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RAIL INSPECTION SYSTEMS ANALYSIS AND TECHNOLOGY SURVEY

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16. Abstract

This study was undertaken to identify existing rail inspection system capabilities and methods which might be used to improve these capabilities. Task I was a study to quantify existing inspection parameters and Task II was a cost effectiveness study to utilize the results of Task I. in defining the total costs incurred in inspecting and replacing rail and in defining the most cost effective inspection system.

Some of the major findings from these studies were that the practices of stopping for hand check and to mark flaws and of manually processing all data were the major factors presently limiting inspection speeds. It was concluded that use of automatic data processing and elimination of the stops would allow speeds to be increased to about 25 mph (40 kmph) and inspection costs would be reduced by about a factor of 2. It was also concluded that with extensive transducer and carriage development, speeds up to 50 mph (80 kmph) were feasible and would further reduce inspection costs from 0 up to a maximum of about 30 percent depending upon usage. A recommendation was made to develop an inspection vehicle with an ultimate speed capability of 50 mph (80 kmph) or higher.

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PREFACE

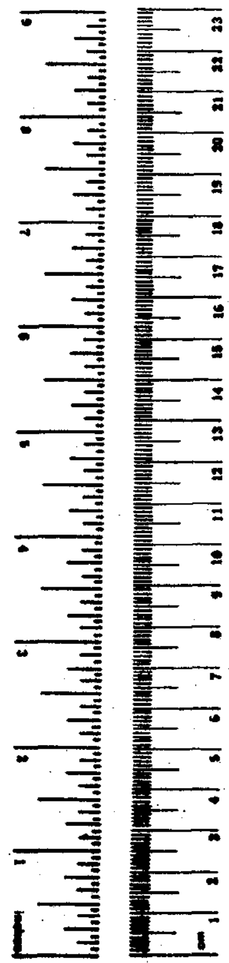
This report presents the final results of a program having the objective of determining cost versus speed and sensitivity tradeoffs for different rail flaw inspection systems. The report was prepared by Battelle's Columbus Laboratories (BCL) under Contract DOT-TSC-979 from Transportation Systems Center and was sponsored by the Office of Research and Development of the Federal Railway Administration (FRA). Mr. Harry Ceccon was the technical monitor for this contract. The cooperation, suggestions, and assistance provided by Mr. Ceccon, Mr. Robert Ryan of TSC, and Mr. William B. O'Sullivan, and Mr. John Mould of FRA are gratefully acknowledged.

The authors are also grateful for the cooperation of the many persons in the railroad community who freely gave of their time, allowed us access to their records, and allowed us to observe their rail inspection practices.

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

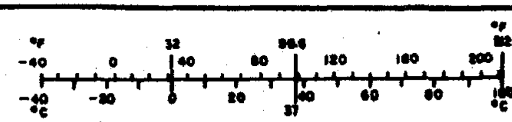


TABLE OF CONTENTS

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

TABLE OF CONTENTS (Continued)

LIST OF TABLES

LIST OF TABLES (Continued)

LIST OF TABLES (Continued)

LIST OF ILLUSTRATIONS

LIST OF ILLUSTRATIONS (Continued)

LIST OF ILLUSTRATIONS (Continued)

INTRODUCTION

In order to improve the rate at which rail can be accurately and reliably inspected, the Federal Railroad Administration is sponsoring this program to develop improved rail inspection techniques. This program which is being implemented by the Transportation Systems Center, is divided into two major tasks--the first ending in March, 1976, and the second ending in November, 1976. Task I is further divided into five items of work, relating to (1) categorization of three major U. S. railroads in a form needed for determining flaw inspection requirements; (2) determination of optimum operating speeds for the various track categories; (3) analysis of transducer inspection system performance/cost tradeoffs; (4) analysis of transducer data acquisition and processing performance/cost tradeoffs; and (5) analysis of cost tradeoffs for systems having varying speed and resolution capabilities. Phase II uses the inspection system cost information and the rail categorization data developed during the Phase I work to define the optimum inspection system.

SUMMARY AND CONCLUSIONS

Categorization of Railroad System Trackage

There are a number of factors that must be considered in the economic evaluation of alternative rail inspection systems. This analysis, requires the categorization of railroad system trackage into segments that reflect the major factors that affect the economics of alternative rail inspection vehicle capabilities.

In addition to the economic analysis requirements, there is a need to categorize tracks to reflect the variation in physical features that directly affect the design and performance of the rail inspection system. For example, if the speed of a system must be lower for the inspection of a bolted joint than for a welded joint, it is necessary to categorize tracks relative to type of rail joint. As another example, overall inspection speed might depend on the number of flaws found because of the need to stop and verify by hand checks. Thus, there is a need to know the expected flaw rate for a given category. This flaw rate, in turn, may depend on the inspection frequency, traffic levels, type of rail, track geometry, and many other factors. Since these factors depend on the physical characteristics and use of a track, the trackage must be categorized to permit an estimation of performance of alternative inspection system configurations.

The most appropriate major breakdown of track is by traffic volume. The following traffic levels have been chosen to define three major categories:

High - greater than 10×10^6 gross annual tons (9×10^9 Kg)
Medium - 1×10^6 to 10×10^6 gross annual tons (9×10^8 to 9×10^9 Kg)
Low - less than 1×10^6 gross annual tons. (9×10^8 Kg)

Within this major categorization by traffic volume, it is necessary to identify subclasses that relate to inspection speed and/or economic impact of inspection speed. The data required in each subcategory include physical characteristics (miles, miles of double track, number of turnouts, and number of grade crossings), service (average annual tonnage and cumulative tonnage), performance (annual defects by type, how detected, and time since last inspection for service-detected failures), and general track condition (miles in each FRA classification).

At the outset of the study, three railroads were contacted and arrangements made for these railroads to cooperate in providing data needed in the study including track categorization data. These railroads were chosen for, among other reasons, the degree to which they appeared to represent the environment and transportation activities of the nation's railroads.

Railroad A is one of the larger railroads operating in the Eastern/Midwest area of the United States, with a mixture of general freight and coal traffic. Railroad B is also a large railroad that operates between the West Coast and Midwest cities. This railroad carries high tonnages at a top speed of 70 mph (113 km/hr). The traffic on this railroad is primarily general freight with an increasing number of unit coal trains. Railroad C is a large railroad operating primarily in the southern region of the country.

Available data from the railroads necessitated the simplification of the ideal track categorization scheme. This scheme retains the major traffic categories. Within these categories, track is broken down by welded rail and jointed rail. Various physical, service, and performance data were collected for each of these categories and subcategories. Categorization data for the railroads providing data are summarized in Table 1. A summary of the defects by type of welded and jointed rail for each density category is presented in Table 2.

As indicated in Tables 1 and 2, the defect occurrence rate is significantly higher with jointed rail than it is with welded rail. Further, as one would expect, the number of joint area defects is significantly higher with jointed rail. These factors will have an influence not only on the required type of inspection methods, but also on inspection speed or, more correctly, the system configuration required to achieve a desired speed. In turn, speed and inspection methods will impact the economics of inspection system alternative configurations. It should be noted that except

TABLE 1. SUMMARY OF TRACK CATEGORIZATION *

Density Category	Type Joints	Rail-road	Track Length Miles	Track Length Kilometers	Turnouts Per Mile	Turnouts Per Kilometer	Grade Crossings Per Mile	Grade Crossings Per Kilometer	Average Annual Tonnage	Cumulative Tonnage	Total Defects(a) Per Mile	Total Defects(a) Per Kilometer	Annual Number of Derailments(b)
High	All	A	6,300	10,137	0.7	0.4	1.2(c)	0.7	19.1	361	0.35	0.22	12
		B	4,575	7,361	0.5	0.3	2.1	1.3	31.8	264	0.76	0.47	2
		C	4,318	6,948	0.8	0.5	1.4	0.9	19.3	NA (d)	0.60	0.37	2
	Welded	A	3,500	5,632	NA	NA	NA	NA	NA	NA	0.25	0.16	3
		B	1,348	2,169	NA	NA	NA	NA	NA	NA	0.03	0.02	NA
		C	3,872	6,230	NA	NA	NA	NA	NA	NA	0.36	0.23	NA
	78' Bolted	A	0	0	NA	NA	NA	NA	NA	NA	NA	NA	NA
		B	873	1,405	NA	NA	NA	NA	NA	NA	0.10	0.06	NA
		C	0	0	NA	NA	NA	NA	NA	NA	NA	NA	NA
	Other Bolted	A	2,800	4,505	NA	NA	NA	NA	NA	NA	0.48	0.30	9
		B	2,354	3,788	NA	NA	NA	NA	NA	NA	1.41	0.88	NA
		C	447	719	NA	NA	NA	NA	NA	NA	2.62	1.63	NA
Medium	All	A	3,600	5,792	1.3	0.8	2.3	1.4	4.8	NA	1.03	0.64	39
		B	2,448	3,939	0.5	0.3	NA	NA	4.0	NA	0.51	0.32	1
		C	3,883	6,248	0.8	0.5	1.9	1.2	3.9	NA	2.34	1.45	4
	Welded	A	1,100	1,770	NA	NA	NA	NA	NA	NA	0.25	0.16	4
		B	0	0	NA	NA	NA	NA	NA	NA	NA	NA	NA
		C	1,173	1,887	NA	NA	NA	NA	NA	NA	0.43	0.27	NA
	Bolted	A	2,500	4,023	NA	NA	NA	NA	NA	NA	1.38	0.86	35
		B	2,448	3,939	0.5	0.3	NA	NA	4.0	NA	0.51	0.32	NA
		C	2,710	4,360	NA	NA	NA	NA	NA	NA	3.17	1.97	NA

TABLE 1. (Continued)

Density Category	Type Joints	Rail-road	Track Length Miles	Track Length Kilometers	Turnouts Per Mile	Turnouts Per Kilometer	Grade Crossings Per Mile	Grade Crossings Per Kilometer	Average Annual Tonnage	Cumulative Tonnage	Total Defects(a) Per Mile	Total Defects(a) Per Kilometer	Annual Number of Derailments(b)
Los	All	A	794(e)	1,278(e)	0.4	0.2	1.2	0.7	0.4	NA	0.24	0.15	1
		B	3,255	5,237	0.6	0.4	NA	NA	0.3	NA	0.31	0.19	4
		C	2,894	4,656	1.0	0.6	1.6	1.0	0.4	NA	1.14	0.71	4
	Welded	A	200(e)	322(e)	NA	NA	NA	NA	NA	NA	0.25	0.16	0
		B	0	0	NA	NA	NA	NA	NA	NA	NA	NA	NA
		C	156	251	NA	NA	NA	NA	NA	NA	0.13	0.08	NA
	Bolted	A	594(e)	956(e)	NA	NA	NA	NA	NA	NA	0.23	0.14	1
		B	3,255	5,237	0.6	0.4	NA	NA	0.3	NA	0.31	0.19	NA
		C	2,738	4,405	NA	NA	NA	NA	NA	NA	1.19	0.74	NA

(a) Defect defined as conditions resulting in rail replacement in mainline tracks.
(b) Rail-caused derailments in mainline tracks - 1974 for railroads A and B and 1975 for railroad C.
(c) System averages.
(d) Data not available or not applicable.
(e) Data collected only for this mileage. Total low-density mileage is 1,900 miles (3,057 km).

NA - Not Available

* 1974 data for railroads A and B. 1975 data for Railroad C.

where otherwise indicated, data on <u>defects</u> for the sample railroads refers to those defects that are determined to be sufficiently serious to require a <u>rail replacement</u>. Thus, the criteria for defining a defect may vary with track usage and policies related to inspection and to the corrective actions that can be taken once a defect is found. This explains at least in part the apparent low defect rate in the low density category.

Examination of Table 2 indicates that there are significant differences in the defect rates of the different railroads. For example, Railroad C had approximately nine times the bolt-hole failure rate in the sample data period (1975) in the medium-density, bolted-joint category. as Railroad A. Further, it appears as if there are some differences between the railroads relative to the classification of defects. For example, Railroad B has a much higher reported occurrence of detailed fractures, but does not report transverse defects as a separate and unique type of defect as does Railroad A.

Determination of Optimum Operating Speeds

In studying track categories and how they affect inspection speeds, it was found that the primary track related factors affecting the average inspection speeds were the following:

(1) The time spent on sidings waiting for revenue traffic to clear the track.

(2) The frequency of stops required for hand checking or tagging of defective track.

(3) Time spent in transferring the inspection car.

Secondary track-related features affecting inspection speed were the number of discontinuities such as turnouts, frogs, and grade crossings encountered, track geometry errors, curves, and badly worn relaid rail. The above speed factors are also a function of other factors besides track categories, such as requirements for an identification of flaws immediately after inspection, and the speed and accuracy at which the inspection car can operate.

TABLE 2. SUMMARY OF ANNUAL DEFECTS (PERSONNEL AND CAR DETECTED) AND DEFECT RATE BY TYPE*

Type No.	Description	Rail-road	Total Defects	Percent of Total	Defects		High Density Welded		High Density Bolted(d)		Medium Density Welded		Medium Density Bolted		Low Density Welded		Low Density Bolted	
					Per Mi	Per Km	Per Mi	Per Km	Per Mi	Per Km	Per Mi	Per Km	Per Mi	Per Km	Per Mi	Per Km	Per Mi	Per Km
1	Bolt-hole failure	A	2821	46.0	0.26	0.16	0.01	0.01	0.14	0.09	0.01	0.01	0.50	0.31	0.01	0.01	0.13	0.08
		B	680	11.9	0.07	0.04	0.00	0.00	0.11	0.07	-	-	0.07	0.04	-	-	0.04	0.02
		C	3080	20.5	0.28	0.17	0.04	0.03	0.99	0.61	0.03	0.02	0.64	0.40	0.01	0.01	0.26	0.16
2	Head and web separation in joint area	A	977(a)	15.9	0.09	0.06	0.01	0.01	0.05	0.03	0.01	0.01	0.17	0.11	0.01	0.01	0.04	0.02
		B	106	1.9	0.01	0.01	0.00	0.00	0.01	0.01	-	-	0.02	0.01	-	-	0.01	0.01
		C	3028	20.3	0.27	0.17	0.04	0.02	0.59	0.37	0.05	0.03	0.73	0.45	0.01	0.01	0.21	0.13
3	Head and web separation out of joint area (b)	A	324	5.3	0.03	0.02	0.03	0.02	0.01	0.01	0.02	0.01	0.03	0.02	0.03	0.02	0.01	0.01
		B	--	--	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		C	291	2.0	0.03	0.02	0.00	0.00	0.03	0.02	0.03	0.02	0.07	0.04	0.00	0.00	0.02	0.01
4	Horizontal web crack	A	67	1.1	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.00	0.00
		B	109	1.9	0.01	0.01	0.00	0.00	0.01	0.01	-	-	0.03	0.02	-	-	0.00	0.00
		C	151	1.0	0.01	0.01	0.00	0.00	0.01	0.01	0.01	0.01	0.03	0.02	0.01	0.01	0.02	0.01
5	Crushed head	A	18	0.3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		B	95	1.7	0.01	0.01	0.00	0.00	0.03	0.02	-	-	0.00	0.00	-	-	0.00	0.00
		C	0.0	0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	Broken base	A	18	0.3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		B	53	0.9	0.01	0.01	0.00	0.00	0.00	0.00	-	-	0.00	0.00	-	-	0.01	0.01
		C	75	1.0	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.02	0.01
7	Vertical split head (broken or cracked)	A	219	3.6	0.02	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.02	0.01	0.01	0.01
		B	501	8.8	0.05	0.03	0.00	0.00	0.02	0.01	-	-	0.06	0.04	-	-	0.09	0.06
		C	3471	23.2	0.31	0.19	0.01	0.01	0.11	0.07	0.04	0.02	0.72	0.44	0.00	0.00	0.51	0.32
8	Break in rail(b)	A	282	4.6	0.03	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.03	0.02	0.03	0.02	0.01	0.01
		B	--	--	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		C	25	0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

TABLE 2 (Continued)

Type No.	Description	Rail-road	Total Defects	Percent of Total	Defects Per Mi	Defects Per Km	High Density Welded Per Mi	High Density Welded Per Km	High Density Bolted(d) Per Mi	High Density Bolted(d) Per Km	Medium Density Welded Per Mi	Medium Density Welded Per Km	Medium Density Bolted Per Mi	Medium Density Bolted Per Km	Low Density Welded Per Mi	Low Density Welded Per Km	Low Density Bolted Per Mi	Low Density Bolted Per Km
9	Engine burn fracture	A	249	4.1	0.02	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.03	0.02	0.02	0.01	0.01	0.01
		B	89	1.6	0.01	0.01	0.00	0.00	0.02	0.01	-	-	0.01	0.01	-	-	0.00	0.00
		C	1894	12.6	0.17	0.11	0.05	0.03	0.48	0.30	0.09	0.06	0.46	0.29	0.02	0.01	0.05	0.03
10	Horizontal split head (broken or cracked)	A	111	1.8	0.01	0.01	0.01	0.01	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.00
		B	133	2.3	0.01	0.01	0.00	0.00	0.02	0.01	-	-	0.01	0.01	-	-	0.01	0.01
		C	895	6.1	0.08	0.05	0.07	0.04	0.12	0.08	0.06	0.04	0.15	0.09	0.01	0.01	0.03	0.02
11	Shelly spots	A	7	0.1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		B	235	4.1	0.02	0.01	0.00	0.00	0.07	0.04	-	-	0.01	0.01	-	-	0.00	0.00
		C	--	--	-	-	-	-	-	-	-	-	-	-	-	-	-	-
12	Piped rail(b)	A	7	0.1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		B	--	--	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		C	43	0.00	0.0	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01
13	Partial break(b)	A	18	0.3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		B	--	--	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		C	--	--	-	-	-	-	-	-	-	-	-	-	-	-	-	-
14	Transverse fissure	A	220	3.6	0.02	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.02	0.01	0.01	0.01
		B	400	7.0(e)	0.04	0.02	0.00	0.00	0.01	0.01	-	-	0.07	0.04	-	-	0.06	0.04
		C	1111	7.4	0.10	0.06	0.01	0.01	0.23	0.14	0.03	0.02	0.28	0.17	0.04	0.02	0.03	0.02
15	Compound fissure	A	12	0.2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		B	11	0.2	0.00	0.00	0.00	0.00	0.00	0.00	-	-	0.00	0.00	-	-	0.00	0.00
		C	--	--	-	-	-	-	-	-	-	-	-	-	-	-	-	-
16	Detail fracture	A	12	0.2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		B	1392	24.4	0.14	0.09	0.01	0.01	0.35	0.22	-	-	0.09	0.06	-	-	0.01	0.01
		C	246	1.6	0.02	0.01	0.03	0.02	0.04	0.02	0.02	0.01	0.03	0.02	0.00	0.00	0.01	0.01

TABLE 2 (Continued)

Type No.	Description	Rail-road	Total Defects	Percent of Total	Defects		High Density Welded		High Density Bolted(d)		Medium Density Welded		Medium Density Bolted		Low Density Welded		Low Density Bolted	
					Per Mi	Per Km	Per Mi	Per Km	Per Mi	Per Km	Per Mi	Per Km	Per Mi	Per Km	Per Mi	Per Km	Per Mi	Per Km
17	Broken or defective weld	A	285	4.6	0.03	0.02	0.06	0.04	-	-	0.04	0.02	-	-	0.06	0.04	-	-
		B	45	0.8	0.00	0.00	0.02	0.01	0.01	0.01	-	-	-	-	-	-	-	-
		C	240	1.6	0.02	0.01	0.06	0.04	0.00	0.00	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00
18	Transverse defect(b)	A	461	7.5	0.04	0.02	0.04	0.02	0.01	0.01	0.02	0.01	0.05	0.03	0.04	0.02	0.02	0.01
		B	--	--	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		C	--	--	-	-	-	-	-	-	-	-	-	-	-	-	-	-
19	Fracture from welded engine burn (b)	A	6	0.1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		B	--	--	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		C	--	--	-	-	-	-	-	-	-	-	-	-	-	-	-	-
20	Flaking or slivered(b)	A	1	0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		B	--	--	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		C	--	--	-	-	-	-	-	-	-	-	-	-	-	-	-	-
21	Head checks(b)	A	2	0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		B	--	--	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		C	--	--	-	-	-	-	-	-	-	-	-	-	-	-	-	-
22	Corrugated(b)	A	0	0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		B	--	--	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		C	--	--	-	-	-	-	-	-	-	-	-	-	-	-	-	-
23	Mill defects(f)	A	0	0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		B	--	--	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		C	4	0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
24	Engine burn - not fractured (b)	A	14	0.3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.00
		B	--	--	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		C	--	--	-	-	-	-	-	-	-	-	-	-	-	-	-	-

TABLE 2 (Continued)

Type No.	Description	Rail-road	Total Defects	Percent of Total	Defects Per Mi	Defects Per Km	High Density Welded Per Mi	High Density Welded Per Km	High Density Bolted(d) Per Mi	High Density Bolted(d) Per Km	Medium Density Welded Per Mi	Medium Density Welded Per Km	Medium Density Per Mi	Medium Density Per Km	Low Density Welded Per Mi	Low Density Welded Per Km	Low Density Bolted Per Mi	Low Density Bolted Per Km
25	Damaged[c]	A	--	--	0.00	0.00	-	-	-	-	-	-	-	-	-	-	-	-
		B	1145	20.1	0.11	0.07	0.00	0.00	0.27	0.17	-	-	0.06	0.04	-	-	0.04	0.03
		C	--	--	-	-	-	-	-	-	-	-	-	-	-	-	-	-
26	Other[c]	A	--	--	0.00	0.00	-	-	-	-	-	-	-	-	-	-	-	-
		B	439	7.7	0.04	0.02	0.00	0.00	0.10	0.06	-	-	0.03	0.02	-	-	0.02	0.01
		C	399	2.7	0.04	0.02	0.06	0.03	0.01	0.01	0.01	0.01	0.05	0.03	0.03	0.02	0.01	0.01
27	Worn[g]	A	--	--	0.00	0.00	-	-	-	-	-	-	-	-	-	-	-	-
		B	263	4.6	0.03	0.02	0.00	0.00	0.05	0.03	-	-	0.02	0.01	-	-	0.02	0.01
		C	--	--	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Total	A	6133	100.0	0.57	0.35	0.25	0.16	0.41	0.25	0.25	0.16	1.44	0.89	0.25	0.16	0.23	0.14
		B	5696	99.9	0.55	0.34	0.03	0.02	1.06	0.66	-	-	0.51	0.32	-	-	0.31	0.19
		C	14954	100.0	1.33	0.84	0.36	0.23	2.62	1.63	0.43	0.27	3.17	1.97	0.13	0.08	1.19	0.74

(a) Total head and web separations - Railroad B does not report by location.
(b) Not reported by Railroad B or Railroad C.
(c) Not reported by Railroad A.
(d) Includes 78-ft (two 39-ft rails welded together) lengths for Railroad B.
(e) Includes compound fissures.
(f) Not reported by Railroad B.
(g) Not reported by Railroad A or Railroad C.

* 1974 data for railroads A and B. 1975 data for railroad C.

The speed and accuracy at which inspection cars operate in the U. S. was found to be limited primarily by the rate at which the operator could process the data presented to him and the number and type of transducers used to inspect the track. Inspection speeds were typically found to be between 4 and 13 mph (6 and 21 Km/hr), with the low speed representing operations in yard areas and the high speed representing use of a magnetic car on good track. Average speeds tend to be in the 20 to 40 mile/8-hr day (32 to 64 Km/8-hr day) range, with the higher speeds being obtained by magnetic cars. On cars(*) in which the data are not analyzed on board, much higher speeds are attained. Inspection speeds of 18 to 62 mph (29 to 100 Km/hr) with daily averages in excess of 100 (160 Km) miles are reported for these cases.(*) In addition to observing existing practice, calculations were made to determine the effects of stopping for hand checks or reducing speed to cross discontinuities such as frogs, and on the effects of track profile errors on carriage dynamics and maximum speeds. These analyses showed that slowing to cross track discontinuities would normally have a negligible effect on the average operating speed, but that stopping to make hand checks or tagging defective track is the primary factor controlling average inspection speed. For this analysis, it was assumed that 5 seconds would be required to stop after a defect was crossed, that stopping and starting would occur with 0.1 g acceleration rates, that the back up speed would be 10 mph (16 Km/hr), and that the inspection car would be stopped for 60 seconds. With these assumptions, the calculations indicated that for normal distances between stops, average inspection speed was reasonably independent of the maximum inspection speed, and that a 20-mph (32 Km/hr) vehicle would normally have a higher average operating speed than a 50-mph (80 Km/hr) vehicle. This apparent contradiction occurs because of the excessive overshoot and back up time that occurs with very high speed vehicles.

Observations, conversations with operators and manufacturers, and calculations indicate that most existing carriage systems can operate satisfactorily with little or no changes to speeds of about 20 to 25 mph(**)

(*) Reported in European practice.

(**) Performance to these speeds on poor track may require improvements in the carriage systems.

(32 to 40 Km/hr) on good track. However, a weakness observed in all ultrasonic carriage systems is that only manual alignment control is provided, and that some information is lost on curves or other discontinuities when the operator cannot rapidly adjust the alignment. For satisfactory operation even at existing speeds, automatic carriage alignment should be provided. For operation at speeds to 50 mph (80 Km/hr), improvements in carriage design will probably be required. However, observation of the Russian inspection systems and calculations indicate that development of an inspection system to operate to speeds of 50 mph (80 Km/hr) is feasible* on any track which has 50 mph (80 Km/hr) or higher speed limits.

The overall conclusions reached in evaluating potential inspection speeds were as follows:

(1) No significant increases in speed can be obtained unless the requirement for stopping the car to make hand checks and tagging the track is eliminated.

(2) The number of transducers now being used to inspect the track is marginal in terms of the ability to identify all important flaws.

(3) Speed is now operator-limited; therefore, increasing inspection speed while maintaining or improving detection reliability must be accompanied by use of partial or full automatic data processing.

(4) Slowing down to pass track features is not an important factor in determining average operating speeds; however, carriage systems that will cross track features with little or no decrease in speed are needed, and their procurement appears practical.

(5) Development of a 20 to 25 mph (32 to 40 Km/hr) inspection system that will detect 15 percent flaws should be practical with moderate changes in the transducers and carriage system and with the addition of partial or full automatic data processing.*

* For use to these speeds on poor quality track extensive carriage development work may be required.

** Performance to these speeds on poor track may require improvements in the carriage system.

(6) Development of a 50 mph (80 Km/hr) inspection system that will detect 15 percent of head area flaws should be feasible with extensive transducer, carriage, and automatic data processing work.

Evaluation of Ultrasonic Inspection Systems

Capabilities of ultrasonic inspection systems were evaluated by reviewing the literature, observing both ultrasonic and combined ultrasonic magnetic systems in operation, by interviews with rail inspection experts, and by analytical techniques. The review of the literature produced negligible useful information, but by use of observations, interviews and analytical techniques, approximate capabilities of the different systems were determined.

The primary conclusions reached from these studies was that the major reasons that existing ultrasonic systems fail to detect some flaws are that:

(1) The flaws occur in a section of the rail not inspected by the system.

(2) The transducers are not properly oriented relative to the flaw.

(3) Surface defects such as burns, shells, and welds interfere with the transmission of the ultrasonic signal.

It was also found that in most cases ultrasonic transducer performance is not limiting inspection speeds.

An analysis of several ultrasonic transducer configurations was made to determine the potential capabilities of several configurations.

Table 3 and the following explanatory notes summarize the results of this investigation of ultrasonic techniques. The values in Table 3 are in many cases judgments which are based on the observed performance of existing systems and in other cases on theoretical or combined theoretical judgment factors such as

TABLE 3a. SUMMARY OF TRANSDUCER EVALUATION DATA* (ENGLISH UNITS)

	Defect Size		DEFECT TYPE								
			Transverse Head Defects				Horizontal Split Head				
Transducer Type	Area, Percent	Length in.	Number Flaws Detected, Percent	Maximum Operating Speed, mph	Location in Section G-Gage C-Center F-Field	Minimum Distance from Joint, in.	Number Flaws Detected, Percent	Maximum Operating Speed, mph	Location in Section, G-Gage C-Center F-Field	Minumum Distance from Joint, in.	Number Flaws Detected Percent
Normal ultrasonic	1	1		N/A			99(a)	44-50+ (e)	C	<1(b)	50
	5	2					99(a)	50+ (e)	C	<1(b)	50
	15	4					99(a)	50+ (e)	C	<1(b)	50
45° pulse echo ultrasonic forward and backward, gated for full Vee	1	1	0	4-5(e)	-			N/A			
	5	2	10	9-11(e)	C	2(b)					
	15	4	50	15-19(e)	C	2(b)					
45° thru transmission ultrasonic forward and backward	1	1	0	6-9, 50+(f)	-	-	95	27-39, 50+(f)	C	3(b)	
	5	2	50	14-20, 50+(f)	C	2-14	95	44-50+, 50+(f)	C	3(b)	
	15	4	95	25-36, 50+(f)	C	2-14	95	44-50+, 50+(f)	C	3(b)	
30/60 skew ultrasonic pulse echo, four transducers (forward and backward)	1	1	20	11-16(e)	G-F	1		N/A			
	5	2	70	25-36(e)	G-F	1					
	15	4	90	44-50+(e)	G-F	1					
30/60 skew ultrasonic thru transmission, four transducers (forward and backward)	1	1	0	16-28, 50+(f)	-	-	95	40-50+, 50+(f)	G-C-F		99
	5	2	50	36-50+, 50+(f)	G-C-F	2	95	50+, 50+(f)	G-C-F		99
	15	4	95	50+, 50+(f)	G-C-F	2	95	50+, 50+(f)	G-C-F		99
70° - 80° ultrasonic pulse echo six transducers	1	1	0	18-25(e)	-	-		N/A			
	5	2	50	40-50+(e)	G-C-F	1					
	15	4	80	44-50+(e)	G-C-F	1					
80° - ultrasonic pulse echo six transducers	1	1	0	37-50+(e)	-	-					
	5	2	50	44-50+(e)	G-C-F	1		N/A			
	15	4	80	44-50+(e)	G-C-F	1					
Longitudinal residual magnetic	1	1	0	-	-	-		N/A			
	5	2	40	15-20	G-C-F	20					
	15	4	90	15-20	G-C-F	2					
Transverse residual magnetic	1	1		N/A				N/A			50
	5	2									50
	15	4									95
Direct current by contact	1	1	0	-(h)	-	-	0	-	G-C-F	20	0
	5	2	60	50(h)	G-C-F	20	30	50	G-C-F	20	30
	15	4	95	50(h)	G-C-F	20	90	50	G-C-F	20	90
Direct current by contact with surface sensors (d)	1	1	90	50(h)	G-C-F	4	50	50	G-F	4	90
	5	2	95	50(h)	G-C-F	4	90	50	G-F	4	95
	15	4	99	50(h)	G-C-F	4	95	50	G-F	4	99

(a) System will not distinguish between burns, welds, battered ends, or chipped ends and listed defect.

(b) Ability to inspect close to the end of the rail requires use of B scan data presentation system or use of sophisticated automatic data processing system.

(c) With sophisticated logic, 45° system could be effectively used in combination with 0° system to determine size and orientation of web defects.

(d) This system is not known to exist. Extensive development would be required.

(e) Lower speed assumes a fluid path length of about 2.6 inches (typical large-wheel system) and a total electronic and fluid path delay time of 100 μ-sec. Higher speed assumes a very short fluid path length (sled or small wheel system without opposing reflectors) and total electronic and fluid path delay time of 25 μ-sec or less.
The centerline of the U-sonic wave intersects the flaw 8 times during passage or the pulse rate will produce a pulse per 0.2-inch of travel (5 PPi), which ever gives the lower speed.

(f) As (e) except that speed following comma assumes that gating used is such that more than one pulse can be in the rail at any given time.

NA - Not Available

TABLE 3a. SUMMARY OF TRANSDUCER EVALUATION DATA* (ENGLISH UNITS) (CONTINUED)

Vertical Split Head		Crack or Piping in Web				
Maximum Operating Speed, mph	Minimum Distance from Joint, in.	Number Flaws Detected, Percent	Maximum Operating Speed, mph	Minimum Distance from Joint, in	Size Information Provided E-Excellent, Good F-Fair, P-Poor	Comments
40-50+[(e)] 50+[(e)] 50+[(e)]	<1[(b)] <1[(b)] <1[(b)]	99[(a)] 99[(a)] 99[(a)]	44-50+[(e)] 50+[(e)] 50+[(e)]	<1[(b)] <1[(b)] <1[(b)]	E E E	Partial loss of base indicates possible serious bulging in piped rail. Complete loss of base provides failsafe[(g)] detection of all large horizontal defects in web or head.
N/A		Note (c)			F F F	System has potential of detecting flaws under 24-in. long surface defects. Detection of flaws close to joint requires very complex or manual data processing.
N/A		Note (c)			F-G F-G F-G	Loss of signal provides failsafe[(g)] detection of all large defects in web or center of head. Detection of flaws close to joint requires very complex or manual data processing
N/A		N/A			F-G F-G F-G	System has potential of detecting flaws under up to 10-in. long surface defects.
40-50+, 50+[(f)] 50+, 50+[(f)] 50+, 50+[(f)]	2 2 2	N/A			F-G F-C F-G	System has potential of detecting flaws under 2-3 in. long surface defects with complex or manual data processing. Providing failsafe detection of large vertical flaws and large transverse defects inside of head
N/A		N/A			- P-F P-F	Six transducers required for full interogation of the head with these transducers - fewer could be used in combination with other systems.
N/A		N/A			- P-F P-F	Six transducers required for full interogation of the head with these transducers - fewer could be used in combination with other systems.
N/A		N/A			- P P	Speed limitation imposed by weight and size restriction of high rail vehicle. Speed can be increased by increasing sizes and weights in approximate proportion to speed.
15-50 15-50 15-50	1 1 1	N/A			G G G	Speed limitation imposed by weight and size restriction of high rail vehicle. Speed can be increased by increasing sizes and weights in approximate proportion to speed.
50 50 50	20 20 20	N/A			- F F	System is too heavy to use on high rail vehicle. Speed is limited only by distance between points where current is induced into the rail.
50 50 50	4 4 4	N/A			F F F	System is too heavy to use on high rail vehicle. Speed is limited only by distance between points where current is induced into the rail

(g) Failure safe as used in this context means that the presence of a flaw, or instrumentation problem will always produce a flaw induction whereas non-fail safe would imply a system in which an instrumentation (coupling) problem developed at the same time as a flaw is passed would not produce a flaw indication.

(h) Use of this system at high speeds may require either use of constant current control system and/or missing significant rail at joints.

* Pulse rep rate and flow size calc. based on 132-lb rail.
Transverse defects assumed round except engine burn crack which is assumed rectangular with a 3:1 ratio.

TABLE 3b. SUMMARY OF TRANSDUCER EVALUATION DATA* (METRIC UNITS)

Transducer Type	Defect Size: Area Percent	Defect Size: Length, cm	Transverse Head Defects: Number Flaws Detected, percent	Transverse Head Defects: Maximum Operating speed, (km/hr)	Transverse Head Defects: Location in Section G-Gage C-Center F-Field	Transverse Head Defects: Minimum Distance from Joint, cm	Horizontal Split Head: Number Flaws Detected, percent	Horizontal Split Head: Maximum Operating Speed, (Km/hr)	Horizontal Split Head: Location in Section, G-Gage C-Center F-Field	Horizontal Split Head: Minimum Distance from Joint, cm	Number Flaws Detected percent
Normal ultrasonic	1	3			N/A		99(a)	71-80+(e)	C	<3(b)	50
	5	5					99(a)	80(e)		<3(b)	50
	15	10					99(a)				50
45° pulse echo ultrasonic forward and backward, gated for full Vee	1	3	0	6-8(e)	-			N/A			
	5	5	10	14-18(e)	C	5(b)					
	15	10	50	24-31(e)	C	5(b)					
45° thru transmission ultrasonic forward and backward	1	3	0	10-14,80+(f)	-	-	95	43-60,80+(f)	C	8(b)	
	5	5	50	23-32,80+(f)	C	5-36	95	71-80+,80+(f)	C	8(b)	
	15	10	95	40-58,80+(f)	C	5-36	95	71-80+,80+(f)	C	8(b)	
30/60 skew ultrasonic pulse echo, four transducers (forward and backward)	1	3	20	18-26(e)	G-F	3		N/A			
	5	5	70	40-58(e)	G-F	3					
	15	10	90	71-80+(e)	G-F	3					
30/60 skew ultrasonic thru transmission, four transducers (forward and backward)	1	3	0	26-45,80+(f)	-	-	95	64-80+,80+(f)	G-C-F		99
	5	5	50	58-80+,80+(f)	G-C-F	5	95	80+,80+(f)	G-C-F		99
	15	10	95	80+, 80+(f)	G-C-F	5	95	80+,80+(f)	G-C-F		99
70° - ultrasonic pulse echo six transducers	1	3	0	29-40(e)	-	-		N/A			
	5	5	50	64-80+(e)	G-C-F	3					
	15	10	80	71-80+(e)	G-C-F	3					
80° - ultrasonic pulse echo six transducers	1	3	0	60-80+(e)	-	-		N/A			
	5	5	50	71-80+(e)	G-C-F	3					
	15	10	80	71-80+(e)	G-C-F	3					
Longitudinal residual magnetic	1	3	0	-	-	-		N/A			
	5	5	40	24-32	G-C-F	51					
	15	10	90	24-32	G-C-F	5					
Transverse residual magnetic	1	3		N/A				N/A			50
	5	5									50
	15	10									95
Direct current by contact	1	3	0	-	-	-	0	N/A	G-C-F	51	0
	5	5	60	80	G-C-F	51	30		G-C-F	51	30
	15	10	95	80	G-C-F	51	90		G-C-F	51	90
Direct current by contact with surface sensors (d)	1	3	90	80	G-C-F	10	50	N/A	G-F	10	90
	5	5	90	80	G-C-F	10	90		G-F	10	95
	15	10	99	80	G-C-F	10	95		G-F	10	99

(a) System will not distinguish between burns, welds, battered ends, or chipped ends and listed defect.

(b) Ability to inspect close to the end of the rail requires use of B scan data presentation system or use of sophisticated automatic data processing system.

(c) With sophisticated logic, 45° system could be effectively used in combination with 0° system to determine size and orientation of web defects.

(d) This system is not known to exist. Extensive Development would be required.

(e) Lower speed assumes a fluid path length of about 6.6 cm (typical large-wheel system) and a total electronic and fluid path delay time of 100 μ-sec. Higher speed assumes a very short fluid path length (sled or small wheel system without opposing reflectors) and total electronic and fluid path delay time of 25 μ-sec or less. The centerline of the U-sonic wave intersects the flaw 8 times during passage or the pulse rate will produce a pulse per 5 mm of travel (2 P/cm), which gives the lower speed.

(f) As (e) except that speed following comma assumes that gating used is such that more than one pulse can be in the rail at any given time.

TABLE 3b. SUMMARY OF TRANSDUCER EVALUATION DATA* (METRIC UNITS) (CONTINUED)

Transducer Type	Vertical Split Head: Maximum Operating Speed, (Km/hr)	Vertical Split Head: Minimum Distance from Joint, cm	Crack or Piping in Web: Number Flaws Detected, percent	Crack or Piping in Web: Maximum Operating Speed, (Km/hr)	Crack or Piping in Web: Minimum Distance from Joint, cm	Size Information provided E-Excellent, G-Good F-Fair, P-Poor	Comments
Normal ultrasonic	60(e) 80(e) 80(e)	<3(b) <3(b) <3(b)	99(a) 99(a) 99(a)	71-80+(e) 80+(e) 80+(e)	<3(b) <3(b)	E E E	Partial loss of base indicates possible serious bulging in piped rail. Complete loss of base provides failsafe(g) detection of all large horizontal defects in web or head.
45° pulse echo ultrasonic forward and backward, gated for full Vee	N/A		Note(c)	N/A		F F F	System has potential of detecting flaws under 24-in. long surface defects. Detection of flaws close to joint requires very complex or manual data processing.
45° thru transmission ultrasonic forward and backward	N/A		Note(c)	N/A		F-G F-G F-G	Loss of signal provides failsafe(g) detection of all large defects in web or center of head. Detection of flaws close to joint requires very complex or manual data processing.
30/60 skew ultrasonic pulse echo, four transducers (forward and backward)	N/A			N/A		F-G F-G F-G	System has potential of detecting flaws under up to 10-in. long surface defects.
30/60 skew ultrasonic thru transmission, four transducers (forward and backward)	64-80+, 80+ 80+, 80+ 80+, 80+	5 5 5		N/A		F-G F-G F-G	System has potential of detecting flaws under 2-3 in. long surface defects with complex or manual data processing. Providing failsafe detection of large vertical flaws and large transverse defects inside of head.
70° - ultrasonic pulse echo six transducers	N/A			N/A		- P-F P-F	Six transducers required for full interogation of the head with these transducers - fewer could be used in combination with other systems.
80° - ultrasonic pulse echo six transducers	N/A			N/A		- P-F P-F	Six transducers required for full interogation of the head with these transducers - fewer could be used in combination with other systems.
Longitudinal residual magnetic	N/A			N/A		- P P	Speed limitation imposed by weight and size restriction of high rail vehicle. Speed can be increased by increasing sizes and weights in approximate proportion to speed.
Transverse residual magnetic	24-80 24-80 24-80	3 3 3		N/A		G G G	Speed limitation imposed by weight and size restriction of high rail vehicle. Speed can be increased by increasing sizes and weights in approximate proportion to speed.
Direct current by contact	80 80 80	51 51 51		N/A		- F F	System is too heavy to use on high rail vehicle. Speed is limited only by distance between points where current is induced into the rail.
Direct current by contact with surface sensors (d)	80 80 80	10 10 10		N/A		F F F	System is too heavy to use on high rail vehicle. Speed is limited only by distance between points where current is induced into the rail.

(g) Failure safe as used in this context means that the presence of a flaw, or instrumentation problem will always produce a flaw induction whereas non-fail safe would imply a system in which an instrumentation (coupling) problem developed at the same time as a flaw is passed would not produce a flaw indication.

(h) Use of this system at high speeds may require either use of constant current control system and/or missing significant rail at joints.

* Pulse rep rate and flow size calc. based on 66 kg/m rail. Transverse defects assumed round except engine burn crack which is assumed rectangular with a 3:1 ratio.

(1) The maximum practical pulse repetition rates based upon travel time within the rail

(2) The minimum number of pulses required to detect a defect with maximum and repeatable effects on the received signals.

(3) Ultrasonic beam patterns and paths

(4) Shapes and locations of typical defects.

Most of the common, serious types of defects that occur in the head and web are represented in Table 3. Most of these can be detected by more than one ultrasonic technique. This possibility increases the overall probability of detection and provides additional information regarding size, geometry and orientation. Two exceptions are the horizontal split head that does not extend over the web and the vertical split head. Only one technique in Table 3, the $30^{o}/60^{o}$ Skew Through-Transmission method is listed as being capable of detecting these defects. Other systems, not listed in Table 3 using lateral transducers, either at 90^{o} or skewed relative to the rail also detect these defects. These lateral transducer systems would have approximately the same performance rating as the $30^{o}/60^{o}$ system for the split head defects.

The results of the study indicate that ultrasonic inspection methods are capable of detecting all serious flaws in rail heads and webs. In many cases, they can be detected at speeds of 50 mph (80 Km/hr) if good coupling and alignment can be maintained and if the data acquisition and processing are sufficiently fast.

Evaluation of Magnetic Inspection Systems

Evaluation of the magnetic methods of rail inspection has involved the following steps: (1) review of the basic rail inspection techniques and specific inspection systems, (2) observations of rail inspection systems during normal operation, (3) survey of the literature for information pertaining to analysis of rail inspection methods and similar techniques, and (4) analysis to estimate the inspection speed capabilities and sensitivities to various types and size of defects. Acquisition of empirical data pertaining to defect sensitivity and detection reliability at various speeds and track conditions has been minimal. Consequently, most of the conclusions pertaining to the capabilities of the magnetic methods have been derived from simple mathematical models and observation of rail inspection systems.

The investigation has been directed toward the evaluation of two basic types of magnetic inspection: (1) the electric current methods and (2) the magnetic flux leakage methods. The electric current methods provide a flow of current along the length of the rail either by direct contact or by the relative motion of a strong magnetic field. Defects distort the current flow and are detected by sensor coils that respond to perturbations in the magnetic field associated with the current. The magnetic flux leakage methods require no current flow, since defects are detected by sensing distortions in either the applied or retained magnetic fields. The rail is usually magnetized in the longitudinal direction by large electromagnets.

Analytical studies and some experimental data obtained from the literature indicate that inspection speed of the magnetic methods is limited primarily by the distance between electrical contacts or the spacing between the magnetizing poles, depending on the type of inspection system employed. The electric current methods that use direct contact can theoretically operate at speeds in excess of 50 miles per hour (80 kilometers per hour). In comparison, the residual magnetic method is estimated to have a top speed of only 17 miles/hour (27 Km/hr) with systems of reasonable size.

Operation of the electric current by contact systems at high speeds requires the use of widely spaced contact brushes to allow time for the current to penetrate into the rail. With widely spaced brushes it will be impossible to inspect close to an insulated joint, and extensive development work may be required to develop this type of system to work close to uninsulated joints on jointed rail.

Analytical evaluation and observation of rail inspection systems have revealed factors that affect the sensitivity of the magnetic methods. Surface anomalies such as engine wheel burns, shells, slivers, head checks, corrugations, and weld repairs are the major factors that limit reliable detection of small defects. These surface anomalies can cause noise signals that are comparable to the signals obtained from dangerous defects. Visual examination of the rail from the inspection cars is presently employed to identify many of the surface anomalies. Signals from small surface anomalies that are difficult to identify visually are rejected by electronic comparaters (a method of clipping). The clipping also limits detection of smaller defects. Therefore, the threshold level used in the clipping network is a major factor in establishing the maximum sensitivity of the magnetic systems.

Defects that occur near track features and under surface anomalies are frequently missed by the magnetic inspection systems. For example, bolted joints distort the flow of current or magnetic flux and cause signal indications that mask the signals from defects. It is generally agreed that defects within 2 to 4 in. (5 to 10 cm) of the bolted joint gap cannot be detected, and many inspection personnel do not believe that reliable detection inside the joint bars can be achieved using magnetic methods. Similarly, it is difficult to detect defects that lie under wheel burns and other surface anomalies.

Mathematical modeling of the magnetic techniques indicates that the electric current methods provide better sensitivity to transverse fissures than do the magnetic flux leakage methods. The sensitivity of the magnetic flux leakage methods is inversely proportional to the thickness of the fissure (dimension along the length of the rail). Consequently, even large cracks can go undetected. On the other hand, the thickness of transverse fissures has relatively little effect on the sensitivity of the electric current methods. Calculations indicate that transverse fissures covering an area of 10 percent of the cross sectional area of the rail head can be detected by the electric current methods even if the width is less than 0.0004 inch (0.01 millimeter). In contrast, it would be difficult to detect the same defect by the magnetic flux leakage techniques.

A potential method for improving sensitivity and reliability of rail inspection at greater speeds is the incorporation of a surface-sensitive eddy current detector with the ultrasonic and magnetic inspection methods. The eddy current sensor might be designed to provide a signal response only to unharmful anomalies on the rail surface. Combined with the conventional detection methods that respond to all defects, it is possible to reduce the indications from surface flaws and enhance the signals from dangerous defects. These concepts show promise for detecting transverse defects under wheel burns or other surface anomalies. Extensions of this technique can also be employed to provide more reliable high-speed inspection of the rail close to the rail joints.

All of these factors have been included in developing judgments on the overall capabilities of the different magnetic inspection systems. Table 3 summarizes the conclusions reached on the capabilities of major systems now in operation, and on a possible new system.

Data Handling System Requirements and Tradeoffs

Data analysis and handling techniques now in use were found to consist of the following

(1) On-board visual interpretation of B-scan signals obtained from ultrasonic transducers, followed by manual recording of flaw data.

(2) On-board visual interpretation of paper strip recordings of signals obtained from both magnetic and ultrasonic transducers.

(3) On-board visual evaluation of the appearance of the rail.

(4) Use of simple pulse counting circuits or multiple transducers to identify the presence of bolt holes, or bolt hole sized longitudinal defects.

(5) On-board recording of B-scan type data on film for later analysis in the laboratory.

(6) Stopping and making one or more types of visual or manual checks.

The use of techniques 1, 2, 3, and 6 were found to be the major factors presently limiting maximum inspection speeds. The use of automatic bolt hole identification techniques removes part of the operator's work load and allows a slight increase in speed to be obtained. Recording data for later analysis allows a substantial increase in inspection vehicle speed, but results in a significant delay before a defect is identified. Some U. S. railroads consider this delay a major liability.

After evaluating the above data handling system, it was concluded that to substantially increase inspection speeds without the delays associated with laboratory analysis of recorded data, a partial or fully automatic on-board data processing system is required. To evaluate both the potential effectivensss and costs of automatic data processing systems, several different configurations and capabilities were considered. From this study, it was concluded that the initial development of an automatic data processing system should concentrate (1) on the development of a combination logic-transducer subsystem which would identify normal rail ends, and (2) on the development of logic-transducer systems which would identify normal rail, including normal joints. In its earliest development stage, the data processing system might only be capable of separating normal from abnormal rail, and the operator would then analyze only data which have been identified as abnormal to identify flaws. The advantage to be obtained from this first step system would be that, because the operator does not have to evaluate data from all normal rail and joints, higher speeds can be obtained and more transducers can be provided to give more accurate information on flaws. After a system was developed to identify normal track, development on both the logic and transducers would make it possible to automatically positively identify an increasing number of flaws and reduce the operator's workload and/or increase speeds. In evaluating data handling systems to accomplish the above tasks, the system shown in block diagram form in Figure 1 was identified as having the potential of meeting initial goals and of having the flexibility of being programmed to meet future goals.

