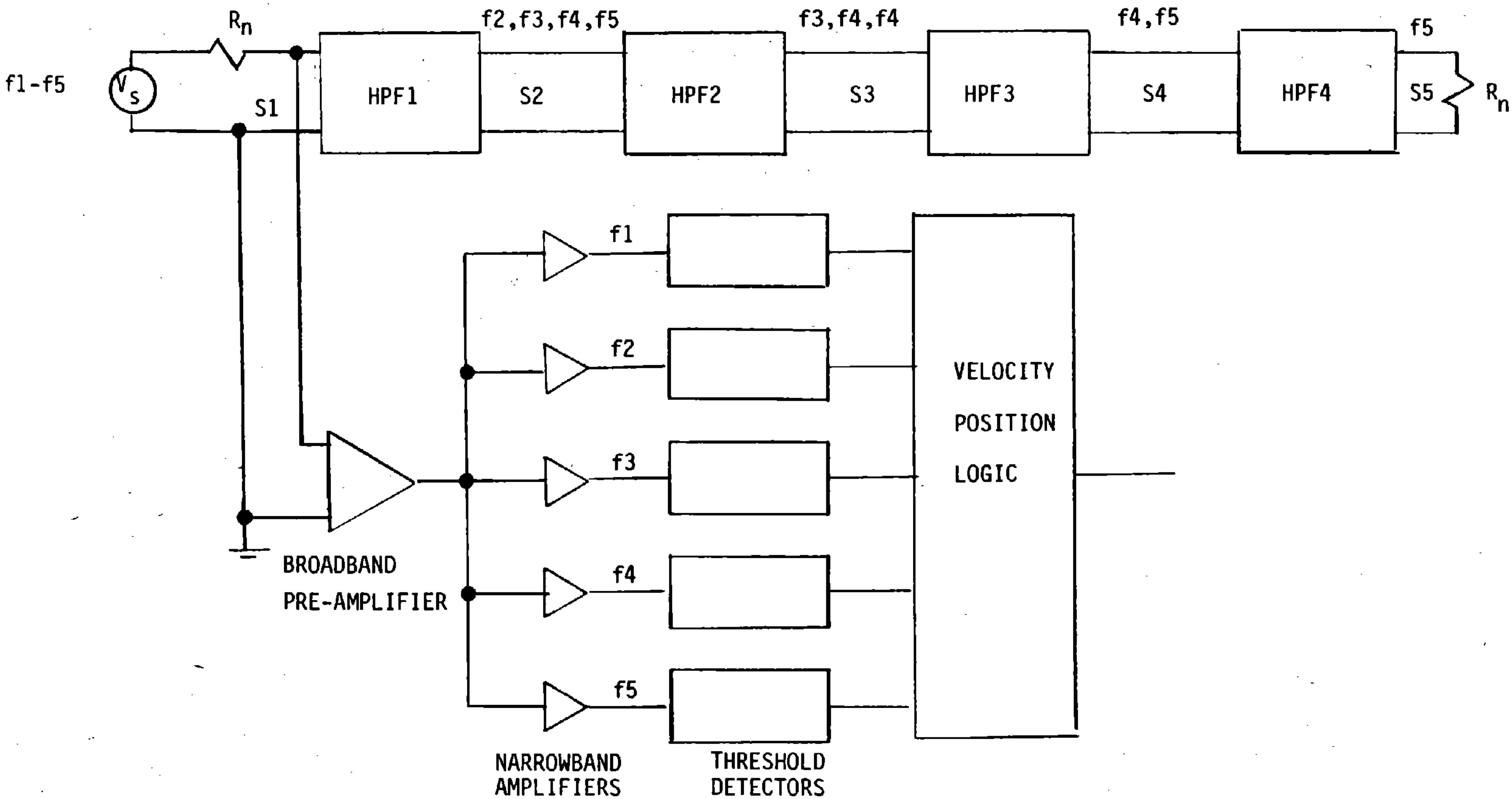


Figure A-1 FREQUENCY PARTITIONED TRANSMISSION LINE of each of the 5 signal channels, unchanged in phase relative to the generator and each other.

The output of these narrow band channels are processed by threshold detectors previously set to indicate the steady state no object present condition of each transmission line segment. The output of these detectors are presented to a velocity/position logic system which interprets the presence and sequence of detection of signal disturbances identified as to transmission line segment by the chosen signal frequency. The resulting combinations of the 5 detector outputs is processed by simple logic algorithm to determine velocity and position of a train configuration detected by the frequency partitioned transmission line system. For instance, a train entering the system from either end will first be signaled by a perturbation of either F1 or F5. Thus, the system immediately knows the sense of direction. As the system passes through the block, the next frequency to detect its position will be the frequency adjacent to the entering end.