Hardware for this system would consist of filtering and gating circuits on each transducer to average the data and divide it into signals representing different sections of the rail. Microcomputers would receive, store, and analyze these data in real time to identify abnormal conditions. For high-speed systems, there might be a microcomputer for each transducer or gate. Upon occurrence of abnormal data, complete sets of abnormal data would be transferred to a central computer (perhaps two for high speeds) which would evaluate data from all transducers and, if possible, identify the flaw. If a flaw were positively identified, the central computer would cause the track to be marked with paint and a permanent record to be produced. If the central computer could not identify a flaw, paint would be applied and data

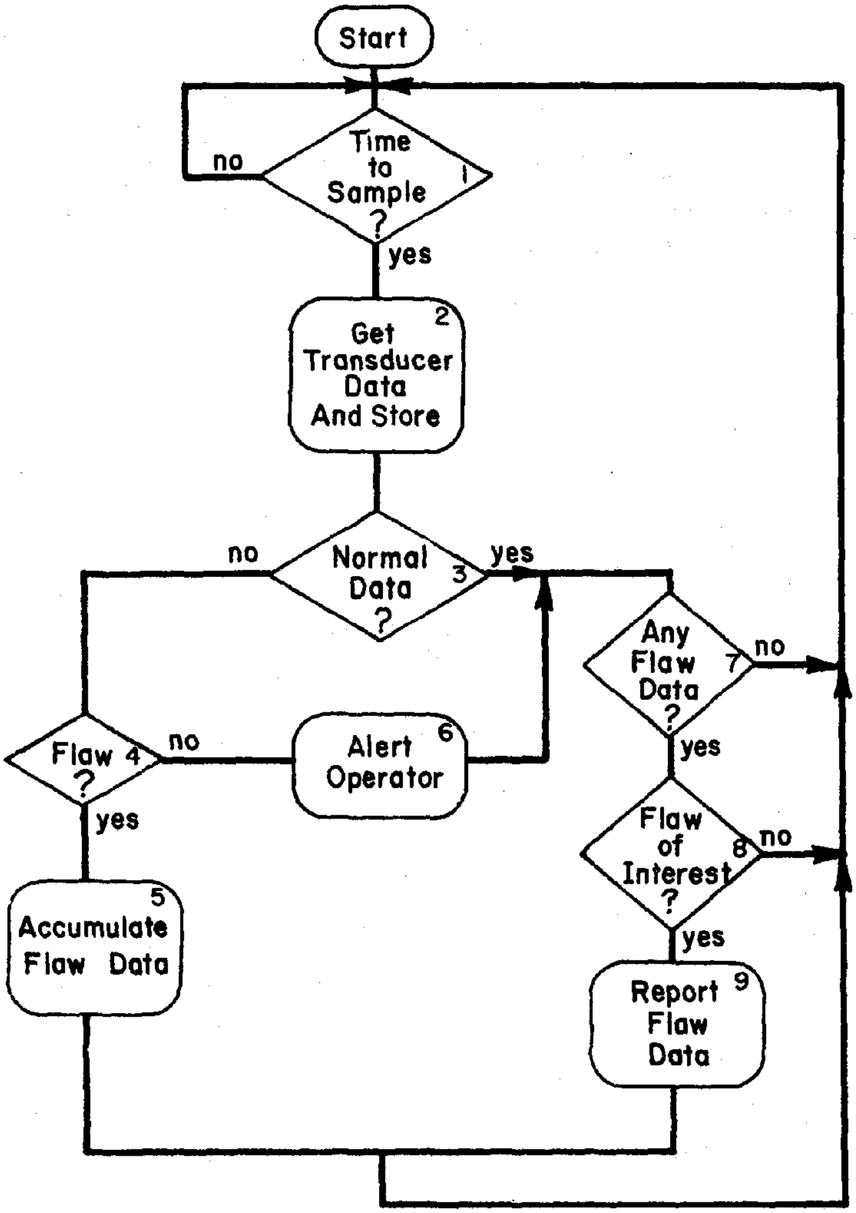


FIGURE 1. OVERALL DATA PROCESSING SYSTEM FLOW CHART

from the transducer would be presented to the operator, probably in B-scan or strip chart form, and the operator would make the decision in a conventional manner. If high inspection speeds are being used, the operator might also be presented with a TV picture of the section of the rail where the abnormal data were obtained. When the operator reaches a decision, he would enter his decision and the computer would produce a record of the decision.

Analysis of Cost/Performance Tradeoffs Between Systems

In order to determine the costs of systems that would operate at various speeds up to 50 mph (80 Km/hr) and with the capability of resolving transverse type flaw areas equal to 1 percent, 5 percent, or 15 percent of the head area and longitudinal type flaws with lengths of 1, 2, or 4 in. (2.5, 5.1, or 10.2 cm) estimates were made of the system complexities that would be required to achieve several performance levels.

The analysis started with a basic state of the art system consisting of about 10 ultrasonic transducers, a low-speed magnetic system, and manual data processing. This basic system was then modified by adding or substituting components to obtain improved performance. Some of these modifications were to add ultrasonic transducers and to provide a more sophisticated (possible multifrequency eddy current) magnetic system to improve the resolution capability, and to provide the use of automatic data processing, automatic carriage position control, and a special TV visual inspection system to allow increased operating speeds. Cost estimates for these different systems were based on extrapolations, where possible, from the costs of existing systems; however, many of the systems, or system components have not been developed and only rough estimates of procurement costs for the systems could be made. In initially evaluating the speed performance capability of the different systems, it was concluded that in general, specific inspection system features imposed definite speed limitations. For example, it was concluded that the practice of instantaneously manually evaluating the data on board the inspection car limits inspection speeds, when resolving 15 percent flaws, to about 10 mph (16 Km/hr). Automatic or remote, delayed data processing removes this speed limitation; however, other limitations in visually inspecting track and in carriage and wheel systems impose another speed limitation at about 25 mph (40 Km/hr). This speed limitation can be overcome by improving the carriage systems and using a special video tape recording system to provide the operator with more time for visual inspection of suspect areas of the track. In addition, it was assumed that problems in detecting 1 percent flaws would be severe enough to limit inspection speeds for those sized flaws to about 3 mph (5 Km/hr) even with very sophisticated detection and processing equipment. For some of the larger flaws, it is believed that several combinations of transducer, vehicle, and data processing systems could be combined to provide reliable detection of specific flaws. Cost estimates were made for several of the systems. Table 4 lists the estimated range of capital and operating costs for the systems evaluated. These estimates assume a number of operational stops within the available testing time, thus reducing the effective inspection speed below the maximum possible for each alternative.

TABLE 4. ESTIMATED CAPITAL AND OPERATING COSTS

Operating Speed		Defect Size		
mph	Km/hr	15 percent head area 4 in. (10.2 cm) long	5 percent head area 2 in. (5.1 cm) long	1 percent head area 1 in. (2.5 cm) long
3	5	$228,000 - 668,000 $5.85/mile - 8.35/mile $3.65/Km - 5.20/Km	$263,000 - 773,000 $17.70/mile - 26.20/mile $11.00/Km - 16.30/Km	$1,521,000 $37.10/mile $23.10/Km
10	16	$228,000 - 668,000 $5.85/mile - 8.35/mile $3.65/Km - 5.20/Km	$352,000 - 850,000 $7.40/mile - 9.45/mile $4.60/Km - 5.90/Km	-
25	40	$375,000 - 1,061,000 $3.80/mile - 4.70/mile $2.35/Km - 2.90/Km	$460,000 - 1,096,000 $4.15/mile - 4.75/mile $2.60/Km - 2.95/Km	-
50	80	$550,000 - 1,186,000 $2.90/mile - 3.00/mile $1.80/Km - 1.85/Km	$1,346,000 $3.25/mile $2.00/Km	

Cost Analysis of Alternative Inspection Systems

The basic capital and operating costs for various inspection systems determined previously and summarized in Table 4 were used to estimate the total line-haul inspection costs of each of these test railroads. These total costs include the general and administration (G & A), development, finance, and support costs as well as the previously developed capital and operations costs. The average cost for the three railroads (using current inspection frequencies) for each inspection speed and sensitivity is as follows:

Sensitivity, %	Speed mph (kph)	Cost Per Mile (Kilometer), $
15	10 (16)	31.00 (19.25)
15	25 (40)	14.00 (8.70)
15	50 (80)	12.00 (7.45)
5	10 (16)	39.00 (24.25)
5	25 (40)	14.50 (9.00)
5	50 (80)	14.50 (9.00)

It is concluded from this analyses that:

(1) Significant rail inspection cost reduction costs per mile (kilometer) could be derived from higher speed inspection systems.

(2) High-rail all ultrasonic inspection systems are generally the least cost type systems but do have limitations particularly with regard to water capacity that will reduce productive testing time, particularly at the higher speeds.

(3) The difference in cost between 5% and 15% inspection sensitivities is relatively small.

(4) Optimum inspection frequency and sensitivity are dependent on rail flaw propagation characteristics which are not well known at this time.

Recommended Rail Flaw Inspection System

The recommended inspection system is based on costs and on the desirability of having an inspection vehicle with the capability of being modified over time to utilize the latest inspection technology to achieve the most cost effective performance possible. The recommended system utilizes a rail type vehicle and has a potential nominal maximum operating speed of 50 mph (80 kph). The inspection system should have a capability to detect transverse defects with an area equal to 5% of the rail head or less and longitudinal flaws of 2 inches (5.1 cm) or less. The use of a combination of magnetic and ultrasonic sensors or all ultrasonic sensors is a design decision that should be determined at the time the system is being designed. This determination should be based on the technology available at that time to produce a vehicle that performs the needed rail inspection in the most cost effective manner.

Although it is desired and considered feasible to ultimately operate at 50 mph (80 kph) or higher, adequate technology is not presently available to operate at these speeds; however, the inspection vehicle should be developed so that as improved transducers, data processing and carriage systems are developed, these improved systems can replace older slower systems to ultimately allow operation at speeds of 50 mph (80 kph) or greater.

TECHNICAL DISCUSSION

Item 1 - Track Categorization

Purpose of Classification

The physical characteristics of track and the use made of track vary significantly within a railroad system and between railroads. The range of variation is from high speed, high volume, heavy rail, highly maintained mainline track to low speed, low volume, light weight, and perhaps poorly maintained track. Track maintenance demands, including rail inspection to achieve an acceptable level of track-related safety are, therefore, dependent to a large degree on track physical characteristics and traffic levels.

An important aspect of the definition of an "optimum rail flaw detection system" is the cost impact of the system. At one end of the spectrum of rail inspection system possibilities is a system that is extremely sensitive, is highly reliable (in terms of detecting even very small rail flaws), and is capable of high speed operations. At the other extreme is a system that detects only flaws larger than a specific minimum size, is less reliable in detecting flaws, and operates at a relatively low speed. The sophisticated system will be the most expensive but because of the many factors that impact cost, such as inspection system productivity, interference with normal traffic, traffic level-flaw growth rate, and derailment consequences, it might be the most cost-effective system, particularly for high-speed high density lines.

There are a number of factors that must be considered in the economic evaluation of alternative rail inspection systems. This analysis, which will be described under Items 6, 7, and 8 requires the categorization of railroad system trackage into segments that reflect the major factors that affect the economics of alternative rail inspection vehicle capabilities.

In addition to the economic analysis requirements, there is a need to categorize tracks to reflect the variation in physical features that directly affect the design and performance of the rail inspection system. For example, if the speed of a system must be lower for the inspection of a bolted joint than for a welded joint it is necessary to categorize tracks relative to type of joint. As another example, overall inspection speed might depend on the number of flaws found because of the need to stop and verify by hand checks. Thus, there is a need to know the expected flaw rate for a given track category. This flaw rate in turn may depend on the inspection frequency, traffic levels, type of rail, track geometry, and many other factors. Since these factors depend on the physical characteristics and use of a track, the trackage must be categorized to permit an estimation of performance of alternative inspection system configurations.

Categorization of Track for Inspection Purposes

As discussed in the preceding section, it is necessary in establishing a track categorization scheme and in determining the track data required from railroads, to have a reasonably well defined methodology in mind for the cost analysis (items 6, 7, 8) analysis. The ultimate objective is to provide some insight into the relationships of rail inspection vehicle speed, measuring capabilities, and costs and the benefits derived as expressed in terms of reduced rail-caused derailment, maintenance, and operational costs.

It is recognized that the above relationships will depend on the physical characteristics of the track as well as the traffic on the track and, of course, the capabilities of the inspection vehicle. Thus, there is a need to categorize track in a way that relates directly to rail inspection requirements. The most appropriate major breakdown of track is viewed to be by traffic volume. The railroads that have been contacted categorize track by traffic volumes. However, based on discussions with three leading railroads there is no industry-wide track categorization or even a definition of the traffic levels on "main" and "branch" lines.

Approach to Collecting Railroad Data

During the proposal stage and again at the outset of the study, three railroads were contacted, and arrangements made for these railroads to cooperate in providing data needed in the study--including track categorization data. These railroads were chosen for, among other reasons, the degree to which they appeared to represent the environment and transportation activities of the nation's railroads. Realizing the normal lack of complete and accessible data maintained by railroads, an important criterion in selecting representative railroads was the availability of track data. One of the chosen railroads is a leader in the degree to which track physical and performance data are computerized.

These three railroads made available, for examination, track records normally maintained by these railroads. Thus, the analysis and data discussed in sections that follow are based on three railroads. Railroad A can be classified as one of the larger railroads operating in the Eastern/Midwest area of the United States with a mixture of general freight and coal traffic. Railroad B is also a large railroad that operates between the West Coast and Midwest cities. This railroad carries high tonnages at a top speed of 70 mph (113 km/hr). The traffic on this railroad is primarily general freight with an increasing number of unit coal trains.

Railroad C is the largest railroad operating in the Southern/Southeastern region.

It is the judgment of the study team that three categories of traffic levels will be adequate for the analysis of alternative inspection systems. The following traffic levels have been chosen to define these three major categories:

High - greater than 10×10^6 gross annual tons (9×10^9 Kg)
Medium - 1×10^6 to 10×10^6 gross annual tons (9×10^8 to 9×10^9 Kg)
Low - less than 1×10^6 gross annual tons. (9×10^8 Kg)

Within this major categorization by traffic volume, it is necessary to identify subclasses that relate to inspection speed and/or economic impact of inspection speed. There are various factors that affect inspection speed. First, there are the major physical attributes of a rail that have a direct impact on inspection speed. Two attributes or subcategories in this area are the type of rail joints and the rail weight. Second, there is the historical experience of the rail that affects flaw occurrence rate. Attributes that relate to this experience include the age of the rail (date rolled) and the date rolled. Finally, there is the overall general condition of the track of which the rails are a part. One way of indicating this is through some combination of track geometry measurements.

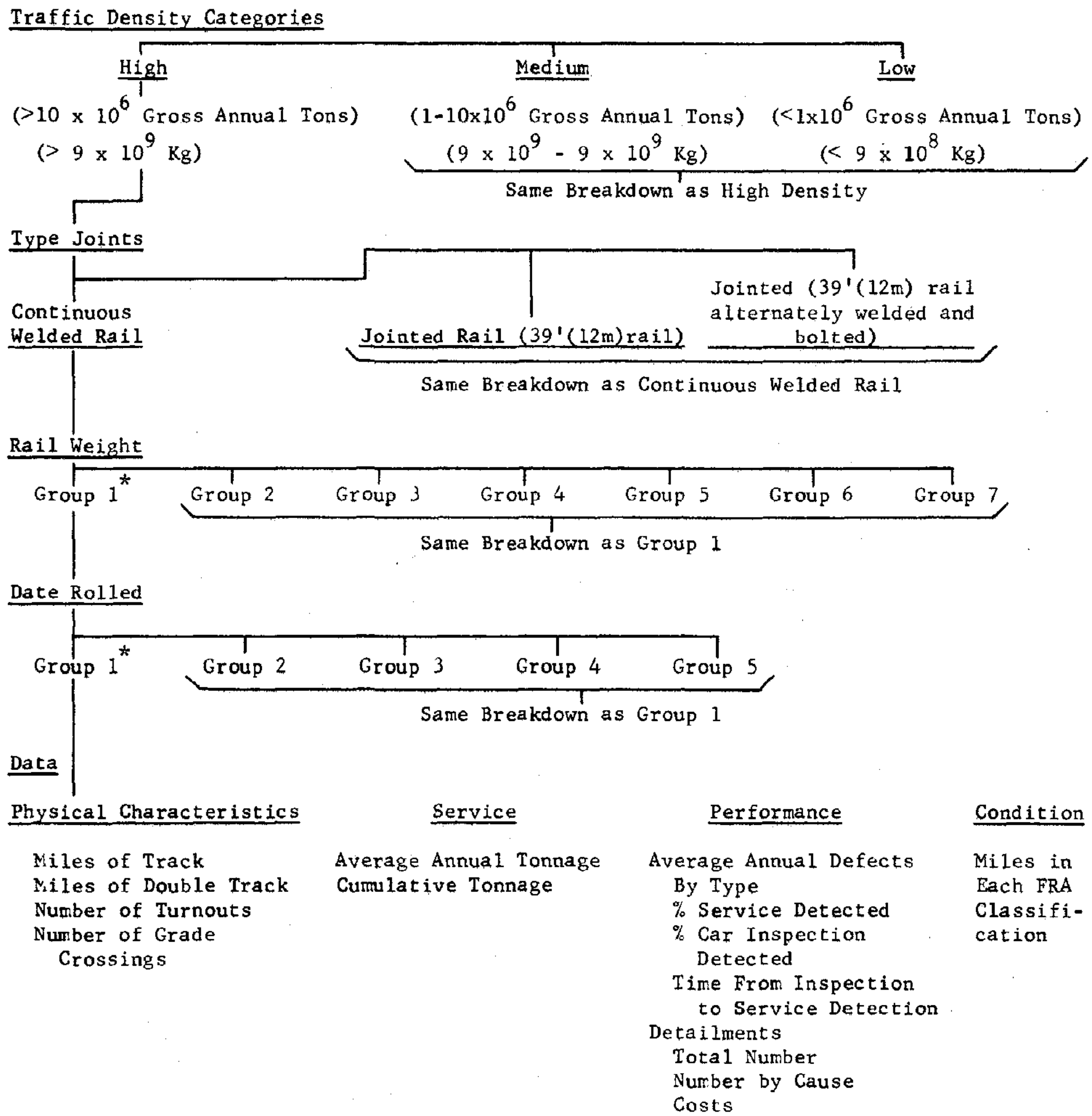
The track categorization scheme illustrated in Figure 2 was chosen as an ideal goal in collecting track data from cooperating railroads. As illustrated in this figure, the data required in each subcategory includes physical characteristics (miles, miles of double track, number of turnouts, and number of grade crossings), service (average annual tonnage and cumulative tonnage), performance (annual defects by type, how detected, and time since last inspection for service failures), and general track condition (miles in each FRA classification). It was the objective of work done on Item 1 to collect track data from railroads and to break these data down into the major and subcategories shown in Figure 2. Such a data breakdown would provide a basis for formulating and evaluating alternative rail inspection systems and for the economic analyses in Items 6, 7, and 8.

Data Collection and Analysis

The limited supply of source documents made it necessary to record much of the data collected in the offices of the railroads. Thus, for practical reasons, it became necessary to arbitrarily select a sample, in some instances, from the available data sources.

A summary of the data that were collected from Railroad A follows:

(1) Defects by line number - This is a 100 percent sample of the number of personnel-detected defects, car-detected defects, miles, and defects per mile for all line segments which recorded a failure in 1974.



(*) See attached notes for explanation of groupings.

FIGURE 2. IDEAL TRACK CATEGORIZATION AND DATA REQUIREMENTS

(2) Rail defects resulting in derailments (1974) - This is a 100 percent sample of rail-related derailments. Information on each occurrence includes

   (a) Line segment number
   (b) Milepost
   (c) Year rail rolled
   (d) Year rail laid
   (e) Welded or jointed rail
   (f) Type of detection (this doesn't seem to be necessary since these are supposed to be derailments. Nevertheless, some are indicated to have been detected failures.)
   (g) Date detected
   (h) Type defect
   (i) Number of cars derailed
   (j) Date last inspection (not recorded in all instances).

(3) Defects detected (personnel and inspection car) by type of defect.

(4) Days from detection to repair by type of defect. This is a sample of approximately 400 defects on 10 different divisions. How the defect was detected was also noted.

(5) Welded rail defects. There were 1199 welded rail defects out of a total of 6,131 reported defects in 1974. A sample of approximately 83 welded rail defect entries was examined and the year rolled and year laid recorded.

(6) Rail use history. A copy of this printout was obtained. This printout does not tie back specifically to the line number designation used in reporting defects. Further, this report covers new rail territory which is understood to be only in the high traffic density category.

A summary of the data that were collected from Railroad B follows:

(1) Record of actual inspection passes (location over time) for all inspection vehicles for 1974.

(2) Record of actual rail service failures that occurred in 1974. These failures are defined as those that are undetected until the rail breaks. These do not necessarily cause derailments. They may actually show up as a failure in the signaling system. Data were recorded on the time of these failures relative to the previous rail inspections.

(3) Number of turnouts in randomly selected sections of mainline and branch tracks.

(4) Number of rail weight and age transitions in selected mainline and branch tracks.

(5) Summary of Sperry rail service testing results and car operations.

(6) Mainline statistics and branchline statistics. These are a series of printouts breaking down the physical inventory of rail in different ways including the following:

  (a) Total miles and failures (defects causing rail to be replaced)
  (b) Miles and average million gross ton-miles (MGT) per mile by year laid
  (c) Miles by accumulated tonnage categories
  (d) Miles, average rail age per mile, MGT, and average MGT per mile
  (e) Breakdown of rail of each rail section of different lengths (39 ft (12m), 78 ft (24m), and CWR) by age and accumualated tons
  (f) Breakdown of miles of rail by year laid and defects (by type) for each rail length
  (g) Miles of rail of each weight laid in each year.

(7) Detailed data on each rail removed from service including type of defect and how the defect was detected.

Railroad C analyzed their computerized track data to provide the following for each track category as applicable:

(1) Miles of track
(2) Average number of turnouts per mile
(3) Average number of grade crossings per mile
(4) Miles of double track, jointed and welded.
(5) Average annual tonnage
(6) Average number of rail-flaw inspection car passes per year
(7) Miles of welded rail track
(8) Miles of bolted joint track
(9) Average number of rail weight and/or age changes per mile
(10) Annual number of rail defects by type and method of detection
(11) Number of rail caused derailments (1 year)
(12) Current rail inspection car performance
(13) Current rail inspection car costs
(14) Rail-caused derailment costs
(15) Rail replacement cost and time.

Because of the manner in which data are recorded and the content of these recorded data, it was impractical--if not impossible--to break the selected railroads trackage down into the ideal categorization described in an earlier section. Consequently, it was necessary to simplify the categorization scheme for these railroads to that shown in Figure 3. This simplified categorization along with supplemental information that will be described in the discussion that follows will serve the intended purpose of analyzing inspection vehicle requirements and performance in a railroad environment. The degree to which these data are representative of all railroads is not known and can be determined only with the analysis of other railroads. Further, data were made available for a one-year period, 1974 in the case of Railroads A and B and 1975 for Railroad C. Consequently, the degree to which the data are representative of the sample railroads over a longer time period is not known.

Track for the selected railroads is categorized in accordance with the simplified scheme as illustrated in Tables 5, 6, and 7. As shown in Tables 5, 6, and 7, certain data were available only to the extent of the density category and were not sufficient in detail to distinguish between welded and jointed rail. In these instances, the use of the data for the total density category should be adequate. For example, there are no data to specifically indicate the number of turnouts on welded and jointed rail tracks. At the same time, there is no basis for assuming this number will depend on the type of rail joints. Thus, the average number for the density category applies equally to jointed and welded rail tracks. In the case of defects for Railroad A, no data existed to break

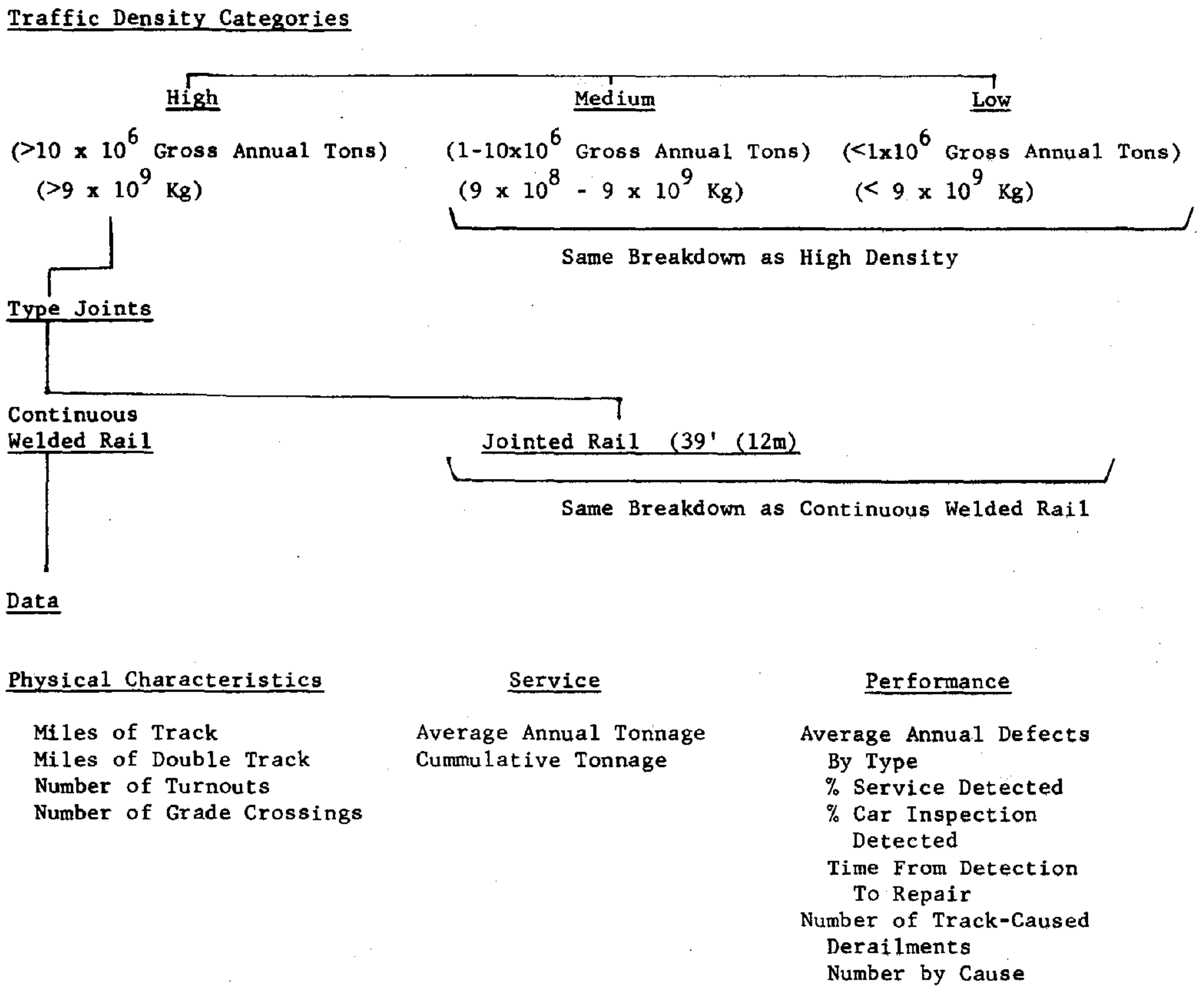


FIGURE 3. SIMPLIFIED TRACK CATEGORIZATION AND DATA REQUIREMENTS

TABLE 5. TRACK PHYSICAL CHARACTERISTICS

Traffic Density Category	Type of Joints	Railroad	Track Length: Miles	Track Length: Kilometers	Track Length: Percent of Total	Double Track: Miles	Double Track: Kilometers	Double Track: Percent of Category Miles	Turnouts: Per Mile	Turnouts: Per Km	Grade Crossings: Per Mile	Grade Crossings: Per Km	Weight(c) Transitions: Per Mile	Weight(c) Transitions: Per Km	Age Transitions: Per Mile	Age Transitions: Per Km
High	All	A	6,300	10,137	55.7	2,130	3,427	31.3	0.7	0.4	1.2	0.7	0.1	0.1	0.2	0.1
		B	4,575	7,361	44.5	1,249	2,010	27.3	0.5	0.3	2.0 (a)	1.3	0.1	0.1	0.7	0.4
		C	4,318	6,948	38.9	500	805	11.6	0.8	0.5	1.4	0.9	0.4	0.2	--	--
	Welded	A	3,500	5,632	28.7	--	--	--	--	--	--	--	--	--	--	--
		B	1,348	2,169	13.1	--	--	--	--	--	--	--	--	--	--	--
		C	3,872	6,230	34.9	404	650	9.4	--	--	--	--	--	--	--	--
	78' Bolted	A	0	0	0	--	--	--	--	--	--	--	--	--	--	--
		B	873	1,405	8.5	--	--	--	--	--	--	--	--	--	--	--
		C	0	0	0	--	--	--	--	--	--	--	--	--	--	--
	Other Bolted	A	2,800	4,505	27.0	--	--	--	--	--	--	--	--	--	--	--
		B	2,354	3,788	22.9	--	--	--	--	--	--	--	--	--	--	--
		C	447	719	4.0	96	154	2.2	--	--	--	--	--	--	--	--
Medium	All	A	3,600	5,792	28.7	0	0	0	1.3	0.8	2.3	1.4	0.1	0.1	0.2	0.1
		B	2,448	3,939	23.8	0	0	0	0.5	0.3	--	--	0.1	0.1	0.2	0.1
		C	3,888	6,248	35.0	181	291	4.7	0.8	0.5	1.9	1.2	0.4	0.2	--	--
	Welded	A	1,100	1,770	9.0	--	--	--	--	--	--	--	--	--	--	--
		B	0	0	0	--	--	--	--	--	--	--	--	--	--	--
		C	1,173	1,887	10.6	151	243	3.9	--	--	--	--	--	--	--	--
	Bolted	A	2,500	4,023	19.7	--	--	--	--	--	--	--	--	--	--	--
		B	2,448	3,939	23.8	--	--	--	0.5	0.3	--	--	--	--	--	--
		C	2,710	4,360	24.4	30	48	0.8	--	--	--	--	--	--	--	--

TABLE 5 (Continued)

Traffic Density Category	Type of Joints	Railroad	Track Length: Miles	Track Length: Kilometers	Track Length: Percent of Total	Double Track: Miles	Double Track: Kilometers	Double Track: Percent of Category Miles	Turnouts: Per Mile	Turnouts: Per Km	Grade Crossings: Per Mile	Grade Crossings: Per Km	Weight(c) Transitions: Per Mile	Weight(c) Transitions: Per Km	Age Transitions: Per Mile	Age Transitions: Per Km
Low	All	A	794(b)	1,278(b)	6.5(b)	0	0	0	0.4	0.2	1.2	0.7	0.3	0.2	0.5	0.3
		B	3,255	5,237	31.7	0	0	0	0.6	0.4	--	--	0.4	0.2	0.4	0.2
		C	2,894	4,656	26.1	26	42	0.9	1.0	0.6	1.6	1.0	0.6	0.4	--	--
	Welded	A	200(b)	322(b)	1.6(b)	--	--	--	--	--	--	--	--	--	--	--
		B	0	0	0	--	--	--	--	--	--	--	--	--	--	--
		C	156	251	1.4	19	31	0.7	--	--	--	--	--	--	--	--
	Bolted	A	594(b)	956(b)	4.9(b)	--	--	--	--	--	--	--	--	--	--	--
		B	3,255	5,237	31.7	--	--	--	0.6	0.4	--	--	--	--	--	--
		C	2,738	4,405	24.7	6	10	0.2	--	--	--	--	--	--	--	--

(a) System Averages.
(b) Sample of 794 miles of 1,900 total miles in low density category.
(c) Weight and age transitions combined for Railroad C.

TABLE 6. TRACK SERVICE CHARACTERISTICS

Traffic Density Category	Type of Joints	Railroad	Service Characteristics: Average Annual Tonnage, millions	Service Characteristics: Average Cumulative Tonnage, millions
High	All	A	19.1	361
		B	31.8	264
		C	19.3	--
	Welded	A	--	--
		B	--	--
		C	--	--
	78' Bolted	A	--	--
		B	--	--
		C	--	--
	Other bolted	A	--	--
		B	--	--
		C	--	--
Medium	All	A	4.8	--
		B	4.0	--
		C	3.9	--
	Welded	A	--	--
		B	--	--
		C	--	--
	Bolted	A	--	--
		B	4.0	--
		C	--	--
Low	All	A	0.4	--
		B	0.3	--
		C	0.4	--
	Welded	A	--	--
		B	--	--
		C	--	--
	Bolted	A	--	--
		B	0.3	--
		C	--	--

TABLE 7. TRACK PERFORMANCE CHARACTERISTICS

Traffic Density Category	Type of Joints	Rail-road	Total Number of Defects Annually[a]	Number of Defects[a] Per Mile	Number of Defects[a] Per Km	Personnel-Detected Defects[a] Per Mile	Personnel-Detected Defects[a] Per Km	Car Detected Defects[a] Per Mile	Car Detected Defects[a] Per Km	Percent Personnel-Detected	Percent Car-Detected	Average Days to Repair After Detection	Detailments[b] Total Number	Detailments[b] Percent of Total Rail-Caused	Average Months Since Last Inspection
				Performance Characteristics									Detailments(b)		
High	All	A	2,224	0.35	0.22	0.10	0.06	0.26	0.16	27.2	72.8	1.9	12	23.1	7.5
		B	3,457	0.76	0.47	0.37	0.23	0.39	0.24	48.9	51.1	--	2	28.6	--
		C	2,578	0.60	0.37	0.01	0.01	0.58	0.36	2.1	97 9	--	2	20.0	--
	Welded	A	874	0.25	0.16	--	--	--	--	--	--	--	3	5.8	--
		B	42	0.03	0.02	0.02	0.01	0.01	0.01	66.7	33.3	--	--	--	--
		C	1,407	0.36	0.23	0.01	0.01	0.35	0.22	3.6	96.4	--	--	--	--
	78' Bolted	A	--	--	--	--	--	--	--	--	--	--	--	--	--
		B	85	0.10	0.06	0.04	0.02	0.06	0.04	38.8	61.2	--	--	--	--
		C	--	--	--	--	--	--	--	--	--	--	--	--	--
	Other Bolted	A	1,350	0.48	0.30	--	--	--	--	--	--	--	9	17.3	--
		B	3,330	1.41	0.88	0.69	0.43	0.72	0.45	48.9	51.1	--	--	--	--
		C	1,171	2.62	1.63	0.01	0.01	2.61	1.62	0.3	99.7	--	--	--	--
Medium	All	A	3,720	1.03	0.64	0.55	0.34	0.48	0.30	53.8	46.2	7.3	39	75.0	2.3
		B	1,241	0.51	0.32	0.16	0.10	0.35	0.22	31.0	69.0	--	1	14.3	--
		C	9,085	2.34	1.45	0.05	0.03	2.29	1.42	2.3	97.7	--	4	40.0	--
	Welded	A	275	0.25	0.16	--	--	--	--	--	--	--	4	7.7	--
		B	--	--	--	--	--	--	--	--	--	--	--	--	--
		C	505	0.43	0.27	0.00	0.00	0.43	0.27	0.00	100.0	--	--	--	--
	Bolted	A	3,445	1.38	0.86	--	--	--	--	--	--	--	35	67.3	--
		B	1,241	0.51	0.32	0.16	0.10	0.35	0.22	31.0	69.0	--	--	--	--
		C	8,580	3.17	1.97	0.08	0.05	3.09	1.92	2.3	97.7	--	--	--	--

TABLE 7. (Continued)

				Performance Characteristics									Derailments(b)		
				Number of Defects(a)		Detected Defects(a)		Car Detected Defects(a)							
Traffic Density Category	Type of Joints	Rail-road	Number of Defects Annually(a)	Per Mile	Per Km	Per Mile	Per Km	Per Mile	Per Km	Percent Personnel-Detected	Percent Car Detected	Average Days to Repair After Detection	Total Number	Percent of Total Rail-Caused	Average Months Since Last Inspection
Low	All	A	187	0.24	0.15	0.13	0.08	0.11	0.07	54.6	45.4	--	1	1.9	--
		B	998	0.31	0.19	0.11	0.07	0.20	0.12	34.9	65.1	--	4	57.1	--
		C	3,291	1.14	0.71	0.07	0.04	1.07	0.67	5.8	94.2	--	4	40.0	--
	Welded	A	50	0.25	0.16	--	--	--	--	--	--	--	0	--	--
		B	--	--	--	--	--	--	--	--	--	--	--	--	--
		C	20	0.13	0.08	0.00	0.00	0.13	0.08	0.00	100.0	--	--	--	--
	Bolted	A	137	0.23	0.14	--	--	--	--	--	--	--	1	1.9	--
		B	998	0.31	0.19	0.11	0.07	0.20	0.12	34.9	65.1	--	--	--	--
		C	3,271	1.19	0.74	0.07	0.04	1.13	0.70	5.8	94.2	--	--	--	--

(a) Rail-replacement-causing defects in mainline tracks.
(b) Rail-caused derailments in mainline tracks.

the method of detection down by type of rail joints. If such a breakdown is required, a reasonable approximation could be derived by using the same personnel to car-detected defect ratio as experienced for the total defects in the density category.

As indicated in Figure 4 and Table 8, certain defects may produce a remedial action other than rail removal. Some of these actions may result in an operating restriction and some may not depending on the class of track. For example, a vertical or horizontal split head of less than 2 inches (3 cm) in length requires a reinspection in 90 days and a limit of speed to 50 miles per hour (80 kilometers per hour). If the railroad is currently limiting speed to this level or below, there is no train performance penalty and no corrective action is required.

No data were obtained from Railroad B indicating the actual number of defects found. For Railroad A, a total of 4106 defects were detected during the car inspection of 8,557 miles (13,768 km). This compares with reported mainline rail removals of 3,431 resulting from inspection car detected defects. This number was determined from a printout of all replaced rails in mainline tracks by line number. Thus, there is a difference of 675 which represents the number of defects that were disposed of by some means other than rail replacement or defects that were detected in other than mainline rails. Rail replacement reporting errors could account for a portion of this difference. The 675 defects represents approximately 16 percent of the total defects found by the inspection car. The total detected defect rate for Railroad A is 0.48 per car inspected mile (0.30 per km) as compared with 0.40 rail replacement defects per mile (0.25 per km).

The remainder of this report will relate to rail replacement defects in mainline tracks.

In analyzing alternative rail inspection vehicles, certain data not included specifically in Tables 5, 6, and 7 may be useful. These data include the available time for operating the vehicle on the track to be tested, number of rail defects present during each inspection, the number of rail test vehicle stops for hand checking that might be expected, a breakdown of the expected rail defects by type, and the nominal speed limits imposed on the tracks.

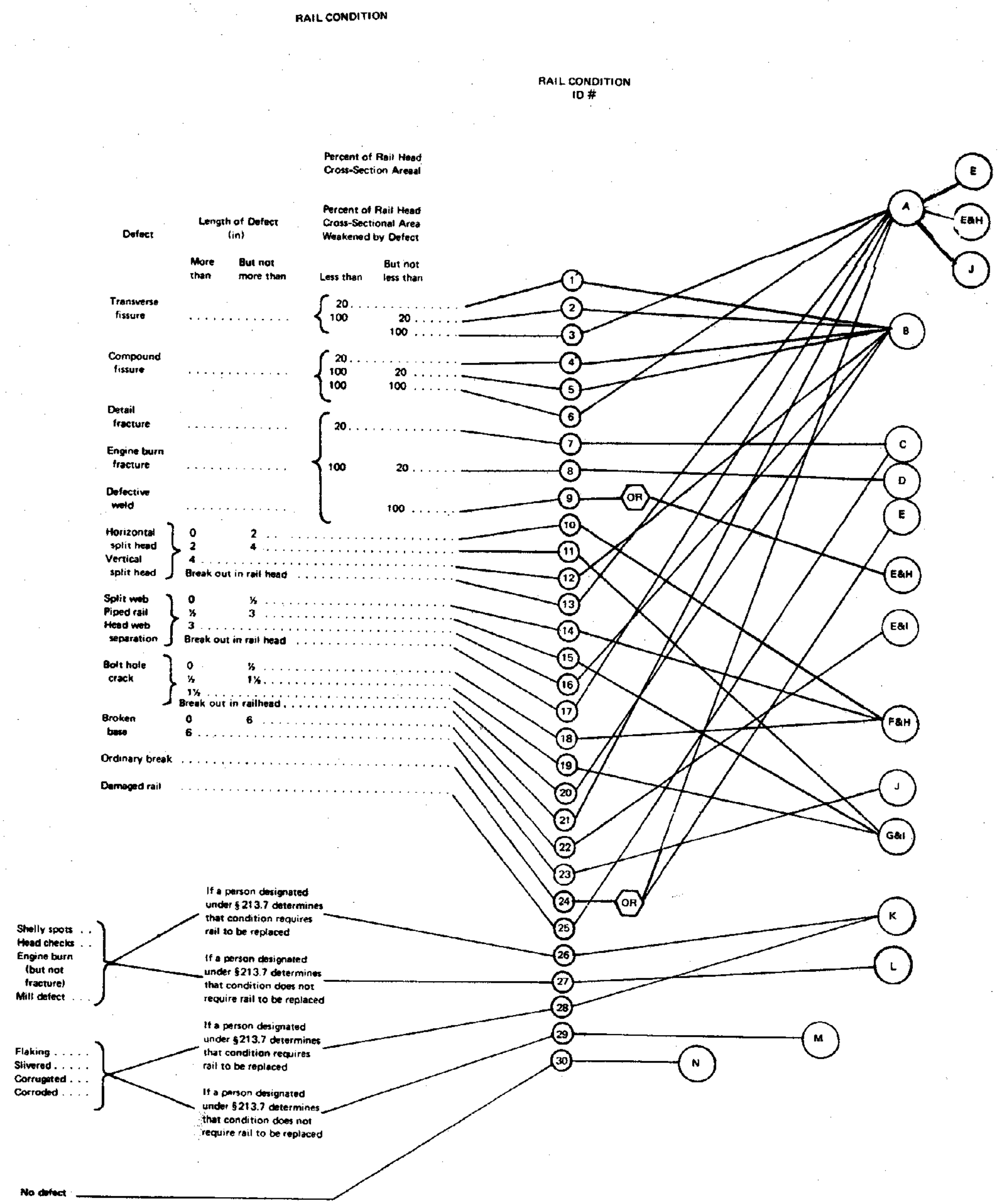


FIGURE 4. DECISION LOGIC BETWEEN RAIL CONDITION AND REMEDIAL ACTION ALTERNATIVES

TABLE 8. COST IMPLICATION FOR COMBINATIONS OF CLASS OF TRACK AND REMEDIAL ACTION

Class of Track \ Action[2]	A Assign person designated under §213.7[1] to personally supervise each operation over each defective rail.	B Limit operating speed to 10 m.p.h. over defective rail.	C Apply joint bars bolted only through the outermost holes to defect within 20 days after it is determined to continue the track in use. In the case of classes 3 through 6 track, limit operating speed over defective rail to 30 m.p.h. until joint bars are applied; thereafter, limit speed to 50 m.p.h. or the maximum allowable speed under §213.9 for the class of track concerned, whichever is lower.	D Apply joint bars bolted only through the outermost holes to defect within 10 days after it is determined to continue the track in use. Limit operating speed over defective rail to 10 m.p.h. until joint bars are applied; thereafter, limit speed to 50 m.p.h. or the maximum allowable speed over §213.9 for the class of track concerned, whichever is lower.	E&H E Apply joint bars to defect and bolt in accordance with §213.121(d) and (e). H Limit operating speed over defective rail to 50 m.p.h. or the maximum allowable speed under §213.9 for the class of track concerned, whichever is lower.	E&I E Apply joint bars to defect and bolt in accordance with §213.12(d) and (e). I Limit operating speed over defective rail to 30 m.p.h. or the maximum allowable speed under §213.9 for the class of track concerned, whichever is lower.
1	• Incur site supervision costs • Incur operations slow-down costs during Action A	• No change in operations	• Incur repair cost • Incur operations interruption cost during repair • No slow-down costs	• Incur repair cost • Incur operations interruption cost during repair • No slow-down costs	• Incur repair cost • Incur operations interruption cost before and during repair • No slow-down cost	• Incur repair cost • Incur operations interruption costs before and during repair • No slow-down cost
2	Ditto	• Incur slow-down cost	• Incur repair cost • Incur operations interruption cost during repair • No slow-down costs	• Incur repair cost • Incur operations interruption cost during repair • Incur prerepair slow-down costs	Ditto	Ditto
3	Ditto	Ditto	• Incur repair cost • Incur operations interruption costs during repair • Incur prerepair slow-down cost • Incur postrepair slow-down cost for passenger operations	• Incur repair costs • Incur operations interruption costs during repair • Incur slow-down cost before repair • Incur slow-down costs after repair for passenger operation	• Incur repair cost • Incur operations interruption costs before and during repair • No slow-down cost for freight • Slow-down cost for passenger	• Incur repair cost • Incur operations interruption costs before and during repair • Incur slow-down cost
4	Ditto	Ditto	• Incur repair cost • Incur operations interruption costs during repair • Incur slow-down costs	• Incur repair cost • Incur operations interruption costs during repair • Incur before and after repair slow-down costs	• Incur repair cost • Incur operations interruption costs before and during repair • Incur slow-down cost	Ditto
5	Ditto	Ditto	Ditto	Ditto	Ditto	Ditto
6	Ditto	Ditto	Ditto	Ditto	Ditto	Ditto

(1) Refers to section in Code of Federal Regulations, Title 49 Transportation
(2) Speed limits
Class 1 - 10 mph (16 kph) freight trains
Class 2 - 25 mph (40 kph) freight trains
Class 3 - 40 mph (64 kph) freight trains
Class 4 - 60 mph (97 kph) freight trains
Class 5 - 80 mph (129 kph) freight trains
Class 6 - 110 mph (177 kph) freight trains

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TABLE 8. COST IMPLICATION FOR COMBINATIONS OF CLASS OF TRACK AND REMEDIAL ACTION (CONTINUED)

Class of Track	F&H F Inspect rail ninety days after it is determined to continue the track in use. H Limit operating speed over defective rail to 50 m.p.h. or the maximum allowable speed under §213.9 for the class of track concerned, whichever is lower.	G&I G Inspect rail thirty days after it is determined to continue the track in use. I Limit operating speed over defective rail to 30 m.p.h. or the maximum allowable speed under §213.9 for the class of track concerned, whichever is lower.	J Replace Rail	K Limit speed to 20 m.p.h. and schedule the rail for replacement.	L Inspect the rail for internal defects at intervals of not more than every 12 months.	M Inspect the rail at intervals of not more than every 6 months.	N Inspect the rail as required in §213.237
1	• No change in operations • Incur reinspection costs	• No change in operations • Incur reinspection costs	• Incur repair costs • Incur operations interruption costs before and during repair	• Incur repair costs • No change in operations • Incur operations interruption costs during repair	• Incur reinspection costs • No change in operations	• Incur reinspection costs • No change in operations	• No incremental cost implicated
2	Ditto	Ditto	Ditto	• Incur slow-down costs before repair • Incur repair costs • Incur operations interruption costs during repair	Ditto	Ditto	Ditto
3	• No change for freight operations • Incur slow-down cost for passenger operations • Incur reinspection costs	• Incur slow-down costs • Incur reinspection costs	Ditto	Ditto	Ditto	Ditto	Ditto
4	• Incur slow-down costs • Incur reinspection costs	Ditto	Ditto	Ditto	Ditto	Ditto	Ditto
5	Ditto	Ditto	Ditto	Ditto	Ditto	Ditto	Ditto
6	Ditto	Ditto	Ditto	Ditto	Ditto	Ditto	Ditto

Inspection Vehicle Time on Track by Track Category. Data were obtained on the time performance of existing inspection vehicles on the test railroads. These data are presented in Table 9.

Railroad A nominally schedules one rail inspection annually for high-density lines and approximately once every two years for medium density. Low-density rails are inspected only when the railroad feels there is a need. Other data obtained indicate that only 24 percent of this railroad's low-density lines is inspected annually. Railroad B averages 3.5 rail detector car inspection passes per year on high-density lines, 1.4 on medium-density lines, and 1.0 on low-density lines. Railroad C averages 2.9 rail detector car passes per year on high density lines, 2.3 on medium density lines, and 1.4 on low density lines. Thus, the data in Table 9 are biased in favor of the higher-density lines. Data are not available to indicate how the inspection vehicle performance factors in Table 9 vary with traffic density. The percentage of time to and from tieups and for railroad transfers should be about the same for all categories.

TABLE 9. CURRENT RAIL INSPECTION VEHICLE TIME PERFORMANCE

Activity Category	Railroad	Performance Minimum	Performance Average	Performance Maximum
Service hours per testing day	A	7.7	9.9	9.5
	B	8.1	9.3	9.3
	C	--	8.4	--
Percent of time testing	A	56.9	66.0	72.0
	B	58.4	61.3	63.5
	C	--	66.8	--
Percent to and from tie-up	A	1.9	3.0	4.7
	B	1.9	2.2	2.6
	C	--	1.7	--
Percent traffic delay	A	12.4	19.0	26.7
	B	22.8	23.7	26.2
	C	--	11.7	--
Percent railroad transfer	A	10.6	12.0	16.5
	B	11.8	12.9	14.0
	C	--	19.8	--

TABLE 10. TRACK CATEGORY RATIOS

Item	Railroad	Ratio to High Density Medium	Low
Grade Crossings	A	1.9	1.0
	B	--	--
	C	1.3	1.1
Turnouts	A	1.9	0.6
	B	1.0	1.2
	C	1.0	1.2
Average annual tonnage	A	0.25	0.02
	B	0.13	0.01
	C	0.20	0.02

TABLE 11. ADJUSTED RAIL INSPECTION VEHICLE TIME PERFORMANCE

	Railroad	High Density	Medium Density	Low Density
Service hours per testing day	A	9.0	9.0	9.0
	B	9.3	9.3	9.3
	C	8.4	8.4	8.4
Percent time testing	A	65	70	75
	B	60	65	70
	C	67	67	67
Percent to and from tie-up	A	3	3	3
	B	2	2	2
	C	2	2	2
Percent traffic delay	A	20	15	10
	B	25	20	15
	C	11	11	11
Percent railroad transfer	A	12	12	12
	B	13	13	13
	C	20	20	20

It is only the traffic delay percentage and, therefore, the testing time percentage that vary. It would seem that reasonable approximations of these percentages could be made based on the knowledge of the number of turnouts and/or grade crossings and relative traffic levels. Using the high-density category as a base, the other categories relate as shown in Table 10.

Based on the above ratios, the breakdown shown in Table 11 is estimated to be reasonably representative of the sampled system.

Actual Number of Defects by Track Category. Based on a 100 percent sample of data for the two test railroads for 1974, the detected rail-replacement-causing defects are as shown in Table 12.

TABLE 12. ANNUAL DEFECTS BY METHOD OF DETECTION

		Density					
		High		Medium		Low	
		Defects					
Detection Method	Railroad	Per Mile	Per km	Per Mile	Per km	Per Mile	Per km
Inspection vehicle	A	0.26	0.16	0.48	0.30	0.11	0.07
	B	0.39	0.24	0.35	0.22	0.20	0.12
	C	0.58	0.36	2.29	1.42	1.07	0.67
Track personnel	A	0.10	0.06	0.55	0.34	0.13	0.08
	B	0.37	0.23	0.16	0.10	0.11	0.07
	C	0.02	0.01	0.05	0.03	0.07	0.04
Total	A	0.35	0.22	1.03	0.64	0.24	0.15
	B	0.76	0.47	0.51	0.32	0.31	0.19
	C	0.60	0.37	2.34	1.45	1.14	0.71

The defect rates in Table 12 indicate the expected defect rate per rail inspection pass only in those cases where there is a single inspection in a year. This applies to the high density category for Railroad A and the low-density category for Railroad B. The actual number of defects that might be found during a given inspection pass depends on the sensitivity of the inspection system, as well as the inspection frequency. At a minimum, the total number of defects that could be found in a year for any category, with sufficiently frequent inspections, is the sum of the number found by the inspection vehicle(s) and the number found by track personnel. This represents what could be found with current detection sensitivities which in the case of transverse defects is, perhaps, in the 10-15 percent range. Detection sensitivities in the 1-5 percent range could be expected to initially yield a greater number of car-detected defects. However, the expected increase cannot be accurately estimated based on the current understanding of defect initiation and propagation. It should be noted that after a transition period the flaw occurrence rate should be the same for all inspection sensitivities.

In order to provide a basis for estimating the impact of alternative inspection speeds, sensitivities, and frequencies, an approximation of the current, per inspection, defect rate will be developed.

In the high-density category for Railroad A, the per inspection detected flaw rate with current inspection capabilities is approximately 0.26 per mile (1.16 per km). Thus, the maximum number of flaws present during an annual inspection (Railroad A's current schedule) of high-density track is 0.26 (car-detected) plus 0.10 (track personnel-detected) or 0.36 per mile (0.22 per km). This may be somewhat high because some of the personnel-detected flaws would not yet be initiated (or have not reached the detection threshold level) at the time of inspection. At the same time, there may be flaws present that are smaller than the current threshold.

Railroad B schedules car inspection of high-density lines approximately 3.5 times per year. Thus, the per inspection car-detected flaw rate is approximately 0.11 per mile (0.07 per km) with current inspection car capabilities. The approximate number of flaws that are present during an inspection pass is 0.11 (car-detected) plus 0.11 (personnel-detected) or 0.22 per mile (0.14 per km). Again, there may be additional flaws present that are below current detection sensitivity levels.

Railroad C inspects high density lines 2.9 times annually. Consequently, the per car inspection detected flaw rate is 0.20 per mile (0.12 per km) with current inspection capabilities. The approximate number of flaws present during an inspection pass is 0.20 (car detected) plus 0.01 (personnel detected) or 0.21 per mile (0.13 per km).

Railroad A inspects medium density lines semiannually based on the one year (1974) sample period. Thus, the per inspection defect rate is as shown in Table 12. If these inspections were made more frequently, there would likely be a change in the relative portions of car and personnel detected defects and initially perhaps a higher defect rate. After a transition period, the steady-state annual defect rate should be approximately as shown in Table 12. However, with more frequent inspections, the number of service failures and rail-caused derailments should decrease. Railroad B operates rail inspection vehicles over medium-density tracks approximately 1.4 times per year. Thus, the per inspection car-detected flaw rate is approximately 0.25 per mile (0.16 per km) plus 0.11 per mile (0.07 per km) or 0.36 defects per mile (0.23 per km), present during an inspection pass for Railroad B, medium density.

Railroad C inspects the rails in medium density lines 2.3 times annually. Thus, the per pass defect rate is 1.0 per mile (0.62) per km) car detected plus 0.2 per mile (0.01 per km) or 1.02 per mile (0.63 per km) total.

Railroad B inspects low-density lines annually. Consequently, the annual flaw rates for this railroad's low-density tracks are as shown in Table 12. Since the low density lines of Railroad A are not inspected at regular intervals. the approximate 1:1 ratio of personnel to inspection car-detected defects requires some examination. Because of the low percentage of rail checked by an inspection car and the relatively large defect size that must occur to be personnel-detected, one would expect that the actual number of flaws in the low-density rails would be significantly higher than the reported <u>detected</u> flaws. This number can be estimated by looking at the ratio of car-detected to personnel-detected flaws in those cases where the low-density track is inspected. Based on a sample of 459 miles

(24 percent of low-density track miles) of low-density track that was car-inspected, and an assumed single inspection, the detected rates become 0.18 (car-detected) and 0.10 personnel-detected). Thus, the maximum number of rail-replacement-causing flaws present in low-density track that could be expected during an inspection at an assumed 4-year interval of low-density tracks would be 0.28 defects per mile)0.17 per km). This number is lower than one might expect based on the use of fairly heavily-used relaid rail in many instances and upon very limited observations and comments from railroad people. This lower-than-expected flaw rate is partially explainable by the low level of track usage. Further, some assumptions made in the calculation of this rate may be incorrect. For example, it was assumed that where a number was recorded for the car-detected defects in a low-density line segment, the entire line segment was car-inspected. This is not necessarily true. If only a portion of the segment was inspected by the inspection car, the detected flaw rate would be higher than indicated. Lacking better data, it is suggested that a flaw rate of perhaps 0.15 (detectable by current capabilities) plus 0.10 (personnel) or 0.25 defects per mile (0.16 per km) total be a reasonable estimate for low-density lines. This number compares favorably with one small sample on another railroad where 12 defects were found by the inspection car in a 51-mile branch line (0.24 defects per mile or 0.15 per km). This also compares reasonably well with the rate for Railroad B.

Railroad C inspects low density lines 1.4 times annually. Thus, the per pass defect rate is 1.01 per mile (0.63 per km) car detected, plus 0.02 per mile (0.01 per km) personnel detected or 1.03 per mile (0.64 per km) total.

Railroad A has as its goal the complete use of welded rail. This includes branch lines, yards, and sidings, as well as the primary system tracks. Railroads B and C also are increasing their use of continuous welded rail. Consequently, it is beneficial to provide a further insight into the experience of these railroads relative to welded rail. Table 13 summarizes the current status of welded rail in place in the sampled railroads.

TABLE 13. WELDED RAIL SUMMARY, SAMPLED RAILROAD

Traffic Density Category	Rail-road	Length Miles	Length km	Welded Rail Miles	Welded Rail km	Percent Welded Rail in Category	Percent of the Total Welded Rail Track
High	A	6300	10,137	3500	5632	55.6	72.9
	B	4575	7361	1348	2169	29.5	100
	C	4318	6948	3872	6230	89.7	74.4
Medium	A	3600	5792	1100	1770	30.6	22.9
	B	2448	3939	0	0	0	0
	C	3883	6248	1173	1887	30.2	22.6
Low	A	1900	3057	200	322	10.5	4.2
	B	3255	5237	0	0	0	0
	C	2894	4656	156	251	5.4	3.0

During 1974, Railroad A experienced 1,199 welded rail defects. Based on a sample of approximately 7 percent of these welded rail defects, and the distribution of defects between density categories, an approximate breakdown of welded rail defects by type is shown in Table 14 for Railroad A. The 7 percent sample was not entirely representative in that the percentages by type of defect applied to the known number of welded rail failures produce numbers of failures of welded rail in excess of the known totals for all failures of certain types. Thus, the breakdown provided by the sample is used directly for certain failure categories, such as weld defects and bolt-hole cracks, while for other type failures, the distribution between welded and bolted-joint track is made on the basis of mileage and the distribution of total failures by density category. Table 14 includes a breakdown of bolted-joint rail defects by density category and type of defect. The breakdowns of all defects for Railroads B and C are based on 100 percent samples of all rails removed from service because of defects during 1974 in the case of Railroad B and 1975 for Railroad C.

The total distribution and proportional distribution of defects by miles of track in each density category may be somewhat questionable

TABLE 14. SUMMARY OF ANNUAL DEFECTS (PERSONNEL AND CAR DETECTED) AND DEFECT RATE BY TYPE *

Type No.	Description	Rail-road	Total Defects	Percent of Total	Defects Per Mi	Defects Per Km	High Density Welded Per Mi	High Density Welded Per Km	High Density Bolted(d) Per Mi	High Density Bolted(d) Per Km	Medium Density Welded Per Mi	Medium Density Welded Per Km	Medium Density Bolted Per Mi	Medium Density Bolted Per Km	Low Density Welded Per Mi	Low Density Welded Per Km	Low Density Bolted Per Mi	Low Density Bolted Per Km
1	Bolt-hole failure	A	2821	46.0	0.26	0.16	0.01	0.01	0.14	0.09	0.01	0.01	0.50	0.31	0.01	0.01	0.13	0.08
		B	680	11.9	0.07	0.04	0.00	0.00	0.11	0.07	-	-	0.07	0.04	-	-	0.04	0.02
		C	3080	20.5	0.28	0.17	0.04	0.03	0.99	0.61	0.03	0.02	0.64	0.40	0.01	0.01	0.26	0.16
2	Head and web separation in joint area	A	977(a)	15.9	0.09	0.06	0.01	0.01	0.05	0.03	0.01	0.01	0.17	0.11	0.01	0.01	0.04	0.02
		B	106	1.9	0.01	0.01	0.00	0.00	0.01	0.01	-	-	0.02	0.01	-	-	0.01	0.01
		C	3028	20.3	0.27	0.17	0.04	0.02	0.59	0.37	0.05	0.03	0.73	0.45	0.01	0.01	0.21	0.13
3	Head and web separation out of joint area (b)	A	324	5.3	0.03	0.02	0.03	0.02	0.01	0.01	0.02	0.01	0.03	0.02	0.03	0.02	0.01	0.01
		B	--	--	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		C	291	2.0	0.03	0.02	0.00	0.00	0.03	0.02	0.03	0.02	0.07	0.04	0.00	0.00	0.02	0.01
4	Horizontal web crack	A	67	1.1	0.01	0.01	0.01	0.01	0.00	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.00	0.00
		B	109	1.9	0.01	0.01	0.00	0.00	0.01	0.01	-	-	0.03	0.02	-	-	0.00	0.00
		C	151	1.0	0.01	0.01	0.00	0.00	0.01	0.01	0.01	0.01	0.03	0.02	0.01	0.01	0.02	0.01
5	Crushed head	A	18	0.3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		B	95	1.7	0.01	0.01	0.00	0.00	0.03	0.02	-	-	0.00	0.00	-	-	0.00	0.00
		C	0.0	0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
6	Broken base	A	18	0.3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		B	53	0.9	0.01	0.01	0.00	0.00	0.00	0.00	-	-	0.00	0.00	-	-	0.01	0.01
		C	75	1.0	0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.00	0.02	0.01
7	Vertical split head (broken or cracked)	A	219	3.6	0.02	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.02	0.01	0.01	0.01
		B	501	8.8	0.05	0.03	0.00	0.00	0.02	0.01	-	-	0.06	0.04	-	-	0.09	0.06
		C	3471	23.2	0.31	0.19	0.01	0.01	0.11	0.07	0.04	0.02	0.72	0.44	0.00	0.00	0.51	0.32
8	Break in rail(b)	A	282	4.6	0.03	0.02	0.02	0.01	0.01	0.01	0.01	0.01	0.03	0.02	0.03	0.02	0.01	0.01
		B	--	--	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		C	25	0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

TABLE 14. (CONTINUED)

Type No.	Description	Rail-road	Total Defects	Percent of Total	Defects		High Density Welded		High Density Bolted(d)		Medium Density Welded		Medium Density Bolted		Low Density Welded		Low Density Bolted	
					Per Mi	Per Km	Per Mi	Per Km	Per Mi	Per Km	Per Mi	Per Km	Per Mi	Per Km	Per Mi	Per Km	Per Mi	Per Km
9	Engine burn fracture	A	249	4.1	0.02	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.03	0.02	0.02	0.01	0.01	0.01
		B	89	1.6	0.01	0.01	0.00	0.00	0.02	0.01	-	-	0.01	0.01	-	-	0.00	0.00
		C	1894	12.6	0.17	0.11	0.05	0.03	0.48	0.30	0.09	0.06	0.46	0.29	0.02	0.01	0.05	0.03
10	Horizontal split head (broken or cracked)	A	111	1.8	0.01	0.01	0.01	0.01	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.00	0.00
		B	133	2.3	0.01	0.01	0.00	0.00	0.02	0.01	-	-	0.01	0.01	-	-	0.01	0.01
		C	895	6.1	0.08	0.05	0.07	0.04	0.12	0.08	0.06	0.04	0.15	0.09	0.01	0.01	0.03	0.02
11	Shelly spots	A	7	0.1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		B	235	4.1	0.02	0.01	0.00	0.00	0.07	0.04	-	-	0.01	0.01	-	-	0.00	0.00
		C	--	--	-	-	-	-	-	-	-	-	-	-	-	-	-	-
12	Piped rail(b)	A	7	0.1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		B	--	--	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		C	43	0.00	0.0	0.00	0.00	0.00	0.01	0.01	0 00	0.00	0.00	0.00	0.00	0.00	0.01	0.01
13	Partial break(b)	A	18	0.3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		B	--	--	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		C	--	--	-	-	-	-	-	-	-	-	-	-	-	-	-	-
14	Transverse fissure	A	220	3.6	0.02	0.01	0.02	0.01	0.01	0.01	0.01	0.01	0.02	0.01	0.02	0.01	0.01	0.01
		B	400	7.0(e)	0.04	0.02	0.00	0.00	0.01	0.01	-	-	0.07	0.04	-	-	0.06	0.04
		C	1111	7.4	0.10	0.06	0.01	0.01	0.23	0.14	0.03	0.02	0.28	0.17	0.04	0.02	0.03	0.02
15	Compound fissure	A	12	0.2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		B	11	0.2	0.00	0.00	0.00	0.00	0.00	0.00	-	-	0.00	0.00	-	-	0.00	0.00
		C	--	--	-	-	-	-	-	-	-	-	-	-	-	-	-	-
16	Detail fracture	A	12	0.2	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		B	1392	24.4	0.14	0.09	0.01	0.01	0.35	0.22	-	-	0.09	0.06	-	-	0.01	0.01
		C	246	1.6	0.02	0.01	0.03	0.02	0.04	0.02	0.02	0.01	0.03	0.02	0.00	0.00	0.01	0.01

TABLE 14. (CONTINUED)

Type No.	Description	Rail-road	Total Defects	Percent of Total	Defects Per Mi	Defects Per Km	High Density Welded Per Mi	High Density Welded Per Km	High Density Bolted(d) Per Mi	High Density Bolted(d) Per Km	Medium Density Welded Per Mi	Medium Density Welded Per Km	Medium Density Bolted Per Mi	Medium Density Bolted Per Km	Low Density Welded Per Mi	Low Density Welded Per Km	Low Density Bolted Per Mi	Low Density Bolted Per Km
17	Broken or defective weld	A	285	4.6	0.03	0.02	0.06	0.04	-	-	0.04	0.02	-	-	0.06	0.04	-	-
		B	45	0.8	0.00	0.00	0.02	0.01	0.01	0.01	-	-	-	-	-	-	-	-
		C	240	1.6	0.02	0.01	0.06	0.04	0.00	0.00	0 01	0.01	0.00	0.00	0.00	0.00	0.00	0.00
18	Transverse defect(b)	A	461	7.5	0.04	0.02	0.04	0.02	0.01	0.01	0.02	0.01	0.05	0.03	0.04	0.02	0.02	0.01
		B	--	--	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		C	--	--	-	-	-	-	-	-	-	-	-	-	-	-	-	-
19	Fracture from welded engine burn (b)	A	6	0.1	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		B	--	--	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		C	--	--	-	-	-	-	-	-	-	-	-	-	-	-	-	-
20	Flaking or slivered(b)	A	1	0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		B	--	--	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		C	--	--	-	-	-	-	-	-	-	-	-	-	-	-	-	-
21	Head checks(b)	A	2	0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		B	--	--	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		C	--	--	-	-	-	-	-	-	-	-	-	-	-	-	-	-
22	Corrugated(b)	A	0	0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		B	--	--	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		C	--	--	-	-	-	-	-	-	-	-	-	-	-	-	-	-
23	Mill defects(f)	A	0	0.0	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
		B	--	--	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		C	4	0.0	0.00	0.00	0.00	0.00	0 00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
24	Engine burn - not fractured (b)	A	14	0.3	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.01	0.01	0.00	0.00
		B	--	--	-	-	-	-	-	-	-	-	-	-	-	-	-	-
		C	--	--	-	-	-	-	-	-	-	-	-	-	-	-	-	-

TABLE 14. (CONTINUED)

Type No.	Description	Rail-road	Total Defects	Percent of Total	Defects		High Density Welded		High Density Bolted(d)		Medium Density Welded		Medium Density		Low Density Welded		Low Density Bolted	
					Per Mi	Per Km	Per Mi	Per Km	Per Mi	Per Km	Per Mi	Per Km	Per Mi	Per Km	Per Mi	Per Km	Per Mi	Per Km
25	Damaged(c)	A	--	--	0.00	0.00	-	-	-	-	-	-	-	-	-	-	-	-
		B	1145	20.1	0.11	0.07	0.00	0.00	0.27	0.17	-	-	0.06	0.04	-	-	0.04	0.03
		C	--	--	-	-	-	-	-	-	-	-	-	-	-	-	-	-
26	Other(c)	A	--	--	0.00	0.00	-	-	-	-	-	-	-	-	-	-	-	-
		B	439	7.7	0.04	0.02	0.00	0.00	0.10	0.06	-	-	0.03	0.02	-	-	0.02	0.01
		C	399	2.7	0.04	0.02	0.06	0.03	0.01	0.01	0.01	0.01	0.05	0.03	0.03	0.02	0.01	0.01
27	Worn(g)	A	--	--	0.00	0.00	-	-	-	-	-	-	-	-	-	-	-	-
		B	263	4.6	0.03	0.02	0.00	0.00	0.05	0.03	-	-	0.02	0.01	-	-	0.02	0.01
		C	--	--	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Total	A	6133	100.0	0.57	0.35	0.25	0.16	0.41	0.25	0.25	0.16	1.44	0.89	0.25	0.16	0.23	0.14
		B	5696	99.9	0.55	0.34	0.03	0.02	1.06	0.66	-	-	0.51	0.32	-	-	0.31	0.19
		C	14954	100.0	1.33	0.84	0.36	0.23	2.62	1.63	0.43	0.27	3.17	1.97	0.13	0.08	1.19	0.74

(a) Total head and web separations - Railroad B does not report by location.
(b) Not reported by Railroad B or Railroad C.
(c) Not reported by Railroad A.
(d) Includes 78-ft (two 39-ft rails welded together) lengths for Railroad B.
(e) Includes compound fissures.
(f) Not reported by Railroad B.
(g) Not reported by Railroad A or Railroad C.

*1974 data for railroads A and B. 1975 data for railroad C.

for Railroad A. However, there is no apparent basis to select some other distribution. While in the high-density lines the rails are subjected to significantly more use, failures caused by this use may be offset by generally better track condition and maintenance.

Using the above numbers of defects by density category, the frequency of occurrence of car-detected defects in welded and bolted-joint rail will be as shown in Table 15.

TABLE 15. SUMMARY OF DETECTED DEFECTS BY CATEGORY AND TYPE JOINTS

Traffic Density Category	Rail-road	Detected Defects[b]		Miles		Kilometers		Defects Per Mile[b]		Defects Per km[b]	
		Welded	Bolted	Welded	Bolted[a]	Welded	Bolted	Welded	Bolted	Welded	Bolted
High	A	874	1350	3500	2800	5632	4505	0.25	0.48	0.16	0.30
	B	42	3415	1348	3227	2169	5192	0.03	1.06	0.02	0.66
	C	1407	1171	3872	447	6230	719	0.36	2.62	0.23	1.63
Medium	A	275	3445	1100	2500	1770	4023	0.25	1.38	0.16	0.86
	B	--	1241	0	2448	--	3939	--	0.51	--	0.32
	C	505	8580	1173	2710	1887	4360	0.73	3.17	0.45	1.97
Low	A	50	137	200[c]	594[c]	322[c]	956[c]	0.25	0.23	0.16	0.14
	B	--	998	0	3255	--	5237	--	0.31	--	0.19
	C	20	3271	156	2738	251	4405	0.13	1.20	0.08	0.75

(a) Bolted-joint data for Railroad B includes 78-ft (24m) sections that are made up of two 39-ft (12m) sections welded together.
(b) Rail replacement-causing defects.
(c) Sample of 794 miles (1280 Km) of 1900 total miles (3060 total Km) in density category.

As described earlier, the above rates are on an annual basis with current inspection car schedules. These schedules are as shown in Table 16.

TABLE 16. CURRENT INSPECTION CAR SCHEDULES

Traffic Density Category	Railroad	Inspection Frequency Inspections Per Year
High	A	1
	B	3.5
	C	2.9
Medium	A	0.5
	B	1.4
	C	2.3
Low	A	0.25
	B	1.0
	C	1.4

In those cases where the inspection frequency is greater than one, the defects per inspection can be estimated by dividing the annual defects by the inspection frequency.

Table 17 is a breakdown of the type of defect by method of detection. Railroad A data are based on a sample of 396 defects, or approximately 6.5 percent of all defects. It will be noted that this sample is not precisely representative of the total defect population as indicated by the percent of total defects by type. Railroad B and Railroad C data are based on 100 percent samples.

TABLE 17. DETECTION METHOD BY TYPE DEFECT

			Inspection Car Detected		Track Personnel Detected	
Defect Number	Description	Rail-road	Number Detected	Percent of Defects of This Type	Number Detected	Percent of Defects of This Type
1	Bolt-hole failure	A	63	52.5	57	47.5
		B	603	88.7	77	11.3
		C	2,866	93.1	214	6.9
2	Head and web separation in joint area	A	53	73.6	19	26.4
		B[a]	60	56.6	46	43.4
		C	2,873	94.9	155	5.1
3	Head and web separation out of joint area[b]	A	12	57.1	9	42.9
		B	--	--	--	--
		C	288	99.0	3	1.0
4	Horizontal web crack	A	1	25.0	3	75.0
		B	60	55.0	49	45.0
		C	151	100.0	0	0.0
5	Crushed head	A	--	--	--	--
		B	4	4.2	91	95.8
		C	0	0	0	0
6	Broken base	A	0	0	5	100.0
		B	15	28.3	38	71.7
		C	64	85.3	11	14.7
7	Vertical split head	A	26	96.3	1	3.7
		B	410	81.8	91	18.2
		C	3,461	99.7	10	0.3
8	Break in rail[b]	A	3	15.0	17	85.0
		B	--	--	--	--
		C	8	32.0	17	68.0
9	Engine burn fracture	A	17	60.1	11	39.9
		B	44	49.4	45	50.6
		C	1,889	99.7	9	0.3
10	Horizontal split head	A	6	40.0	9	60.0
		B	108	81.2	25	18.8
		C	894	99.9	1	0.1
11	Shelly spots[d]	A	0	0.0	3	100.0
		B	146	62.1	89	37.9
		C	--	--	--	--
12	Piped rail[b]	A	--	--	--	--
		B	--	--	--	--
		C	43	100.0	0	0.0
13	Partial break[b][d]	A	--	--	--	--
		B	--	--	--	--
		C	--	--	--	--
14	Transverse fissure[e]	A	23	79.3	6	20.7
		B	385	96.3	15	3.7
		C	1,097	98.7	14	1.3

TABLE 17. (Continued)

Defect Number	Description	Rail-road	Inspection Car Detected: Number Detected	Inspection Car Detected: Percent of Defects of This Type	Track Personnel Detected: Number Detected	Track Personnel Detected: Percent of Defects of This Type
15	Compound fissure	A	--	--	--	--
		B	0	0.0	11	100.0
		C	--	--	--	--
16	Detail fracture	A	--	--	--	--
		B	1,335	95.9	57	4.1
		C	246	100.0	0	0.0
17	Broken or defective weld	A	8	38.1	13	61.9
		B	12	26.7	33	73.3
		C	225	93.8	15	6.2
18	Transverse defect (b) (d)	A	22	84.6	4	15.4
		B	--	--	--	--
		C	--	--	--	--
19	Fracture from welded engine burn (b) (d)	A	1	100.0	0	0.0
		B	--	--	--	--
		C	--	--	--	--
20	Flaking or slivered (b) (d)	A	--	--	--	--
		B	--	--	--	--
		C	--	--	--	--
21	Head checks	A	--	--	--	--
		B	--	--	--	--
		C	--	--	--	--
22	Corrugated (b)	A	--	--	--	--
		B	--	--	--	--
		C	--	--	--	--
23	Mill defects (b)	A	--	--	--	--
		B	--	--	--	--
		C	3	75.0	1	25.0
24	Engine burn - not fractured (b)(d)	A	1	33.3	2	66.7
		B	--	--	--	--
		C	--	--	--	--
25	Damaged (c) (d)	A	--	--	--	--
		B	54	4.7	1,091	95.3
		C	--	--	--	--
26	Other (c)	A	--	--	--	--
		B	34	7.7	405	92.3
		C	390	97.3	11	2.7
27	Worn (c) (d)	A	--	--	--	--
		B	2	0.8	261	99.2
		C	--	--	--	--

(a) Total head and web separations - Railroad B does not report by location.
(b) Not reported by Railroad B.
(c) Not reported by Railroad A.
(d) Not reported by Railroad C.
(e) Combined with compound fissure for Railroad C.

Required Number of Stops per Mile. Summaries of rail car annual operational performance were provided by Railroads A and B. In the case of Railroad A, this represented all of the rail car inspection activities for the railroad for 1974. The summary for Railroad B represented only a part of the total rail car inspection activities for 1974. Data from these summaries pertaining to vehicle stops relative to defects found and miles inspected are presented in Table 18. It should be pointed out that even for Railroad A the number of defects found will not correspond with annual defect data included elsewhere in this report. This situation occurs because the defect data in other parts of the report are based on the actual number of rails removed which include a substantial portion of defective rails that are detected by track personnel. Further, the detected defects are not necessarily all of a serious enough nature to require rail removal. In addition, this is a 60 percent sample of Railroad A's car inspection for 1974.

It will be noted that the sum of successful ultrasonic and magnetic hand tests is not equal to the total number of defects. The difference between these values represents the number of defects confirmed by visual means.

Based on the data in Table 18 the ratio of total stops to defects found ranges from 4 to 6. Limited observations of inspection vehicle operations indicate that on certain lines this ratio may be higher than the above averages, ranging up to perhaps 12:1.

The actual number of stops for visual tests are not recorded. The difference between total stops and the sum of magnetic and ultrasonic hand tests represents visual tests and operational stops. It is understood that these stops, including operational stops, are included in the reported testing time frame. If it is assumed that these stops are equally divided between operational stops and stops for visual tests, the ratio of stops for defect verification to the actual defects found is in the 3 to 5 range. Again, it must be recognized that these are system-wide averages. Since high density tracks are inspected more frequently than low-density tracks, the range of stops to defects found may easily vary up to values of 10:1 or perhaps more on some track segments.

TABLE 18. SUMMARY OF RAIL INSPECTION CAR PERFORMANCE

Railroad	Miles Suspected	Total Defects Found	Total Stops	Stops For Induction Hand Tests	Number of Confirming Induction Hand Tests	Stops For Ultrasonic Hand Tests	Number of Confirming Ultrasonic Hand Tests
A*	5,318	2,668	10,358	914	302	6,829	1,676
B	16,138	3,245	20,211	2,502	914	7,928	1,457

* This is a sample of approximately 60 percent of the inspection service for Railroad A.

Using the same operational stop - visual check stop ratio, the operational stopping frequency can be estimated. Railroad A is estimated to have experienced 1308 operational stops (1/2 the difference between total stops and the sum of magnetic and ultrasonic hand test stops) for 5,318 test miles or 0.25 operational stops per mile (0.16 per km). Railroad B is estimated to experience 0.30 operational stops per mile (0.19 per km). Calculations of effective inspection speed in Item 5 are based on an assumption that these operational stops occur within the recorded testing time frame.

Speed Limits. The timetable speed limits vary widely depending on a number of factors, including train weight. These limits are primarily affected by the design of the signaling system (block lengths). Typical train speed limits for Railroad A are as shown in Table 19. Railroad B operates trains over their high-class main lines at speeds up to 70 mph (113 km/hr). Railroad C operates trains at a nominal speed of 60 mph (97 km/hr) on tangent track.

TABLE 19. NOMINAL SPEED LIMITS, RAILROAD A

Type Track	Speed Limit mph	Speed Limit km/hr
Yards	10	16.1
Coal field branch lines	15–25	24.1–40.2
Trunk branch lines	25–30	40.2–48.3
High-class main lines	50	80.4

Item 2 - Determination of Optimum Operating Speeds

Field Observations

Track categories which have the potential of affecting inspection speed are discontinuities such as frogs and switches that may force a speed reduction in the area of the discontinuity, flaws, or suspected flaws that may require a complete stop, and track surface geometry errors that may limit speeds due to excessive carriage motions. Some typical practices observed on U. S. railroads in inspecting at these discontinuities were to stop for all detected and suspected flaws, to slow down at discontinuities such as frogs and switches, and on some systems, to slow down and raise the carriage assembly at track discontinuities. There were no cases observed where speed was reduced because of track geometry errors. Observations were made while inspecting track with large geometry errors and in these cases, low inspection speeds were used because of low speed limits on the track and because of the operator's inability to evaluate data at rates that would be required for higher speeds. An evaluation of data taken on the TSC car showed that coupling efficiency was almost independent of speed at speeds up to a maximum test speed of 15 mph (25 Km/hr). A conversation with a manufacturer of ultrasonic wheels produced the information that tests have shown that ultrasonic wheels can operate satisfactorily at speeds to 30 mph (48 Km/hr) under laboratory conditions.

In addition to the track features that were observed to affect speed, some cases were seen or discussed where speed was limited by dirt, grease, or rust on the track surface, by the presence of nonuniform relaid rail, and by the presence of extra bolt holes in the rail, or by the presence of weld repair areas in the track. The presence of contaminants on the surface of the track was found to cause delays because several passes over a section of rail were sometimes required to get the rail clean enough to obtain a reliable inspection. Speeds were reduced when operating on nonuniform relaid rail because of difficulties in maintaining transducer alignment. In some cases, it was not possible to positively identify extra bolt holes or weld repair areas from the vehicle and stops were made for hand checks.

Calculations of Effect of Slowing for Track Features

In addition to observing present practices, calculations were made to determine theoretical relationships between track categories and inspection speeds. To calculate the effect frogs, etc. made, it was assumed that track features that may have to be crossed at slow speeds will be seen before they are reached, and the operator will start slowing the inspection vehicle before he reaches the discontinuity. Comfort and vehicle performance criteria limit both the acceleration and deceleration capabilities of an inspection vehicle to a range of about 0.1 to 0.15 g. If it is assumed that the operator decelerates from his normal operating speed to a complete stop and then immediately accelerates back to normal spead at acceleration rates of 0.1 to 0.15 g, his efficiency (or ratio of average speed to maximum speed, as a function of distance between stops) and maximum operating speeds will be shown in Figures 5 and 6. These curves show that if the distance between slowdowns is 1 mile or greater, the overall effect of this type of track feature will not be highly significant for speeds up to 50 mph (80 Km/hr). At speeds up to 20 mph (32 Km/hr), the effect of slowing down for track features would be very minimal.

Calculations on Effect of Stopping for Hand Checks

If the inspection car is required to stop for hand checks of suspected flaws and/or to tag identified flaws, several different sequences of events may occur at each stop. The following sequence of events is reasonably typical of the events that now occur.

(1) After a defect is passed, an "evaluation" time elapses before a decision is made to stop.

(2) The vehicle decelerates over a finite distance and for a finite time to a complete stop.

(3) The vehicle accelerates to a maximum reverse speed and travels in reverse at that speed for a finite time.

(4) The vehicle decelerates to a stop.

(5) The crew leaves the car for the hand check or tagging operation.

(6) The vehicle accelerates back to normal operating speed.

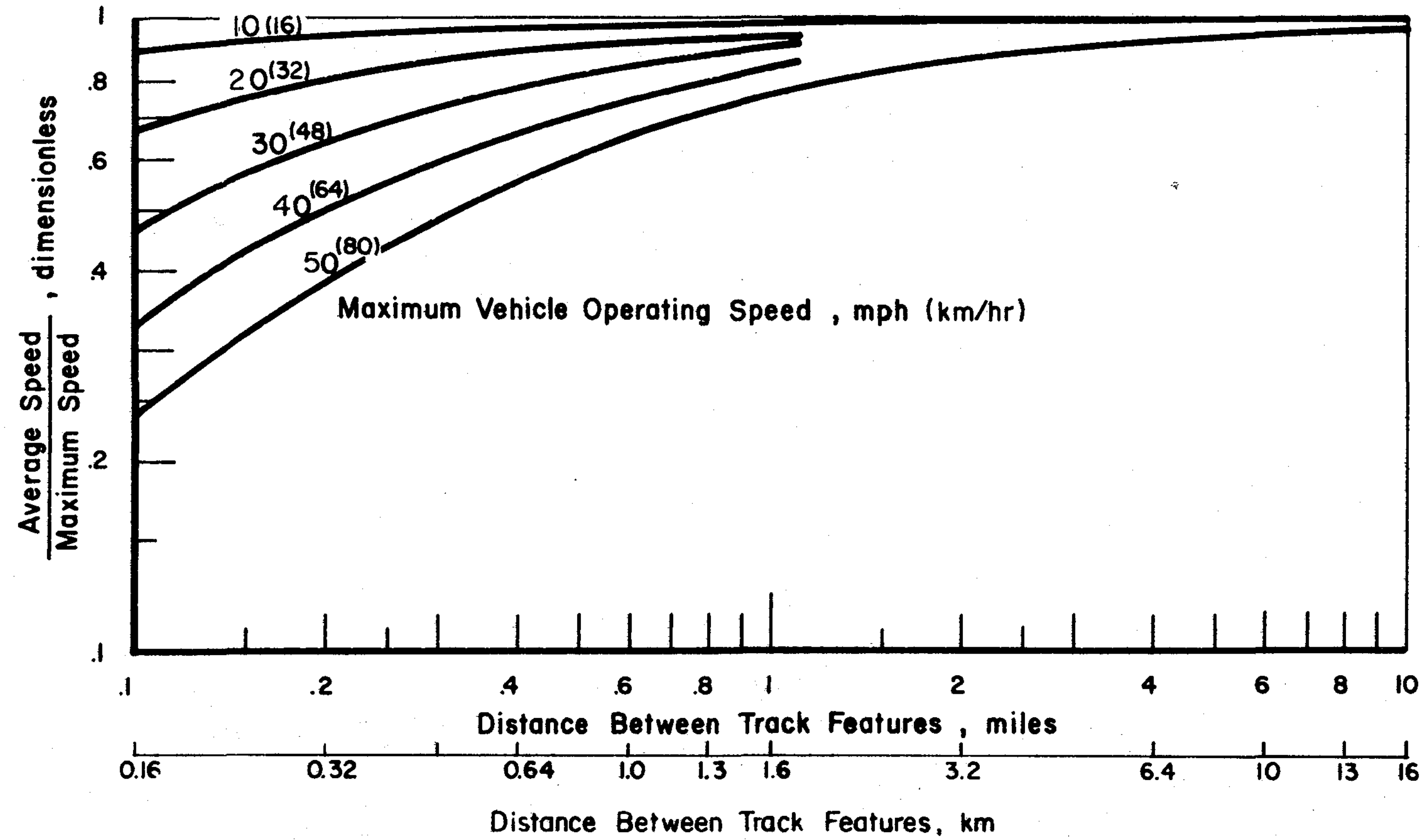


FIGURE 5. SPEED REDUCTION DUE TO TRACK FEATURES WITH A VEHICLE ACCELERATION AND DECELERATION CAPABILITY OF 0.1 G

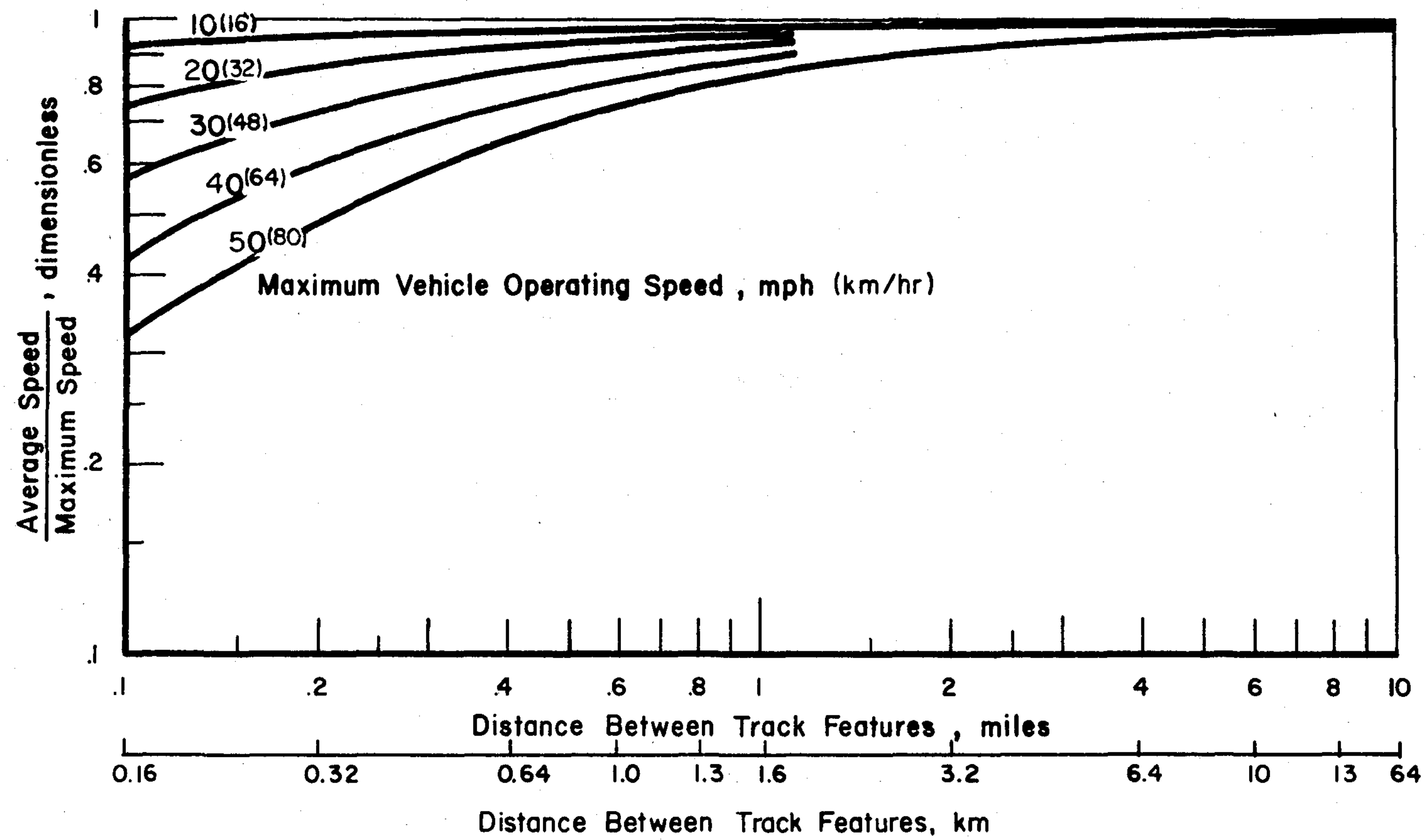


FIGURE 6. SPEED REDUCTION DUE TO TRACK FEATURES WITH A VEHICLE ACCELERATION AND DECELERATION CAPABILITY OF 0.15 G

Each of the above steps can result in a different amount of lost time. In addition, other steps in addition to those listed can be performed. For example, the operator may reinspect the suspect area with the car.

For calculation purposes, it was assumed that only the six steps listed above were performed, and that

(1) The "evaluation" time that elapsed before deciding to stop was 5 seconds

(2) All accelerations and decelerations were at 0.1 g

(3) The maximum reverse speed was 10 mph (16 Km/hr) (15 Km/hr)

(4) The car was stopped for tagging or hand checks for 60 seconds

(5) Normal inspection speeds were in the range of 10 to 50 mph (16 to 80 Km/hr). (16 to 80 Km/hr).

With these assumptions, Figure 7 shows the average operating speed that would be obtained as a function of distance between stops. The track categorization study indicated that the number of defects detected will normally be in the range of 0.1 to 1.4 defects per inspection mile. Observation of present practice indicates that, with present equipment, the number of stops made is 3 to 10 times higher than the number of defects, or the average distance between stops will usually be in the range of 0.1 to 1.0 mile (0.16 to 1.6 Km).

Figure 7 shows that with the conditions assumed above and present stopping practices, average operating speeds above about 10 mph (16 Km/hr) are probably not practical regardless of the maximum speed capability of the inspection vehicle. Another interesting factor shown in Figure 7 is that for systems with a maximum reverse speed of 10 mph (16 Km/hr) and acceleration capability of 0.1 g, operating with low to moderate distance between stops, vehicles with a 20 mph (32 Km/hr) maximum speed capability will usually have a higher average operating speed than vehicles with a maximum speed of 50 mph (80 Km/hr). This apparent contradiction occurs because of the excessive "overshoot" and time used in backing by the higher speed cars. Further economic analyses of these systems shows that there is no economic advantages to be gained from significantly increased vehicle inspection speeds unless the requirement for hand checks is eliminated.

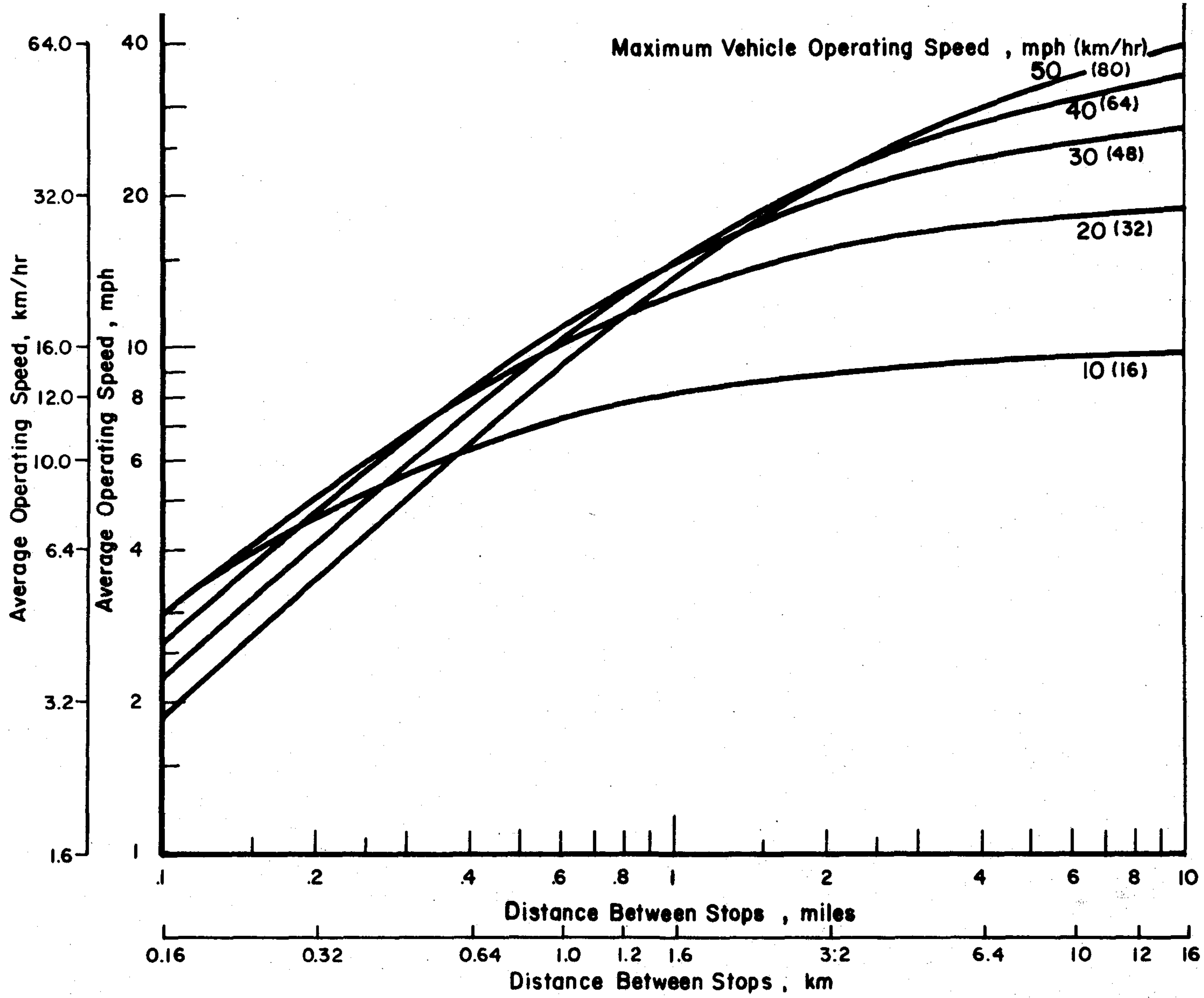


FIGURE 7. AVERAGE OPERATING SPEED OF VEHICLES MAKING STOPS FOR HAND CHECKS OR TAGGING DEFECTIVE RAILS

Calculation of Dynamic Carriage Motions

In order to determine the relationships between carriage motions, track geometry errors, and inspection speed, it was assumed that the rail geometry error was in the form of a rectified sine wave or

$$X = |A \sin \omega t| , \qquad (1)$$

where X = instantaneous position error, in. (mm)

A = p-p magnitude of the error - commonly referred to as "low joint" error, in. (mm).

It was also assumed that the carriage system was a lightly damped one degree of freedom system. With the above assumptions, a step change in velocity is the excitation to the carriage that can cause severe dynamic carriage motions. The magnitude of this step velocity change is $\Delta\dot{X} = 2A\omega$, where $\Delta\dot{X}$ is the velocity change and ω is the frequency at which the rectified sine wave passes under the carriage. If it is assumed that 39 ft (12 m) rail lengths are used, the carriage has a natural frequency ω_n (rad/sec) and the speed of the inspection vehicle is V mph (Km/hr). The maximum relative dynamic displacement of the carriage relative to the track surface near a joint will be about

$$\Delta X = 0.236\ VA/\omega_n,\ \text{in.} \qquad (2)$$
$$\Delta X = 0.147\ VA\ \omega_n,\ \text{mm} \quad .$$

These relationships have been plotted and are presented in Figure 8 for a wide range of carriage natural frequencies and vehicle speeds.

The magnitude of carriage motions that can be tolerated depends upon how the couplant is introduced and maintained between the rail and transducer, and upon the nominal vertical transducer spacing used. With a wheel-type transducer system or a sled-type system which maintains a large transducer-to-rail spacing and a deep pool of couplant between the transducer and rail, large relative motions can be tolerated. It is estimated that zero-peak motions as large as 0.1 in. (3 mm) would not cause

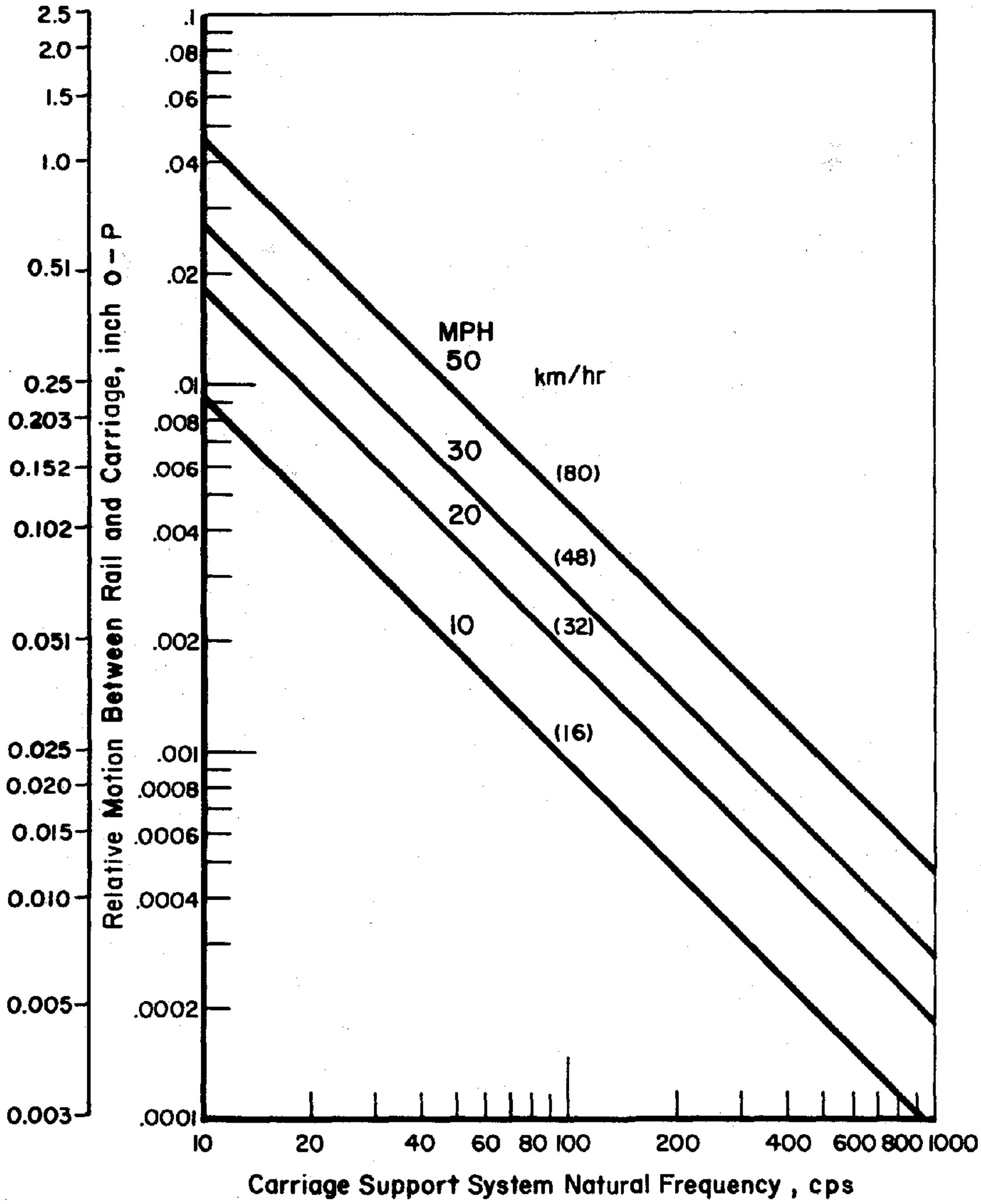


FIGURE 8. RELATIVE MOTION BETWEEN RAIL AND CARRIAGE WITH 0.25-IN. (6.4-mm) LOW JOINTS.

problems in the transducer system. Care would have to be taken to insure that large relative motions did not cause excessive stresses in the tire, support, or sealing systems.

With a simple sled-type system that does not use a deep pool of couplant, allowable motions would be much smaller, and would depend upon the specific sled design used. With some simple sleds, relative motions would have to be held to less than 0.001 in. (0.03 mm) to maintain coupling.

In designing the carriage system it is desirable to use the lowest practical suspension natural frequency in order to minimize shock and vibration damage to the carriage system. The peak acceleration of the carriage system caused by low joints will be

$$G = 0.007\ AV\ f_n \quad \text{(English units)} \qquad (3)$$
$$G = 0.0002\ AV\ f_n \quad \text{(Metric units)}$$

where G = zero-peak acceleration, g's, and the other terms are as defined above.

Figure 9 shows the acceleration levels which would be expected with 0.25-in. (6.4 mm) low joints. Higher amplitude rail profile errors would cause increased accelerations in approximate proportion to the increase in error amplitudes.

The carriage acceleration amplitudes that can be tolerated depend upon how the carriage system is restrained and how ruggedly it is constructed. If peak levels exceed 1 g, the carriage should be loaded against the rail with a spring or other forcing device to maintain contact between the carriage and rail. With a lightweight ruggedly constructed carriage, peak acceleration levels as high as about 100 g should not cause excessive problems.

In summary, from the standpoints both of transducer-rail clearances and carriage acceleration limit factors, it appears feasible to construct a carriage which will operate satisfactorily up to speeds of 50 mph (80 Km/hr) on Class 6 track. Further work would be required to develop a carriage system for satisfactory operation to speeds of 50 mph (80 Km/hr); however, it is estimated that existing systems would work satisfactorily with little or no modification up to speeds of about 20 mph (32 Km/hr).