The logic system can measure time between sequential frequency detections to give a estimate of average velocity through the transmission line segment. Thus, its position through the sequence is followed and its velocity within limits is measured. With appropriately designed transmission line segment length, the velocity information is adequate to fall into categories of signal activation delays to guarantee a minimum warning time to a crossing.

If the train should halt within the block, the system is aware of this condition since the next frequency segment is not perturbed to indicate that a train is within the system between two known points and is not moving out of this location. The system knows when a train has entirely cleared the block as indicated by the undisturbed condition of all segments. The logic can be given rules that enable it to distinguish between legitimate objects entering the system and false alarms. For instance, the detection of a metallic mass by any of the sections except the two end sections as a first detection is illegal. Thus, objects must be detected first in an end section to be classified and treated as a train system passing through the block. Presence detection is defined as a suitably large distrubance of the normal steady state vacant segment condition, reducing false alarm signals.

The high pass filters look like matched resistive terminations along the transmission line within their pass band but can vary drastically from this impedance within their stop band. Thus, frequencies that are stopped by the succeeding filter will experience some reflection due to the impedance presented by the stopping filter input termination. In the configuration chosen, this stop band impedance is made to appear to be a predominantly capacitive tending toward infinite reactance at zero frequency. Frequencies below the cut-off frequencies of a succeeding filter are attenuated drastically through the filter and thus appear in the forbidden transmission line segment at greatly reduced energy and any reflection experienced at this frequency are similarly attenuated once again on trying to return through the filter. In this manner, each transmission line segment is very effectively isolated from signal energy below the cut-off frequency of the filter preceding that transmission line segment. The threshold detectors can be set such that all reflections affecting the frequency of that particular channel indicates as a presence detection and only the normal steady state preset condition of that frequency channel is accepted as no train present.

In this manner, the combination of detection of coupling of each signal frequency and the sequence of appearance of a presence condition together give information identifying position, velocity, and identification of trains. The filter component size ranges are such that very rugged, and simple filters can be used and the system requires no critical and high speed timing or counting circuits. The electronics can consist of rugged inexpensive operational amplifiers and combinational logic circuits. The narrow band amplifiers associated with each detector channel can be easily designed using twin T feedback operational amplifiers or other types of bandpass active filters.

FILTER CONFIGURATION

Figure A.2a illustrates a typical filter design. HPF4 was chosen for this example with a cut-off frequency F_c equal 2.7 MHz and a peak attenuation frequency f equal to 2.16 MHz. This combination of frequencies defines a composite filter consisting of two m derived n sections with m = 0.6 for flattest impedance matching in the pass band. These two n sections match a constant k midsection. The T termination of the m derived sections is chosen to provide an impedance approaching infinity below cut-off. In the pass band the filter is designed to match approximately 300 ohms resistive.