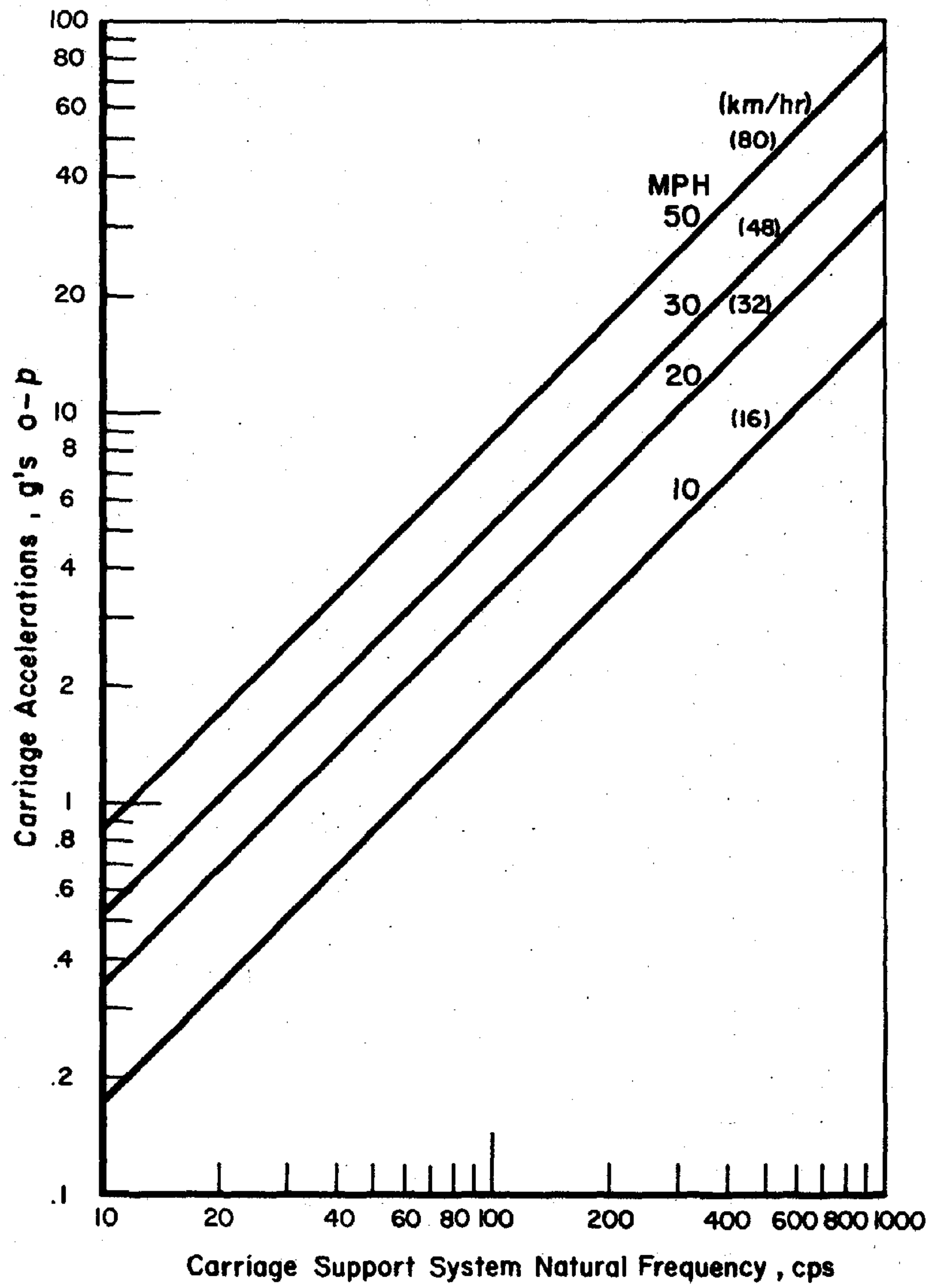


FIGURE 9. CARRIAGE ACCELERATION CAUSED BY 0.25-IN. (6.4-mm) LOW JOINTS

Item 3 - Inspection System Capabilities and Tradeoffs

Evaluation of Ultrasonic Inspection Systems

Review of Literature. A review of patents issued on devices and techniques for ultrasonic inspection revealed many ideas for transducer configurations and techniques for providing and maintaining coupling between the transducer and rail. One of the more useful ideas presented was the use of a moving column of water to maintain coupling[1, 2, 3, 4], but these references provided no information on the practicality of the concepts. Information on speed capabilities of systems in use in Europe indicated that speeds of up to 43 mph (70 Km/hr) are being used.[5] Daily inspection speed rates in excess of 186 mi/day (300 Km/day) were claimed for systems in which the flaw data were recorded and analyzed at a later date. Information on the Sperry rail detection system[6] indicated that some automatic data processing was being used to identify bolt holes. In general, however, the data obtained from the literature were superficial, and did not provide enough information to make useful judgements or comparisons of the capabilities of the different inspection systems.

Inspection Field Trips. More useful information was obtained from field trips where evaluations could be based upon on-the-spot observations and discussions with testing personnel. Four systems using ultrasonic inspection techniques were observed. The basic differences between these systems were primarily:

(1) Type of data display used
(2) Type of coupling device used
(3) Transducer configuration used.

Data Display. One form of data display observed was an oscillographic display commonly referred to as "B-scan". This display used two oscilloscope screens located one above the other. The oscilloscope displays can be stored temporarily for photographing or for further study. Both rails were displayed simultaneously using four channels for each rail. Figure 10 shows the general format of the display, and Figure 11 is a photograph of

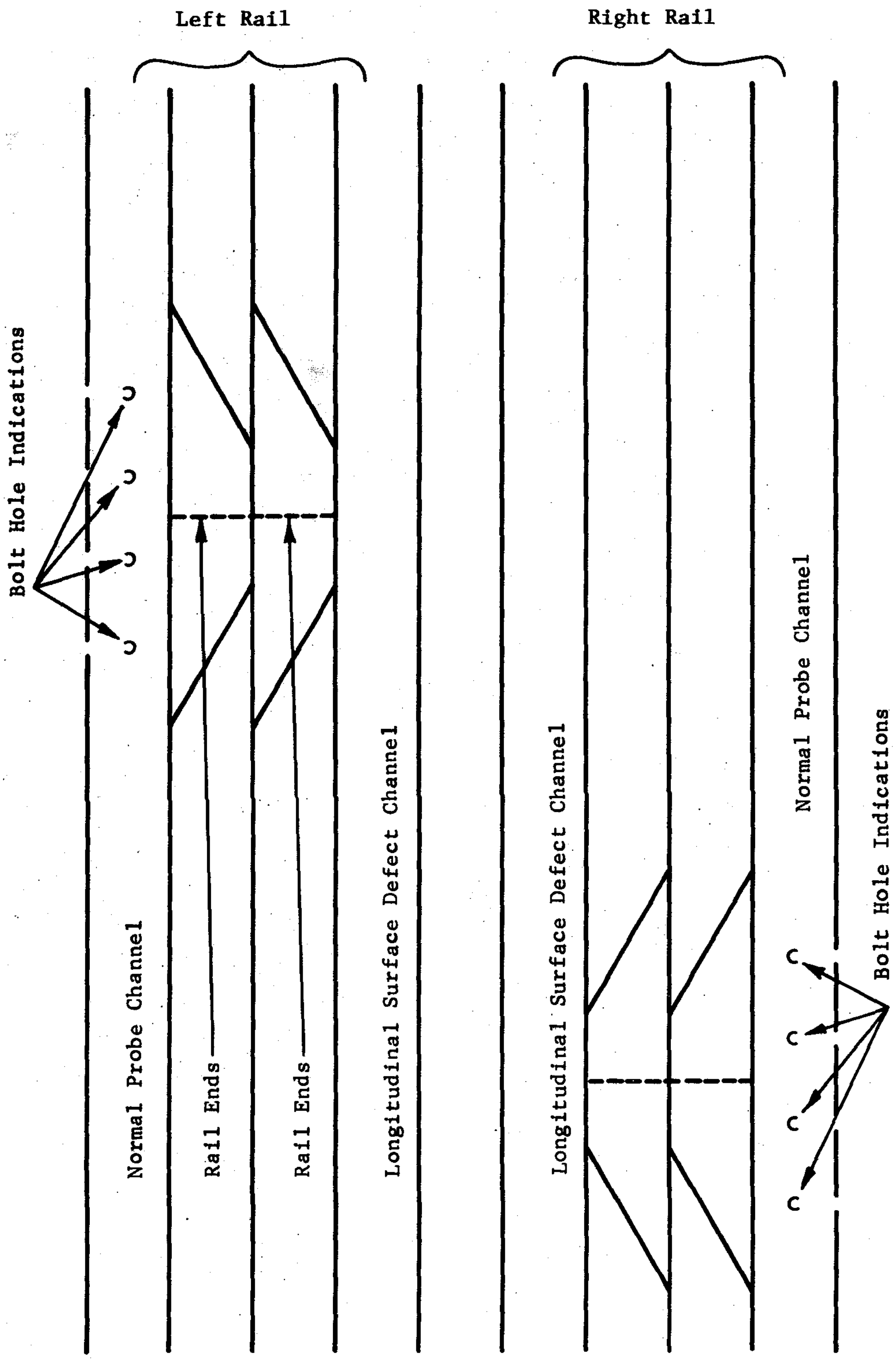


FIGURE 10. SCHEMATIC OF TYPICAL B-SCAN INDICATIONS OF GOOD RAIL

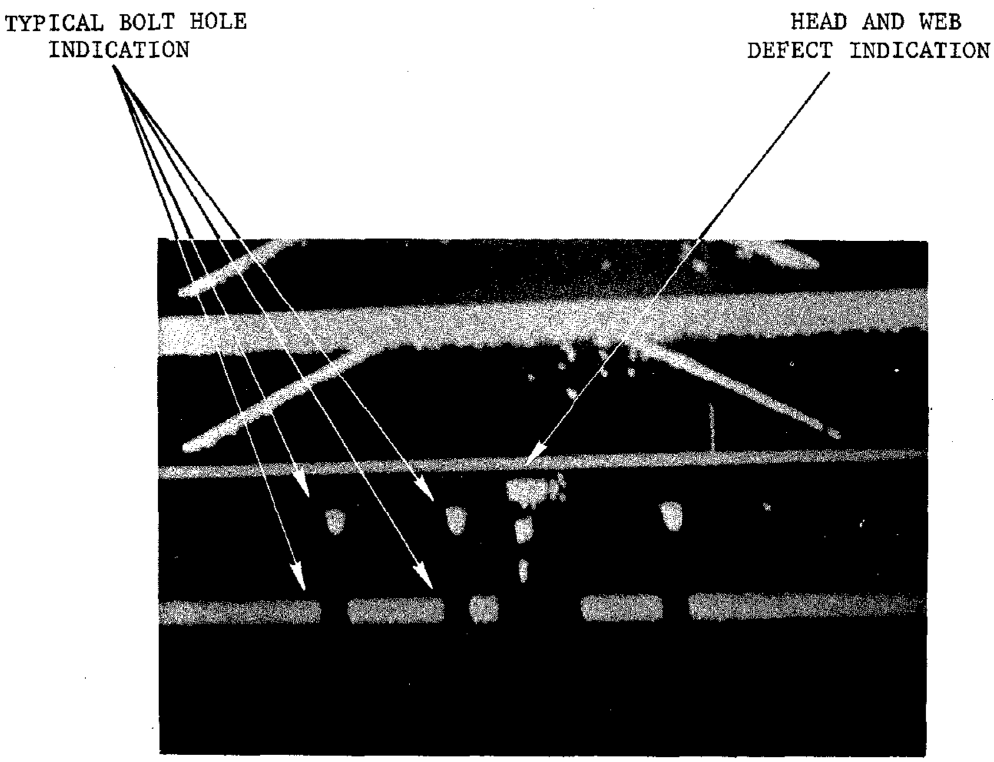


FIGURE 11. B-SCAN DISPLAY OF HEAD AND WEB DEFECT AT A RAIL JOINT

the display showing a defect at a joint. The picture on the oscilloscope screen is built up from top to bottom on one screen at a time as the car progresses along the track. During continuous inspection, the picture on each screen is stored until that particular screen is full; then it is erased as the picture starts to form on the other screen. All initial judgments are based upon the visual displays, with one man of the crew constantly watching the oscilloscope screens for anomalies.

A second type of display observed was one using multichannel strip-chart recorders. These recorders used pens having only a short travel and providing no amplitude information (event record only). The length of time the pen was deflected indicates the amount of time the transducer was sensing a defect, but the magnitude of the transducer signal was not normally available. For this system an oscilloscope was also provided for A-scan presentations.

A variation of the simple strip chart recorder was the use of the strip chart recorder in conjunction with a limited amount of automatic data processing equipment. On one system observed, automatic gain control and distance amplitude correction were provided for each transducer channel. Automatic pulse repetition rate was also provided and set at 6 pulses per inch for speeds from 6 to 18 mph (10 to 29 Km/hr). A selfcheck system was used to periodically monitor the system for proper operation. An electronic logic system was used to identify bolt holes.

This was basically a pulse counting system which relied on the automatic pulse repetition rate control to determine the length of the flaw. The system counts the number of loss of back signals and the number of echo signals on 0° and 37.5° transducer channels. When the count exceeds a preset level, an audio alarm and a square pulse are printed on the slow speed paper tape. An indicator on the equipment cabinet indicates the number of counts and the channel 0° or 37.5°, that caused the alarm. The counters are automatically reset after a set test distance. If a reset distance is too long, extra bolt or signal holes could cause an alarm; if it is too short, certain types of flaws could be missed. The alarm count and the reset distance must therefore be a compromise between the minimum flaw size and the number of anomalous indications which must be verified by hand testing. This system was observed operating on relaid rail in a branch line and it was observed that on this rail, numerous anomalous alarms resulted from extra bolt holes and weld repair of chipped or battered rail ends.

From observing the two basic types of display systems, it was concluded that in general, the B-scan system provides the operator with much more detailed information on which to base a decision than the systems using strip charts. The advantage of this is that given similar transducer configurations, he can make more accurate decisions on the probable presence of flaws. The disadvantage is that in having more data to process, he is limited to a lower inspection speed. Another possible disadvantage of the use of B-scan systems as used in the U. S. is that a permanent record of all inspection data is not produced.

Coupling Devices. The most common coupling device used in the U.S. is the ultrasonic wheel. These wheels are usually small-approximately 4-10 in. (10 to 25 cm) in diameter. To transmit the ultrasonic signals, coupling is enhanced by spraying water on the rail in front of the wheel. The advantages of the wheel are that it has a moderately long average life of about 30 days and provides adequate coupling on most rail with water consumption rates of about 2 gallons per mile (5P/Km), according to one manufacturer, and it will operate satisfactorily at speeds up to 30 mph (48 Km/hr). Its disadvantages are that, because of its small size, only a limited number of transducers can be used in a single wheel and complete freedom of transducer location is not possible. Also, maximum refraction angle is limited to approximately 70° for 2.25 MHz transducers in wheels.

The second type coupling device used is a long sled type device Two versions were observed. One was a device in which the transducers are housed in a long, hollow ski filled with water. The bottom of the ski consists of a rubber diaphragm which is coupled to the track by means of a thin film of water. The diaphragm must be changed after varying intervals of time which depend upon rail surface condition (3 days typical).

Another system observed used an easily changed plastic shoe for coupling between the transducer and rail. This system was reported to be capable of satisfactorily operating to speeds above 50 mph (80 Km/hr). Water consumption rates reported for the sled type systems were in the range of 4 to 8 gallons per mile (9 to 19 ℓ/Km). Some of the advantages of the sled type coupling systems are that (1) although they require frequent replacement of their coupling surface, it can be changed in a short time (~ 5 minutes) and at a low cost, (2) a large number of transducers can be used and placed at almost any desired location, (3) with proper construction, it can be operated to speeds of 50 mph (80 Km/hr) or greater, and (4) the high angle transducers used to inspect the head can be operated at a shallower angle.

Transducer Configurations. Several different transducer configurations were observed on the different systems. Common combinations observed in systems using ultrasonic wheels for coupling were the use of 70^o forward and backward looking transducers located to detect transverse types of defects in the center of the head, and normal transducers located so as to detect bolt hole cracks or other web defects. On one system, it was claimed that the 70^o transducers covered the entire head area. One wheel type system observed, in addition to the 0^o and 70^o transducers, also used 37.5^o transducers gated to the base of the rail to detect defects in the web.

A typical transducer configuration used in a sled type system is shown in Figure 12. This system used 82^o forward and backward looking transducers, side looking transducers to detect vertical split heads, and normal transducers to detect defects in the web. Other configurations were also observed. One configuration, claimed to be very effective in detecting detail fractures, projected a beam downward and sideways into the rail, bounced off the bottom of the head and if a detail fracture was present, a corner reflection would be produced and a strong echo returned to the transducer.

No firm data were acquired on the reliability of the different observed transducer systems, but from observing operations and discussing performance with personnel, it was concluded that the 70^o and 82^o systems normally being used, failed to detect a large number of transverse type defects. An estimate placed the number of missed defects at about 25 percent. These defects were missed in some cases because they were in the side of the head, while the transducer was located in the center of the

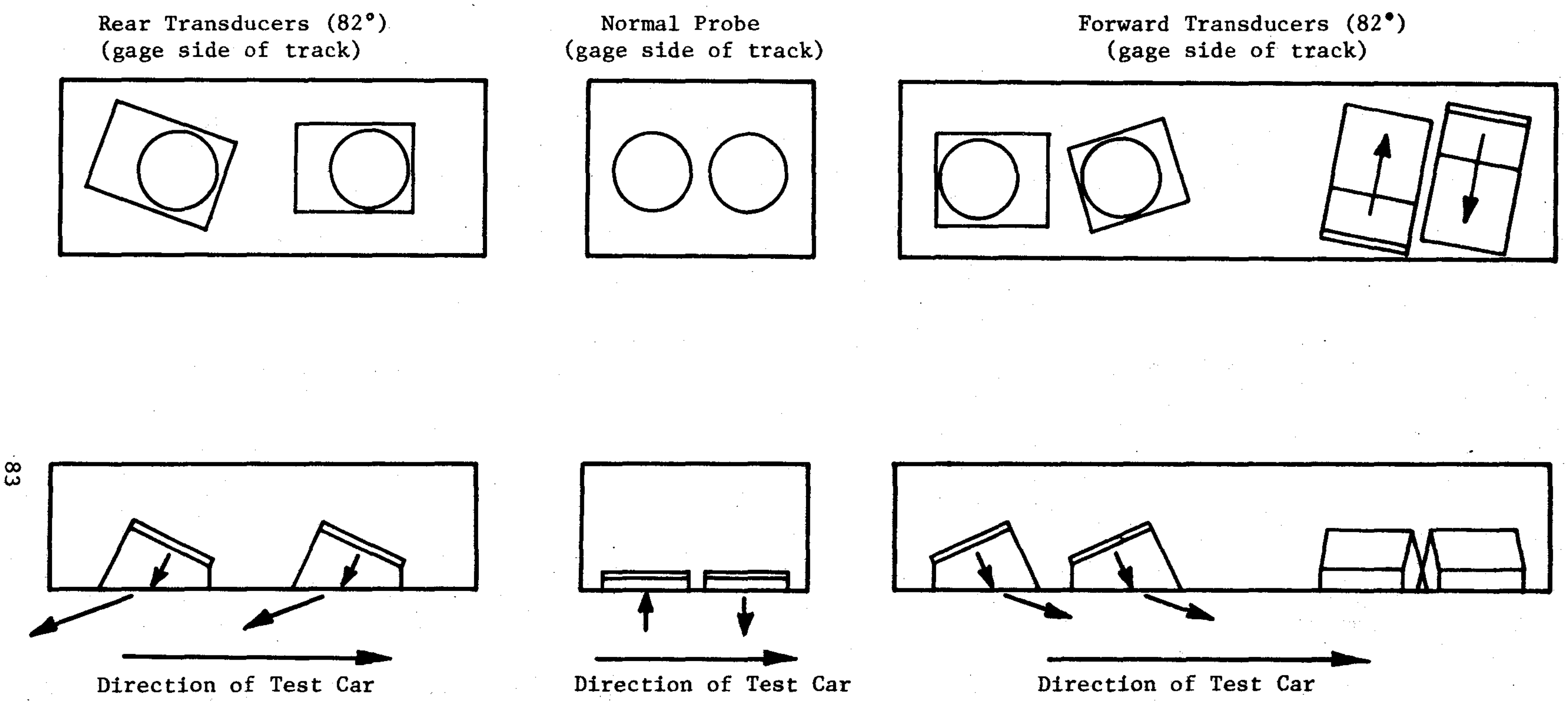


FIGURE 12. SCHEMATIC OF TRANSDUCERS IN SLED TYPE ULTRASONIC SYSTEM SHOWING RELATIVE POSITIONS IN THE RUNNER AND THE DIRECTIONS OF BEAM PROPAGATION

head, and in some cases because they were not oriented in a direction that would return an echo to the transducer.

Analysis of Basic Capabilities. The potential capabilities of ultrasonic inspection methods are determined by the nature of the defects, the characteristics of ultrasonic waves, and the structure of the test medium (rail).

The defect is detected by its influence upon the ultrasonic beam that is incident upon it. The important factors are its location, its size and surface (smooth or rough), its shape or geometry, and its orientation. Each defect may be considered to be a new ultrasonic source having its own radiation pattern, including both the reflected beam and the diffraction pattern on the shadow side, if the defect is smaller than the beam cross-section or if the beam overlaps an edge of the defect.

The defect must be located in a position that permits it to cause a distinct indication. It appears that all serious defects in the head and web of rails can be detected by at least one ultrasonic method, if the effects of surface defects can be circumvented by an otherwise effective transducer arrangement. A defect located in an obscure position for one test method may be "in the open" to another method. Factors affecting the ability to detect defects according to location are (1) proximity to other reflectors (rail surfaces, bolt holes, etc.), (2) large grain boundaries (for instance, some welds) surrounding the defect, (3) shielding by nonserious surface conditions such as shelling, flaking, slivers, and heat-check cracks at an engine burn, or (4) location in a "dead" zone where reflections or shadows may be obscured by the initial pulse in pulse-echo or by other factors such as diffraction or multipath waves (in through-transmission).

The shape or geometry of a defect determines the nature of the reflections from its surface at any given incidence angle. A large, smooth, planar surface causes specular reflection. The reflection pattern spreads by an amount dependent upon the wavelength of the ultrasound, the area of incidence, and the incidence angle. Mode conversion usually occurs at a boundary when incidence is other than normal. The generated modes may include longitudinal, shear, and surface waves. The only exception is the incident shear wave that is polarized parallel to the surface. In this case, only shear waves are reflected. The longitudinal waves and shear waves are reflected at different angles.

Reflections from large defects with irregular surfaces or rough surfaces may be somewhat omnidirectional so that they may be detected even though their general orientation is not optimum for the angle of incidence. Cylindrical surfaces reflect cylindrical waves, as do long narrow defects -- regardless of surface geometry. Spherical surfaces reflect spherical waves.

The characteristics of the beam that are important to the effectiveness of detection methods are its spread, its velocity, its attenuation, and its uniformity. The beam spread contributes to the attenuation of the intensity of the waves. Other contributing factors are scattering and absorption within the medium, both of which are functions of frequency, each increasing with frequency. Beam spread is a function of the ratio of wavelength to the lateral dimensions of the beam. This ratio is usually kept as low as is practical, i.e., large transducer dimensions and small wavelength. Therefore, sensitivity and directionality increase with increased frequency while effective penetration of the beam decreases with increased frequency. Experience indicates that 2.25 MHz is a good choice for tail testing.

Regarding uniformity, often ultrasonic transducers do not emit the uniform beam theoretically predicted for a piston source. The cause of this nonuniformity is usually found in the construction of the transducer.

The rail geometry affects ultrasonic inspection. The thickness of webs of all rail sizes restrict the lateral dimensions of transducers that transmit waves into the web to about 1/2 in. (12 mm). The transducer must be kept centered over the web within narrow limits. Otherwise, echoes from the head and web fillet, particularly with the normal probe, will cause false indications. In addition, the geometry of the rail is such that mode conversion and multipath waves may cause either false indications, or they may "hide" the "shadows" of defects in through-transmission techniques, especially those which involve long travel distances. Positions of the transducers might be optimized to minimize these effects.

The two techniques considered during this research program were pulse-echo and through-transmission. The pulse-echo methods provide information involving time of travel of the ultrasonic pulses, (distance to reflecting surface), amplitude of the reflected energy, and the time period during which a reflection is received from a given region. This is the most widely used method in nondestructive testing. As many gates as are necessary can be used to show the locations of defects.

Through-transmission method is based upon detecting "shadows" caused by defects. This method provides signal "loss of amplitude" and the period of time that the signal falls below a reject level. The defect detectability of this method depends primarily on

(1) The ratio of defect area to beam size

(2) The separation between the defect and the transducers.

Some limitations of the through-transmission method that must be considered in this application are signals from multipath reflections, amplitude variations due to minor geometry changes, and couplant conditions (not only loss of couplant but also variations in distance between surface and transducer and in pressure upon the couplant) and direct electrical cross-talk between transducers.

<u>Calculation of Maximum Practical Inspection Speeds</u>. The maximum practical speed of inspection is related (1) to the effects of speed on coupling conditions, (2) to the sizes of defects to be identified, (3) to the size of the rail, and (4) to the pulse-repetition rate that can be used without interference. The maximum pulse repetition rate and the size of the rail are related by the velocity of sound in the rail. The minimum pulse repetition rate for any given speed and the size of the defects are related by the number of interrogations of the defects that are needed to give a reliable indication of the presence of the defect.

In calculating the optimum speeds for any of the defect conditions and rail sizes, the coupling was assumed to be ideal. However, a considerable effort was devoted to the calculation of the maximum practical pulse repetition rates, based on rail sizes.

The maximum practical pulse repetition rates are based upon the time required for a pulse to travel from the transducer through the rail to a predetermined position in the rail and back to the sensor. The sensor may be the original source or it may be a separate transducer. Assumptions are based upon calculated conditions for optimum speed rather than upon conventional practice. However, the limits of current practice were also calculated in order to compare potential with current capabilities. The following assumptions were made in arriving at the calculated values.

(1) Delay times of 25 and 100 μ-sec were used to account for fluid path and electronic delay times. The shorter delay time is considered representative of sled systems and small wheel systems. The longer delay time of 100 μ-sec is considered a worst-case condition that might be encountered in a well designed large wheel with many transducers.

(2) Only one pulse could be in a rail at any given time.

(3) The velocity of shear waves (all angle beams) was assumed to be 1.272×10^5 in./sec (3.231×10^5 cm/sec)

(4) The velocity of longitudinal waves (normal beams) was assumed to be 2.303×10^5 in./sec (5.850×10^5 cm/sec) in steel.

The maximum pulse repetition rates calculated for various sizes of rail are given in Table 20.

Nonconventional Probe Configurations. The capabilities of presently used ultrasonic methods for detecting typical defects in rails have been discussed. Additional approaches to detecting defects often missed by the present methods were also included in the analysis.

Some of these additional techniques are illustrated in Figures 13, 14, and 15. Figure 12 shows a skew technique in which a signal is bounced off the bottom side of the head and travels down the rail head to detect transverse, horizontal, and vertical defects in the head. This configuration might be used as a pulse echo system, or receiver R_2 could be added to obtain through-transmission signals. The location of receiver R_2 must be carefully selected to avoid problems from multipath reflections. Figure 13 shows one set of transducers; other sets would probably be used to scan both sides of the head and possibly to inspect under burns from both directions.

TABLE 20. CALCULATED MAXIMUM PRACTICAL PULSE REPETITION RATES FOR VARIOUS RAIL SIZES

Rail Weight lb.	Rail Weight Kg/m	θ, degrees	PENETRATION DEPTH: Through rail head, pulse-echo, 100 μ-sec delay	Through rail head, pulse-echo, 25 μ-sec delay	10 inches pulse-echo, 100 μ-sec delay	10 inches pulse-echo, 25 μ-sec delay	Single bounce off-base pitch catch or pulse-echo gated to base, 100 μ-sec delay	Single bounce off-base pitch catch or pulse-echo gated to base, 25 μ-sec delay	Single bounce off-base to head, pulse-echo, 100 μ-sec delay	Single bounce off-base to head, pulse-echo, 25 μ-sec delay
85	42	0	8816	26,018	--	--	6894	14,276	--	--
		45	7440	16,834	3888	5488	4644	7125	3024	3911
		70	5844	10,404	3888	5488	--	--	--	--
		80	4165	6058	3888	5488	--	--	--	--
135	65	0	8681	24,877	--	--	6178	11,511	--	--
		45	7199	15,646	3888	5488	3870	5452	2399	2925
		70	5542	9483	3888	5488	--	--	--	--
		80	3869	5451	3888	5488	--	--	--	--
140	69	0	8481	23,304	--	--	6116	11,299	--	--
		45	10,000	14,111	3888	5488	3808	5330	2352	2855
		70	5133	8346	3888	5488	--	--	--	--
		80	3488	4723	3888	5488	--	--	--	--
155	77	0	8481	23,304	--	--	5906	10,585	--	--
		45	10,000	14,111	3888	5488	3599	4929	2194	2626
		70	5133	8346	3888	5488	--	--	--	--
		80	3488	4723	3888	5488	--	--	--	--

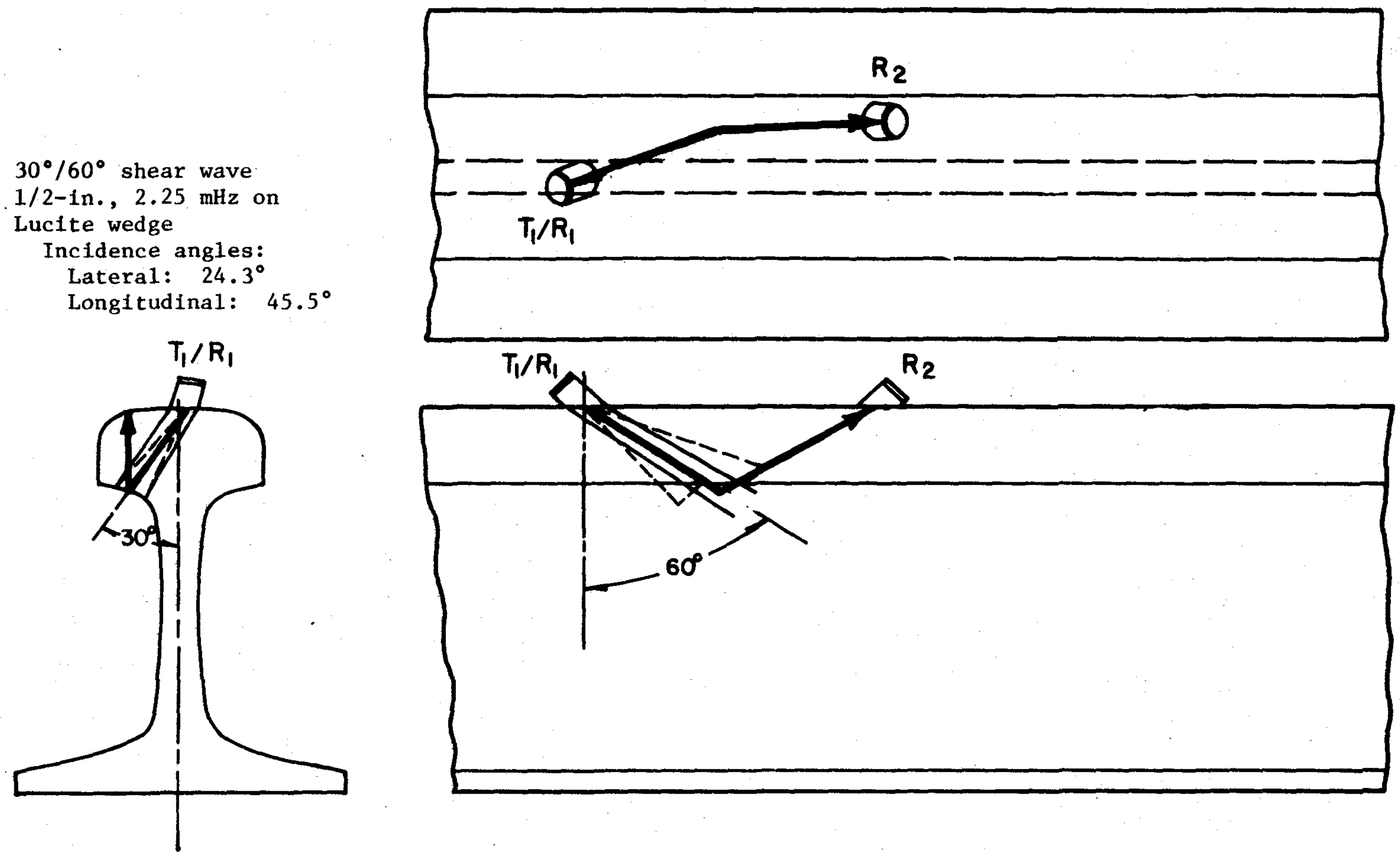


FIGURE 13. SKEW SYSTEM

45° shear wave
2.25 mHz on Lucite
transducers
Incidence angle: 35.8°

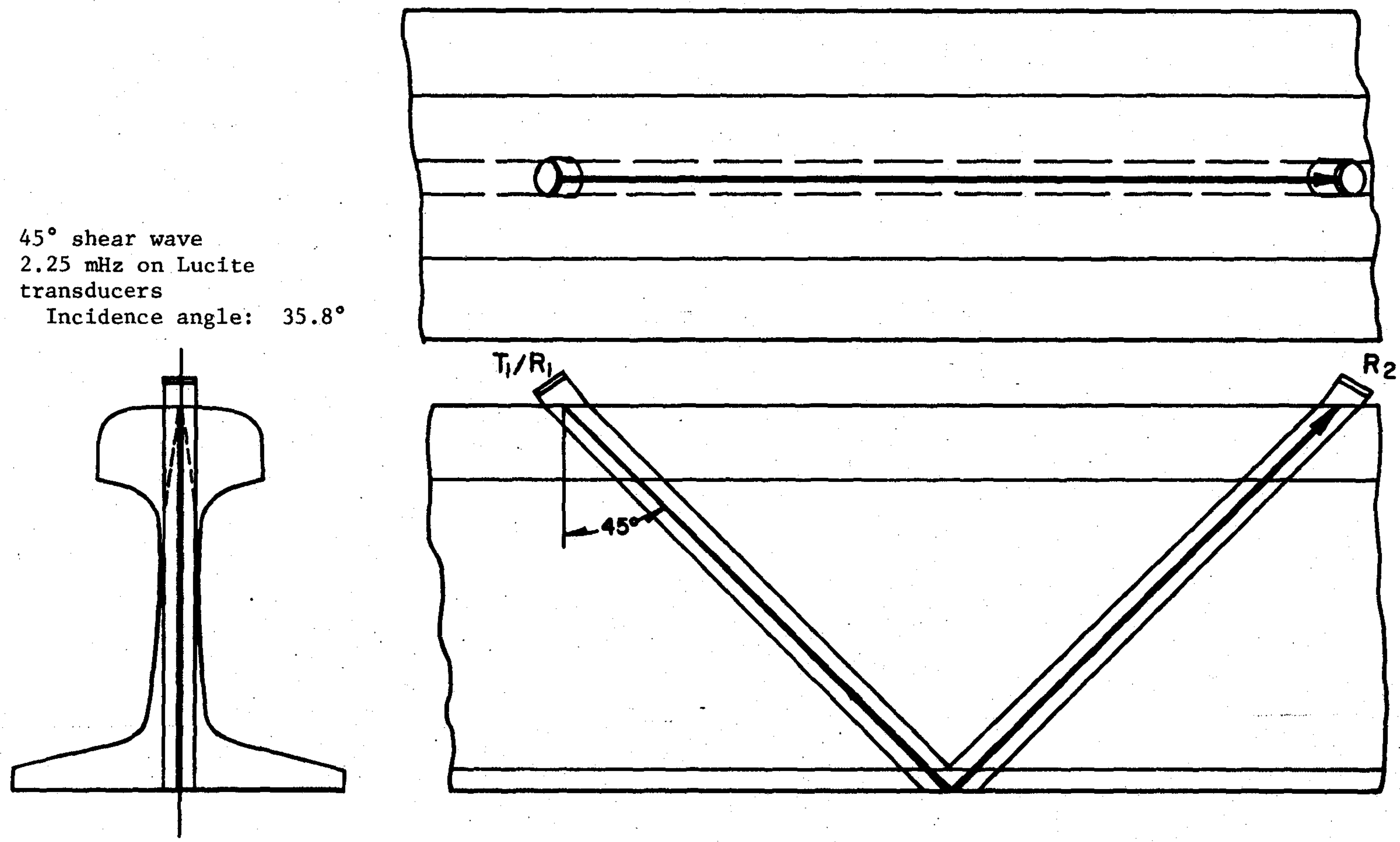


FIGURE 14. 45-DEGREE PROBE SYSTEM

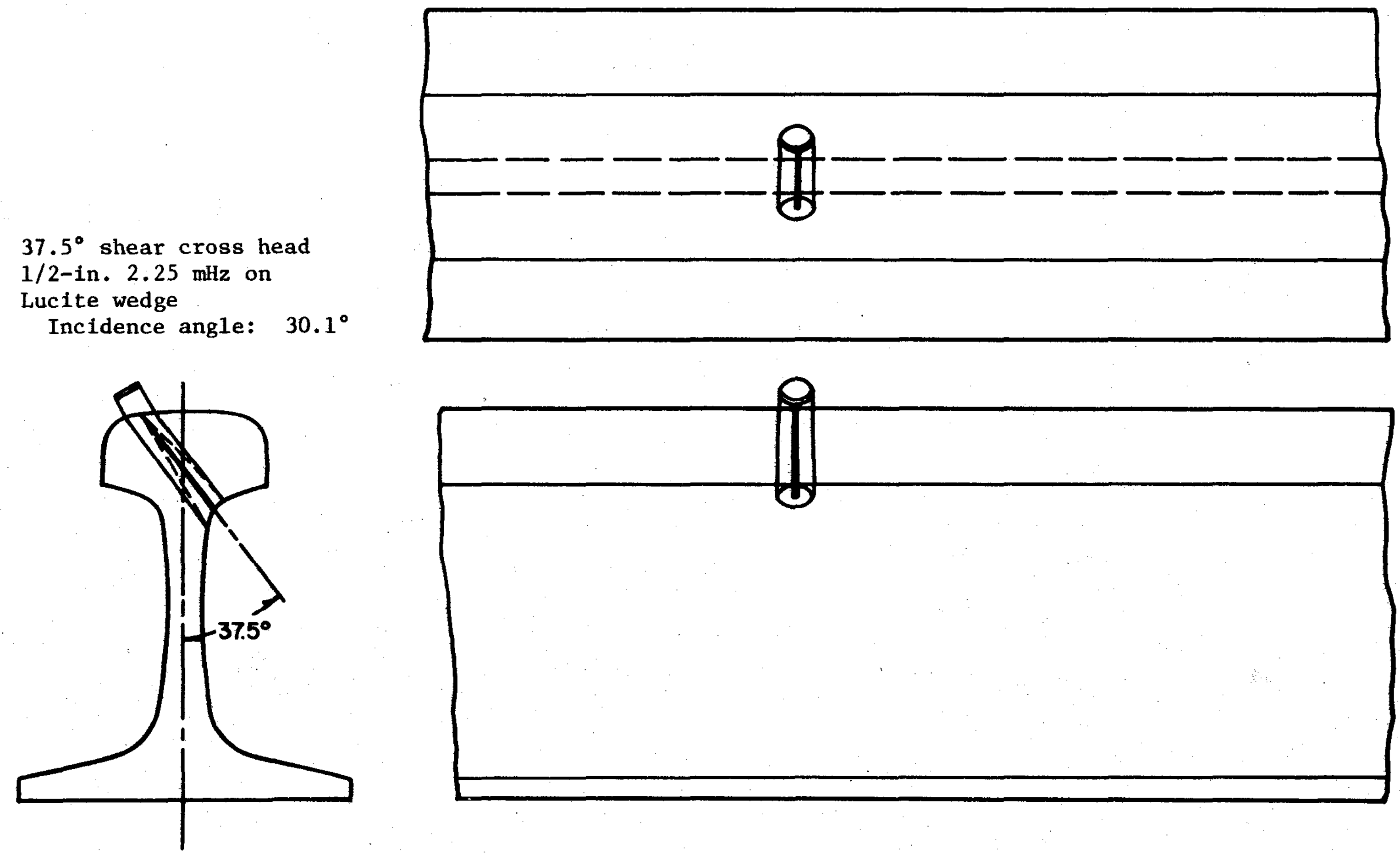


FIGURE 15. ONE-HALF OF CROSSED-DIFFERENTIAL SYSTEM

Figure 14 shows a 45° configuration which can also be used as a pulse echo or through transmission system. Additional receivers can be added to this system to improve detectability of flaws which are not oriented vertically in the rail, or to provide additional information on the size, location, and/or orientation of detected flaws. Figure 15 shows one half of a transducer system which could be used in the differential mode to provide a sensitive indication of vertical split heads, or single transducers installed as shown might be gated for loss of back signal to indicate vertical split head.

The conclusions reached from the analysis of these and conventional systems is that there are ultrasonic transducer configurations that will reliably detect all large flaws ($\geq$ 15 percent of head area or 4 in (102 mm) long) of interest in the head and web at speeds up to 50 mph (80 Km/hr) if they are not masked by surface flaws. This conclusion is based on the assumption (believed to be valid) that adequate coupling can be achieved. The analysis also shows that many 1 percent transverse type defects can be detected at speeds up to 20 mph (32 Km/hr) if very good coupling and transducer alignment can be maintained and if metallurgical abnormalities in the rail are small. The analysis of conventional 70° and 80° probes and the 45° and 30°/60° skew pulse echo system shown in Figures 13 and 14 shows that when these systems are used there is a good probability of detecting transverse types of defects under surface flaws. In the case of the 45° pulse echo system using full Vee, speeds at which 15 percent defects are detected are limited to about 22 mph (35 Km/hr) in smaller rail and 19 mph (31 Km/hr) in larger rails assuming total delay time in the electronics and couplant path of 25 μ-sec.

Table 21 provides the incidence angles of longitudinal waves in Lucite and in water required to produce the various refraction angles and wave modes of interest in steel. The values for water are based upon the velocity of sound in water at 68 F (20 C). In addition to the design information that it provides, Table 21 shows what slight changes in incidence angle can do to the refraction angles. These changes may be the result of shifts in position of the probe on the rail head relative to the sides,

TABLE 21. INCIDENCE ANGLES IN LUCITE AND WATER FOR VARIOUS REFRACTION ANGLES IN STEEL

Wave Modes	Refraction Angle in Steel, (degrees)	in Lucite, (degrees)	in Water at 20 C (degrees)
Longitudinal	0	0	0
Longitudinal	Critical	27.2	14.7
Shear	30 (only for skew)	24.3	13.2
Shear	37.5	30.1	16.2
Shear	45	35.8	19
Shear	60	45.5	23.4
Shear	70	51	25.5
Shear	80	54.5	26.8
Shear	82	54.7	27
Shear	85	55.4	27.2
Shear	Critical	55.8	27.3

TABLE 22. APPROXIMATE BEAM SPREAD AT VARIOUS REFRACTION ANGLES. 1/2-IN. DIAMETER DISC AT 2.25 MHZ ON A LUCITE WEDGE

Wave Modes	Refraction Angle, degrees	Beam Spread, degrees $\theta/2$	θ
Longitudinal	0		28.5
Shear	0		15.7
Shear	45		18.1
Shear	70		29.2
Shear	80	27.2	Heavy into surface
Shear	82	34.4	Heavy into surface

shifts in orientation, and slight variations in the surface contour. The difference between an 80^{o} refracted angle and critical angle (90^{o} refracted angle) is produced by shifting the incidence angles by only 1.3^{o} in Lucite and by only 0.5^{o} in water. Calculations of effects of changes of contour on refraction must be based upon incidence through water since this is the coupling medium most generally used. The effects of changes in incidence angle on refraction decreases with decreasing refraction angle requirements. Such variations in refraction angle significantly affect the sensitivity of a system to defects. These variations are minimized through use of thin coupling films and by using couplants in wheels which have negligible velocity changes over wide temperature ranges.

The velocity of sound in each of the materials used to calculate incidence angles of Table 21 are as follows:

Longitudinal wave, in Lucite	1.05×10^{5} in/sec	2.67×10^{5} cm/sec
Longitudinal wave, in water, at 20 C	0.584×10^{5} in/sec	1.483×10^{5} cm/sec
Longitudinal wave, in steel	2.303×10^{5} in/sec	5.85×10^{5} cm/sec
Shear waves in steel	1.28×10^{5} in/sec	3.24×10^{5} cm/sec.

Table 22 provides beam profile data for various refraction angles of a 2.25 MHz beam originating in a 1/2-in. (12 mm) diameter disc mounted on a Lucite wedge. The beam spread angle in the table is the spread in the longitudinal direction.

The distance that the probe moves along the track during the time that a single pulse makes a round trip in the rail (pulse-echo) influences the design of the transducer arrangements. Typical values are given in Table 23.

TABLE 23. DISTANCE A PROBE TRAVELS ALONG THE TRACK DURING THE ROUND TRIP OF AN ULTRASONIC PULSE IN A PULSE-ECHO SYSTEM (Rail height 7.3 in. (19 cm)

				Probe Movement During Pulse Round Trip Inches					
						70°-82° (20-in. (508 mm) round trip on axis)		30°-60° skew (20-in. (508 mm) round trip	
mph	Km/hr	in./sec	m/sec	0°	45° Vee	in.	mm	in.	mm
10	16	176	4.47	0.011	0.0625	0.028	0.711	0.028	0.711
20	32	352	8.94	0.022	0.125	0.055	1.40	0.055	1.40
30	48	528	13.40	0.033	0.188	0.083	2.11	0.083	2.11
40	64	704	17.9	0.045	0.250	0.111	2.82	0.111	2.82
50	80	880	22.4	0.056	0.313	0.138	3.51	0.138	3.51

The 45° Vee would seldom be used at speeds exceeding 15 mph (24 Km/hr). Table 23 shows that the displacement of the transducer along the track during the travel time of a pulse can be compensated for by the transducer dimensions and receiver position.

Practical Limitations. Data on the several transducers systems has been summarized and compiled into Table 24 so that the relative capabilities of the systems can be compared readily. Practical aspects based on field observations have been used in evaluating reliability and size factors. Theoretical upper speed limits are based upon pulse repetition rates (as discussed earlier), and speeds shown in the table are the highest practical speeds believed feasible. Various factors affecting the practical application of ultrasonic techniques to rail inspection are reflected in the values in this table, and are discussed in more detail below.

TABLE 24a. ULTRASONIC INSPECTION SYSTEM CAPABILITIES (ENGLISH UNITS)

Technique	Area, percent / Length	Defect Size: Transverse Defects (30)	Defect Size: Surface Defects (30)	Longitudinal Defects (30)	Transverse Defects in Rail Head: Transverse Fissure — Flaws Detected, %; Primary Location in Section, Gage, Center, Field; Min Distance From Joint, in.	Compound Fissure — Flaws Detected, %; Location in Section, Gage, Field, Center; Min Distance From Joint, in.	Detail Fracture From Shelling (G+F), Head Check (G) and Welded Bond Connection (F) — Flaws Detected, %; Location in Section, Gage, Center, Field; Min Distance From Joint, in.	Engine Burn and Welded Burn Fracture — Flaws Detected, %; Location in Section; Min Distance From Joint, in.
Ultrasonic Normal Pulse-Echo	1 1 5 2 15 4 >20 –	N/A	N/A	44 50+ 50+ –	N/A	N/A	N/A	N/A
Ultrasonic, 45° Vee Pulse Echo, Forward and Backward	1 1 5 2 15 4 >20 –	4-6 9-11 16-19 18-22	4-6 9-11 (31) 16-20 20-30	27-33 27-33 (32) 27-33	0 10 C 2 50 C 2 (27) 90 C 2	0 10 C 2 50 C 2 (27) 90 C 2	N/A	0 – – – 0 – – – 0 – – – 0 – – –
Ultrasonic, 45° Vee Through-Transmission Forward and Backward	1 1 5 2 15 4 >20 –	7-9, 50+ 15-20, 50+ 25-35, 50+ 29-41, 50+	3-6, 50+ 7-10, 50+ 13-18, 50+ 16-23, 50+	27-38, 50+ 44-50, 50+ 44-60, 50+ –	0 50 C 2 90 C 2 (27) 99 C 2	0 50 C 2 90 C 2 (27) 99 C 2	N/A	(8)
30°-60° Skew Pulse Echo Forward and Backward (28)	1 1 5 2 15 4 >20 –	11-16 25-36 44-50+ 50+	6-8 13-18 22-32 28-40	N/A	0 5 C 1 10 C 1 50 C 1	10 G-F 1 50 G-F 1 80 G-F 1 99 G-F 1	20 G-F 1 90 G-F 1 99 G-F 1 99 G-F 1	0 5 C 1 50 C 1 90 C 1
30°-60° Skew Through-Transmission Forward and Backward (28)	1 1 5 2 15 4 >20 –	16-28, 50+ 38-50+, 50+ 50+, 50+ 50+, 50+	8-14, 50+ 19-22, 50+ 32-50+, 50+ 41-50+, 50+	40-50+, 50+ 50+, 50+ 50+, 50+ –	0 10 C 2 50 C 2 90 C 2	0 60 G-F 2 95 G-F 2 99 G-F 2	0 50 G-F 2 95 G-F 2 99 G-F 2	0 10 C 2 30 C 2 60 C 2
70° Pulse-Echo, Forward and Backward (28)	1 1 5 2 15 4 >20 –	18-25 40-50+ 44-50+ 44-50+	– 21-29 36-50 45-50+	N/A	0 30 C 1 70 C 1 95 C 1	0 50 G-F 1 80 G-F 1 95 G-F 1	0 40 G-F 1 70 G-F 1 75 G-F 1	0 0 10 C 1 50 C 1
80° Pulse-Echo, Forward and Backward (28)	1 1 5 2 15 4 >20 –	37-50+ 44-50+ 44-50+ 44-50+	19-26 42-50+ 50+ 50+	N/A	0 30 C 1 70 C 1 95 C 1	0 50 G-F 1 80 G-F 1 90 G-F 1	0 50 G-F 1 80 G-F 1 95 G-F 1	0 0 60 C 1 70 C 1

Max., Operating Speeds, km/hr

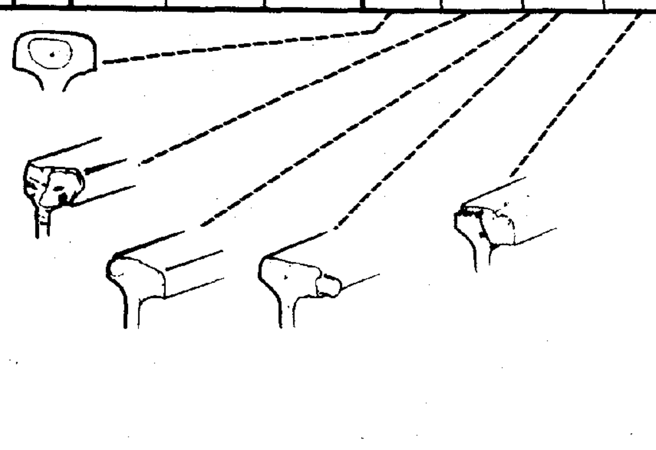


TABLE 24a. ULTRASONIC INSPECTION SYSTEM CAPABILITIES (ENGLISH UNITS) (CONTINUED)

Horizontal Split Head – Joint: Flaws Detected, % / Min Distance From Joint, in.	Horizontal Split Head – Through Web: Flaws Detected, %	Horizontal Split Head – Not Through Web: Flaws Detected, %	Vertical Split Head – Joint: Flaws Detected, % / Min Distance From Joint, in.	Vertical Split Head – Body: Flaws Detected, %	Weld Defects – Center Head: Flaws Detected, %	Weld Defects – Center Base: Flaws Detected, %	Weld Defects – Head, Gage Side: Flaws Detected, %	Web Defects – Head & Web Separation – Joint: Flaws Detected, % / Min Distance From Joint, in.	Head & Web Separation – Body: Flaws Detected, %	Split Web – Joint: Flaws Detected, % / Min Distance From Joint, in.	Split Web – Body: Flaws Detected, %	Piped Rail – Joint: Flaws Detected, % / Min Distance From Joint, in.	Piped Rail – Body: Flaws Detected, %	Bolt Hole Cracks: Flaws Detected, %	Corroded Base, Center – Joint: Flaws Detected, % / Min Distance From Joint, in.	Corroded Base, Center – Body: Flaws Detected, %	Sudden Rupture, Body Only: Flaws Detected, %	Size Information Provided*	False Indications (see notes referred to)	Defect Not Detected Due to (see reference notes)
① 99 <1 99 <1	99 99 99	0 0 0	50 1 50 1 50 1	50 50 50	N/A	N/A	N/A	① 99 <1 99 <1	99 99 99	① 99 1 99 1	② 99 99	③ 50 <1 99 <1	③ 50 99	99 99 99	0 5 1 10 1	0 5 10	N/A	E	11,12,13, 14,15,16, 17,24	
N/A	N/A	N/A	N/A	N/A	0 10 50 90 ④	20 60 90 99 ④	N/A	N/A	N/A	0 0 0	0 0 0	0 0 0 3	0 0 0	90 95 99	5 2 60 2 ㉗ 90 2 99 2	5 60 90 99	⑤ 99	F	14,25	11, 12, 13, 23, 24
② ⑦	95 95 99	N/A	N/A	N/A	0 50 90 99 ②	0 20 80 80 ②	N/A	② ⑦ Exception defects must be >2-1/2 in. long to be detected.	70 99 99	0 0 0 ② ⑦	10 60 99	0 0 50 ② ⑧	0 40 90 ③	0 50 60 ② ⑨	0 10 <3 20 <3 ②	0 10 20	⑤ 99	F-G	11,12,13, 14,17,24 25	
N/A	N/A	N/A	N/A	N/A	N/A	N/A	20 75 90 99	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	⑤ 99	F	18,19, 25	11, 12, 13, 23, 24
0 20 2 95 2	95 95 95	10 50 90	0 0 99 2	99 99 99	20 90 99 99	N/A	0 50 99 99	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	⑤ 99	F-G	11,12,13, 18,19,20, 24,25	11, 12, 13, 23, 24
N/A	N/A	N/A	N/A	N/A	0 25 70 75	N/A	0 40 75 99	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	⑤ 99	P	18,19, 21,22, 25	11, 12, 23
N/A	N/A	N/A	N/A	N/A	0 50 80 90	N/A	0 40 75 90	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	⑤ 99	P-F	18,19,21 22,25	11, 12, 23

① Denotes Note No.

*P – Poor
F – Fair
G – Good
E – Excellent

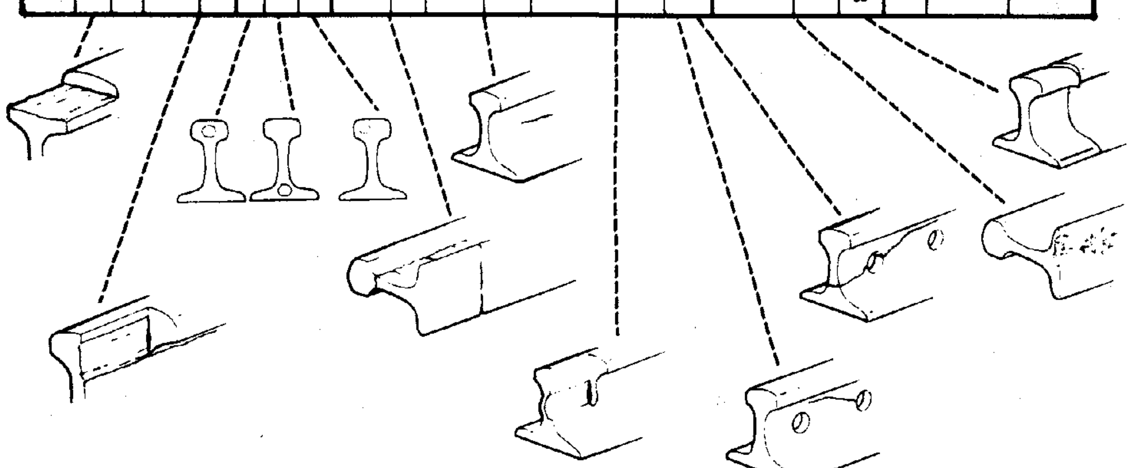


TABLE 24b. ULTRASONIC INSPECTION SYSTEM CAPABILITIES (METRIC UNITS)

Technique	Max., Operating Speeds, km/hr; Area, percent / Length, cm	Defect Size: Transverse Defects (30)	Defect Size: Surface Defects (30)	Defect Size: Longitudinal Defects (30)	Transverse Defects in Rail Head: Transverse Fissure — Flaws Detected, %, Primary Location in Section, Gage, Center, Field, Min Distance From Joint, cm	Transverse Defects in Rail Head: Compound Fissure — Flaws Detected, %, Location in Section, Gage, Field, Center, Min Distance From Joint, cm	Transverse Defects in Rail Head: Detail Fracture From Shelling (G+F) Head Check (G) and Welded Bond Connection (F) — Flaws Detected, %, Location in Section, Gage, Center, Field, Min Distance From Joint, cm	Transverse Defects in Rail Head: Engine Burn and Welded Burn Fracture — Flaws Detected, %, Location in Section, Min Distance From Joint, cm
Ultrasonic Normal Pulse-Echo	1 2 5 5 15 10 20 –	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Ultrasonic, 45° Vee Pulse Echo, Forward and Backward	1 3 5 5 15 10 20 –	6-8 14-18 26-31 29-36	3-4 7-9 13-16 16-20	43-53 43-53 43-53 –	0 – – 10 C 5 50 C 5 90 C 5	0 10 C 5 50 C 5 90 C 5	N/A	0 0 0 0
Ultrasonic, 45° Vee Through-Transmission Foward and Backward	1 3 5 5 15 10 20 –	11-14, 80+ 24-32, 80+ 40-58, 80+ 47-60, 80+	5-8, 80+ 11-16, 80+ 21-29, 80+ 26-37, 80+	43-63, 80+ 71-80, 80+ 71-80, 80+ –	00 – – 50 C 5 90 C 5 99 C 5	0 50 C 5 90 C 5 99 C 5	N/A	(6)
30°-60° Skew Pulse Echo Forward and Backward (28)	1 3 5 5 15 10 20 –	10-13 21-29 35-51 45-64	10-13 21-29 35-51 45-64	N/A	0 – – 5 C 3 10 C 3 60 C 3	10 G-F 3 50 G-F 3 80 G-F 3 99 G-F 3	20 G-F 3 90 G-F 3 99 G-F 3 99 G-F 3	0 5 C 3 50 C 3 90 C 3
30°-60° Skew Through-Transmission Forward and Backward (28)	1 3 5 5 15 10 20 –	13-22, 80+ 31-51, 80+ 51-80, 80+ 66-80, 80+	13-23, 80+ 31-51, 80+ 51-80+, 80+ 66-80+, 80+	64-80+, 80+ 80+, 80+ 80+, 80+ –	0 – – 10 C 5 50 C 5 90 C 5	0 60 G-F 5 95 G-F 5 99 G-F 5	0 50 G-F 5 95 G-F 5 99 G-F 5	0 10 C 5 30 C 5 60 C 5
70° Pulse-Echo, Forward and Backward (29)	1 3 5 5 15 10 20 –	34-47 58-80 72-80+	34-47 58-80 72-80+	N/A	0 – – 30 C 3 70 C 3 95 C 3	0 50 G-F 3 80 G-F 3 95 G-F 3	0 40 G-F 3 70 G-F 3 75 G-F 3	0 0 10 C 3 50 C 3
80° Pulse-Echo, Forward and Backward (29)	1 3 5 5 15 10 20 –	31-42 68-80 80+ 80+	31-42 68-80+ 80+ 80+	N/A	0 – – 30 C 3 70 C 3 95 C 3	0 50 G-F 3 80 G-F 3 90 G-F 3	0 50 G-F 3 80 G-F 3 95 G-F 3	0 0 50 C 3 70 C 3

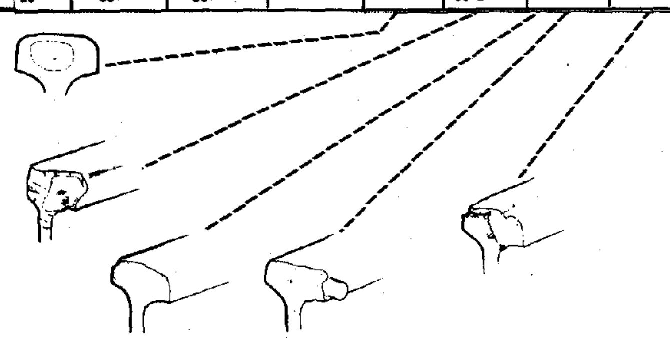
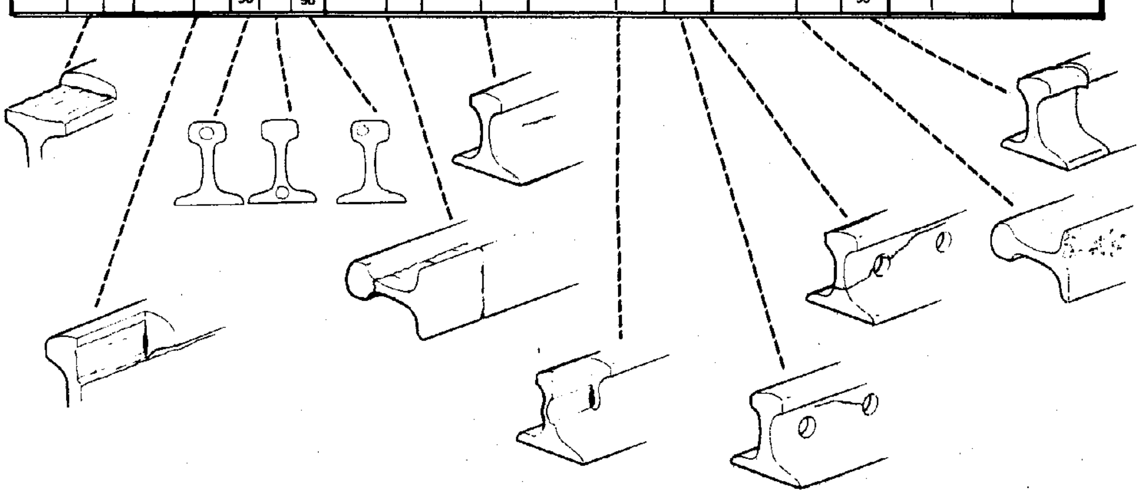


TABLE 24b. ULTRASONIC INSPECTION SYSTEM CAPABILITIES (METRIC UNITS) (CONTINUED)

Defect Types: Longitudinal Defects in Rail Head – Horizontal Split Head – Joint: Flaws Detected, % / Min Distance From Joint, cm	Through Web: Flaws Detected, %	Not Through Web: Flaws Detected, %	Vertical Split Head – Joint: Flaws Detected, % / Min Distance From Joint, cm	Body: Flaws Detected, %	Center Head: Flaws Detected, %	Center Base: Flaws Detected, %	Head, Gage Side: Flaws Detected, %	Weld Defects – Joint: Flaws Detected, % / Min Distance From Joint, cm	Body: Flaws Detected, %	Web Defects – Head & Web Separation – Joint: Flaws Detected, % / Min Distance From Joint, cm	Body: Flaws Detected, %	Split Web – Joint: Flaws Detected, % / Min Distance From Joint, cm	Body: Flaws Detected, %	Bolt Hole Cracks: Flaws Detected, %	Piped Rail – Joint: Flaws Detected, % / Min Distance From Joint, cm	Body: Flaws Detected, %	Corroded Base, Center – Sudden Rupture, Body Only: Flaws Detected, %	Size Information Provided*	False Indications (see notes referred to)	Defect Not Detected Due to (see reference notes)
99 <3 99 <3	99 99 99 –	0 0 0 –	50 3 50 3 50 3	50 50 50	N/A	N/A	N/A	99 <3 99 <3 – –	99 99 99 –	1 99 3 99 3 – –	2 99 <3 99 <3 – –	3 50 <3 99 <3 –	3 50 99	99 99 99 –	0 5 3 10 3 – –	0 5 10 –	N/A	E	11, 12, 13, 14, 15, 16, 17, 24	
N/A	N/A	N/A	N/A	N/A	0 10 50 90	20 60 90 99	N/A	N/A	N/A	0 0 0	N/A	0 0 0	0 0 0	90 95 99 –	5 5 60 5 (27) 90 5 99 5	5 60 90 99	– 5 – – 99	F	14, 25	11, 12 13, 23, 24
(2)(7)	95 95 99 –	N/A	N/A	N/A	0 50 90 99	0 20 60 80	N/A	2 7 Exctption defects must be >6 cm long to be detected	70 99 99 –	0 0 0 (2)(7)	10 60 99 –	0 0 50 – (2)(8)	0 40 90 – (3)	0 50 50 – (2)(9)	0 10 <20 20 <20 – – (2)	0 10 20 –	– 5 – – 99	FG	11, 12, 13, 14, 17, 24 25	
N/A	N/A	N/A	N/A	N/A	N/A	N/A	20 75 90 99	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	– 5 – – 99	F	18, 19, 25	11, 12, 13, 23, 24
0 20 5 95 5 –	95 95 95 –	10 50 90 –	0 0 99 5 –	99 99 99 –	20 90 99 99	N/A	0 50 99 99	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	– 5 – – 99	F-G	11, 12, 13, 18, 19, 20, 24, 26	11, 12, 13, 23, 24
N/A	N/A	N/A	N/A	N/A	0 20 70 75	N/A	0 40 75 99	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	– 5 – – 99	P	18, 19, 21, 22, 25	11, 12, 23
N/A	N/A		N/A	N/A	0 50 80 90	N/A	0 40 75 90	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	– 5 – – 99	P-F	18, 19, 21, 22, 25	11, 12, 23

(1) Denotes Note N

*P – Poor
F – Fair
G – Good
E – Excellent



Notes

1. Battered rails or chipped ends, weld repair, or other surface anomalies may make it impossible to distinguish this defect from surface anomalies.

2. Depends upon logic system. One-inch (2.5 cm) long defect may have appearance of bolt holt to logic system.

3. Piping less than 2 in. (5 cm) long in body of rail probably will bulge little. Battered or chipped rail ends may obscure short piping even if it does bulge.

4. Detectability and speeds apply only if the defect is at or near the center of the rail.

5. Sudden rupture is a complete and sudden break.

6. Typical depths of engine burn cracks are assumed to be

   for 1 percent of rail head - 0.121 inch (3.2 mm)
   for 5 percent of rail head - 0.271 inch (7.1 mm)
   for 15 percent of rail head - 0.470 inch (12.2 mm)
   for 20 percent of rail head - 0.545 inch (14.0 mm)

   (based upon 132 lb (65.5 Kg/m rail).

   If the environment of the defect is satisfactory, i.e., in the absence of head checks, laps, other surface irregularities, and other insignificant surface types of defects the 37.5^{o} to 45^{o} shear wave probes would be effective as follows:

Size of Engine Burn Crack	Detectability Percent
1 percent of rail head	0
5 percent of rail head	0
15 percent of rail head	75
$\geq$20 percent of rail head	95

   Assuming the crack is close to the surface.

7. Probability of detecting a 1-in. (2.5 cm) defect to end of rail with 45^{o} through-transmission at 50 mph (80 Km/hr) is zero. A defect 2-in. (5 cm) long or greater might be detected with 95 percent certainty, assuming the rail ends are not battered, chipped, etc., and the logic system can circumvent bolt-hole corrections. Here a correlation with indications from the normal probe will be most useful.

8. Piping shorter than 3 inches (80 cm) long in the center of the web would not be detected with 45^{o} through transmission.

Notes (Continued)

9. Detection depends upon orientation. 45° through-transmission will always miss bolt hole cracks between hole nearest end and the end of the rail.

10. Size information includes amplitude of signal, time indication persists, and correlation of these parameters between sensing systems.

11. Loss of transmission due to shells or burns.

12. Loss of couplant.

13. Rail wear condition which could result in misorientation of ultrasonic beam.

14. Extra bolt holes.

15. Chipped ends.

16. Wide gap at rail joint. Sure indication that should be called out. Battered end, misalignment, etc., could make look longer than actual.

17. Badly corroded base.

18. Normal rail end.

19. Chipped out shells.

20. Small horizontal split heads which have not progressed over web area and shells (worn rail conditions).

21. Deep burns and shells.

22. Mode conversion to surface waves due to excessive beam spread or transducer misorientation resulting in indications from small surface imperfections.

23. Misorientation of defects.

24. Unfinished welds (not ground off).

25. Misaligned weld joints.

26. Multiple reflections bypassing defect to receiver (position of receiver not optimized).

27. Detection of flaw to within 2 inches (5 cm) of end of rail requires use of B-scan display or complex logic system. Without complex logic system can work only to about 14 (36 cm) inches from end of rail.

Notes (Continued)

28. Transducer configuration is as shown in Figure 13. Analysis assumes forward and rearward looking sets are used on both gage and field sides of the rail head.

29. Analysis assumes that forward and rearward looking transducers are installed to interrogate the gage side, center, and field sides of the rail heads.

30. Where speeds are separated by a hyphen, lower speed assumes a fluid path length of about 2.6 inches (66 mm) (typical large-wheel system) and a total electronic and fluid path delay time of 100 m-sec. Higher speed assumes a very short fluid path length (sled or small wheel system without opposing reflectors) and total electronic and fluid path delay time of 25 m-sec or less.

    The centerlines of the U-sonic wave intersects the flaw 8 times during passage or the pulse rate will produce a pulse per 0.2-inch (5 mm) of travel (5PPi), whichever gives the lower speed.

    For through methods, the relaxing of the constraint which limits the number of pulses in the rail to one permits the attaining of the speed following the comma.

31. For defects oriented perpendicular to the surface, a corner reflection is obtained. If the flaw dimensions are small relative to the beam spread and the flaw is located close to the surface relative to the beam spread the center of the beam will pass over each flaw twice and the flaw will appear almost twice as large as its actual dimensions. Speed values shown in Table 21 are based only on the actual flaw dimension and do not include these corner effects and therefore, theoretical speeds might be up to twice those shown depending upon flaw dimensions and beam spread.

32. Applies only to horizontal cracks open to the end of the rail.

An upper limit on speed occurs at the point at which the couplant supply system fails to provide a uniform layer of couplant between the transducers and the rail in the case of sled systems, or when the turbulence becomes excessive in the case of wheel systems. An additional factor relates to the stresses imposed on the liquid by the moving system which could cause cavitation and, therefore, scattering of the beam. As mentioned previously, reports of high speed inspection cars operating in Europe would indicate that satisfactory coupling conditions can be maintained to greater than 50 miles per hour (80 Km/hr). The influence of these factors on sensitivity (ability to detect defects) has not been determined, however.

The capability of the transducer assembly to follow the surface contour at high speeds, to provide good incidence angles and orientation, and to maintain suitable coupling may be heavily taxed at high speeds. Slight lateral movement of transducers transmitting beams through the head and web may result in receiving echoes from the head and web fillets. These fillet echoes have the appearance of defects. These problems must be controlled by proper design of carriages and alignment control systems. Small depressions or changes in radius of curvature of the cross-section may cause sufficient change in refraction angles and mode conversion to cause false indications such as loss of base and echoes from nondefect surfaces that have the appearance of defect signals. These conditions will contribute to false indications at the higher sensitivities at high speeds.

Wave propagation characteristics of importance include velocities (wavelength), attenuation, and beamspread. Attenuation and beamspread are functions of wavelength. For a given frequency, attenuation of shear waves in steel is higher than it is for longitudinal waves. The higher attenuation and slower speed of the shear wave limits its effective range in rail testing, particularly in high speed testing. Although Table 24 indicates the possibility of locating 1 percent defects at various speeds in the rail, using 45° probes, the attenuation of signals particularly in the pulse-echo mode is usually so high that if a signal were obtained from such a defect using 45° pulse-echo the signal would be at noise level and rejected. For this reason, the probability of detection is given a low rating in Table 24. Experiments in Battelle's ultrasonics laboratory showed justification for a low probability rating on the 45° probe for locating small cracks in the head when used in either the pulse-echo or the through-transmission mode.

Diffraction effects are factors in detecting small defects by the through-transmission techniques. If the defect is smaller than the cross-section of the beam, the "shadow" may disappear within a very short distance. For example, the shadow of a flat, circular discontinuity, 1/4 in. (6.4 mm) in diameter lying in a plane normal to the axis of a 2.25 MHz shear-wave beam that is 1/2 in. (13 mm) in diameter will disappear from the beam within approximately 2 in. (51 mm). This is equivalent to a 1 percent rail head defect lying in the path, at the entry surface, of a typical transducer beam. This property of the through-transmission could be exploited to aid in identification of flaw size.

Several effects are attributable to beamspread and side-lobes. The conventional equation defining beamspread from a transducer is based on the assumption that the transducer transmits uniform intensity over the entire radiating surface. Variations in coupling conditions and nonuniformities in construction may cause the emitted beam to be offset. The radiation pattern differs from the ideal in these cases. Conditions in the surface of the railhead or in the alignment of the transducers that affect the incidence angles of rays in the ultrasonic beam may cause fairly large changes in the beam pattern, and thus affect the reliability of inspection.

Echoes can be received from discontinuities that lie perpendicular to side-lobes of a beam pattern. The reflecting surfaces may be a standard surface of the test material but may be detected as a defect. In present systems used for rail inspection, any such indications are minimized or eliminated in the Reject setting. However, as defect sensitivity requirements become more rigid, such echoes may interfere with the capability to identify true defect indications.

Some false indications may be attributable to beamspread. Beamspread is arbitrarily defined to include the portion of the beam which contains intensities equal to or exceeding half-peak intensity levels. As the beam propagates into a medium, its intensity attenuates. As a result, the effective angle of spread may decrease depending upon the Reject setting. If intensities are increased and Reject settings are decreased in order to increase the distance and sensitivity to smaller defects, the possibility of false indications due to beamspread will also increase.

In addition to fillets (which can cause defect types of signals to occur), surface roughness may be considered as geometrical conditions that affect the sensitivity of ultrasonic testing. The critical roughness of steel using water as couplant is 0.0174-in. (0.442 mm) at 2.25 MHz, longitudinal wave. Roughness asperities of this height, at the surface of incidence would cause a maximum loss of energy. Possibly the only places such conditions would occur on rail would be in the area of wheel burns where heat check cracks may be numerous. These plus a depression often produced by the spinning wheel may account for loss of back-echo at wheel burns.

Surface roughness causes attenuation by scattering. Scattering from grain boundaries also contribute to attenuation. Generally speaking, attenuation due to scattering from grain boundaries does not appear to be a problem with present day ultrasonic inspection systems used on railroads. It can give indications at welded joints, if the grain structure is large, that are similar to defect indications and thus obscure true defect signals at these joints.

Defect types, geometries, locations and surrounding conditions are all important to the defect sensitivity of an inspection system.

It has been assumed that all of the defect types are those that provide discrete discontinuity in the path of the ultrasonic beam so that all rays incident on the surface of the defect are reflected or deflected. The geometry refers to the shape and dimensions of the defect relative to the incident beam. The orientation refers to the manner in which the defect is positioned relative to the surface of the rail. A plane wave incident on a small diameter (on the order of the beam diameter) cylinder reflects as a cylindrical wave. A plane wave incident on a narrow planar discontinuity with one lateral dimension on the order of a wavelength will be reflected as a cylindrical wave. In both cases, the reflected waves are attenuated by spreading to a greater extent than they would if they were reflected as columnated plane waves. In steel, the wavelength of a longitudinal wave at 2.25 MHz is 0.1024 inch (2.601 mm) and for a shear wave, it is 0.057 inch (1.45 mm). All of the angle probes use shear waves. A transverse crack in the head of a 90 lb (45 Kg/m) rail that is 0.057-in. (1.45 mm) deep and 0.560-in. (1.42 mm) long is a 1 percent defect. The probability of detecting such a defect using 45 degree shear waves by either pulse-echo or through-transmission is nearly zero. If an indication is obtained, it may be impossible to sort it from a large number of meaningless indications due to sources such as those previously discussed.

The orientation of large defects may be determined to an extent by comparing data from two overlapping methods. For example a crack at 45 degrees to the normal lying in the center of the rail will cause loss of back echo over the projected area to the horizontal and it would also cause a significant echo from a 45 degree shear wave at normal incidence over a period of time that the beam is incident on its surface.

The conditions surrounding a defect affect the sensitivity of an ultrasonic beam to the defect. The example of a bolt hole crack obscured by the bolt hole is an obvious example. Two other examples include the appearance of a significant crack in the midst of heat checks and a crack within a welded section containing large grain structure. In either case, scattering from the heat checks and from the grain boundaries may obscure the defect. In some cases it may be possible to obtain false echoes from either condition even when a serious defect is not present.

Carriage Dynamics. Carriage dynamics can influence the effectiveness of an ultrasonic inspection of rails in either the lateral or the vertical motion of the system. Lateral motion may affect the angle of incidence due to the geometry of the cross-section of the rail and produce false indications. A normal probe, for example, should emit a beam that is no wider than the web thickness and should remain over the center of the web. Otherwise, false echoes will be obtained by reflections from the head and web fillets. Angular rotation of the probes about an axis parallel to the surface of the rail may cause similar echoes. Loss of amplitude of back-echo will occur as the position of the transducer shifts relative to the web. To avoid such loss of back-echo, the transducer should be centered to within about ±0.15 inch (0.381 cm) of the web centerline. Larger shifts than 0.15 inch (0.381 cm) are required to produce false fillet echoes.

Limitations on bounce (vertical motion) are related (1) to conditions within the transducer assembly (wheel or sled) and (2) to conditions between the external or contacting surface of the transducer assembly and the surface of the rail. For example, in a wheel-type transducer assembly, the transducers are attached to the axle of the wheel. The axle may move up and down relative to the rail and thus affect the distance to the rail surface (delay time). Externally, the area of surface contact may vary on a high bounce. All beams must pass through the same contact area.

It is possible that a wheel-type transducer assembly may bounce high enough to interfere with the transfer of energy into the rail due to the reduction in contact area between the tire and rail. If the compression in a 6-inch(15cm) diameter tire during normal operation causes contact over a length of rail of 1.25 inch (3.18 cm), the maximum upward displacement from the normal should be restricted to less than 0.055 inch (0.140 cm) to avoid interferring with the transmission of energy into and out of the rail. Smaller tolerance on vertical motion is desirable. A difference of 0.055 inch (0.140 cm) in water is equivalent in time of travel to a distance of 0.22 inch (0.56 cm) in steel. With gating controlled by receipt of an echo from the surface of the rail (interface gating), bounce within this limit or possibly higher should not be detrimental to the functioning of the system.

Evaluation of Magnetic Inspection Systems

The magnetic method of rail inspection can be defined as any technique that senses perturbations in a magnetic field to detect defects in the rail. The magnetic field is generated either by a noncontacting magnet near the rail, or by a heavy electric current actually flowing in the rail. Figure 16 indicates the different types of magnetic rail inspection systems that belong to these basic inspection categories.

Electric Current Methods. The electric current methods employ devices that cause current to flow along the length of the rail. When current flows longitudinally in the rail, magnetic flux circulates in the rail head and in surrounding air-filled space. The magnetic flux lines are perpendicular

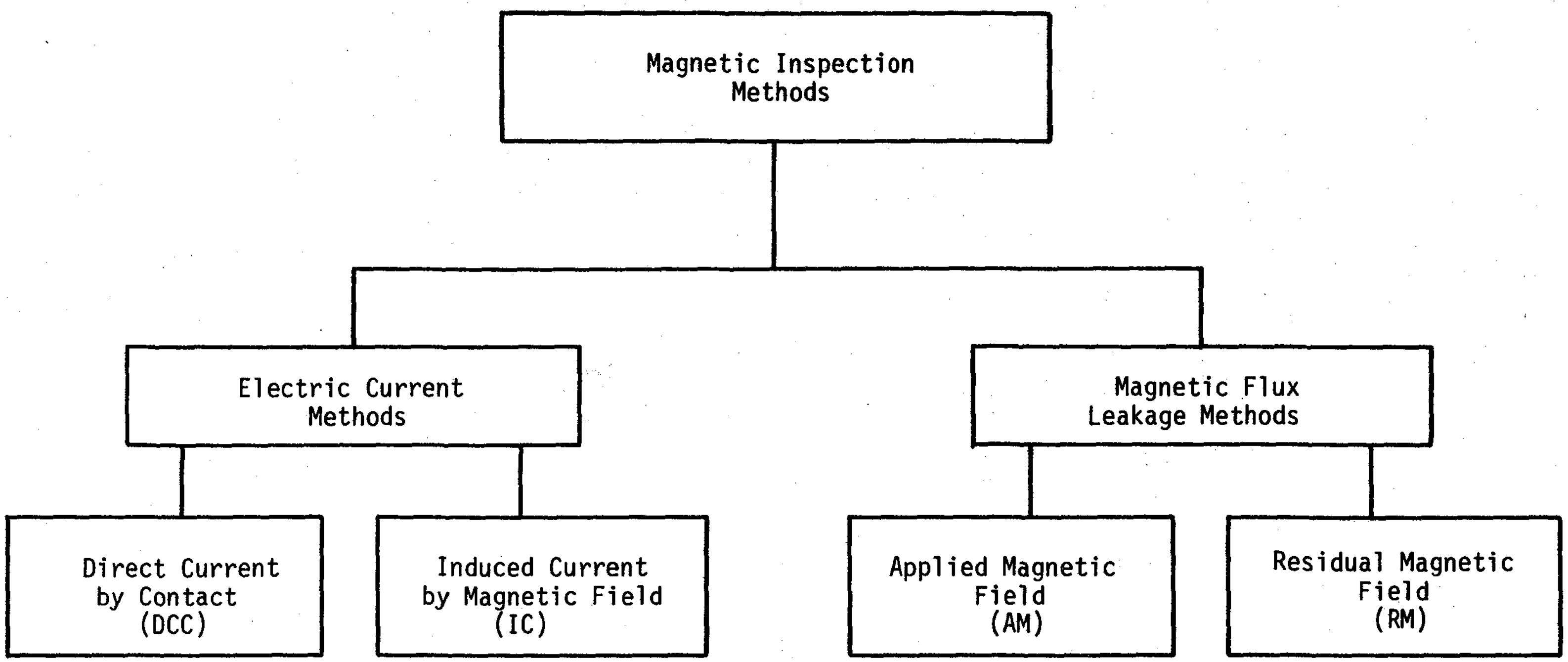


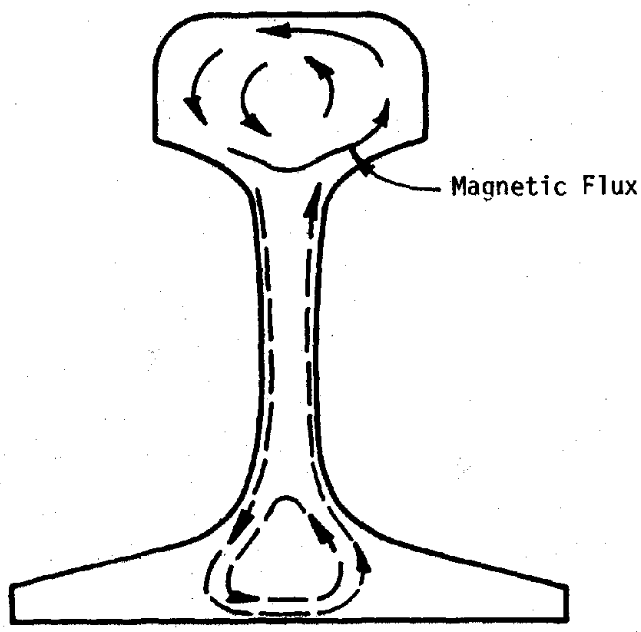
FIGURE 16. CATEGORIZATION OF MAGNETIC RAIL INSPECTION SYSTEMS

to the direction of current flow and their density is proportional to the current density in the rail. Defects in the rail head divert the current flow and thereby alter the associated magnetic flux near the rail. Detection of defects is accomplished by detecting these distortions in surrounding magnetic flux.

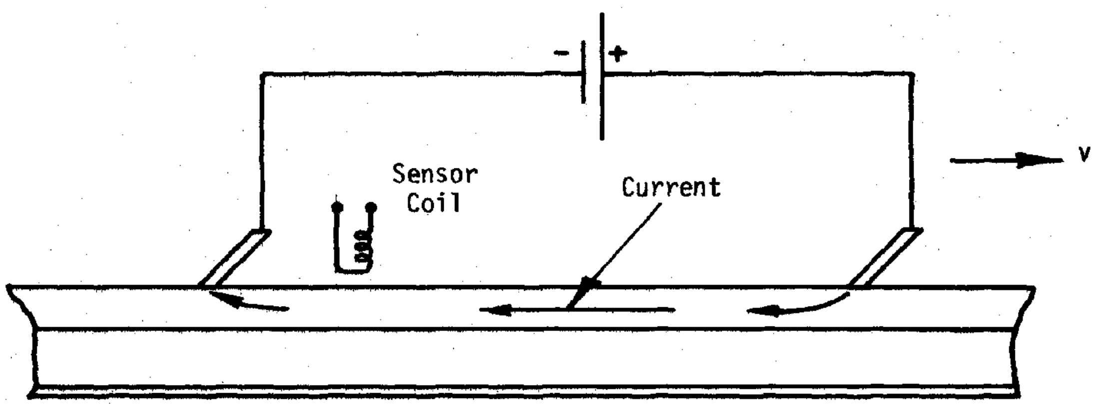
Direct Current Contact (DCC). The so-called current induction method is used on a continuous basis in the United States. Direct-current generators cause current to flow through electrical contacts positioned along the length of the rail, as illustrated in Figure 17. To avoid confusion with other magnetic methods that utilize electric current flow in the rail by noncontacting devices, this method will be referred to as the direct current contact or DCC method.

In practice, DCC systems provide between 2000 to 4000 amperes of current in each rail. These currents are delivered at a relatively low voltage (on the order of 3 volts) so that the power requirements are not excessively high (i.e., less than 30 kw). Some systems incorporate two types of contacts to carry the current: steel bars inclined at an angle of 45 degrees in the direction of travel, and rail car wheels. Contact brushes located at a distance of about 4 feet (1 M) in front of the trailing brushes carry approximately 60 percent of the current. The remaining current is applied through the wheel that is about 35 feet (11 M) in front of the trailing set of brushes. Sensor coils are located between the leading and trailing brushes. Evidently this technique provides satisfactory current densities at adequate penetration depths while maintaining resistance heating in the joint areas at reasonably low levels.

Transverse defects in the rail head have two significant effects on the current flow. First, current flow is directed around the defect, causing a significant change in direction of the current path near the defect. This, in turn, causes a change in the direction of the surrounding magnetic field. Secondly, the current density is increased in the steel that lies adjacent to the defect. Under normal conditions, the total current that flows in the rail remains constant to provide a fairly uniform current density in defect-free rail. Transverse defects (nonconductive) direct this current to the conducting portions of the rail. Since the current



a. Cross Sectional View of Magnetic Flux in the Rail



b. Current Flow

FIGURE 17. PRINCIPAL ILLUSTRATION OF THE DIRECT CURRENT CONTACT METHOD

flows through a smaller cross-sectional area, the current density is increased. Consequently, the detectable flux density is greater near the areas where the current density is increased. Consequently, the detectable flux density is greater near the areas where the current density is increased.

Changes in the directions and intensity of the magnetic flux are detected by magnetic sensors placed near the rail. Although more recent technical developments have provided semiconductor devices that are independent of scanning speeds, the existing method of detecting magnetic flux penetrations is the induction coil. The induction sensor is a small coil of insulated conducting (copper) wire wound on a coil form. The coil forms are usually a low loss-that is, nonconducting--material that may be made of ferromagnetics such as ferrite to increase flux concentrations, and thereby enhance sensitivity. Rapid changes in the magnetic flux that passes through the core cause voltage to be induced between the terminal of the coil winding.

The magnitude of the voltage is proportional to the change in flux density and its rate of change. The induction coils are also directional. Alignment of the axis of the induction coil with the changing magnetic field provides the maximum signal output. Rotation of the coil at right angles to the changing flux provides little or no signal output. Therefore, coil orientation and location play an important part in magnetic rail inspection system designs.

Induced Current by Magnetic Field (IC). The Soviets use electromagnets instead of electrical contacts to induce electric currents in the head of the rail. According to the literature,[7-12] a π-shaped or inverted U-shaped electromagnet is aligned so that a magnetic field flows longitudinally in the rail, as illustrated in Figure 18. The literature indicates that the poles are approximately 2 feet (60 cm) apart. Relative motion of the π-shaped magnet over the rail causes currents to flow in circulating pattern. Figure 18 illustrates only the horizontal components, that is, the x and y directions, of current flow. There are also vertical components associated with the current that flows around the rail. These circulating currents are caused by the longitudinal magnetic field between the

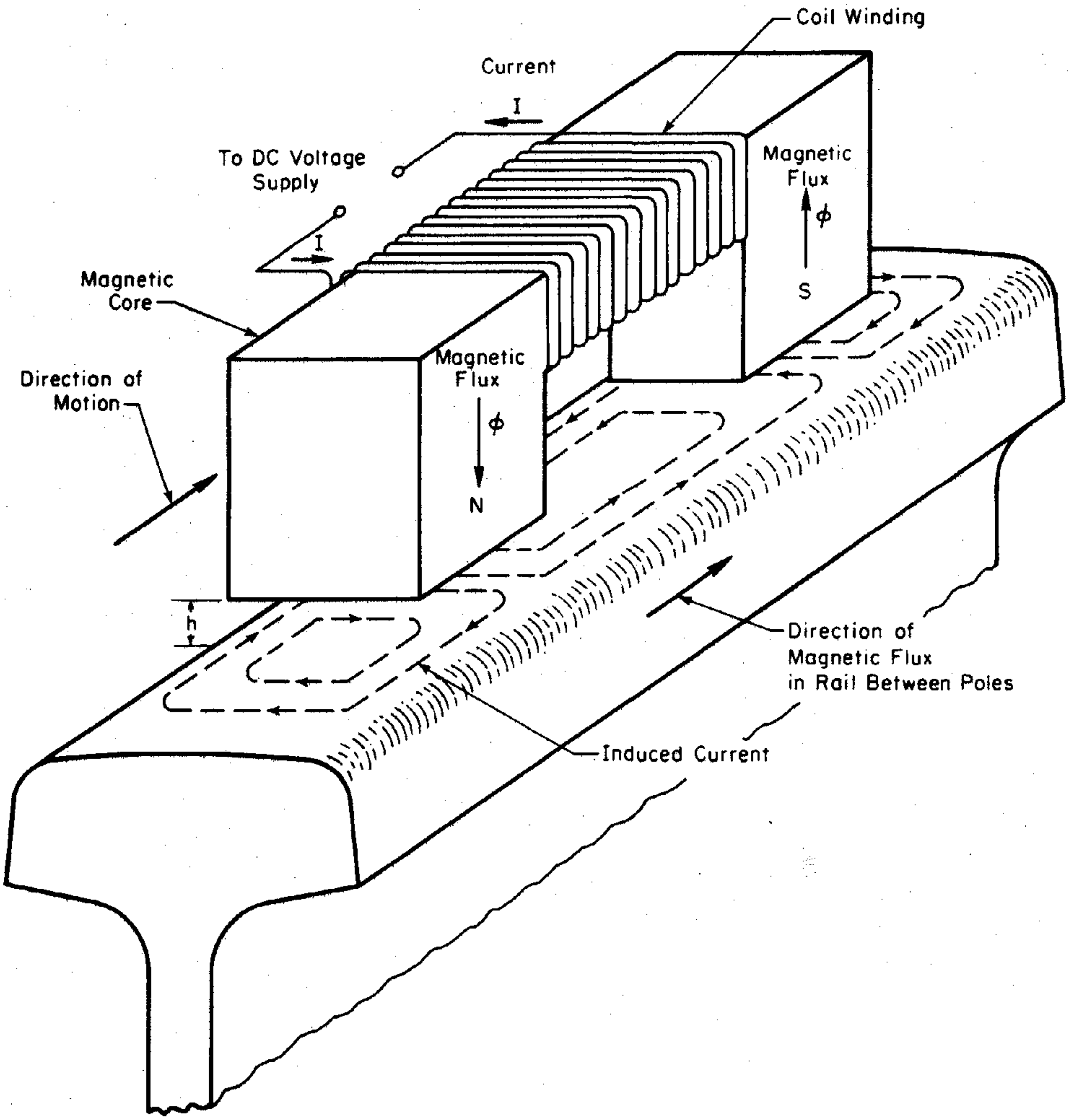


FIGURE 18. SCHEMATIC DIAGRAM OF THE INDUCED CURRENT METHOD

magnetizing poles. According to the Soviets, the horizontal components are more important, since they are influenced to a greater extent by the transverse defects in the rails.

Transverse defects are detected by sensor coils that respond to perturbations in magnetic field above the rail. Like the DCC method, the defects cause the current to change in direction and density, which in turn causes a perturbation in the associated field. Notice that the induced current flows in opposite directions in the symmetrical halves of the rail head. Consequently, the longitudinal current density is a function of the distance from the center of the rail. The current density is 0 near the center, and a maximum near the sides of the rail head. The point of reversal is influenced by several factors including current that circulates circumferentially around the rail head.

Current density is also a function of the velocity of the π-shaped magnet. The greater the velocity the greater the rate of change in magnetic flux at a given point on the rail, and therefore, the greater the surface current density. On the other hand, the increase in velocity decreases the penetration depth of the induced currents. Consequently, the effectiveness of the IC technique is reduced at greater speeds. Speed limitations are discussed in detail in a following section.

Magnetic Flux Leakage Methods. Magnetic flux leakage methods are based on the fact that a defect will divert magnetic flux from its intended path and cause part of this flux to enter the air-filled space near the rail. Flux that leaks or fringes around defects in the rail can be detected by the magnetic sensors described previously. Leakage flux occurs when the magnetization is applied or when there is a residual field after magnetization. Two basic flux leakage techniques; the applied magnetic, AM, and the residual magnetic, RM, are described below.

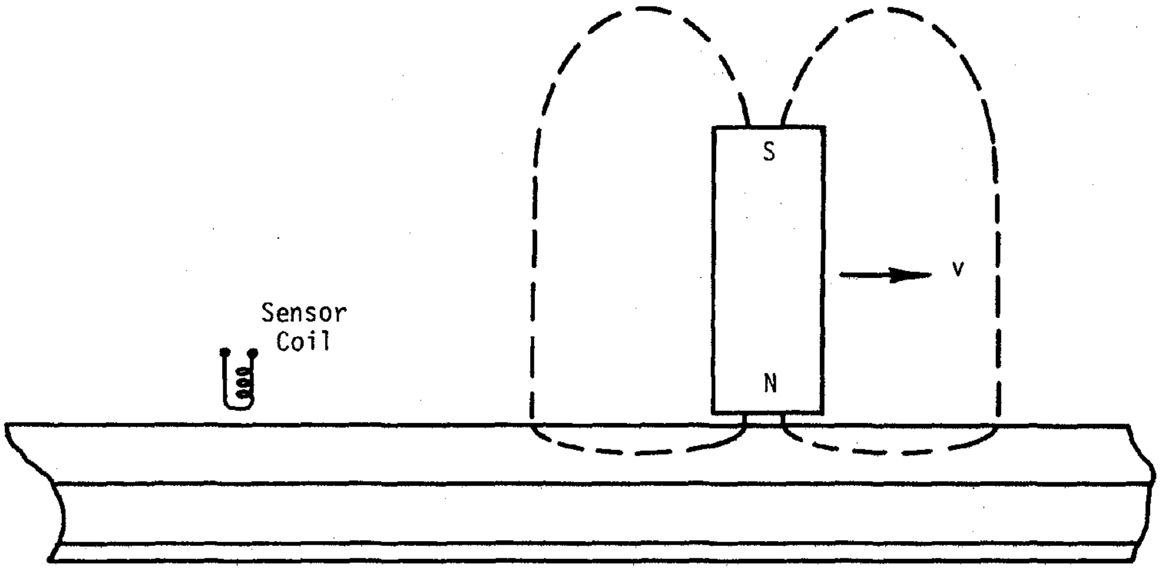
Applied Magnetic (AM). The AM method involves application of a magnetic field to the rail in either the longitudinal or transverse directions. The field is applied so that the flux lines are diverted by the defect discontinuity. A longitudinal field is applied to the rail to detect transverse defects, and a transverse field is applied to detect longitudinal defects.

The greater magnetic reluctance of the defect compared to that of the rail head is the key factor in the AM method. Magnetic reluctance is a measure of resistance to magnetic flux and is analogous to electrical resistance. Since the reluctance of material--that is, air--that fills the defect void is greater than the reluctance of an equivalent volume of rail steel, the flux tends to flow around the defect. This increases the flux density in the steel adjacent to the defect and causes part of the flux to leak into the air surrounding the rail. The extent of flux leakage is a function of several factors, including the cross-sectional area of the defect, the defect volume, defect orientation, and the intensity of the applied magnetization.

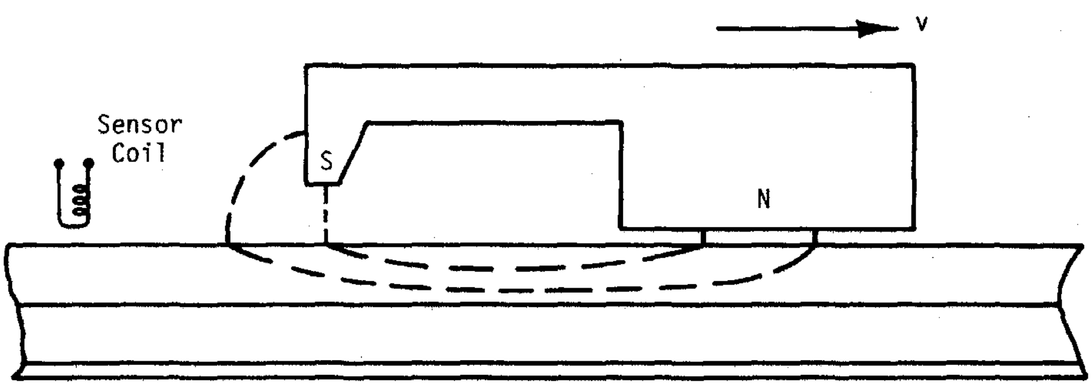
The AM method is not to be confused with the IC technique discussed in the preceding section where the purpose is to generate a current in the rail head. Although the longitudinal field is present in the IC technique, the effect of the induced current predominates when the magnetic poles are relatively close together. On the other hand, if the poles are separated by a relatively large distance, the induced currents become negligibly small at a point midway between the poles. It is assumed that the AM method employs sufficient spacing between the poles that the induced currents can be ignored.

Residual Magnetic (RM). The RM method requires magnetization of the rail so that a magnetic field is retained in the longitudinal direction. This can be accomplished by passing a magnetic pole over the rail as illustrated at the top of Figure 19. In practice, the magnetization unit is a dipole and the magnetic flux lines enter in a direction perpendicular to the rail in the vicinity nearest the pole. The flux returns through the air to the opposite pole of the electromagnet.

The rail head is magnetized longitudinally from left to right as the dipole approaches a given position on the rail. As pole N passes over this position the magnetic field changes direction from the longitudinal toward the transverse, i.e., vertical, direction. The flux enters in a direction that is perpendicular to the rail and has the greatest intensity under pole N. As pole N passes over the position of the rail, the magnetic flux decreases in strength and changes to the longitudinal



a. Vertical Diapole Magnet



b. G-Shaped Magnet

FIGURE 19. PRINCIPAL ILLUSTRATION OF THE RESIDUAL MAGNETIC METHOD

direction. The rail is then magnetized from right to left. The flux density gradually decreases in strength, changes direction to the vertical and returns to pole S. This gradual transition leaves a retained field in the longitudinal direction.

The lower portion of Figure 19 illustrates another magnetizing configuration similar to that employed by a rail inspection system presently used in the United States. It is believed that this G-shaped magnet extends the longitudinal field and therefore aids in providing greater penetration of the magnetic field as the inspection velocity is increased. Maximum velocity is undoubtedly affected by the eddy currents that are generated in the rail as the magnetic field changes intensity and direction at a given point of observation.

Magnetic Transducer Instrumentation. Most of the electronic instrumentation systems employed with the magnetic methods can be described in terms of the basic building blocks illustrated in Figure 20. Magnetic transducers presently in use are coils of insulated conducting wires wound on cores of high resistance but possibly ferromagnetic material. Movement of the coils through the magnetic perturbations associated with a defect induces voltages at the terminals of the coils. Signal voltages are proportional to the rate of change of flux, that is, $d\phi/dt$, that links the turns of the coil. Therefore, signals may result from either a change in direction or change in magnitude of the magnetic field.

Another type o magnetic transducer is the Hall sensor. Hall sensors incorporated with constant current sources and sensitive synchronous detectors will provide a voltage that is proportional to the component of magnetic flux normal to the Hall semiconductor transducers. Hall sensors do not require relative motion through the magnetic field to provide indications of flux perturbations, and therefore, are not influenced by inspection velocity. However, Hall devices are affected by temperature and mechanical forces. These factors, coupled with the requirement for more elaborate electronic instrumentation, may explain the limited use of Hall sensors in rail inspection systems.

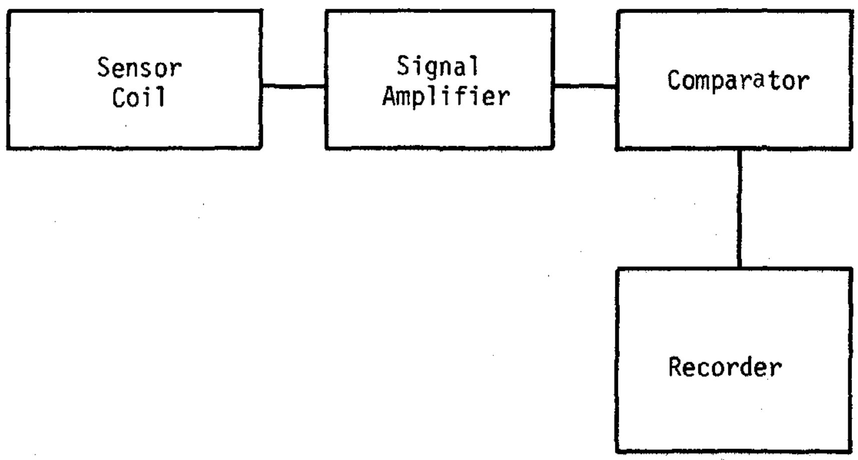


FIGURE 20. BLOCK DIAGRAM OF MAGNETIC SENSOR INSTRUMENTATION

In comparison, coil sensors do not measure the magnitude of the field but detect changes in magnetic field. Therefore, it is not necessary to subtract the steady state signals associated with the constant magnetic fields. Coils can be oriented in any direction with no offset adjustments required. Extremely small perturbations in the magnetic field can be detected by placing the coils in close proximity to the rail and using a sufficient number of turns of wire. Sensitive signal amplifiers limited only by electronic noise can be used to indicate very small defects.

Since signals are frequently caused by rail anomalies other than defects, comparators are used to limit the number of erroneous signal indications. Ideally, the threshold level of the comparator is set to provide reliable detection of harmful defects and yet reduce the number of false indications caused by surface anomalies.

Signals of sufficient level exceed the threshold of the comparator and actuate the pens of a strip chart recorder. Most inspection systems have a chart pen for each sensor coil that scans the rail. Magnetic rail inspection systems in the United States use pens with a fairly short stroke, e.g., 1/8 in (3.2 mm), and chart paper that is only 3 to 4 in. (8 to 10 cm) wide. Therefore, defect indications are recorded only as short pulses containing very little information.

Not shown in Figure 20 are optional filters between the signal amplifier and the comparator. Low pass and high pass filters can reduce the amplitude of signals that are not necessarily associated with harmful defects. For example, low pass filters can reduce the high-frequency content of the signal that is not typical of the internal defects. High pass filters reduce gradual signal variations that are not typical of the harmful flaw. Simple filtering of this sort can be incorporated in the signal amplifier.