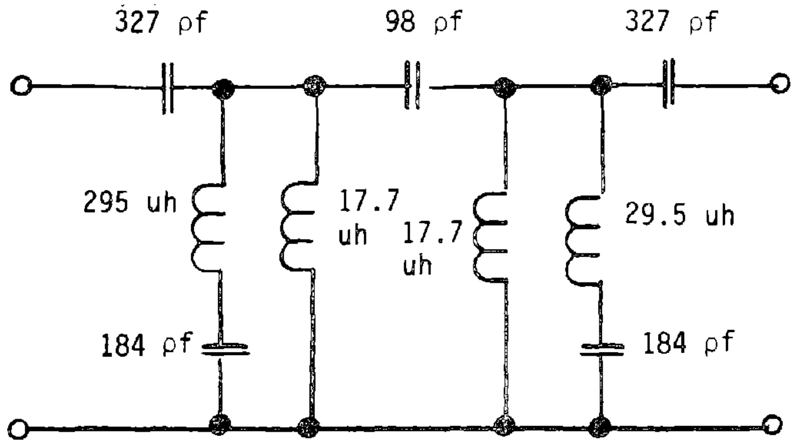


Figure A.2a HIGH PASS FILTER

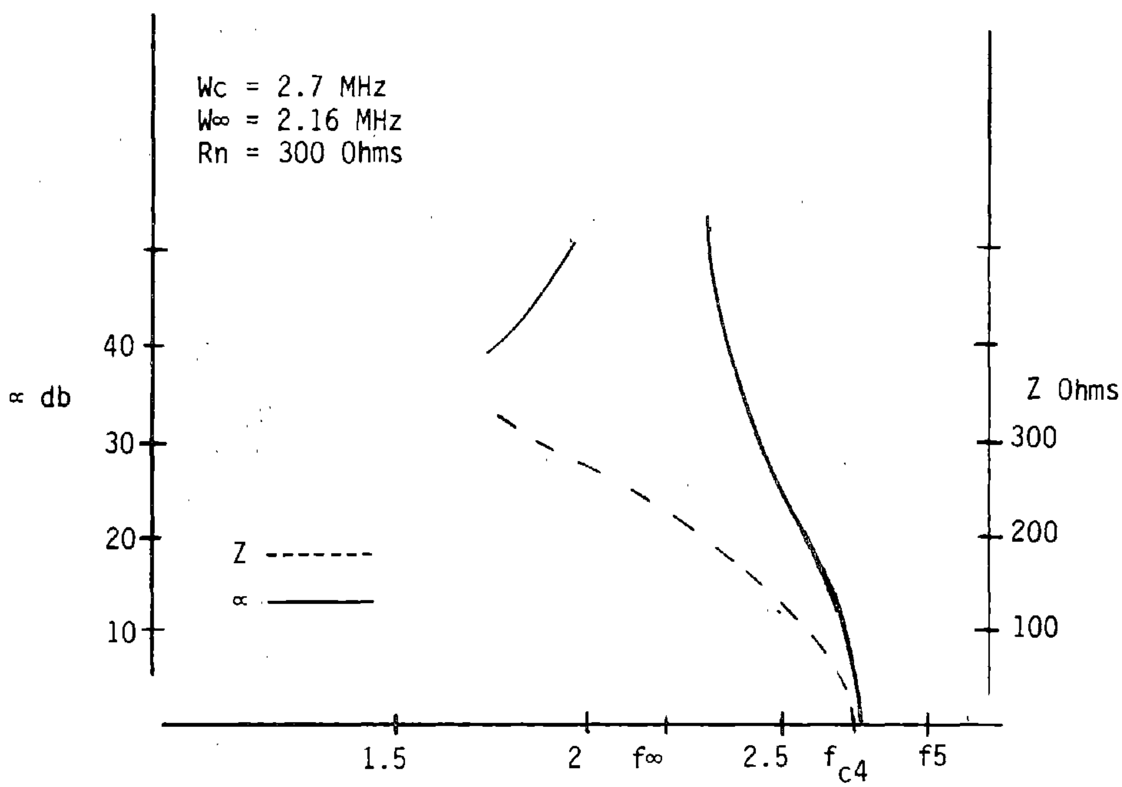


Figure A.2b FILTER PERFORMANCE

Figure A.2b represents the computed attenuation of the sample filter as a function of frequency and also presents the impedance at either end of the filter as a function of frequency. For HPF4, f_{c4} is 2.7 MHz. For this frequency and all frequencies higher, the attenuation alfa is shown to be 0 db. An actual filter will depart somewhat from the ideal figure. Signal frequencies f_5 of 2.85 MHz is shown to be well within the pass band at 0 db attenuation. Signal frequency f_4 of 2.55 MHz will be attenuated by approximately 18 db on passing through HPF4 reducing its energy in segment S_5 to approximately 1/100th of its input power. Any resultant reflections of the residual energy in S_5 will be attenuated by another 18 db on attempting to return to the input. Thus, an insignificant amount of energy from the preceding segment signal frequency appears in segment 5. Also shown in Figure A.2b is the impedance presented to signal frequencies f_5 and f_4 by the input terminal of HPF4. For frequency f_5, the impedance will appear to be close to 300 ohms resistive. For frequency f_4, the filter input termination will appear to be approximately 100 ohms of capacitive reactance. For lower frequencies than f_4, the impedance of the filter terminals will appear to be a high and higher capacitive reactance.

As shown in Figure A2, the component sizes for inductors and capacitors are quite small and can be implemented by very rugged air core coils and high voltage rugged rf capacitors. Filters such as this can be made relatively inexpensively and very rugged. Lighting protection and insensitivity to environment effects are easily accomplished. The passive filter design requires no power other than the signals present in the transmission line system.

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