<u>Speed Limitation of the Magnetic Methods</u>. Skin effect[13] is considered to be the primary factor that limits the speed of the magnetic method. Skin effect is a concentration of the magnetic flux near the surfaces of the rail, and is attributed to the harmonic content of the transient energy imposed on the rail. Magnetic flux and current densities

near the surfaces of the rail, and is attributed to the harmonic content of the transient energy imposed on the rail. Magnetic flux and current densities near the center of the rail are weakened by the skin effect. This results in an appreciable loss of sensitivity of the magnetic method to internal defects.

The depths of penetration of the magnetic flux or current can be calculated for simple geometries such as long solid cylinders using the following formula:

$$\delta = C\sqrt{\frac{\rho}{\mu_r f}} \quad , \tag{4}$$

where,

δ = penetration depth from surface, in. (cm)

C = a constant; 3.168 for the English units and 5.0329 for the metric units

p = electrical resistivity, $\mu\ \Omega$ in. ($\mu\ \Omega$ cm)

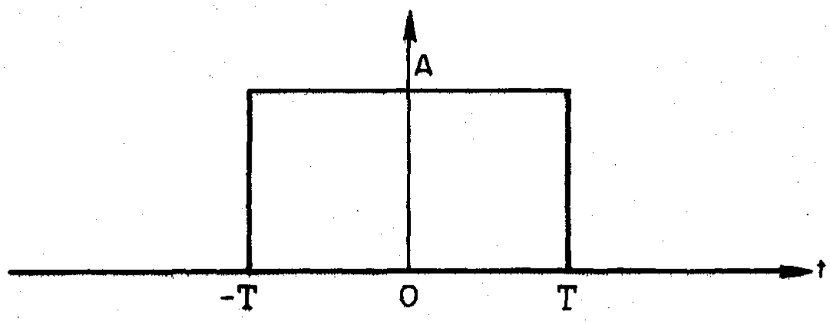
μ_r = relative permeability, no units

f = frequency, Hz.

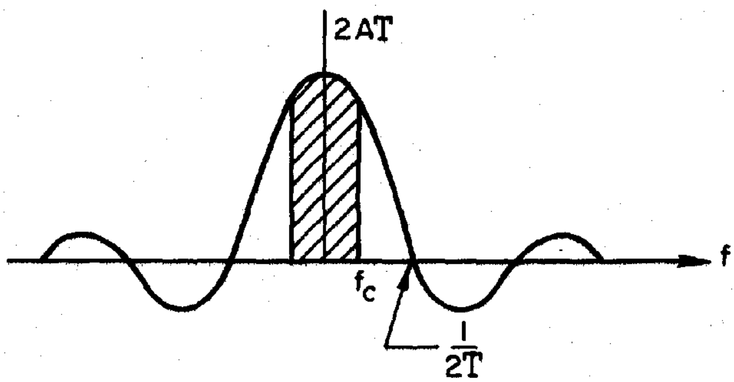
The frequency, f, refers to the harmonic components of the energy pulse experienced at a fixed location along the rail. As the current brushes or magnetizing yoke pass over a point on the rail, the current or magnetic field increases to a maximum and then decreases rapidly to zero or a relatively low level. This transient pulse of energy can be constructed from sinusoidal waveforms. A decrease in the space between contacts or magnetizing poles and an increase in speed cause an increase in amplitude of the high-frequency components.

The current or magnetic field observed at a fixed location along the rail can be approximated by a rectangular pulse of amplitude A, as illustrated in Figure 21 . A, is the magnitude of current or magnetic flux density that occurs near the surface of the rail. The duration of the pulse is proportional to the space between the contacts and inversely proportional to the inspection velocity. Therefore, T is given by the following equation,

$$T = d/2v, \tag{5}$$



a. Energizing Pulse



b. Fourier Transform of Energizing Pulse

FIGURE 21. ENERGIZING PULSE AND ITS FOURIER TRANSFORM

where,

T = time, sec.

d = space between current contacts or magnetic poles, ft (m)

v = inspection velocity, ft/sec (m/sec).

The frequency content of the pulse illustrated in Figure 20b obtained by taking the Fourier transform.[14] The maximum amplitude of the frequency spectrum is 2AT and occurs when f is 0. It is important to note that the amplitude of the Fourier spectrum is relatively small for,

$$f = \frac{1}{2T} .$$

The skin effect reduces the amplitude of current or magnetic flux in the central portions of the rail. This limits the harmonic content of the frequency spectrum to the cross-hatched region shown in Figure 20b. The cutoff frequency, fc, is obtained by solving Equation 1 for f, setting the penetration depth, δ, equal to the distance from the center to the surface of the rail.

$$f_c = \frac{c}{\delta}\ ^{2}\frac{\rho}{\mu_r} = 0.95 \text{ Hz}, \qquad (6)$$

for,

δ = a penetration depth of 2 cm

c = a constant; 3.168 for English units and 5.0329 for metric units

p = an electrical resistivity of 15 μΩ cm

μ_r = a relative permeability of 100.

The inverse Fourier transform of the band limited spectrum gives the time response of the field in the center of the rail. If the width of the excitation pulse is relatively short, i.e., T < 0.2 second, the band limited spectrum can be approximated by a rectangular pulse in the frequency domain. The pulse has an approximate amplitude of 2T and a width of 2 f_c. The inverse transform[14] of the rectangular pulse is the familiar function of general form $\frac{\sin x}{x}$ having a maximum amplitude of ATf_c. Expressing T in terms of contact or pole distance and inspection velocity, the amplitude of the energy at the center of the rail is:

$$A_c = \frac{2Adf_c}{v} \quad , \qquad (7)$$

where,

A_c = amplitude of current or magnetic flux at rail center under dynamic conditions, amps, Gauss

A = amplitude of current or magnetic flux near surface of rail, amps, Gauss

f_c = cutoff frequency determined by the required penetration, Hz

v = velocity of the inspection system, ft/sec (m/sec)

d = distance between electrical contacts or magnetizing poles, ft (m).

The maximum velocity for the various rail inspection techniques can be calculated by solving Equation (7) for v as follows:

$$v_{max} = \frac{2Ad_{max}f_c}{A_c} \quad , \qquad (8)$$

where,

d_{max} = the maximum spacing between electrical contacts or magnetizing poles.

Table 25 lists the rail inspection techniques considered in this investigation and the calculated values for v_{max}. Calculation of v_{max} requires selection of the maximum value of d, the effective spacing between electrical contacts or magnetic poles, and A_c, the required amplitude of either current or flux density at the center of the rail. A_c should be of sufficient magnitude to provide adequate detection of defects located near the center of the rail head.

Calculation of the cutoff frequency, f_c, was based on the assumption that the relative permeability of the rail steel has a constant value of 100. In reality the magnetic permeability is a function of the field strength. The relative permeability has a maximum value at a relatively low level of magnetization and decreases as the field intensity is increased. The Soviets[11] have taken variable permeability into account in a mathematical model of their detection system that employs π-shaped

TABLE 25. CALCULATION OF MAXIMUM SPEED FOR THE MAGNETIC INSPECTION METHODS

	Inspection Method			
Parameters	DCC	IC	AM	RM
A_c	0.5A	0.5A	0.5A	0.25A
d	* 7 m (23 ft)	1.5 m (5 ft)	7 m (23 ft)	1 m (3.28 ft)
f_c	0.95 Hz	0.95 Hz	0.95 Hz	0.95 Hz
μ_R	100	100	100	100
ρ	15 μΩcm	15 μΩcm	15 μΩcm	15 μΩcm
δ	2 cm (0.79 in.)	2 cm (0.79 in.)	2 cm (0.79 in.)	2 cm (0.79 in.)
v_{max}	95.8 Km/hr (59.5 Mi/hr)	20.5 Km/hr (12.7 Mi/hr)	95.8 Km/hr (59.5 Mi/hr)	27.4 Km/hr (17.0 Mi/hr)

(*) This contact spacing is substantially greater than currently used for this inspection technique. Operation with this contact spacing is practical only on welded rail or on uninsulated joints with further development of the technique. The technique will not operate closer to an insulated joint than the contact spacing, d.

electromagnets to induce currents in the rail head. Also, they provide some experimental data to verify their calculations. The Soviet calculations are in good agreement with those obtained from Equation (8).

It is apparent from Equation (8) that the primary factor that limits the maximum inspection speed is the distance, d. For example, the RM method has a relatively low maximum velocity since the effective distance, d, is small. Likewise, the IC method employed by the Soviets has a relatively low maximum velocity. The maximum distance between magnetizing poles for the Soviet IC system is estimated to be 4.9 ft (1.5 m). This estimate is based on observations by Battelle personnel during a recent tour of Soviet rail inspection cars.

With the DCC technique, the spacing d can theoretically be increased to very large values and, therefore, speeds could be increased to almost any desired value; however, on jointed rail there is often a substantial increase in resistance at rail joints. With systems in current use, which do not use constant current control systems, this increase in resistance often causes a significant decrease in current and loss of ability to adequately inspect close to the joint. In addition, increasing the brush spacing to operate at high speeds would increase the time that high currents flow through the bond wires when operating at low speeds, thereby increasing the probability of burning out bond wires while inspecting. It appears probable that these problems can be solved through use of constant current control systems, by using a brush spacing which varies with operating speed, and/or by using decreased measuring currents in conjunction with transducers having increased sensitivity. To operate with this type of system close to insulated joints requires a close brush spacing when operating near the joint. This might be accomplished by using multiple sets of brushes and by slowing down for insulated joints and exciting through the closely spaced brush set. The analysis of the effect of slowing for track anomalies shows that slowing for insulated joints would not significantly affect average operating speeds.

The estimated values for v_{max} given in Table 24 should not imply that defects cannot be detected by the method when operating at speeds greater than v_{max}. Sensitivity of the magnetic methods is a function of location of the defect with respect to the surface of the rail head as well as velocity and distance, d. For example, the Soviets indicate that they use the IC method to detect surface and subsurface defects that are within 0.16 in (4 mm) from the rail head surface while operating at speeds in excess of (50 mi/hr) (80 Km/hr). However, the calculations of Table 24 are based on the assumption that electric currents must penetrate to 0.79 in. (2 cm) the surface and have a magnitude of at least half that of the surface current density. Therefore, it is estimated that the IC method would be limited to speeds below 12.7 mph (20.5 Km/hr) for detection of defects at railhead center.

Estimation of the effective distance, d, for the residual magnetic method required some special considerations. For example, the direction and density of the field near the vertical electromagnets vary with distance from the pole faces. Although the railhead attracts the magnetic flux and extends the field, it is apparent that the flux density drops off considerably as one moves away from the pole face. Therefore, it was assumed that the effective range to the magnetic field can be no more than the height of the electromagnet, i.e., approximately 39 in. (1 m).

Sensitivity of Magnetic Methods to Defect Size. The sensitivity of a nondestructive test has been defined as the smallest defect that can be detected by the test method. A more practical definition of sensitivity is the smallest defect that can be detected without excessive false indications. A false indication is any recorded signal that is not caused by a bona fide or dangerous defect. The maximum number of false indications per unit length of track that one can expect is determined primarily by two factors: (1) the cost of missing a dangerous defect, and (2) the cost of dealing with false indications. These two basic costs can be subdivided into costs associated with the speed of inspection, labor, repairs, and the impact of in-service failures.

Electronic detection systems usually employ some type of nonlinear network to limit the number of false indications. Rail inspection systems use comparators that pass only those signal indications that exceed a preset threshold. By using the comparator, the number of signal variations attributed to instrument noise, small surface flaws and other spurious signal variations are reduced. However, signals from defects are observed at the output only when they exceed the threshold level of the comparator.

It is apparent that the threshold level controls the sensitivity of the inspection as well as the number of false indications. Lowering the threshold level to increase the sensitivity to defects results in a corresponding increase in the number of unwanted indications. Likewise, increasing the threshold decreases sensitivity to flaws and reduces the number of false indications. In most cases, there is an optimum threshold setting that results in a minimum error in terms of missing dangerous defects and the number of false indications. This optimum threshold depends on the rail conditions and a number of other factors. Statistical methods of determining this optimum threshold are discussed in several texts and articles(15) pertaining to the subjects of decision and detection theory.

The statistical method of determining the threshold level is often side-stepped since inspection conditions are variable and the essential data are difficult to obtain. Instead, operator experience and intuition play an important role in establishing the threshold. Therefore, if one is to determine the sensitivity of a rail inspection system, one must measure the threshold levels that are set in practice for each inspection system and track category encountered. The signal amplitudes can then be determined for a variety of defect types and sizes located in different parts of the rail and compared to the threshold level to determine the sensitivity.

Experimental and field data have not been available from the literature and have not been provided by the rail inspection service and equipment companies. Therefore, evaluation of the sensitivity of the magnetic inspection systems during this project was obtained primarily by calculations using available mathematical models. Since the relative threshold levels of the comparators used in the magnetic systems are not known, it was necessary to select a threshold based on calculated signals from hypothetical surface anomalies. Consequently, the sensitivities of the magnetic methods derived from these calculations are only approximate, and may deviate somewhat from the sensitivities obtained with actual rail inspection systems.

The magnetic methods are sensitive to some defects in the rail head but have poor sensitivity to defects in the lower portions of the rail. For example, it is a general consensus that the magnetic techniques are not suitable for detecting bolt hole cracks and defects in the base of the rail. Since contact is limited to the top surface of the rail, and penetration is reduced at high speeds, sensitivity to defects under the rail head is poor. Accessibility of flux sensors, e.g., coils, to the web and base of the rail is another major factor for poor sensitivity to defects in these areas.

The magnetic methods seem to be more sensitive to the transverse defects in the rail head, although vertical and horizontal splits can be detected by magnetic techniques, the transverse defects cause relatively abrupt perturbations in the magnetic field that are well suited for detection. Other reasons for greater sensitivity to transverse defects than to longitudinal defects are related to differences in sensitivity between the electric current methods and the magnetic flux leakage methods. These differences are delineated in the following discussion.

Defect Sensitivity of Magnetic Flux Leakage Methods. Analysis of the magnetic flux leakage methods has been conducted on earlier projects related to the inspection of steel pipe. Coils were placed near the inside surface of the magnetized steel pipe to detect defects on both the inside diameter and outside diameter of the pipe. The results of this analysis have been extended to the detection of internal and surface defects in rail. Similarity between the applied magnetic and residual magnetic methods allows use of these results in drawing conclusions about both techniques.

If the distance between the pole faces is relatively large, and the velocity of the magnetizing yoke is below some critical value, the induced currents are relatively small at a position midway between the magnetic poles. Detection of defects is primarily by the magnetic flux leakage over internal as well as external flaws that disrupt the longitudinal flux path.

Computer programs that model this basic magnetic flux leakage technique have been written during research programs conducted at Automation Industries.[15] These models were used to estimate the sensitivity of the applied magnetic technique disregarding the effects of induced currents. The relaxation method,[17] suitable for modeling on the digital computer, was used to calculate the field components above a rectangular steel plate containing various types of flaws. Figure 22 illustrates the types of defects that were modeled. The computer models are two-dimensional and account for variations in defect geometry only on the longitudinal and vertical directions. The transverse dimensions were assumed to be infinite. Therefore, the rectangular notches are extended across the entire width of the rail. Table 26 summarizes the results of applying the computer model to transverse defects, Defect dimensions are described in terms of the plate thickness, i.e., rail depth, so that data will apply to various sizes of rail.

It is apparent from examination of the signals from flaws listed in Table 26 that fairly large internal defects can go undetected by the magnetic flux leakage technique. For example, the 40-percent internal flaw Type 2, that is 0.001 T wide has a signal level that is less than the minimum surface defect, Type 1. If we assume that the defect signal must be greater than 5 percent to provide reliable detection, this fairly large transverse defect is not detectable.

The calculations illustrate that the sensitivity is highly dependent on the width of the defect. As the gap, D_x, separating the ferromagnetic boundaries of the defect becomes small, the magnitude of the leakage flux decreases proportionally. The smallest gap width evaluated in Table 26 is 0.001 T. If the rail is 1.5 inch (3.8 Cm) thick, then the gap width is 0.015 inch (0.038 cm). Transverse fissures in actual rail are likely to have even smaller gap widths and therefore are more difficult to detect.

Defect gap width is only of minor significance for techniques that utilize electric current flow to detect narrow cracks and fissures. Since the electrical resistivity of the fissure gap is several orders of magnitude greater than the resistivity of steel, the gap resistance is relatively large even for gaps as small as 0.0004 in. (0.001 cm). On the other hand, the magnetic permeability of air is only a few orders of magnitude less than the permeability of steel. Consequently, the reluctance of the narrow gap is low and has relatively little effect on the magnetic field.

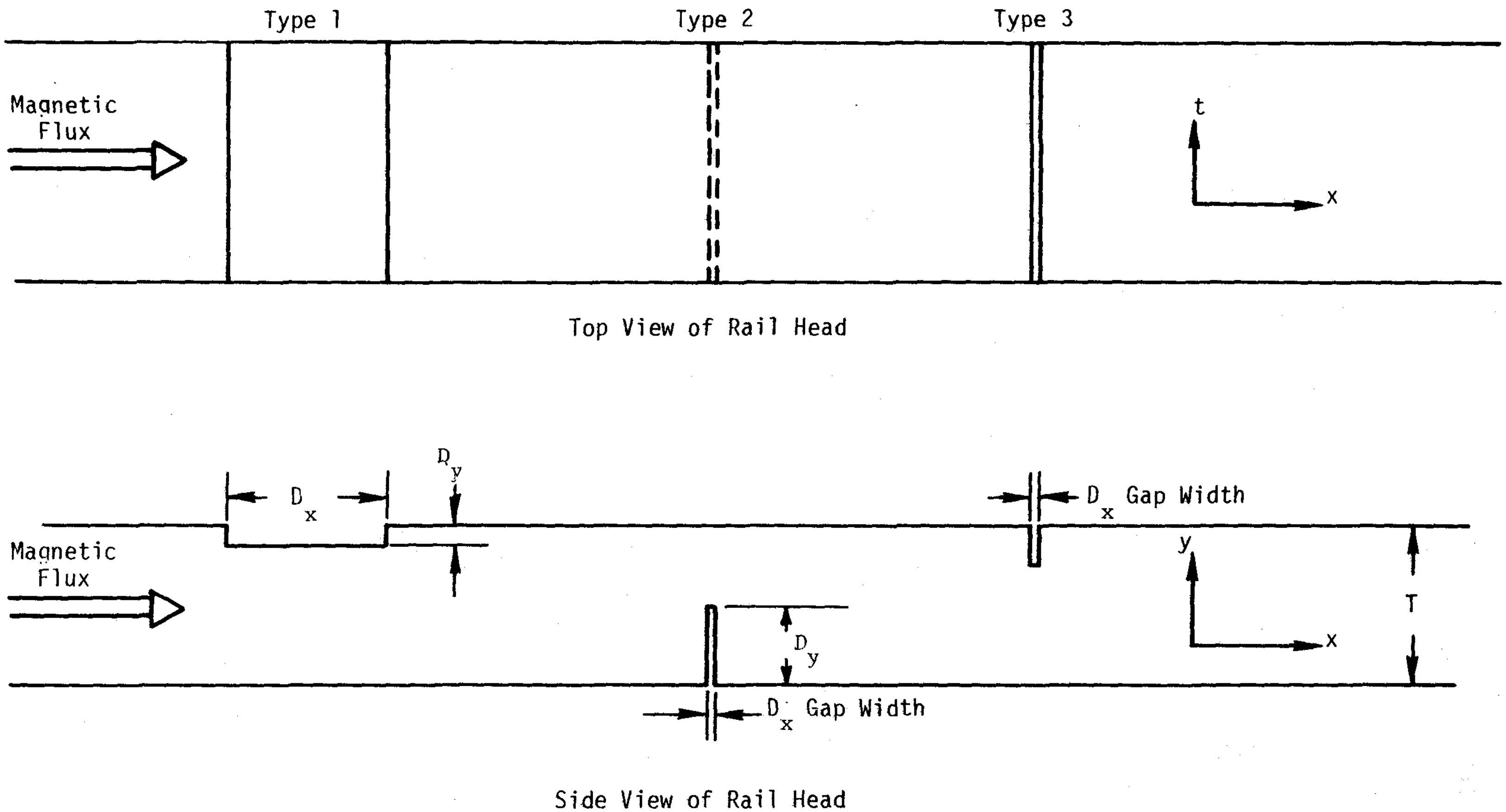


FIGURE 22. DEFECTS IN RECTANGULAR STEEL PLATE FOR MODELING THE MAGNETIC LEAKAGE FLUX TECHNIQUE

TABLE 26. COMPUTER CALCULATIONS OF MAGNETIC FLUX LEAKAGE NEAR HYPOTHETICAL RAIL DEFECTS

Defect Type	Longitudinal Dimension D_x	Vertical Dimension D_y	Area (Percent of Rail Cross Section)	Liftoff	Longitudinal Field Over Defect (Percent of Applied Field)
Type 1	0.9T	0.1T	10	0.2T	45
Type 1	0.9T	0.04T	4	0.2T	18
Type 1	0.9T	0.013T	1.3	0.2T	5.4
Type 2	0.1T	0.8T	80	0.25T	115
Type 2	0.01T	0.8T	80	0.25T	80
Type 2	0.001T	0.8T	80	0.25T	25
Type 2	0.1	0.4T	40	0.25T	23
Type 2	0.01	0.4T	40	0.25T	18
Type 2	0.001T	0.4T	40	0.25T	5
Type 3	0.1T	0.8T	80	0.25T	250
Type 3	0.01T	0.8T	80	0.25T	85
Type 3	0.001T	0.8T	80	0.25T	52
Type 3	0.1T	0.4T	40	0.25T	84
Type 3	0.001T	0.4T	40	0.25T	68
Type 3	0.001T	0.4T	40	0.25T	35
Type 3	0.1T	0.1T	10	0.25T	16
Type 3	0.01T	0.1T	10	0.25T	14
Type 3	0.001T	0.1T	10	0.25T	8
Type 4	0.9T	0.5T	50	0.25T	9.7

T = thickness or depth of rail head.

Type 4 defect is a hardened area on the rail head.

Table 27 gives the calculated values[10] of electrical resistance and magnetic reluctance for narrow defects in rails. These are compared to the calculated values of resistance and reluctance of the approximate shunt path around the defect in the steel rail. Note that the shunt path is longer than the gap width since the magnetic flux is diverted from longitudinal flow by the transverse defect. Comparison of the reluctance values of the defect gap with the reluctance of the shunt path in the steel gives an approximate value for the percentage of diverted flux. Likewise, comparison of the resistance of the gap with the resistance of shunt path gives the percentage of diverted current. Since the reluctance for the narrow gap is comparable to that of the shunt path, relatively little flux is diverted around the defect. However, the electrical resistance at the gap is at least 10^6 times greater than that at the shunt path. Practically all of the current is directed around the flaw and through the shunt path. This conclusion holds for extremely narrow gap widths even if they are filled with salt water.

Since the principles of the residual magnetic method are similar to the applied magnetic leakage flux technique, the detection of narrow fissures is also a problem with the residual method. Although there are some differences between the techniques, it is apparent that the width of the defect gap is a predominant factor in determining the intensity of magnetic field that fringe above transverse defects in steel rail. Based on these observations, it can be concluded that the electric current induction methods have superior sensitivity to transverse defects compared to the applied magnetic leakage and residual magnetic techniques.

Defect Sensitivity of the Electric Current Method. A paper written by V. A. Shcherbinina, V. V. Vlasov, and B. P. Dovnar[12] describes a mathematical model of the magnetic field caused by electric currents flowing around transverse defects on the rail head. This model describes a current of uniform density flowing within a rectangular cross section. Although the model was derived for evaluation of the effect of currents that are induced by T-shaped magnets, it is also applicable to the DCC method where the current flows in only one direction in the rail head.

TABLE 27. CALCULATIONS OF MAGNETIC RELUCTANCE AND ELECTRICAL RESISTANCE OF RAIL DEFECTS

Flux and Current Path	D_x (cm)	D_y (cm)	D_z (cm)	Magnetic Permeability μ (relative)	Reluctance Rel. (henry^{-1})	Electrical Resistivity ρ (μ-Ω-cm)	Resistance R (ohm)
Through Transverse	0.01	2	2	1	$(2.5)\cdot 10^{-3}$	10^{25}	$(2.5)\cdot 10^{22}$
Fissure, Air Filled	0.001	2	2	1	$(2.5)\cdot 10^{-4}$	10^{25}	$(2.5)\cdot 10^{22}$
Through Transverse	0.01	2	2	1	$(2.5)\cdot 10^{-3}$	25	67.5
Fissure, Water Filled	0.001	2	2	1	$(2.5)\cdot 10^{-4}$	25	67.5
Through Steel Shunt Path	4	2	2	2	$(5)\cdot 10^{-4}$	10^{-5}	10^{-5}

(2) Resistance - $R = \frac{\rho \ell}{A}$; Reluctance - $Rel = \frac{\ell}{\mu A}$

where ρ = resistivity

μ = magnetic permeability, relative

ℓ = path length, D_y

A = area D_y D_z

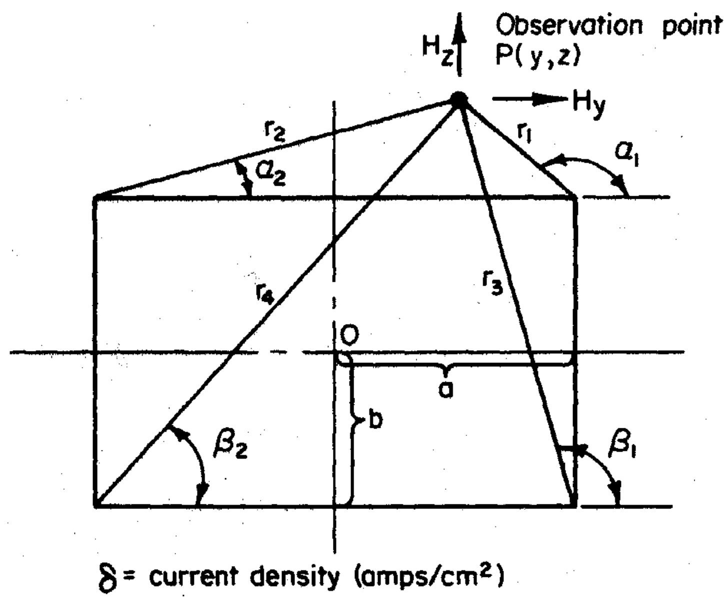
Application of the model initially requires calculating the magnetic field component at the desired position above the rail head for a defect-free section of rail. Next the magnitude of the field component for the corresponding location above a transverse flaw is calculated by dividing the current conducting portion of the rail head into rectangular pieces. The derived formulas are then used to calculate the contributions from each rectangular section.

Figure 23 illustrates calculations of the vertical, H_y, and horizontal, H_z, components of the field associated with a rectangular section. The total field is obtained by adding the contributions from each of the current carrying rectangular filaments. The detectable change in field components over a defect is obtained by taking the difference between the field calculated over a defect and the field calculated over a section that has no defects.

Table 28 lists the values of the vertical components of the magnetic field, H_z, for a defect-free rail head and for rail heads continuing various transverse defects at different alocations. For simplicity, the rail head and the defects were assumed to have a rectangular cross section and defects were located only on the right side of the rail. It was assumed that the total current remains constant, hence the current density in the rail adjacent to a defect increases as the size of the defect increases. In each case, the total field component, H_z, is the sum of the contributions from each rectangular component that carries current. The current density was assumed to be uniform for all current carrying portions of the rail head cross section.

Calculations for Case 2 indicate that 25 percent transverse defects that extend to the top surface of the rail will cause a sizeable decrease in the vertical component of magnetic field. Case 3 is representative of typical surface flaws such as engine burns, chips, and head checks. Case 4 represents minor surface variations that are not necessarily identifiable by visual examinations. These include small pits, shallow head checks, and surface variations due to cold working.

Cases 5 through 8 are calculations of the change in the magnetic field caused by subsurface transverse flaws. Internal flaws of this type



$$H_y = \frac{\delta}{2\pi}\left[(z+b)(\beta_1-\beta_2)-(z-b)(a_1-a_2)+(y+a)\ln\frac{r_4}{r_2}-(y-a)\ln\frac{r_3}{r_1}\right]$$

$$H_z = \frac{\delta}{2\pi}\left[(y+a)(\beta_2-a_2)+(z+b)\ln\frac{r_4}{r_3}-(z-b)\ln\frac{r_2}{r_1}-(y-a)(\beta_1-a_1)\right]$$

FIGURE 23. FORMULA FOR CALCULATING FIELD COMPONENTS AT A POINT ABOVE A SOLID CONDUCTOR OF RECTANGULAR CROSS SECTION

TABLE 28. CALCULATION OF MAGNETIC FIELDS FROM CURRENT FLOW IN RAILS CONTAINING DEFECTS

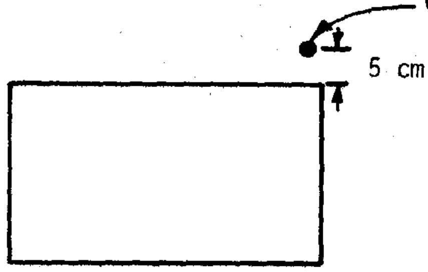
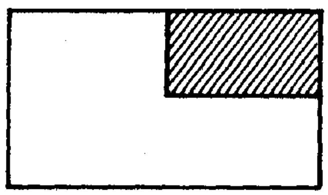
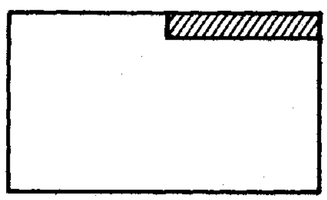
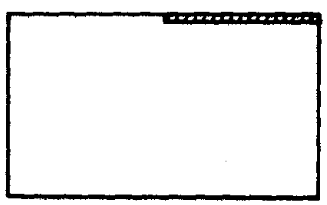
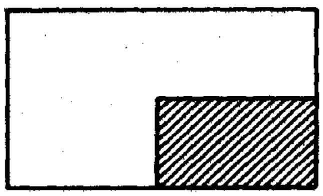
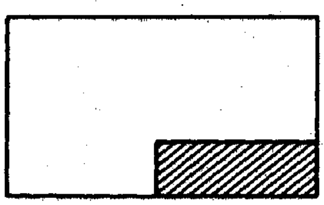
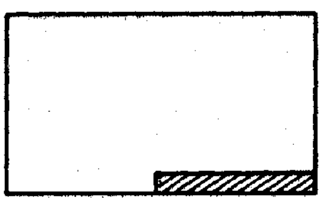
Case	Approximation of Rail Head Cross Section	Defect Size, percent of Rail head Cross Section	Current Density, amp/cm^2	Vertical Field, Hz (oersteds)	Change in Field, Hz (oersteds)
1		0	100	78.72	0
2		25	133.32	61.42	-17.3
3		5.7	106.66	75.42	- 3.3
4		0.57	100.63	77.61	- 1.11

TABLE 28. (Continued)

Case	Approximation of Rail Head Cross Section	Defect Size, percent	Current Density, amp/cm^2	Vertical Field, Hz (oersteds)	Change in Field, Hz (oersteds)
5		25	133.32	89.66	10.94
6		15	117.64	85.89	7.17
7		5	105.26	81.01	2.29
8		1	101.01	79.20	0.48

cause an increase in the vertical component of magnetic field above the defect. Comparing the calculations of Cases 7 and 4, flaws as small as 5 percent of the cross section can be detected with automatic discrimination against minor surface flaws. Detection of internal flaws on the order of 1 percent would require refinements such as the incorporation of a surface detection system for automatic discrimination against the minor surface flaws.

Other Factors Affecting Defect Sensitivity. Variations in defect location and variations in the magnitude of noise signals will change the effective sensitivity of the magnetic inspection methods. The analysis of the electric current and magnetic methods have revealed significant variations in sensitivity with defect location. In general, defects that increase the top and sides of the rail head provide greater signal indications that defects that lie under the surface of the rail head. This is particularly true of the magnetic flux leakage methods where the overlying rail steel tends to bypass the otherwise fringing magnetic field that yields smaller signal responses in comparison to surface defects.

Other major factors that affect the sensitivity of the magnetic methods are track features that distort the flux path or current flow. Bolted joints are particularly troublesome to the magnetic methods, since current and magnetic flux are diverted laterally through the angle bars and signal joints are particularly troublesome to the magnetic methods, since current and magnetic flux are diverted laterally through the angle bars and signal wires that connect the rail sections. Also, the gap between the rail section ends acts effectively as a large defect and provides a correspondingly large signal indication. Small defects near the end are masked by the joint gap signal. Based primarily on information from field surveys, the RM method can sometimes detect defects that are on the order of 15 percent of the rail head cross section as close as 2 inches (5 cm) from the joint gap. Experienced rail inspection personnel indicate that the DCC method can sometimes detect similar defects as close as 4 inches (10 cm) from the joint gap. If the joint is insulated, then the DCC method cannot inspect any closer than d, the distance between the electrical contacts.

Surface anomalies such as engine wheel burns, shells, slivers, head checks, corrugations, and weld repairs constitute another important class of unharmful flaws that cause false indications and mask indications from dangerous defects. Small surface anomalies that cannot be identified by visual examination establish the threshold of the comparators. This in turn limits the size of dangerous defect (e.g., transverse fissure) that can be detected. Transverse defects under larger surface flaws are difficult, if not impossible, to detect by existing magnetic systems. These problems are accentuated at higher inspection speeds.

An Advanced Magnetic Inspection System. A potential method for high-speed inspection of rails involves the incorporation of a surface-sensitive eddy-current detector with magnetic and ultrasonic inspection systems. Figure 24 illustrates the concepts of a combined magnetic and eddy-current technique. As illustrated, the magnetic system is sensitive to most types of dangerous defects but is also sensitive to the relatively harmless surface anomalies. The eddy-current device operating at frequencies on the order of 2,000 Hz is primarily sensitive to the surface defects and for all practical purposes is insensitive to internal flaws. Skin effect limits the penetration depth of the eddy-currents so that only surface cracks cause a significant signal to be produced. Eddy-current systems can be designed to provide a signal response that is proportional to the depth of the surface flaw up to a certain maximum depth, e.g., 1/4 inch (6.4 mm). There is little increase in signal output for surface flaws deepter than this maximum depth.

A simple concept for processing and combining the signals involves sensing the maximum amplitude of the signal from both types of sensors. For example, the maximum signal from the magnetic sensor can be the absolute difference between the positive peak and negative peak. The signals from the eddy-current sensor might be the absolute value of the signal voltage at the point where the peak occurs. Subtracting the maximum value of the eddy-current signal from the maximum value of the magnetic signal is accomplished by a simple network. This result is represented in the hypothetical output illustrated at the bottom of Figure 24.

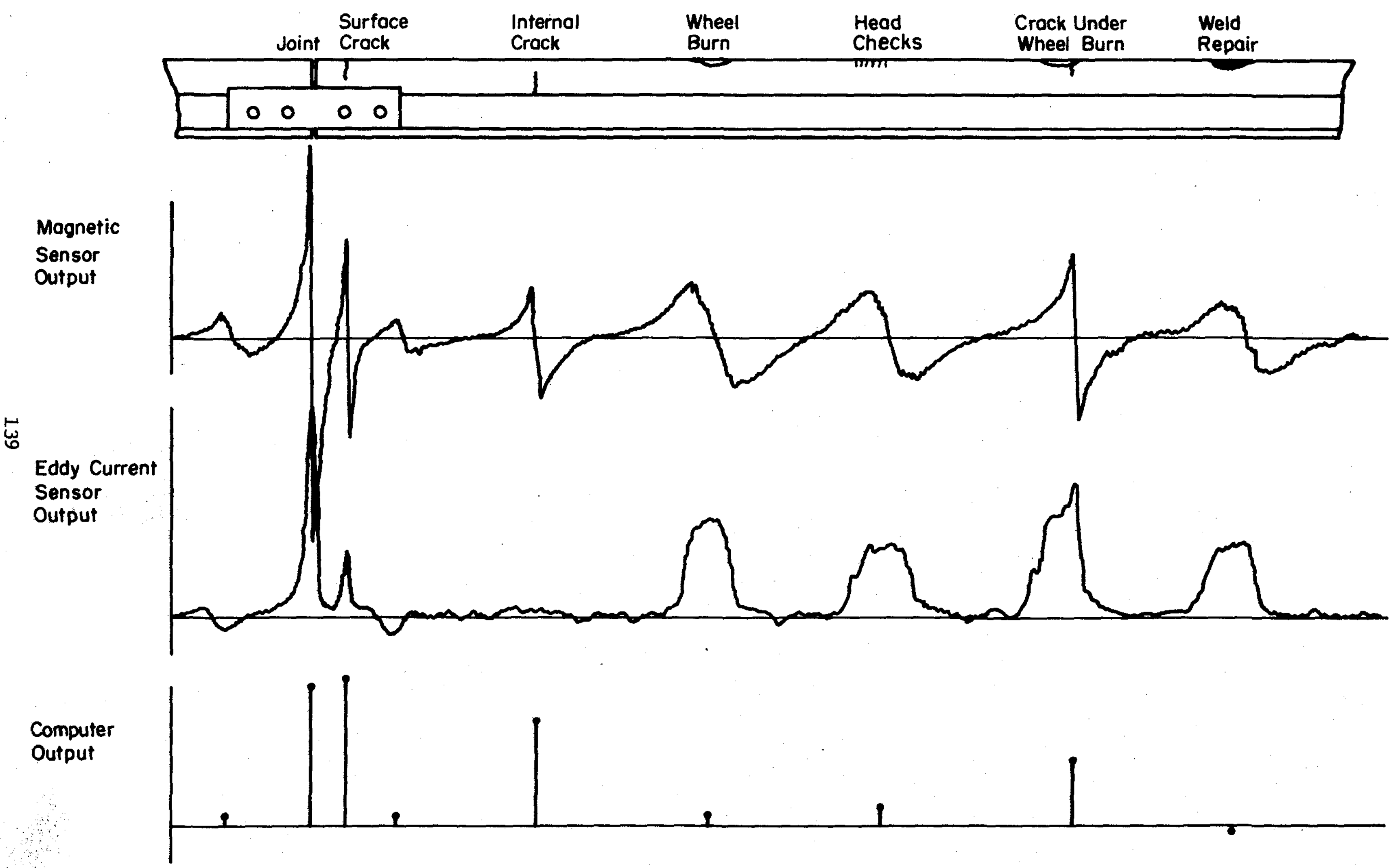


FIGURE 24. IMPROVED DETECTION OF RAIL DEFECTS BY COMBINED MAGNETIC AND EDDY-CURRENT SENSORS

Signals caused by surface flaws would result in a minor indication in the computed output. Signals caused by transverse cracks of appreciable depth cause a significant output even in cases where the crack is under an engine burn or other surface anomaly. Automatic marking of the rail and simultaneous recording of the defect location on the chart would occur only when the defect signal exceeds a preselected threshold. Extensions of this technique might also be employed to provide high-speed inspection of the rail close to the rail joints.

The combination of the eddy-current surface inspection with the conventional magnetic detector had advantages over other discrimination techniques, since the magnetic sensor and eddy-current sensors can be superimposed. In fact, if coils are used as flux sensors, each coil will provide a simultaneous indication of magnetic and eddy-current response. Therefore, problems with synchronizing responses for subsequent signal processing are removed. For example, it has been possible to obtain four separate readouts associated with four excitation frequencies using one inspection coil in multifrequency eddy-current testing. Improvement in sensitivity obtained by combining these signals has been as great as 50 to 1.

Multifrequency or single-frequency eddy-current sensors can also be incorporated with ultrasonic inspection of rail. Eddy-current coils located at strategic locations with respect to the ultrasonic transducers would provide indications of the precise locations of surface anomalies.

Item 4 - Analysis of Data Processing System

System Functions

The function of the rail defect data processing system is to augment or possibly replace the operator in the analysis of the transducer data and in providing the necessary administrative materials to facilitate the changing of defective rails. As a minimum system, the data processing system should remove from the operator the burden of analyzing many miles of normal rail. The maximum capability would be one of complete automation in which the operator only serves as a monitor of the system.

The purpose of this discussion is to delineate the important factors bearing upon the design of such a system and to carry the design to a sufficient degree to bring a focus on the details affecting the cost and performance of the system. Any design beyond the bare preliminary at this point cannot be considered pertinent due to the many variables that would have to be defined in such a study which is considered beyond the scope of the present contract.

There are two basic problems facing the designer of any data processing system: the nature of the tasks that must be performed by the system and the time frame during which they must be performed. In this case, both tasks are quite formidable. The nature of the processing load is, in general:

> acquire data from the transducer system
> decide whether the data represents normal rail
> if the data are not normal, determine if a flaw of a given size and type is present, and if present
> take appropriate action if either a flaw of interest is discovered or a "not normal" but undefined situation occurs.

The entire processing must be done in real-time as a function of the speed of the inspection car. It is possible, however, to split the load between real time and semi-real time processing in this situation by performing the first two tasks in real time synchronized to the speed of the car and performing the remaining two tasks in quasi-real time subject to the constraint of the rate at which flaws occur.

The quality of the data processing lies in the ability of the system first to make the decisions listed above and secondly in the ability to make the decisions in a timely manner. It is this decision-making capability that lies at the heart of the entire system.

A short literature search was made at the beginning of this task in order to obtain the benefit of experience of other researchers with respect to computer automated nondestructive testing. A search of the last 3 years of Materials Evaluation[19] revealed that most of the effort in computer automated systems has been expended in utilizing the effects of acoustic emissions. Only one article[20] was found which described a real time testing system using ultrasonic transducers but the time frame was significantly less than the speeds sought with this system. In addition to the very much reduced time frame, the system used a very simple transducer system not usable with this system, thus also making the decision-making process not relevant to this project. The conclusion reached as a result of this limited search is that there is no directly usable base of experience for the design of this system.

When one analyzes the methodology of the decision-making process used by operators of presently used rail flaw inspection systems, one finds that the process of pattern recognition is the dominant method. The operator recognizes bolt holes and rail ends as a pattern in the output traces and flaws show up as deviations in the pattern. Pattern recognition as a process is one of the fortes of the human mind but is an awkward and time consuming process when performed by a computer. The implications of this statement is that the decision-making process should not be based on pattern recognition but on logical tests based on discrete transducer system outputs. This will require an innovative transducer system design in order to make the system reliable. A complete design of the transducer system is considered outside of the scope of the present contract, thereby making the design of the data processing system more troublesome due to the lack of input definition. Only a general approach will be considered which should serve as a guide to a more complete design.

Overall System Definition

An overall simplified system definition can best be described utilizing the flow chart shown in Figure 25, which represents the entire rail flaw data processing system. The decision step in Block 1 represents the sampling function performed on the transducer system output as a function of the speed of the car. After the elapsed time, the transducer data are gathered and stored as shown in Block 2. In Decision Step 3, a comparison is made between the data just gathered and data considered normal for the transducer.

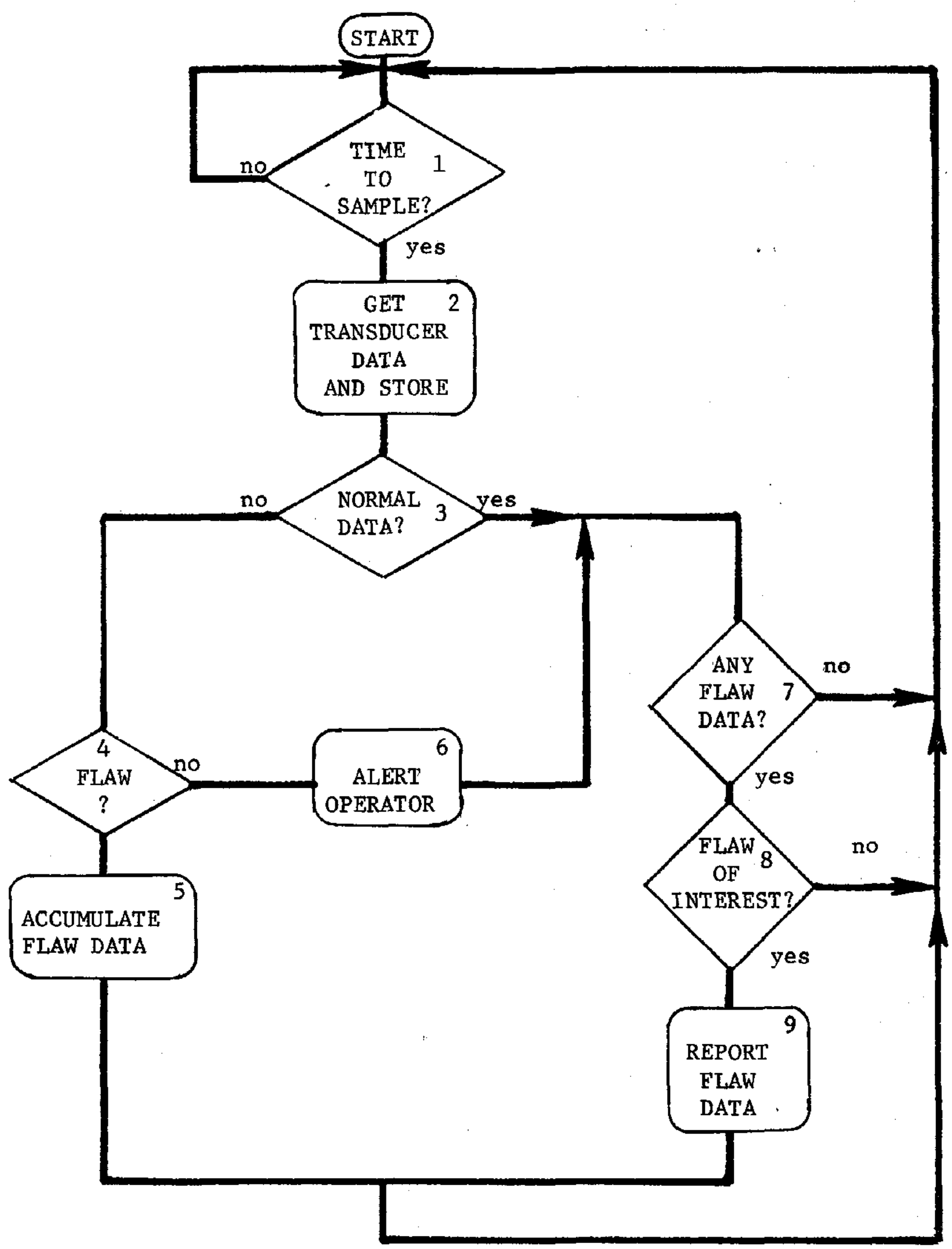


FIGURE 25. OVERALL DATA PROCESSING SYSTEM FLOW CHART

If the data are normal, then the system can be considered to be in one of two states: either the system has been tracking a flaw and this signals the end of the flaw, or previous data have also been normal to this point. The Decision Step in Block 7 distinguishes between these two cases. If previous data have also been normal, the system remains in an idle state until it is time to gather the next set from the transducer system. If, on the other hand, the system must decide whether the flaw is of sufficient size or type to warrant reporting, then this decision is made in Block 8. Assuming the flaw is of sufficient size to report, the system notifies the operator in Block 9; otherwise, the system disregards the flaw and idles until it is time to sample the transducer data again.

In the event the transducer data were not normal in Decision Step 3, the next issue to be decided is whether the data are not characteristic of a flaw, the unknown condition is reported to the operator in Block 6. Otherwise the system accumulates the data in Block 5 and awaits the end of the flaw before reporting it.

For normal rail without flaws, the system would spend its time in the loop represented by Blocks 1, 2, 3, and 7.

At this point, it seems appropriate to discuss the handling of intentional man-made "flaws" such as bolt holes and rail ends. Early in the design of the system, it was recognized that the method used by the operator of rail flaw equipment to detect rail ends and bolt holes by means of pattern recognition would be difficult for this system. This method was ruled out due to the awkwardness and time consuming nature of a computer program required to perform this task. Therefore, some effort was expended in considering the feasibility of programming a separate subsystem of the transducer system which has the sole purpose of detecting rail ends. Such a subsystem is considered feasible, and one such transducer arrangement for this purpose is shown in Figure 26. This arrangement of the transducer would produce the simple pattern of a sharp return at bolt hole height immediately followed by a corner reflection at the bottom of the rail end. This pattern would be expected to occur only at a rail end. This knowledge (that the system is in the vicinity of a rail end without requiring the system to first suspect and then confirm it)

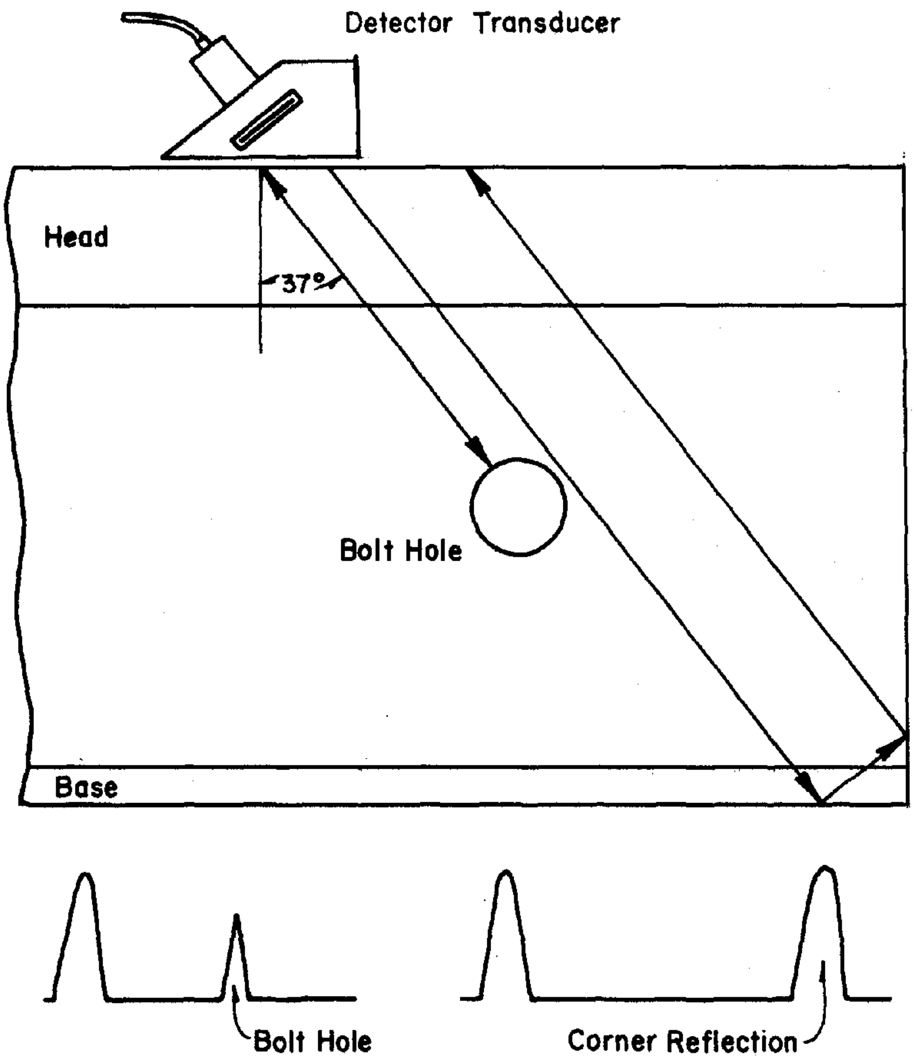


FIGURE 26. RAIL END DETECTOR TRANSDUCER

greatly simplifies the logic and decreases the time required to analyze the transducer data from the actual rail end. The output of this subsystem can be used in the transducer system directly to manipulate the transducer data; or, it could be included with the data and used by the software to distinguish bolt holes and rail ends from real flaws of interest. In either event, the system will be able to recognize bolt holes and rail ends.

The nature of the decision making processes in Blocks 3, 4, and 8 of Figure 25 were examined in sufficient detail to gain some insight into the difficulties that can be expected. For each transducer channel, there is a normal condition that is represented by either the presence of an echo at the proper depth or distance or the absence of an echo. To speed up the decision at Step 3, each of the gate returns could be compared with a given amplitude and the output represented as either a "yes" or "no". If all of the gates are represented by a series of bits in a single computer word, the test can be made in a single instruction.

The normal data decision allows for two possibilities: normal data or abnormal data. If the decision is abnormal data, it does not follow that a flaw has been found. If a transducer expects a through transmitted signal within a certain gate and none appears, there are at least two possibilities to account for the loss of signal: equipment failure such as loss of coupling could account for the loss, or a flaw could be blocking the transmission of the signal. Further checking of this abnormal data condition would be required to confirm the presence or absence of a flaw, and if present, to identify its characteristics. These checks might include evaluating the data obtained from other transducers which inspect the same part of the rail, visual observations by the operator, and ultimately possibly making a hand check of the rail.

The decision to be made in Block 8 attempts to determine if the reported flaw is of sufficient size to warrant attention. In the case of longitudinal flaws, this could be determined by simply counting the number of finite length steps for which the data were accumulated, and then comparing it with a length of interest. For the more vertically aligned flaws, this method is not directly applicable, and it is envisioned that the amplitude of the pulse possibly combined with longitudinal distance information can be correlated with the size of interest. The use of amplitude for this purpose would require very careful control of the alignment of the transmitter and receiver; otherwise serious distortions of the amplitude can result.

In order to obtain the maximum throughput, the tasks indicated in the flow chart can be broken down into subtasks. An advantage in making this division is in defining the minimum amount of effort which must be performed in real time synchronized to the train speed. The results of this division of effort are shown in Figures 27 and 28.

The logic shown in Figure 27 can be considered the data acquisition task and could be delegated to a microprocessor for maximum throughput. The speed of the system would be limited by the processor time required to execute the flow chart. It is also important to realize that the process shown in Figure 27 cannot be easily subdivided further to obtain more speed using software programmed digital logic because it represents the minimum amount of coordinated effort required. Instead, the processing time can only be decreased by a more efficient transducer data format generated with hardwired logic which would simplify the effort required to execute the flow chart shown in Figure 27, thereby decreasing the execution time. If delegated to a microprocessor, the data acquisition module would converse with the central processor only when it had data to report.

Figure 28 represents the workload required of the central processor which further analyzes the flaw data reported by individual subprocessors. The relationship between the tasks shown in Figures 27 and 28 can be visualized as one in which the data acquisition module removes the burden of looking at normal data from the central processor.

Timing Considerations

The entire system including the transducer system can be considered a sampled data system. The first sampling is performed using the transducers based on a pulse repetition rate which is envisioned to vary with the speed of the inspection car. Pulse repetition rates on the order of 500-15,000 pulses per second and upward with a pulse width on the order of 2 μsec

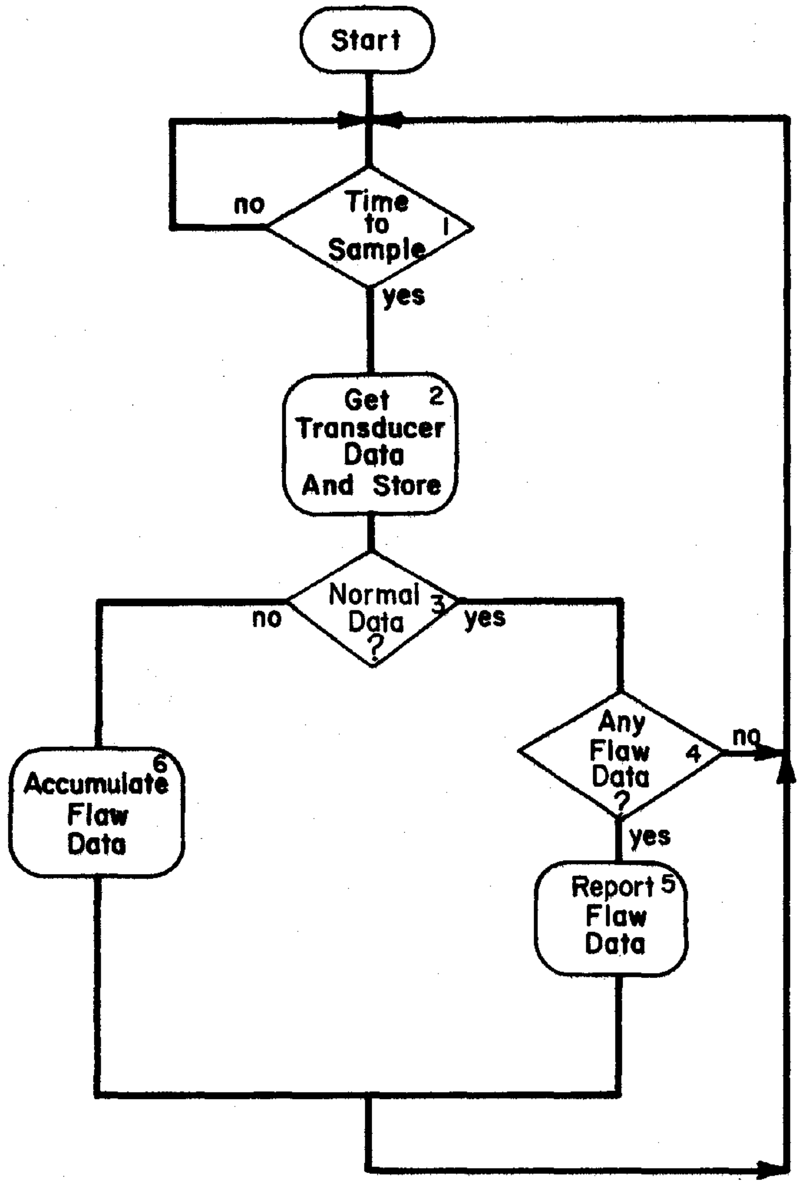


FIGURE 27. FLOW CHART FOR DATA ACQUISITION MODULE

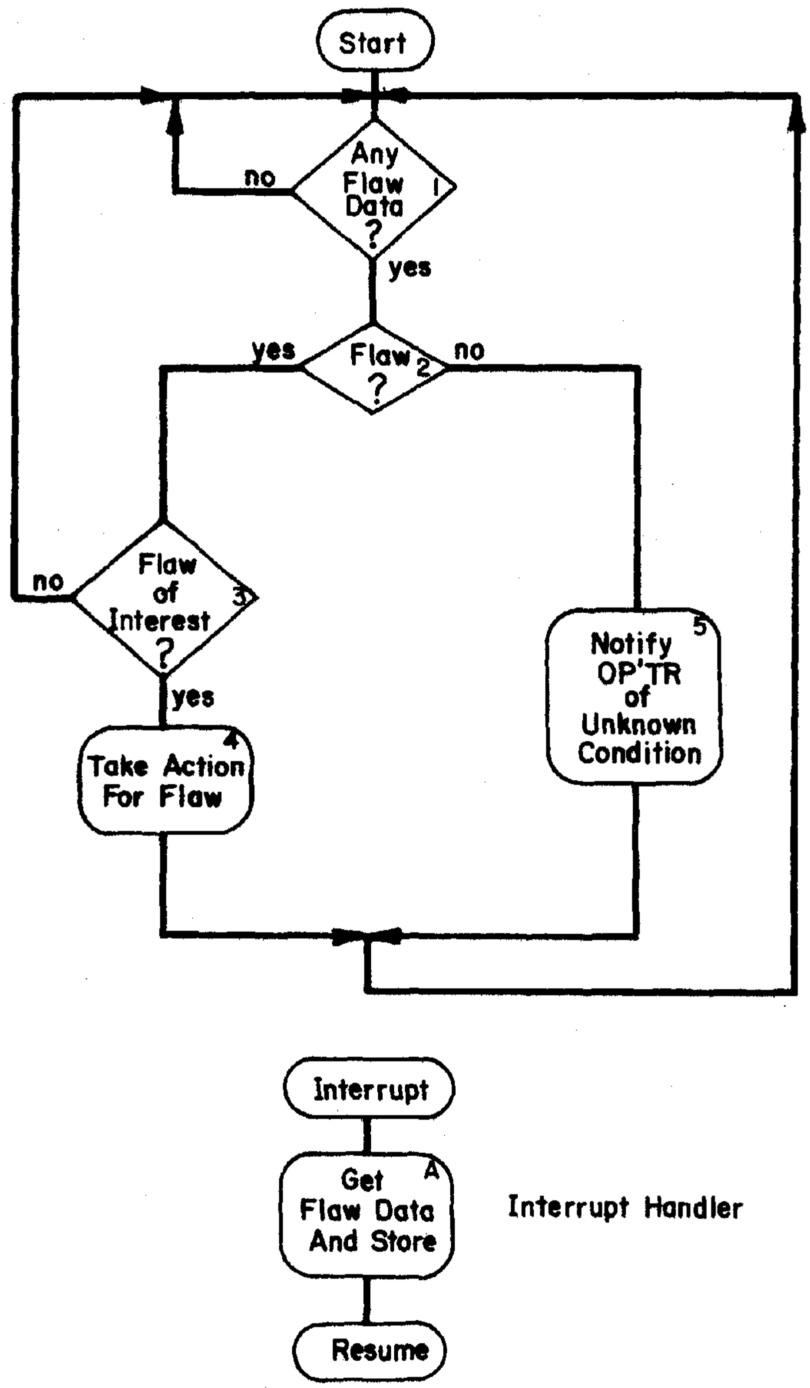


FIGURE 28. FLOW CHART FOR CENTRAL PROCESSOR

can be expected. Direct digital sampling of the pulses is considered impractical due to the high rates which would be required. For example, if each pulse is sampled five times, a sample period of 400 ns would be required. This is too small to be practical.

In order to increase the sample period, a hard wired conditioning network could be used which would summarize or condense the information from several pulses. This network could take the form of a gating and filtering circuit or perhaps a gating and integration network. In either event, the net effect upon the data processing system is that it reduces the effort of sampling each and every pulse to one of sampling the summing or condensing network at some multiple of pulses. The determination of which multiple to use is a function of the resolution desired in the system.

For example, if the minimum resolution desired is 1/4 in. (6.4 mm) for a longitudinal flaw, the network would have to be sampled for an accumulation of data representing 1/4 in. (6.4 mm) of rail travel. If the network was sampled every inch (2.5 cm) instead, the system would be unable to identify flaw length to an accuracy of less than one inch (2.5 cm). In this regard, it is important to realize that the pulse conditioning network does not simply store the information, but instead condenses it.

Utilization of this type of network makes the sampling a function of the rail distance traveled. The effect of train speed and sampling period for varying distances between samples is shown in Figure 29. At a top speed of 50 mph (80 Km/hr) with sampling sufficient to define the flaw length to the nearest 1/4 in. (6.4 mm) the sampling period is 284 μsec. At 20 mph (32 Km/hr) with the same resolution, the period is increased to 710 μsec.

The effect of sampling periods of these lengths is not apparent until one considers the speed at which computers operate. Present day minicomputers typically execute instructions which reference memory on the order of 2 μsec. The transfer of input and output information using direct memory access (DMA) for small amounts of data takes approximately 30 - 50 μsec. Assuming 100 μsec are consumed in handling input/output operations, the program can execute approximately 90 machine language instructions only in performing the noninput/output tasks in Figure 28 at 50 mph (80 Km/hr) and 1/4 in. (6.4 mm) sampling.

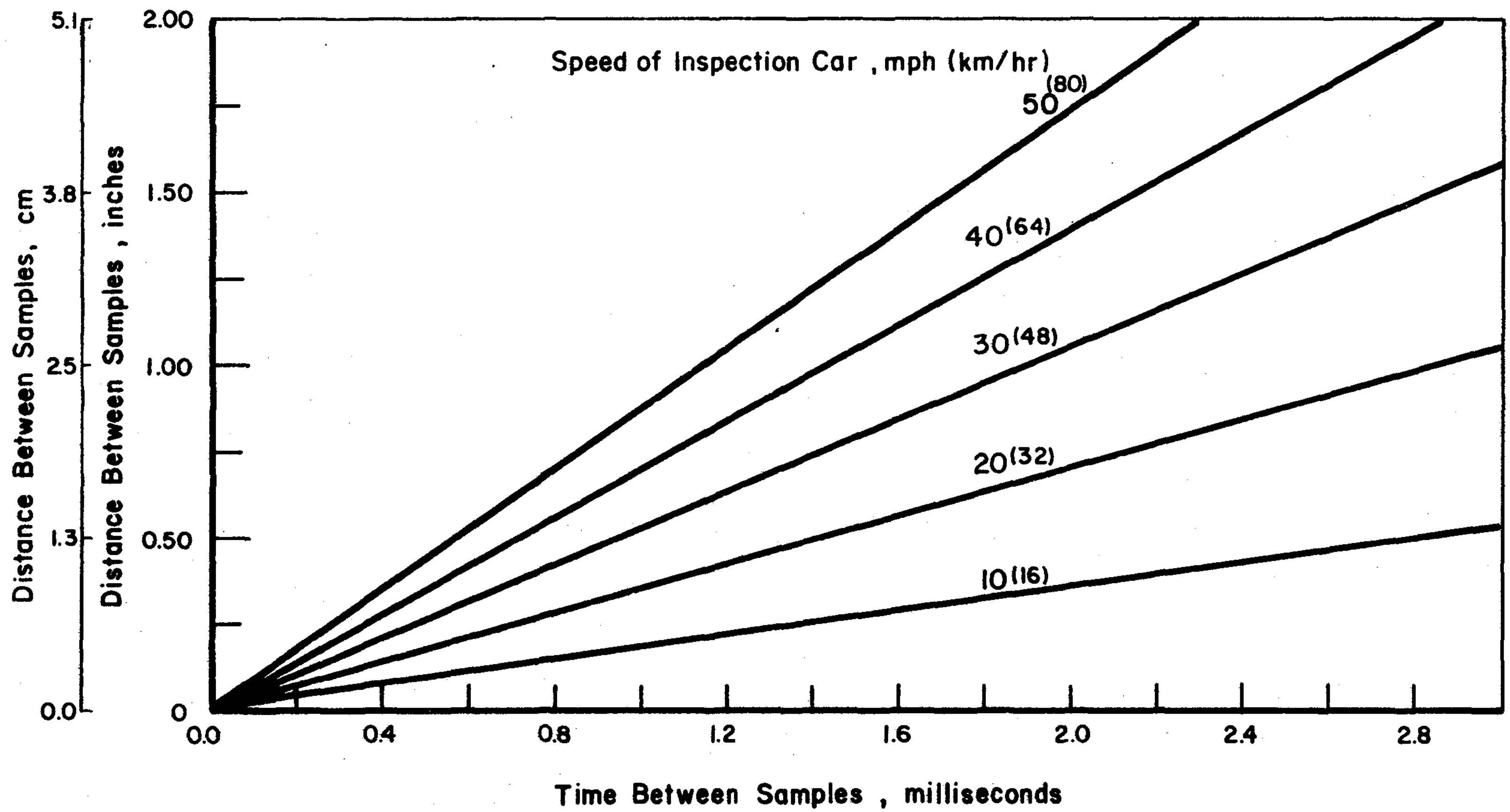


FIGURE 29. RELATIONSHIP BETWEEN TIME, DISTANCE, AND SPEED OF THE INSPECTION CAR

The separation of the tasks in Figures 27 and 28 permits the central processor to operate on an interrupt basis which can be interpreted physically to mean a data collection on a flaws-per-time basis. This operation frame permits the central processor to spend considerable time on each flaw without being burdened with the real time data acquisition task which is being performed by the data acquisition module. To establish a time frame for analyzing the data for flaws of interest, it is considered appropriate to consider the time the system spends traversing a 39-ft (12 m) rail at varying speeds. This information is presented in Figure 30. These times are much less restrictive than those which must be met in the data acquisition module.

The maximum throughput system, therefore, basically is one of operating a real time data acquisition module synchronized to the speed of the car taking data on a samples-per-inch basis, collecting flaw data, and reporting a single flaw to the central processor on an interrupt scheme. The main processor then collects the flaw data, analyzes it to determine if it is of sufficient size and type to merit attention and then reports it. The data acquisition module represents a synchronous subsystem whereas the main processor operates asynchronously.

One further timing difficulty lies in correlating outputs from various transducers which may be mounted to take data which represent different areas of the rail. Various schemes could be used to make the system independent of transducer location. A shift register or data storage could be utilized to provide the displacements in time. In the system described on the preceding pages, the task of proper alignment of data is delegated to the central processor.

Hardware Characteristics of the System

The purpose of this section is to outline the combinations of hardware which could be used to realize the general logic outlined in the flow chart shown in Figure 25. The input to the data processing system comes from the output section of the transducer system. This system

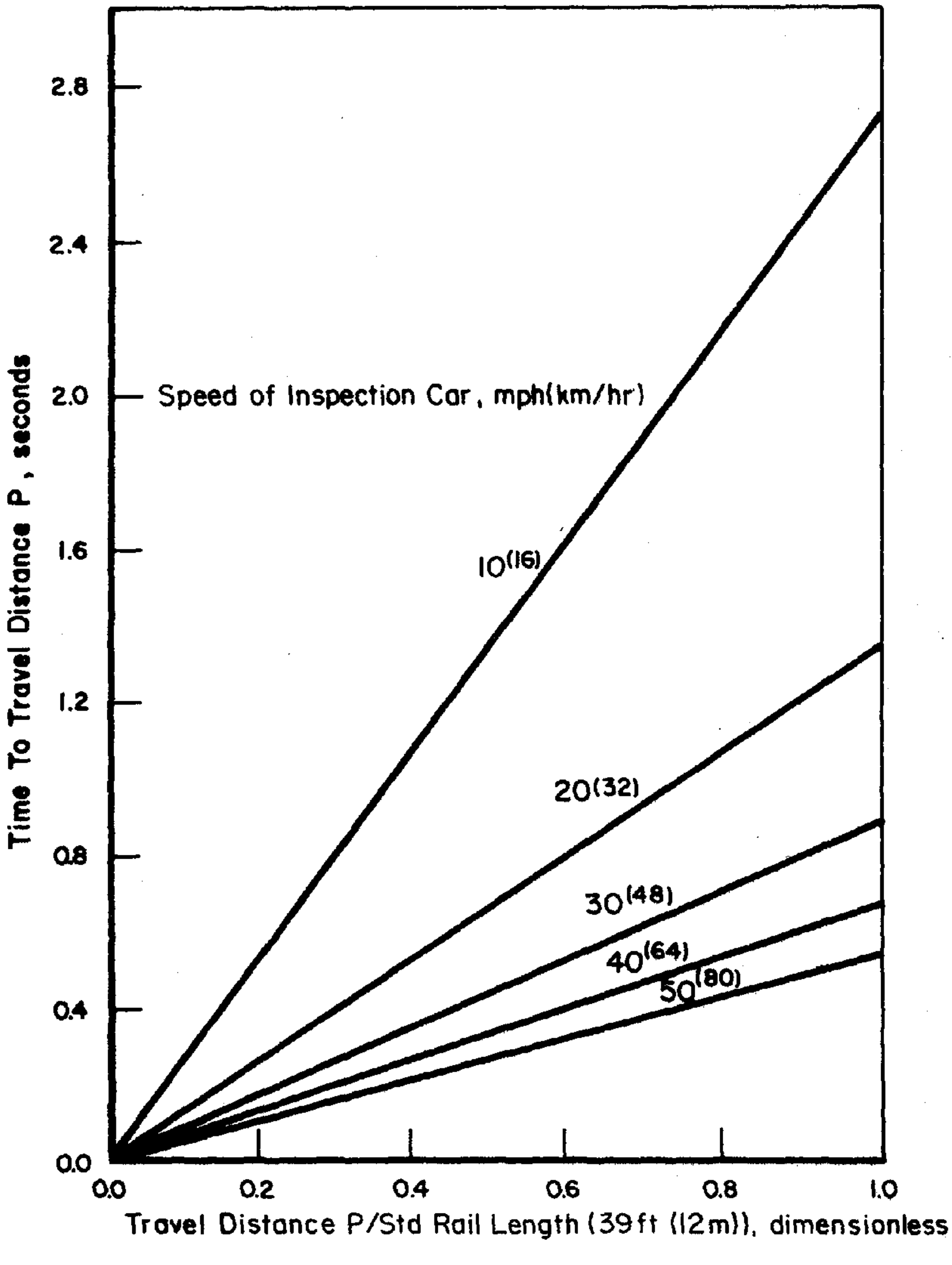


FIGURE 30. TIME TO TRAVERSE A 39-FOOT (12m) RAIL

is envisioned as being a series of ultrasonic transducers each of which is connected to a gating and conditioning network. The network terminates with a digital interface which transforms the data into a form readily accepted by a digital computer. Specific components of the conditioning network would probably be:

> a gating network which divides the pulse time into discrete increments
> a condensing filtering and/or integrating network which summarizes the gate output over some multiple of pulses
> a comparator network which results in a "yes/no" decision for the returning pulse with each gate
> a digital interface which will compact and convert to digital form the output of the comparator circuit, and
> an analog-to-digital converter for converting the pulse amplitude in each gate.

Signal development throughout the transducer system is shown in Figures 31 and 32. The basic measurement mechanism consists of sending a pulse of ultrasonic energy into the rail and "listening" for a return echo. The time periods for which it is possible for a returning echo to appear represent physical lengths into the rail and these periods are represented as gates in Figure 31. The gating network performs the task of dividing the returning pulse into discrete time period gates. The output of each of the gates is then put into a summarizing circuit (possibly a filter or integrator) which makes the variance in output for a particular gate a function of how fast the transducer is passing over a given flaw, rather than a function of the pulse repetition rate. This situation is portrayed in Figure 32 where five pulses representing a 1/4-in. (6.4 mm) rail travel are shown. The output for this transducer would be a representation of the signal over the five pulses for each of the gates i_1 through i_5.

For ease in decision making, a comparator circuit could compare each of the five gates with the amplitude expected and form a "yes/no"

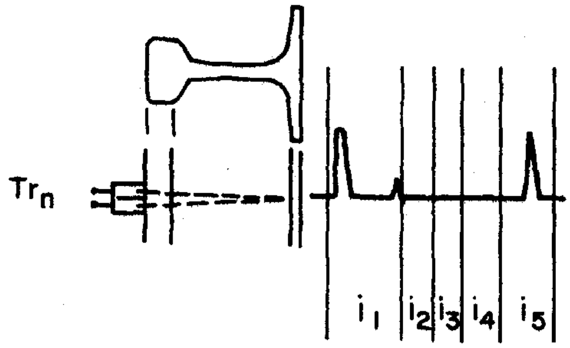


FIGURE 31. SCHEMATIC DRAWING OF GATED PULSE

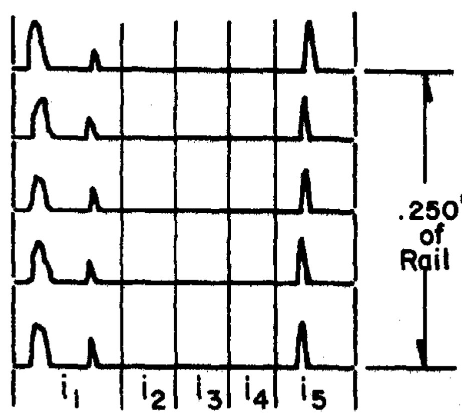


FIGURE 32. SCHEMATIC DRAWING OF GATE OUTPUTS

type response which reflects whether the pulse amplitude was greater than the preset comparator level. An analog-to-digital converter acquires the amplitude in digital form for use in later analysis by the central processor.

The output product of the transducer system, therefore, is a series of digital words which reflect the gate outputs based on "yes/no" decisions and the individual pulse amplitudes. Collectively they represent an n-component vector where n is the number of words. The exact form of the vector has not yet been determined but the essential characteristic is that it would be only a few words for each transducer. It is envisioned that the "yes/no" information would be compacted into one word and be used for the normal data decision shown as Decision Step 3 in Figure 25. A possible vector may take the form of:

word 1	length of vector
word 2	"yes/no" bits for each transducer gate
word 3	amplitude for gate 1
word 4	amplitude for gate 2
.	.
.	.
word n	amplitude for gate n.

The number of gates for a given transducer is expected to vary between 1 and 5, and the number of transducers may vary between 7 and 20 per rail.

Given this input, there are two possible extremes which can be realized in computer hardware to acquire and analyze the information in the manner shown in Figure 25. The first system would be one that uses one central processor which acquires and analyzes all of the data from each and every transducer. To realize the effect of using a system of this type, assume that a program of 2000 machine language instructions (a conservative estimate) would be required to acquire and process the data. A 2 μsec execution speed would require a processing time of 4 msec. This period corresponds to a car speed on the order of 3 mph (5 Km/hr) for sampling each 1/4 in. (6.4 mm) of rail. This extreme is obviously impractical.

To achieve the maximum throughput, the logic illustrated in Figures 27 and 28 could be employed which uses a microcomputer on each transducer to collect the transducer data. This microcomputer also stores any detected abnormal data and at the end of the suspected flaw passes the entire data set to the central processor. This scheme is illustrated in Figure 33 which represents a functional block diagram of the microprocessor channel for each transducer.

Timing estimates for the maximum throughput system are as follows:

service interrupt to collect data	10 μsec
get and store data from transducer	50 μsec
manage memory buffer	20 μsec
run algorithm in Figure 26	40 μsec
post interrupt to central	20 μsec
	140 μsec

This estimate assumes a 1 μsec memory cycle time or 2 μsec for a memory reference instruction. From these estimates, it can be stated that the system should operate up to 50 mph (80 Km/hr) using 1/4 in. (6.4 mm) sampling. Other possibilities of configurations include multiplexing the transducer data using only one analog-to-digital conversion and using one microcomputer to service two or more transducers. Each of these configurations would lower the system performance.

A maximum throughput design would utilize one microprocessor or microcomputer on each transducer for a total on the order of 14 for a minimum system or about 40 for a maximum system (both rails) for the entire system. It would greatly simplify the programming effort (and hardware problems) if the software and hardware for each of the transducer channels could employ the same program. This is deemed to be feasible by employing hardware for each transducer to initialize the programs. This mechanism is shown in Figure 33 as the control and configuration panel. Using this hardware, the operator would employ thumbwheel registers or other devices to indicate the time delay due to transducer mounting, the number of gates, the normal comparator word output, and any other functions deemed appropriate. Normally this information would be written into the software, thus making each program slightly different.

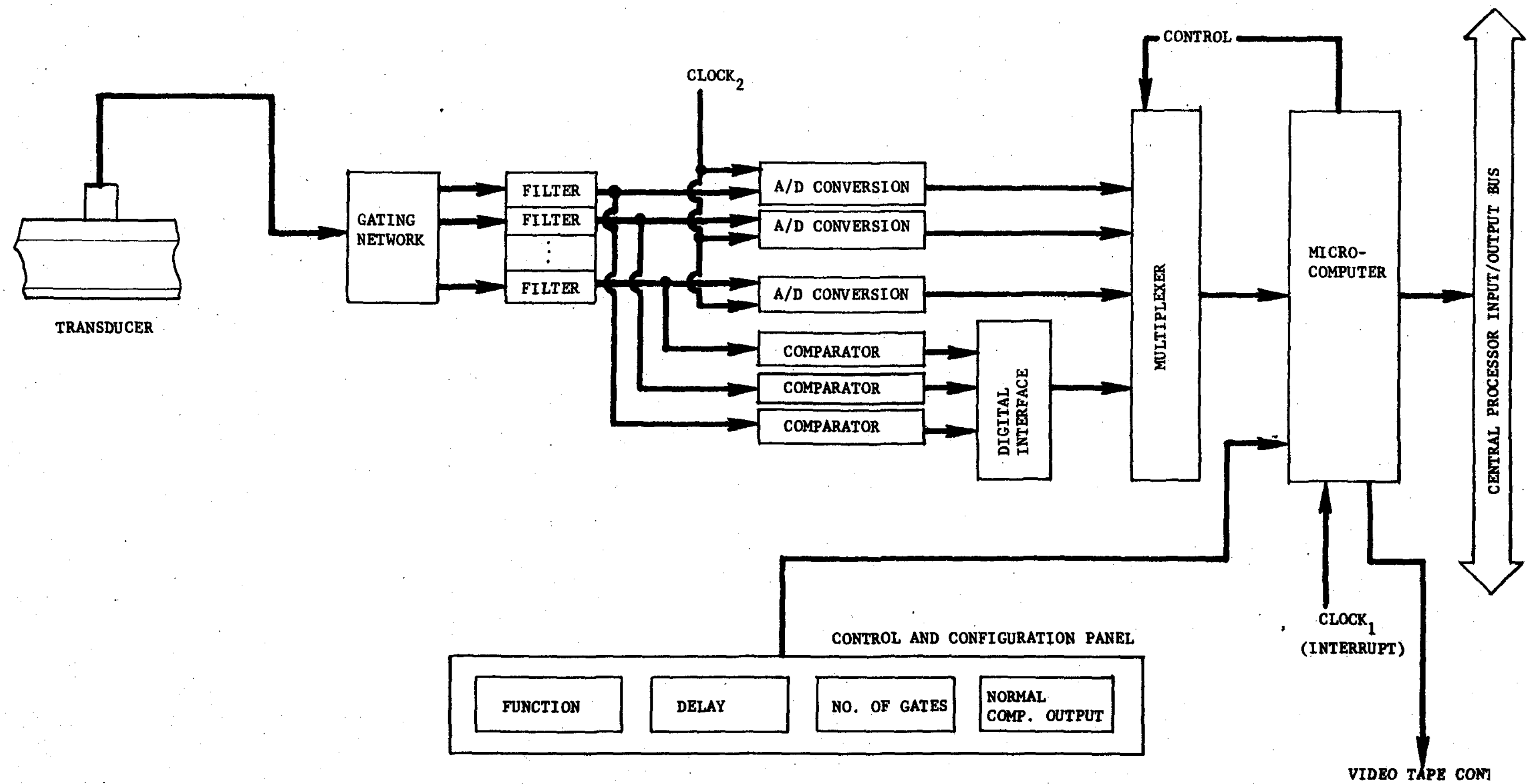


FIGURE 33. BLOCK DIAGRAM OF MAXIMUM THROUGHPUT SYSTEM

The central processor for the system has the task of implementing the logic shown in the flow chart in Figure 28. Its functions are to:

collect flaw data from the transducer channels on receipt of an interrupt

rearrange the data into a format that will facilitate analysis and correlation with other data

decide if the data represent a flaw of interest

actuate the rail paint system if the data represent a flaw interest

alert the operator if an indeterminate situation arises along with transferring the data to the visual data recorder system, and

produce permanent records of inspection data.

The functional schematic of the central processor is shown in Figure 34. The paper tape equipment shown is for the purpose of programming the machine. It is important to realize that the central processor operates asynchronously with the transducer channels collecting data from them only when the channel informs the central processor that it has data to transmit.

Varations on this design concept would consist of having one microcomputer service two or more transducers. This would decrease the number of microcomputers needed but with a corresponding increase in the throughput time because the transducer data would be processed serially instead of in parralel with other data.

In the event the system can neither determine that the data represent a flaw nor does not represent a flaw, the central processor would transfer the data to a visual data processor for the operator to inspect. The visual data processor is shown in Figure 35 and consists of video playback equipment and a strip chart or B scan recorder. Using this system, the operator can use his judgment to determine the significance of the data. The system shown includes three cameras for each rail with two tape decks for each camera -- one to record on and one to use for playback. The three

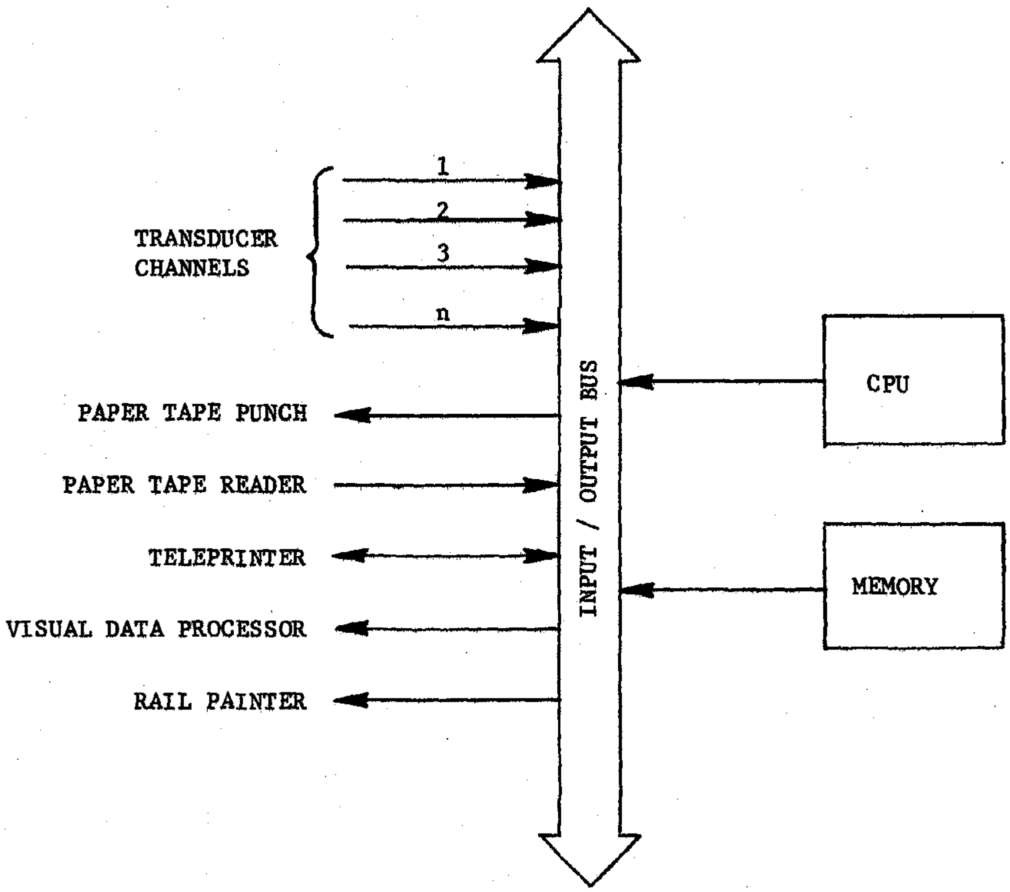


FIGURE 34. SCHEMATIC DRAWING OF CENTRAL PROCESSOR

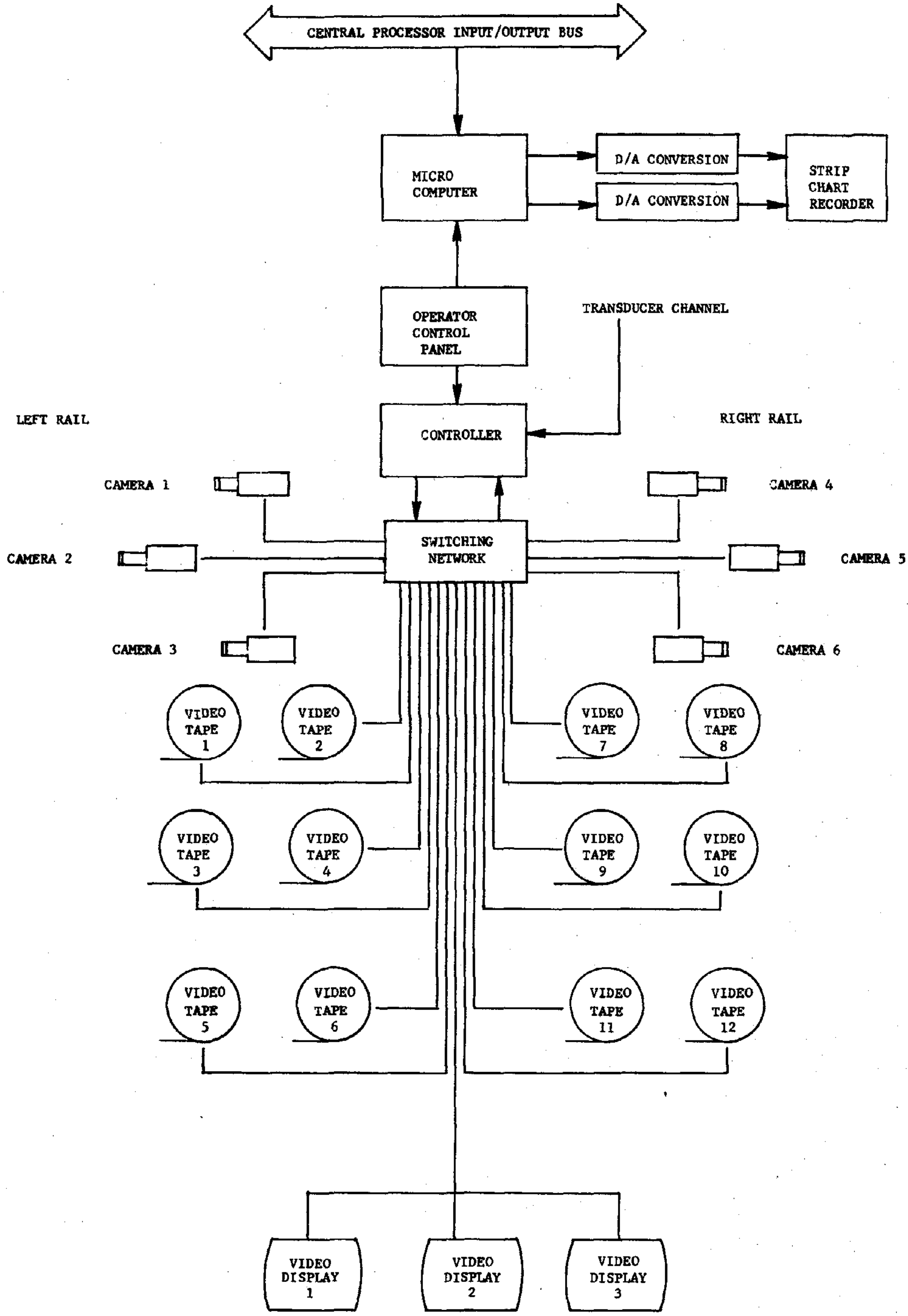


FIGURE 35. FUNCTION BLOCK DIAGRAM OF VISUAL DATA PROCESSOR

Video displays are used to view the rail from three different perspectives. The transducer channels would generate the control signal needed to start storing data on video tape and the visual data processor would have the task of matching the video data with the strip chart data.

Cost Considerations

There are three primary subsystems that comprise the data processing system: the transducer channel, the central processor, and the visual display processor. With the exception of the central processor, the subsystem configurations are primarily dependent upon the throughput speed and sampling rate of the system. The sampling rate is related to the minimum resolution required of the system.

The most stringent conditions envisioned for the system are 1/4 in. (6.4 mm) resolution at an operating speed of 50 mph (80 Km/hr). Under these conditions, the system must be configured to handle the raw data in parallel using the central processor to do the final analysis on a per flaw basis. At 50 mph (80 Km/hr) the operator will no longer be able to maintain visual contact with the rail at the level of detail required, and a video recorder and playback system has been included in this system to aid in identifying rail anomalies that can be observed visually.

The preliminary cost estimates are shown in Table 29. The transducer channel cost of $9000 is a per transducer cost for the maximum throughput system. The minimum system considered for the system utilizes seven transducers per rail for a total of $28,000 for all 14 transducer channels. One method of reducing this cost--at the expense of a somewhat lower throughput speed--would be to process data from more than one transducer with a microcomputer channel. In the equipment shown for the transducer channel in Table 29, this would require all of the equipment except the extra microcomputer. Not all of the $500 would be saved, however, because additional memory would be needed for the extra transducers. Probably a savings on the order of $250 per double channel could be realized for a total of $3500 for a 14-transducer system.

TABLE 29. PRELIMINARY COST ESTIMATES FOR A MINIMUM 14-TRANSDUCER SYSTEM

Subsystem:	Transducer Channel	
	Microcomputer	$ 500
	Analog-to-digital converters	300
	Comparators	300
	Filters	300
	Multiplexer	300
	Control and Configuration Panel	200
	Digital Interface	100
		$2,000
Subsystem:	Central Processor	
	Minicomputer (16K, 16-bit)	$12,000
	Teleprinter (KSR)	2,000
	Paper tape punch and reader	2,500
	I/O Interfaces	7,000
	Installation and check out	$10,000
	Total	$33,000
Subsystem:	Visual Display Processor	$75,000

Item 5 - Analysis of Cost Performance Tradeoffs Between Systems

System Requirements

The objective of Item 5 was to determine the costs of flaw detection systems as a function of the speed at which they would operate and the size flaw that could be reliably detected by those systems. Specific flaw sizes used in this analysis were transverse type flaws with an area of 1 percent, 5 percent, or 15 percent of the head area, and longitudinal type flaws with lengths of 1, 2, and 4 inches (25, 51, and 102 mm). The analysis of existing systems completed under items 3 and 4 has shown that rail inspection speeds are now typically about 10 MPH (16 km/hr). Present inspection speeds in the United States were found to be limited primarily by limitations on the operator's ability to process the data at the rate at which it is produced. From these studies it was concluded that if the operator limitation were removed from the system, speeds could be increased to about 25 MPH (40 km/hr) with minimal improvement in the inspection system hardware. Techniques for removing the speed limitation due to the operator's inability to process data with sufficient speed are to either record the data and process it at a later time, or to use automatic data processing.

Present rail inspection technology in the United States relies heavily on visual inspection of the rail. It is believed that this visual inspection can still be accomplished, assuming the operator is assisted with automatic data processing equipment, at speeds up to about 25 MPH (40 km/hr). To inspect tracks at speeds significantly higher than 25 MPH (40 km/hr) would require that the operator be provided with a means for assisting visual inspection other than direct visual observation of the rail. If this evaluation is to be made by the car personnel at the time of inspection, it would probably be necessary to provide the operator with a special TV visual system. Suspect areas of the rail could be recorded on video tape and played back to the operator to allow him to observe the rail for long enough periods of time to interpret both the transducer data and the visual data. By providing a TV visual system, automatic data processing, and with extensive development of either sled or wheel type ultrasonic or magnetic carriage systems it is believed that reliable inspection can be obtained at speeds up to 50 MPH (80 km/hr).

To reliably detect flaws down to sizes equivalent to 5 percent of the area of the railhead requires the use of more and better transducers than are required to detect 15 percent flaws. Factors limiting maximum inspection speeds for detecting 5 percent flaws are essentially the same as those in detecting 15 percent flaws. However, because a greater quantity of data is being produced at any given speed to detect 5 percent flaws, lower maximum inspection speeds, remote processing or automatic data processing is required.

A 1 percent round transverse type flaw will have a diameter of about 0.20 inches (5 mm) in 90 lb (45 Kg/m) rail, and about 0.24 inches (6 mm) in 132 lb (65 Kg/m) rail. This size flaw is readily detected in the laboratory where the inspector has the time and equipment to inspect using a large number of transducer positions. It also is readily detected in some production operations, especially where specific flaws are anticipated and transducers can be located to detect those specific flaws, and where there are no surface cracks to interfere with detection of deeper defects. However, detection of this size flaw while moving on conventional U.S. railroad track would be very difficult, because surface anomalies normally found on U.S. track would produce signals which would be large relative to the flaw signals, and which would be difficult to distinguish from the genuine flaw signals.

Although difficult, it is believed that a system could be developed to reliably detect 1 percent flaws. The system considered to have the most potential would be a combined magnetic/ultrasonic system using an improved magnetic system with an ability to separate surface and subsurface defect signals, plus an ultrasonic system employing a large number of ultrasonic transducers to thoroughly interrogate all sections of the railhead and web and to produce redundant flaw signals. Operating speeds would be slow ($\sim$3 mph (5 km/hr)) in order to minimize coupling noise effects, and to insure that the signals from a large number of ultrasonic pulses could be averaged over a short travel distance to improve signal-to-noise ratios. Because of the requirement for a large number of transducer signals, extensive automatic data processing would be required to minimize operator error and maximize operating speeds.

Detection of 1 percent flaws would probably be useful in most cases only if the operator can differentiate between these 1 percent flaws and the larger 5 to 15 percent flaws. A major difficulty will be to provide this size discrimination capability, and therefore it is expected that frequent stops for hand checks would be required with a 1 percent detection system - especially during the first years of development.

System Complexity

The required complexity of inspection systems can be visualized by starting first with a basic system designed to meet the basic present operating requirements of being able to reliably detect 15 percent flaws at speeds of about 10 MPH. This basic system can then be modified or expanded by improving transducers and/or adding transducers to enable the system to resolve smaller flaws, and by improving carriages and data processing techniques to allow increased operating speeds. Table 30 shows the improvements which would have to be made to the basic operating system "A" to provide increased speeds and resolutions.

A brief description of each of these systems listed is given below.

System A

The requirements of system A are that it reliably detects 15 percent flaws at speeds up to about 10 MPH. Many existing combination magnetic-ultrasonic systems meet this requirement -- the ultrasonic and magnetic systems complement each other so that defects not readily detected by one are detected by the other. By moderate further development of ultrasonic

TABLE 30. SYSTEM REQUIREMENTS AS A FUNCTION OF FLAW SIZE AND SPEED

Peak Operating Speed, mph	Km/hr	15 Percent Head Area of 4-in. (10.2cm) long	5 Percent Head Area or 2-in. (5.1cm) long	1 Percent Head Area or 1-in. (2.5cm) long
3	5	System A Existing combined ultrasonic-magnetic systems.	System B Similar to A but with added ultrasonic transducers or improved magnetic system to improve resolution.	System C Requires use of large number of ultrasonic transducers, improved magnetic system, automatic data processing, frequent stops for hand checks and automatic carriage locatic control.
10	16	Same as System A above	System D Same as System B except automatic or remote data processing required to handle increased data rate and addition or automatic carriage control.	-
25	40	System E Same as System A except automatic or remote data processing required to handle increased data rate and addition of automatic carriage control.	System F Same as above except requires magnetic system with increased speed capability.	-
50	80	System G Same as System F above plus TV bisual system.	System H Same as System C above plus TV bisual system except no stops for hand checks.	-

systems it is believed that an all-ultrasonic system could also satisfactorily meet the requirements for system A. This development would entail use of additional transducers specifically designed to detect flaws that are presently missed because of poor orientation or because no transducers are inspecting specific areas of the track. This system could be light enough to use on a high-rail car. Manual onboard data processing limits inspection speeds for this system to about 10 MPH.

System B

The requirements of System B are that it reliably detects 5 percent flaws at low speeds-3 mph or so. System B would be essentially the same as A above, except additional ultrasonic transducers or a magnetic system with an improved signal-to-noise ratio would be required to resolve and locate the smaller 5 percent flaws. The necessary signal-to-noise ratio might be obtained in a magnetic system through use of a direct current system, or through development of a new multifrequency type system. This system is limited to a low speed because of the requirement for manually processing a large volume of data. This system would probably be light enough to install on a high-rail vehicle.

System C

The requirements of system C are that it reliably detects 1 percent flaws (diameters down to about 0.2 inch (5 mm)) at low speeds - 3 mph or so. To be useful, however, it should also produce sufficient information to distinguish between the 1 percent and larger (5 percent to 15 percent) flaws. To achieve this capability on railroad track requires use of a large number of transducers, so that transducers will be located in all positions necessary to detect flaws at any location of orientation within the rail, and so that redundant information will be obtained, weighted and compared. It will also be necessary to operate the inspection car very slowly and even when operating slowly, the use of the large numbers of transducers would make it necessary to use automatic data processing an an automatic carriage position control system to limit the operators' work load. Even with these features it will probably not be practical in many cases to adequately define many identified flaws, and, therefore, stops for hand checks will be required to confirm flaw orientation and sizes. This system would probably be too heavy to be installed on a high-rail vehicle.

System D

The requirements of system D are essentially the same as those for System B (5 percent flaws) except for operation at speeds up to 10 mph (16 km/hr). Operation at increased speeds and data rates makes it necessary to use an automatic carriage position control system, and either to use an automatic data processing system or to record the data and process it at a later time. This system would probably be light enough to install on a high-rail vehicle.

System E

The requirements for system E that it reliably detect 15 percent flaws (same as System A), but it must operate at speeds up to 25 mph (40 km/hr). The higher speeds and data processing rates make it necessary to limit the operators' work load through the use of automatic carriage control and remote or automatic data processing.

If this system were all ultrasonic, it would probably be light enough to install on a high-rail vehicle. However, to obtain 25 mph (40 Km/hr) speeds with a magnetic inspection system, the magnetic system would usually be considerably heavier than that required for the lower speeds. Therefore, a magnetic system would probably require use of a regular rail vehicle unless extensive further development results in a system of substantially reduced weight.

System F

The requirements for system F are that it reliably detect 5 percent flaws (same as systems B and D) but it must operate at speeds up to 25 mph

(40 km/hr). If an all ultrasonic system is used, System F should be identical to system D, however, if a combined magnetic ultrasonic system is used a magnetic system with increased speed capabilities must be used. This might be accomplished by using larger and heavier magnets in a residual magnetic system or by using a direct current type system. These magnetic systems would probably be too heavy to use on a high-rail vehicle.

System G

The requirements for system G are that it reliably detect 15 percent flaws (same as systems A and E), but it must operate at speeds up to 50 mph (80 km/hr). To increase speeds from 25 mph (40 km/hr) to 50 mph (80 km/hr) will require the development of substantially improved carriage systems to insure accurate transducer positioning relative to the rail, the use of additional transducers to provide redundant information which will tend to compensate for expected coupling problems, and the use of a TV visual system to give the operator adequate time to visually inspect the rail.

This system, if all ultrasonic, could probably be installed on a high-rail vehicle. However, if a combined state-of-the-art magnetic-ultrasonic system were used, a conventional rail car would probably be required.

System H

The requirements for system H are that it reliably detect 5 percent flaws or equivalent (same as systems B, D, and F), but it must operate at speeds up to 50 mph (80 km/hr). To detect 5 percent flaws (approximately 0.24 inch (6 mm) in diameter at 50 mph (80 km/hr) requires the use of a large number of transducers to thoroughly interrogate the rail and produce redundant data for cross checking. It is expected that the transducer complexity will be about the same as required to detect 1 percent flaws at very low speeds. Also, a lightweight rigid well-controlled carriage system will be required for accurate transducer positioning, and a TV visual system will be required to allow the operator to visually inspect the track.

System Costs

System costs were developed for each of the alternative system configurations described in Table 31. The configurations described in Table 31 are based on the following conclusions as to the capabilities of the various inspection methods:

(1) The AAR type magnetic system is adequate to speeds up to 10 mph (16.1 kph) and sensitivities of 15 percent. At a sensitivity of 5 percent, it is necessary to use a direct current magnetic system or to develop residual magnetic system with an improved ability to differentiate between surface and subsurface defects.

(2) The AAR-type magnetic system may be used in either a high-rail car or a rail car.

(3) Inspection requirements for speeds up to 25 mph (40.2 kph) and sensitivities as low as 5% may be met by totally ultrasonic systems. At speeds above 25 mph (40.2 kph) the totally ultrasonic system is suitable only at sensitivities of 15% or above.

(4) At speeds above 10 mph (16.1 kph) the magnetic system must be of the direct current contact (DCC) type, a much larger, heavier, and more expensive residual magnetic system than the AAR system or possibly a totally new type magnetic system. The DCC system must also incorporate multifrequency techniques at sensitivities better than 15%.

(5) Totally ultrasonic systems may be accomodated in high-rail vehicles as can combination systems that use the AAR-type magnetic system.

(6) Systems that require the DDC magnetic system must use a rail car.

(7) At speeds above 10 mph (16.1 kph) or sensitivities better than 15%, it is necessary to improve the control of the sensor carriage.

TABLE 31. SYSTEM CONFIGURATIONS

System	Miles Per Hour	Km Per Hour	Flaw Size %	Rail Car	High Rail Car	Magnetic System			Number of Ultrasonic Transducers	Auto Carriage Control	Auto Data Processing	Closed Circuit TV
						AAR	DCC	Improved Magnetic*				
A-1	10	16.1	15	X		X			10			
A-2	10	16.1	15		X				10			
A-3	10	16.1	15	X					22			
A-4	10	16.1	15		X				22			
B-1	3	4.8	5	X		X		X	10			
B-2	3	4.8	5		X	X		X	10			
B-3	3	4.8	5	X					30			
B-4	3	4.8	5		X				30			
C	3	4.8	1	X			X	X	52	X	X	
D-1	10	16.1	5	X		X		X	10	X	X	
D-2	10	16.1	5		X	X		X	10	X	X	
D-3	10	16.1	5	X					30	X	X	
D-4	10	16.1	5		X				30	X	X	
E-1	25	40.2	15	X			X		10	X	X	
E-2	25	40.2	15	X					22	X	X	
E-3	25	40.2	15		X				22	X	X	
F-1	25	40.2	5	X			X	X	10	X	X	
F-2	25	40.2	5	X					30	X	X	
F-3	25	40.2	5		X				30	X	X	
G-1	50	80.4	15	X			X	X	10	X	X	X
G-2	50	80.4	15	X					30	X	X	X
G-3	50	80.4	15		X				30	X	X	X
H	50	80.4	5	X			X	X	26	X	X	X

(*) Multifrequency or other magnetic system with improved ability to differentiate between surface and subsurface defect

(8) At speeds above 10 mph (16.1 kph) or sensitivities below 15%, the data rate cannot be adquately handled by operators without the addition of automatic data processing.

(9) At speeds above 25 mph (40.2 kph) the operators cannot obtain visual information on the track without the aid of a special stop action closed circuit television system.

In developing the capital costs for the systems described in Table 31, the following unit costs were used. These unit costs were developed from similar systems now in use where possible. Other costs were obtained from equipment producers, test system manufacturers, test system users, and on engineering estimates of new system developments. No allowance was made for development costs which would be substantial for many of the systems discussed.

(1) Rail car with living quarters, propulsion system, auxiliary power, etc. -- $415,000

(2) High-rail car - $65,000

(3) Magnetic Systems -

  DCC type -- $400,000

  AAR type -- $46,000

  Additional costs for improved magnetic system -- $30,000.

(4) Ultrasonic systems --

  Basic system for rail car -- $125,000

  Basic system for high-rail car -- $85,000

  Plus per transducer -- $8,000.

(5) Carriage system, referenced to System A

System	Cost
B	$ 5,000
C	30,000
D	25,000
E	20,000
F	25,000
G	40,000
H	40,000

(6) Automatic data processing --

Base cost -- $33,000

Per Channel -- $2,000

(7) Stop action closed circuit television -- $75,000.

The installed cost of each inspection system described in Table 31 is estimated in Table 32. Also included in Table 32 is the amount of track that is estimated to be tested annually along with estimates of the inspection vehicle operating and maintenance costs, the operating and maintenance costs per mile (and kilometer) tested, and the total inspection cost per mile (and kilometer) tested.

The amount of track tested for each configuration is in most instances based on a 9 hour day with a 65% access time for testing at maximum testing speed. This is considered to be the most optimistic estimate of inspection vehicle mileage. Later in this section, a comparable analysis is made assuming operational stops (not for hand verification). An analysis of effective testing speeds described under Item 2 of this report indicates that it is impractical to stop for hand tests at inspection speeds substantially above 10 mph (16.1 kph). Thus, for those configurations in Table 32 that apply to these speeds, the estimated testing mileage should be reasonably representative of the maximum that would be experienced in practice if there were no operational stops during the actual testing time. For those configurations that apply to lower speeds, the no-stop for hand test assumption results in testing mileage somewhat higher than will be experienced if these vehicles do stop for hand tests. Specifically, the cases that are most significant are those that relate to Systems A-1, A-2, D-1, D-2, D-3, and D-4. In these instances, inspection mileages from current systems are also included in Table 32 to provide an indication of the impact of stopping for hand tests on inspection vehicle costs. However, to provide a common basis for comparing system costs, the data based on no stops for hand tests is used.

It should be pointed out that the assumption of no stopping for hand tests is merely a convenience for system comparisons. The need for such hand tests may well remain. These tests could be performed by personnel other than inspection vehicle personnel.

TABLE 32. INSPECTION COST-SPEED-SENSITIVITIES RELATIONSHIPS NO OPERATIONAL STOPS

Sensitivity (Flaw Size)	Maximum Inspection Speed mph	Maximum Inspection Speed km/hr	System*(1)	Initial[(2)] Installed Cost $ x 1000	Track Tested[(3)] Annually Miles	Track Tested[(3)] Annually Kilometers	Annual Operating/Vehicle Maintenance Cost $ x 1000	Inspection Vehicle Operations and Maintenance Cost Per Mile $	Inspection Vehicle Operations and Maintenance Cost Per Km $	Total Inspection Cost[(4)] Per Mile $	Total Inspection Cost[(4)] Per Km $
15% Transverse 4 in. (10.2 cm) longitudinal	10	16.1	A-1	618	15,300	24,700	100	6.55	4.06	7.90	4.90
			A-2	228	15,300	24,700	70	4.60	2.85	5.60	3.50
			A-3	668	15,300	24,700	100	6.55	4.06	8.00	5.00
			A-4	278	15,300	24,700	70	4.60	2.85	5.80	4.10
			A-1	618	8,800[(5)]	14,200	98	11.15	6.95	13.50	8.40
			A-2	228	5,200[(6)]	8,370	63	12.10	7.55	15.05	9.35
5% Transverse 2 in. (5.1 cm) longitudinal	3	4.8	B-1	653	4,600	7,360	96	20.90	13.00	25.60	15.90
			B-2	263	4,600	7,360	64	13.90	8.65	17.70	11.00
			B-3	737	4,600	7,360	96	20.90	1300	26.20	16.30
			B-4	347	4,600	7,360	64	13.90	8.65	18.95	11.80
1% Transverse 1 in. (2.5 cm) longitudinal	3	4.8	C	1,521	4,600	7,360	120	26.10	16.20	37.10	23.10
5% Transverse 2 in. (5.1 cm) longitudinal	10	16.1	D-1	742	15,300	24,700	109	7.10	4.45	8.75	5.45
			D-2	352	15,300	24,700	85	5.60	3.45	7.10	4.40
			D-3	850	15,300	24,700	109	7.10	4.45	9.00	5.60
			D-4	460	15,300	24,700	85	5.60	3.45	7.60	4.70

(*) Notes follow table.

TABLE 32 (Continued)

Sensitivity (Flaw Size)	Maximum Inspection Speed mph	Maximum Inspection Speed km/hr	System*(1)	Initial(2) Installed Cost $ x 1000	Track Tested(3) Annually Miles	Track Tested(3) Annually Kilometers	Annual Operation-Vehicle Maintenance Cost $ x 1000	Inspection Vehicle Operations and Maintenance Cost Per Mile $	Inspection Vehicle Operations and Maintenance Cost Per Km $	Total Inspection Cost(4) Per Mile $	Total Inspection Cost(4) Per Km $
5% Transverse 4 in. (10.2 cm) longitudinal	10	16.1	D-1	742	8,800(5)	14,200	107	12.20	7.55	15.00	9.30
			D-2	352	5,200(6)	8,370	78	15.00	9.30	21.90	13.60
			D-3	850	8,800(5)	14,200	107	12.20	7.55	15.40	9.60
			D-4	460	5,200(6)	8,370	78	15.00	9.30	24.00	14.90
15% Transverse 2 in. (5.1 cm) longitudinal	25	40.2	E-1	1,061	38,350	61,670	118	3.10	1.90	4.00	2.50
			E-2	765	38,350	61,670	118	3.10	1.90	3.78	2.35
			E-3	375	38,350	61,670	100	2.60	1.60	3.25	2.00
5% Transverse 2 in. (5.1 cm) longitudinal	25	40.2	F-1	1,096	38,350	61,670	121	3.15	1.95	4.10	2.55
			F-2	850	38,350	61,670	121	3.15	1.95	3.90	2.40
			F-3	460	38,350	61,670	105	2.75	1.70	3.50	2.20
15% Transverse 4 in. (10.2 cm) longitudinal	50	80.4	G-1	1,186	76,700	123,330	139	1.80	1.10	2.35	1.45
			G-2	937	76,700	123,330	139	1.80	1.10	2.20	1.35
			G-3	550	76,700	123,330	135	1.75	1.10	2.25	1.40
5% Transverse 2 in. (5.1 cm longitudinal	50	80.4	H	1,346	76,700	123,330	148	1.95	1.20	2.50	1.55

Table 32 Notes --

(1) See Table 30 for description of systems

(2) All costs are referenced to November, 1975, dollars

(3) Based on 5.9 hour testing day at maximum testing speed without stops except where specifically noted to be otherwise

(4) Includes amortized capital cost. Assumed 15-year life for high-rail type system and 30 years life for rail system

(5) Based on current experience of approximately 34 miles per day for a rail car. This includes stops for hand tests

(6) Based on current experience with a high-rail car. This includes stops for hand tests.

Annual inspection vehicle operations and maintenance cost estimates are based on data from current systems and expected manning requirements for the defined alternative configurations. Total inspection costs per unit of track length is the sum of the per unit length inspection vehicle operators' maintenance cost and a simple amortization of the capital cost of the inspection system over its expected life. The calculated values are based on a rail vehicle life of 30 years and a high-rail vehicle life of 15 years. It is recognized that vehicle life may be dependent on mileage than time. However, the times used are considered to be reasonable and allowances have been made in the operations and maintenance costs to account for greater wear at higher speeds (and, therefore, greater annual mileages).

The capital cost of each inspection system is illustrated in Figure 36. Examination of Figure 36 and Table 32 indicates that for a given inspection approach, capital costs tend to increase with speed and with increased sensitivity. At the same time, there is a considerable overlap of cost-speed-sensitivity relationships for various system configurations. With the exception of configurations that use the AAR-type magnetic system, ultrasonic systems appear to be less costly than those utilizing magnetic systems. Related to this situation, systems that can use a high-rail type car are less costly than those using a rail car. As described below, this cost difference tends to be reduced in significance on a cost per unit length of track inspected primarily because the differences in assured vehicle life.

The per mile (and per kilometer) costs for all systems are illustrated in Figure 37. As shown in this figure, the per mile (kilometer) costs decrease significantly with increased inspection speeds. This is due largely to the fact that there is no need to increase crew size as the speed is increased since automatic data processing is used to keep the manual evaluation burden at reasonable levels.

The service life assumption plays a significant role in the decreased per mile (kilometer) costs. However, even if the assumed life values are high, it is not expected that the general relationships of per mile (kilometer) costs will be significantly changed. In the development

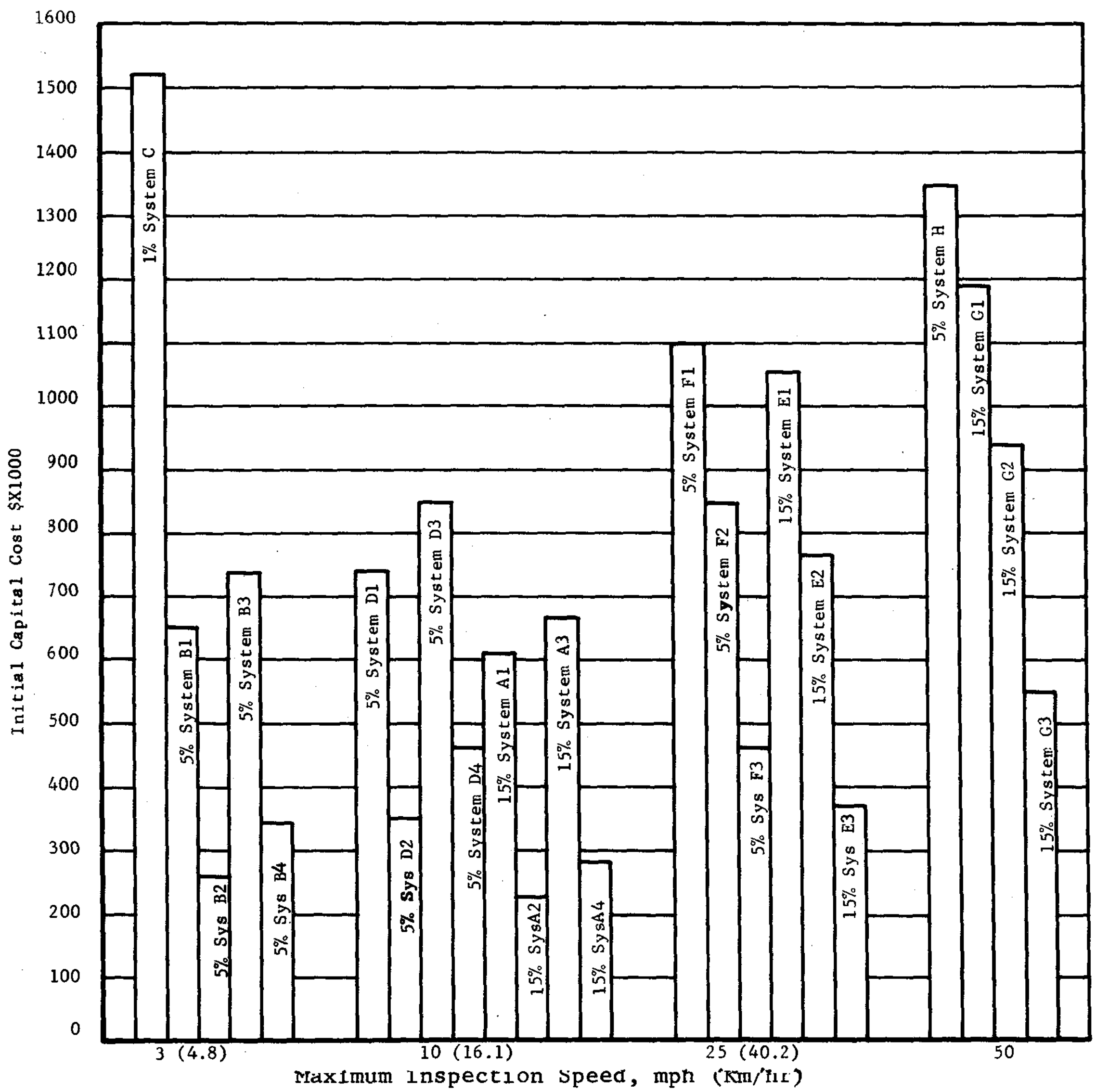


FIGURE 36 . INSPECTION SPEED, CAPITAL COST, SENSITIVITY RELATIONSHIPS

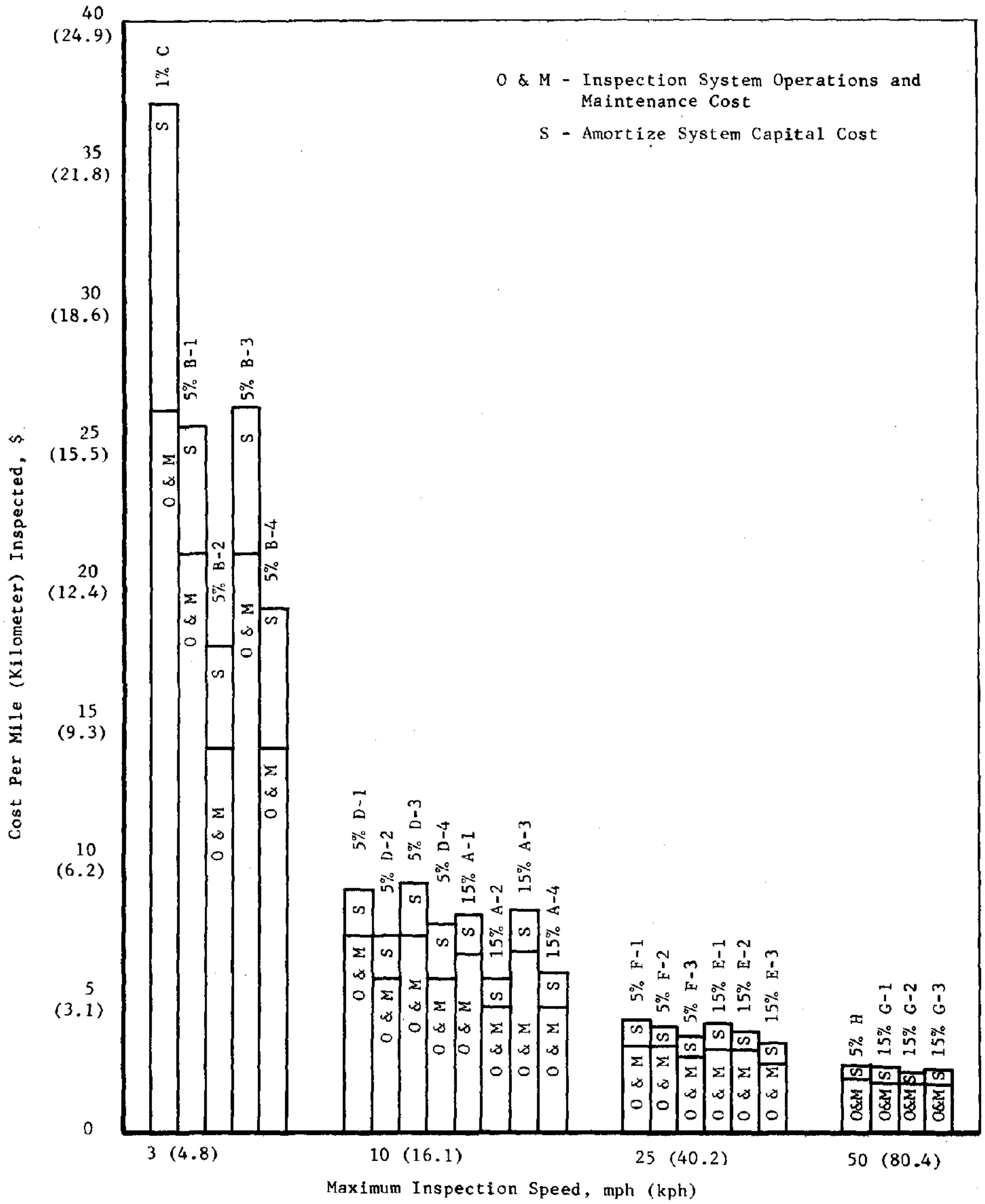


FIGURE 37. INSPECTION SPEED, COST PER MILE (KILOMETER), SENSITIVITY RELATIONSHIPS NO OPERATIONAL STOPS

of the per mile (kilometer) costs, a constant on-track inspection time of 5.9 hours per day was assumed for all speeds. At higher speeds it is expected that there will be some increase in this time because the inspection car will be traveling at speeds more nearly corresponding to normal traffic. This will leave a positive (increasing inspection time) on double tracks and on single tracks with regard to trains moving in the same direction as the inspection vehicle. With regard to opposing trains, there will be an increased number of meets during an inspection day and possible greater delays. However, this should be offset by being able to take advantage of shorter time "windows" available in regular traffic. The net effect is expected to be a somewhat greater time-on-track for inspection.

As indicated earlier, the preceding discussion assumes that testing will occur at maximum testing speeds during the available inspection time (estimated to be approximately 5.9 hours per day) Summary testing data from the sample railroads indicate that even during the available testing periods it is necessary to occasionally stop for operational reasons. These stops occur on an average of every 3 to 4 miles. The duration of these stops is not recorded. If it is assumed that this duration is in the order of 1 minute per stop, the effective inspection speeds relate to maximum inspection speeds as follows:

Maximum Inspection Speed mph (kph)	Effective Inspection Speed mph (kph)	Percent Reduction
3 (4.8)	3 (4.8)	0.0
10 (16.1)	9.5 (15.3)	5.0
25 (40.2)	21.5 (34.6)	14.0
50 (80.4)	38.5 (62.0)	23.0

As seen above, stopping for operational reasons has an increasing effect with an increase in speed. In all instances, the net effect is a decrease in the amount of rail that can be inspected annually and an increased cost per inspected mile.

The estimated maximum annual inspected mileages and inspection mileage costs considering operational stops, are presented in Table 33 and Figure 38. As with Table 32 and Figure 37, the data assumes no stopping

TABLE 33. INSPECTION COST-SPEED-SENSITIVITIES RELATIONSHIPS WITH OPERATIONAL STOPS

Sensitivity Flaw Size)	Maximum Inspection Speed mph	Maximum Inspection Speed km/hr	System*(1)	Initial(2) Installed Cost $ x 1000	Track Tested(3) Annually Miles	Track Tested(3) Annually Kilometers	Annual Operating/ Vehicle Maintenance Cost $ x 1000	Inspection Vehicle Operations and Maintenance Cost Per Mile $	Inspection Vehicle Operations and Maintenance Cost Per Km $	Total Inspection Cost(4) Per Mile $	Total Inspection Cost(4) Per Km $
15% Transverse 4 in. (10.2 cm) longitudinal	10	16.1	A-1	618	14,600	23,500	100	6.85	4.25	8.25	5.15
			A-2	228	14,600	23,500	70	4.80	3.00	5.85	3.65
			A-3	668	14,600	23,500	100	6.85	4.25	8.35	5.20
			A-4	278	14,600	23,500	70	4.80	3.00	6.05	3.75
			A-1	618	8,800(5)	14,200	98	11.15	6.95	13.50	8.40
			A-2	228	5,200(6)	8,370	63	12.10	7.50	15.05	9.35
5% Transverse 2 in. (5.1 cm) longitudinal	3	4.8	B-1	653	4,600	7,360	96	20.90	13.00	25.60	15.90
			B-2	263	4,600	7,360	64	13.90	8.65	17.70	11.00
			B-3	737	4,600	7,360	96	20.90	13.00	26.20	16.30
			B-4	347	4,600	7,360	64	13.90	8.65	18.95	11.80
1% Transverse 1 in. (2.5 cm) longitudinal	3	4.8	C	1,521	4,600	7,360	120	26.10	16.20	37.10	23.10
5% Transverse 2 in. (5.1 cm) longitudinal	10	16.1	D-1	742	14,600	23,500	109	7.50	4.65	9.20	5.70
			D-2	352	14,600	23,500	85	5.80	3.60	7.40	4.60
			D-3	850	14,600	23,500	109	7.50	4.65	9.45	5.90
			D-4	460	14,600	23,500	85	5.80	3.60	7.90	4.90
5% Transverse 2 in. (5.1 cm) longitudinal	10	16.1	D-1	742	8,800(5)	14,200	107	12.20	7.60	15.00	9.30
			D-2	352	5,200(6)	8,370	78	15.00	9.30	21.90	13.60
			D-3	850	8,800(5)	14,200	107	12.20	7.60	15.10	9.45
			D-4	460	5,200(6)	8,370	78	15.00	9.30	24.00	14.90

(*) Notes follow table.

TABLE 33 (Continued)

Sensitivity Flaw Size	Maximum Inspection Speed mph	km/hr	System*(1)	Initial(2) Installed Cost $ x 1000	Track Tested(3) Annually Miles	Kilometers	Annual Operating/ Vehicle Maintenance Cost $ x 1000	Inspection Vehicle Operations and Maintenance Cost Per Mile $	Per Km $	Total Inspection Cost(4) Per Mile $	Per Km $
15% Transverse 4 in. (10.2 cm) longitudinal	25	40.2	E-1	1,061	33,000	53,100	118	3.60	2.25	4.70	2.90
			E-2	765	33,000	53,100	118	3.60	2.25	4.35	2.70
			E-3	375	33,000	53,100	100	3.05	1.90	3.80	2.35
5% Transverse 2 in. (5.1 cm) longitudinal	25	40.2	F-1	1.096	33,000	53,100	121	3.65	2.30	4.75	2.95
			F-2	850	33,000	53,100	121	3.65	2.30	4.50	2.80
			F-3	460	33,000	53,100	105	3.20	2.00	4.15	2.60
15% Transverse 4 in. (10.2 cm) longitudinal	50	80.4	G-1	1,186	59,100	95,100	139	2.35	1.45	3.00	1.65
			G-2	937	59,100	95,100	139	2.35	1.45	2.90	1.80
			G-3	550	59,100	95,100	135	2.30	1.45	2.90	1.80
5% Transverse 2 in. (5.1 cm) longitudinal	50	80.4	H	1,346	59,100	95,100	148	2.50	1.55	3.25	2.00

for hand tests except where specifically indicated. In practice, the lower speed systems (up to and including 10 mph (16.1 kph) will normally stop for hand verification of all defects indicated by the inspection vehicle.

As noted in Table 33 and Figure 38, the various systems relate in much the same manner as is the case where no operational stops are considered. Inspection costs per mile are obviously higher and the greater impact of stops at higher speeds is apparent as indicated by a smaller improvement in inspection costs per mile (kilometer) as speed is increased.

It should be pointed out that the inspection costs described in this section of the report do not include allowances for administrative support or for profits (in the case of leased inspection services). Only the inspection profits (in the case of leased inspection services). Only the inspection vehicle costs (including personnel) are included. Since these costs are the ones that vary with inspection, speed, and sensitivity they provide the proper basis for comparing alternative system configurations. Other costs will be treated in the section that follows.

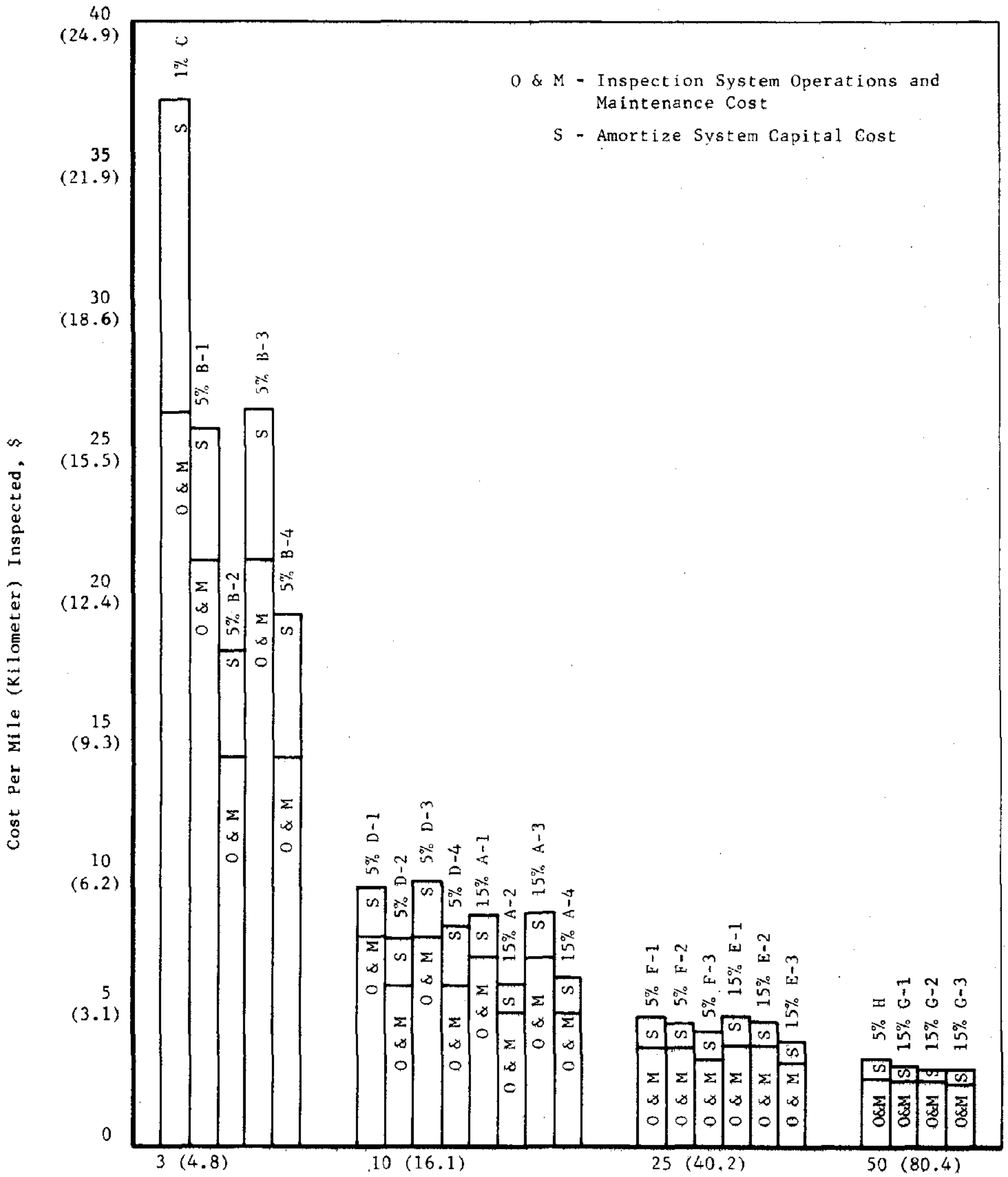


FIGURE 38. INSPECTION SPEED, COST PER MILE (KILOMETER), SENSITIVITY RELATIONSHIPS OPERATIONAL STOPS

Items 6, 7, and 8 - Cost Analysis of Alternative Inspection Systems

A slogan that is typically posted in a manufacturing plant reads "Quality Cannot Be Inspected Into Our Product". The message is, of course, that the quality of the product is what is designed and built into it.

The same situation applies to rails in place in railroad tracks. The initiation and growth of cracks or other types of defects in a rail are not dependent on inspection but on a great number of other factors including design, materials, manufacture, installation, track structure condition, load characteristics, and track environment.

The primary function of rail inspection is to detect flaws that have been initiated but prior to the time at which they reach a point of rail failure that produces a derailment or at least a train delay. One aspect then of a rail flaw inspection systems cost analysis is the expected impact of the system on the occurrence (and costs) of rail failures including derailments.

A second aspect of the cost analysis is the relative cost of each of a number of alternative systems to perform a given inspection task. The cost analysis to be described consists primarily of these two aspects; cost comparisons of alternatives, and expected impact of various applications of alternative systems.

Inspection System Costs

The basic costs of alternative flaw detection vehicles were developed under Item 5. Costs were developed as a function of speed and flaw detection sensitivity. These costs included only simple amortized capital costs and the estimated direct cost of operating each vehicle. Not included were the one time development costs, cost of capital, overhead costs, profits, and external support costs related to each type of vehicle. These costs are estimated in Table 34 and shown graphically in Figure 39.

TABLE 34. INSPECTION COST-SPEED-SENSITIVITIES RELATIONSHIPS WITH OPERATIONAL STOPS

Sensitivity Flaw (Size	Maximum Inspection Speed mph	Maximum Inspection Speed km/hr	System*[1]	Track Tested[2] Annually Miles	Track Tested[2] Annually Km	Initial[3] Installed Cost $ x 1000	Devel. Cost $ x 1000	Annual[4] Purchase and Devel. Cost $ x 1000	Annual Oper./Veh. Maintenance Cost $ x 1000	Annual[5] Support Test Equip. Cost $ x 1000	Support[6] Equipment Operating Cost $ x 1000	Total Ann.[7] Inspection System Cost $ x 1000	Inspection Cost Per Mile $	Inspection Cost Per Kilomete $
15% Trans verse 4 in. (10.2 cm) longi- tudinal	10	16.1	A-1	14,600[8]	23,500	618	-	65.6	100	5.3	77.4	397	27.25	17.00
			A-2	14,600[8]	23,500	228	-	30.0	70	5.3	77.4	292	20.00	12.50
			A-3	14,600[8]	23,500	668	150	71.1	100	5.3	77.4	406	27.75	17.25
			A-4	14,600[8]	23,500	278	150	36.9	70	5.3	77.4	303	20.75	13.00
			A-1	8,800[9]	14,200	618	-	65.6	98	-	-	262	29.75	18.50
			A-2	5,200[10]	8,370	228	-	30.0	63	-	-	149	28.75	17.75
5% Trans- verse 2 in. (5.1 cm) longi- tudinal	3	4.8	B-1	4,600	7,360	653	200	69.7	96	-	-	265	57.75	35.75
			B-2	4,600	7,360	263	200	35.1	64	-	-	159	34.50	21.50
			B-3	4,600	7,360	737	230	78.7	96	-	-	280	60.75	37.75
			B-4	4,600	7,360	347	230	46.3	64	-	-	176	38.50	23.75
1% Trans- verse 1 in. (2.5 cm) longi- tudinal	3	4.8	C	4,600	7,360	1,521	1,840	165.3	120	-	-	456	99.25	61.75
5% Trans- verse 2 in. (5.1 cm) longi- tudinal	10	16.1	D-1	14,600[8]	23,500	742	870	80.5	109	5.3	77.4	436	29.75	18.50
			D-2	14,600[8]	23,500	352	870	48.5	85	5.3	77.4	346	23.75	14.75
			D-3	14,600[8]	23,500	850	1,100	92.5	109	5.3	77.4	455	31.25	19.25
			D-4	14,600[8]	23,500	460	1,100	63.4	85	5.3	77.4	370	25.25	15.75
5% Trans- verse 2 in (5.1 cm) longi- tudinal	10	16.1	D-1	8,800[9]	14,200	742	870	80.5	107	-	-	300	34.00	21.25
			D-2	5,200[10]	8,370	352	870	48.5	78	-	-	202	39.00	24.25
			D-3	8,800[9]	14,200	850	1,100	92.5	107	-	-	314	36.25	22.50
			D-4	5,200[10]	8,370	460	1,100	63.4	78	-	-	226	43.50	2[illegible]

(*) Notes follow table.

TABLE 34 (Continued)

Sensitivity Flaw (Size	Maximum Inspection Speed mph	Maximum Inspection Speed km/hr	System*(1)	Track Tested(2) Annually Miles	Track Tested(2) Annually Km	Initial(3) Installed Cost $ x 1000	Devel. Cost $ x 1000	Annual(4) Purchase and Devel. Cost $ x 1000	Annual Oper./Veh. Maintenance Cost $ x 1000	Annual(5) Support Test Equip. Cost $ x 1000	Support(6) Equipment Operating Cost $ x 1000	Total Ann.(7) Inspection System Cost $ x 1000	Inspection Cost Per Mile $	Inspection Cost Per Kilometer $
15% Transverse 4 in. (10.2 cm) longitudinal	25	40.2	E-1	33,000	53,100	1,061	770	114.1	118	5.3	82.5	512	15.50	9.75
			E-2	33,000	53,100	765	840	83.0	118	5.3	82.5	462	14.00	8.75
			E-3	33,000	53,100	375	840	51.5	100	5.3	82.5	383	11.50	7.25
5% Transverse 2 in. (5.1 cm) longitudinal	25	40.2	F-1	33,000	53,100	1,096	970	118.3	121	5.3	82.5	523	15.75	9.75
			F-2	33,000	53,100	850	1,100	93.0	121	5.3	82.5	483	14.75	9.00
			F-3	33,000	53,100	460	1,100	63.4	105	5.3	82.5	410	12.50	7.75
15% Transverse 4 in. (10.2 cm) longitudinal	50	80.4	G-1	59,100	95,100	1,186	1,120	128.4	139	5.3	147.8	673	11.50	7.00
			G-2	59,100	95,100	937	1,350	102.2	139	5.3	147.8	631	10.75	6.75
			G-3	59,100	95,100	550	1,350	75.9	135	5.3	147.8	582	9.75	6.00
5% Transverse 2 in. (5.1 cm) longitudinal	50	80.4	H	59,100	95,100	1,346	1,770	157.1	148	5.3	147.8	733	12.50	7.75

Table 34 Notes.

(1) See Table 30 for description of system.

(2) Based on 5.9 hour testing day. Except where otherwise noted, testing distance based on effective testing speed which includes allowance for operational stops during the testing time.

(3) All costs are referenced to November, 1975 dollars.

(4) Assumed 15-year life for high-rail type system and 30-year life for rail system. Cost of capital is assumed to be 10 percent per year. A fleet of 50 vehicles is assumed.

(5) Where the inspection vehicle does not stop for hand verification tests of suspected flaws it is assumed that a separate high-rail vehicle is provided for this purpose. A purchase cost of $45,000, a vehicle life of 15 years, and a 10 percent annual interest rate is assumed.

(6) Based on Railroad B's joint testing vehicle cost and assumed crew size of one (accompanies primary test vehicle and therefore requires no additional operating personnel). Estimated cost of $2.50 per mile ($1.55 per kilometer).

(7) Includes estimate for G&A and profits. Based on current inspection costs of approximately $25-$35 for the A1 system (stops for hand tests), the multiplying factor is estimated to be 1.6.

(8) No stops for hand tests. This type system would normally stop for hand tests but this condition is included for completeness.

(9) Based on current experience of approximately 34 miles per day for a rail car. This includes stops for hand tests.

(10) Based on current experience with a high rail car. This includes stops for hand tests.

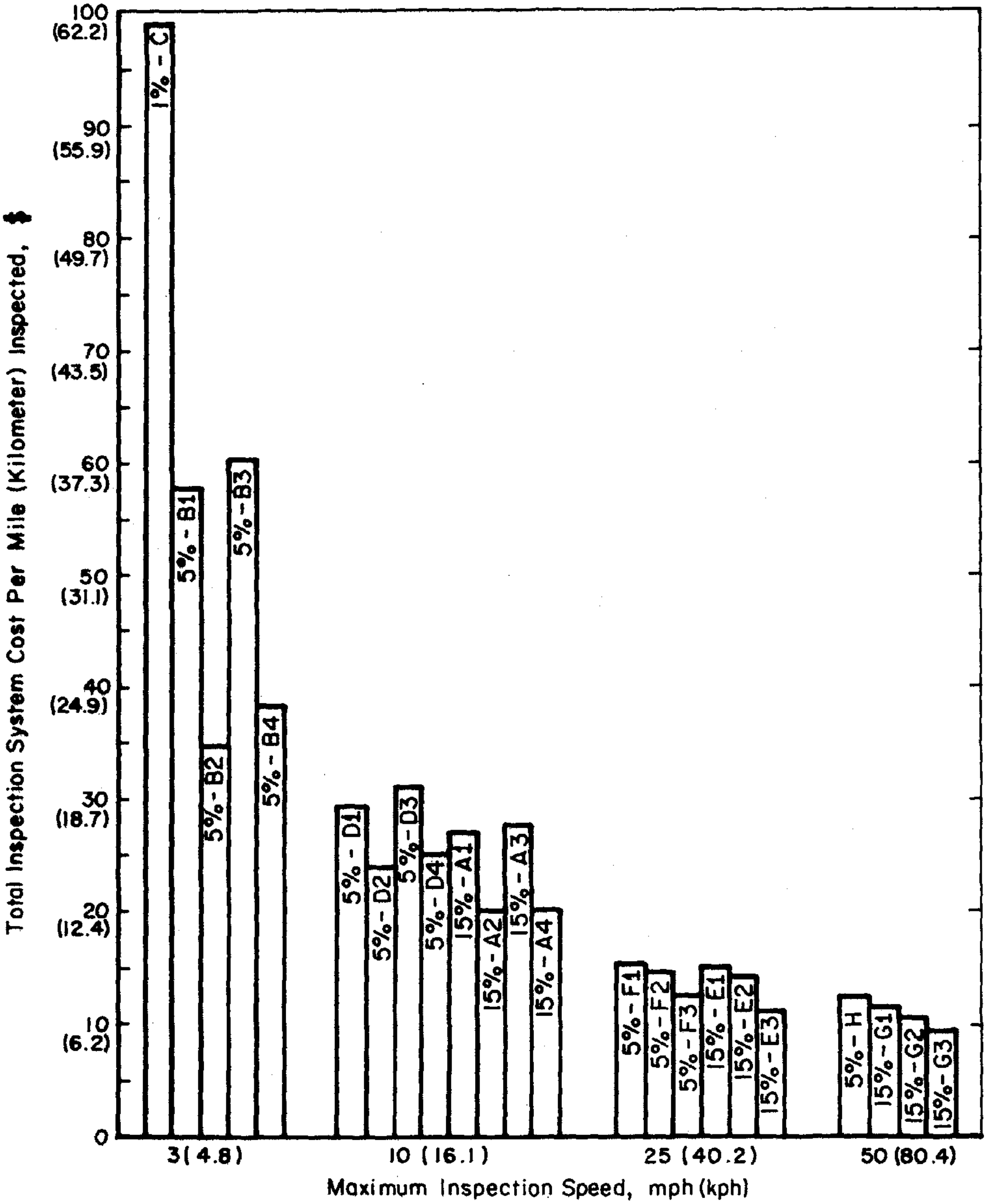


FIGURE 39. INSPECTION SPEED COST PER MILE (KILOMETER), SENSITIVITY RELATIONSHIPS

The bases for the first cost and the operations/maintenance costs were discussed under Item 5. Development costs shown in Table 34 are based on engineering judgment and past experience with the development of comparable equipment. The annualized purchase and development costs are arrived at by summing the estimated purchase and development costs and calculating the annual amount required to pay for this investment at an interest rate of 10 percent over the life of the vehicle system (assumed to be 30 years for a rail vehicle and 15 years for a high-rail vehicle).

This analysis assumes that the current practice of hand test verification of suspected flaws detected by the inspection vehicle will continue at an inspection speed of 10 mph (16 kph). These tests are assumed to be conducted by the crew of the inspection vehicle. At inspection speeds above 10 mph (16 kph), it is assumed that these hand tests are performed by a high-rail vehicle staffed with one person. This vehicle would travel with the primary inspection vehicle. The cost of the hand test vehicle is based on a high-rail joint tester used by Railroad B. The initial cost of this type of vehicle is approximately $45,000 with an estimated life of 15 years. Again, a 10 percent interest rate is used to estimate the annual cost of the vehicle. The operating/maintenance cost estimate for the vehicle is also based on Railroad B's experience. The cost used in the analysis is $2.50 per mile ($1.55 per kilometer).

The system costs discussed up to this point have not included any allowance for G and A and profits. Profits are applicable to leased services. Using the current leased service inspection costs of $25-35 per mile and estimated system operations, maintenance, development, and purchase costs, a multiplying factor of 0.6 (of operations, maintenance, development, and purchase costs) for G and A and profit is derived. This factor has been used in the analysis.

Examination of Table 34 and Figure 39 indicates that as inspection speed is increased, the inspection cost decreases. These data assume, as noted in Table 34, that the inspection vehicle is not restricted in speed, by track conditions, below the maximum speed capabilities of the vehicle.

This assumption is not valid for many branch lines and some lesser used main lines. It is necessary, therefore, to examine alternative inspection systems in the context of actual railroad systems. One would expect less of a difference in the inspection costs between the 25 and 50 mph (40.2 - 80.4 kph) alternatives than between alternatives at lower speeds. For this analysis, a track speed limit of 40 mph (64 kph) was assumed for medium density lines and a 20 mph (32 kph) speed limit was assumed for low density lines. No inspection speed limit was assumed for high density tracks.

In examining the application of the various inspection systems to specific railroads, it is necessary to consider the miles of track to be inspected annually. In doing this, the current inspection frequencies of the railroads providing data to this study were used. Further, in the case of the "A" and "D" inspection system configurations, it is assumed that the vehicle will stop for hand tests. Thus, the mileages that are appropriate to hand testing are used.

The inspection costs for various speeds and sensitivities for Railroad A are presented in Table 35 and Figure 40. Costs for Railroad B are presented in Table 36 and Figure 41 and for Railroad C, Table 37 and Figure 42. Figure 43 shows the speed, sensitivity, and cost relationships based on the average figures for all systems for the three railroads. As seen in these tables and figures, there is a significant reduction in inspection costs per mile (kilometer) as maximum inspection speed is increased from 10 mph (16.1 kph) to 25 mph (40.2 kph). Increasing the inspection speed to 50 mph (80.4 kph) produces a relatively small reduction in costs for any of the given inspection system configurations. Two primary reasons for this are the increased costs of the faster systems and the operating speed limits imposed by the tracks. The former effect is the primary one relative to Railroad A since that railroad inspects very little of their low density trackage where the speed restrictions are the most severe. The latter effect is somewhat more noticeable on Railroads B and C which do a substantial amount of rail inspection of low density lines.

TABLE 35. INSPECTION SYSTEM COSTS - RAILROAD A

Sensitivity, Percent	Maximum[1] Inspection Speed mph	Maximum[1] Inspection Speed kph	Annual Inspected Miles	Annual Inspected Km	Inspection System	Annual Develop. and Pur. Cost $ x 1000	Annual Oper. and Maintenance Cost $ x 1000	Annual Hand Test Equipment Cost $ x 1000	Annual Hand Test Oper. and Maintenance Cost $ x 1000	Total[2] Annual Cost $ x 1000	Inspection System Cost Per Mi $	Inspection System Cost Per Km $
15	10	14	10,775	17,337	A-1	80	122	-	-	323	30.00	18.65
					A-2	62	145	-	-	331	31.00	19.10
					A-3	87	132	-	-	334	31.00	19.30
					A-4	76	145	-	-	354	33.00	20.40
5	10	14	10,775	17,337	D-1	98	133	-	-	370	34.50	21.35
					D-2	100	176	-	-	442	41.00	25.50
					D-3	113	134	-	-	395	36.50	22.80
					D-4	131	176	-	-	492	45.50	28.35
15	25	40	10,775	17,337	E-1	38	39	2	27	169	15.50	9.75
					E-2	27	39	2	27	152	14.00	8.80
					E-3	17	39	2	27	126	11.50	7.25
5	25	40	10,775	17,337	F-1	39	39	2	27	171	16.00	9.85
					F-2	31	39	2	27	157	14.50	9.10
					F-3	21	35	2	27	135	12.50	7.80
15	50	80	10,775	17,337	G-1	26	28	1	27	131	12.00	7.55
					G-2	20	25	1	27	119	11.00	6.90
					G-3	15	27	1	27	112	10.50	6.50
5	50	80	10,775	17,337	H	31	30	1	27	143	13.50	8.25

(1) The numbers shown are vehicle limits. Assumed truck limits for medium density lines is 40 mph (64 kph) and for low density lines 20 mph (32 kph). The track limit is higher than any inspection vehicle speed considered for high density lines.

(2) Includes allowance for G&A and profits (0.6 x direct inspection costs).

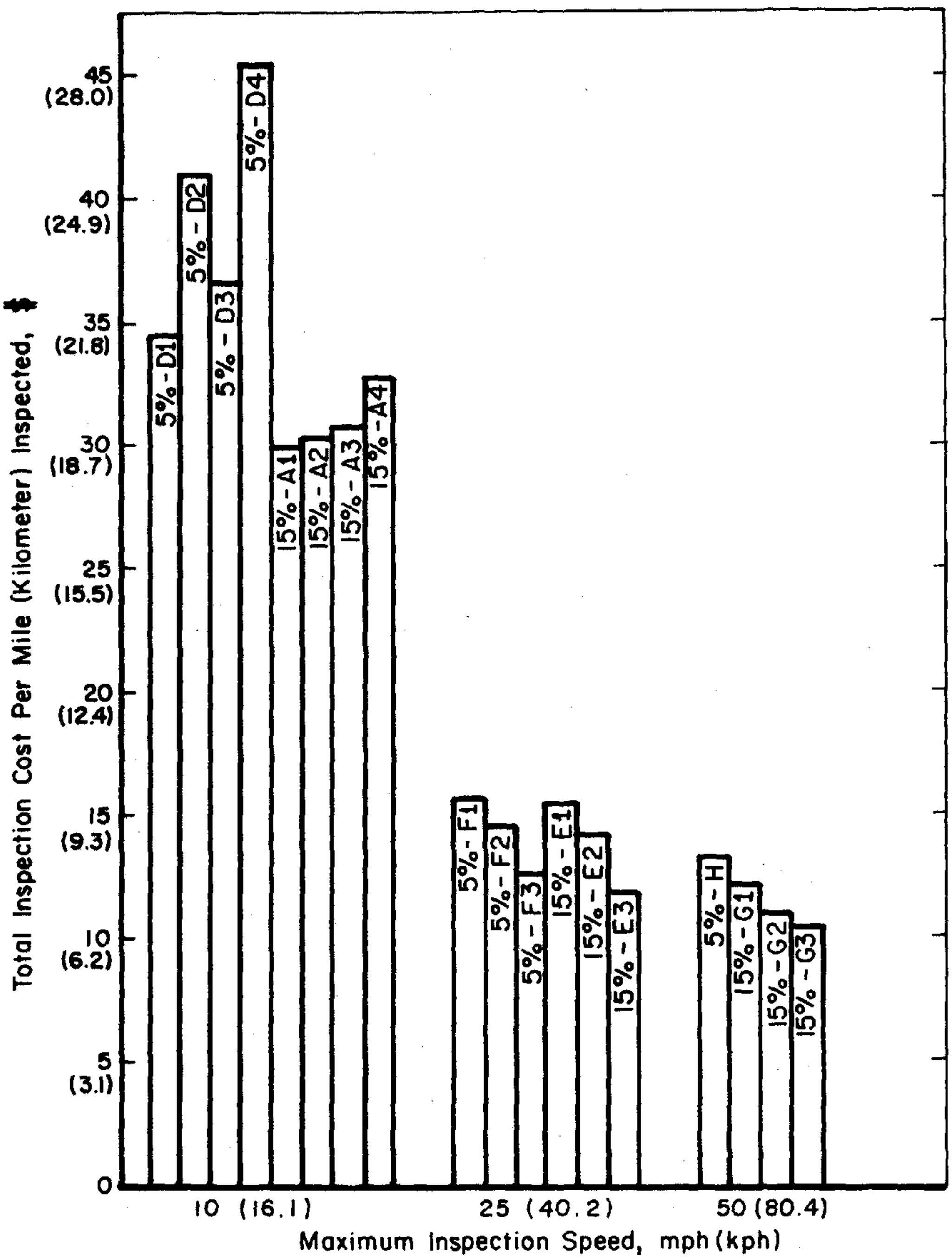


FIGURE 40. INSPECTION SPEED, COST PER MILE (KILOMETER), SENSITIVITY RELATIONSHIPS - RAILROAD A

TABLE 36. INSPECTION COSTS - RAILROAD B

Sensitivity, Percent	Maximum[1] Inspection Speed mph	kph	Annual Inspected Miles	Kilos.	Inspection System	Annual Develop. and Pur. Cost $ x 1000	Annual Oper. and Maintenance Cost $ x 1000	Annual Hand Test Equipment Cost $ x 1000	Annual Hand Test Oper. and Maintenance Cost $ x 1000	Total[2] Annual Cost $ x 1000	Inspection System Cost Per Mi $	Per Km $
15	10	14	22,695	36,516	A-1	169	258	-	-	684	30.00	18.70
					A-2	131	306	-	-	699	31.00	19.15
					A-3	183	258	-	-	706	31.00	19.35
					A-4	161	306	-	-	748	33.00	20.50
5	10	14	22,695	36,516	D-1	208	280	-	-	780	34.50	21.35
					D-2	212	348	-	-	896	39.50	24.55
					D-3	239	281	-	-	832	36.50	22.75
					D-4	277	372	-	-	1038	46.00	28.45
15	25	40	22,695	36,516	E-1	82	85	4	57	365	16.00	10.00
					E-2	60	85	4	57	329	14.50	9.00
					E-3	37	72	4	57	272	12.00	7.45
5	25	40	22,695	36,516	F-1	85	87	4	57	373	16.50	10.20
					F-2	67	87	4	57	344	15.00	9.40
					F-3	46	77	4	57	294	13.00	8.05
15	50	80	22,695	36,516	G-1	60	63	3	57	293	13.00	8.00
					G-2	48	63	3	57	275	12.00	7.55
					G-3	36	62	3	57	254	11.00	6.95
5	50	80	22,695	36,516	H	74	69	3	57	324	14.00	8.85

(1) The numbers shown are vehicle limits. Assumed truck limits for medium density lines is 40 mph (64 kph) and for low density lines 20 mph (32 kph). The track limit is higher than any inspection vehicle speed considered for high density lines.

(2) Includes allowance for G&A and profits (0.6 x direct inspection costs).

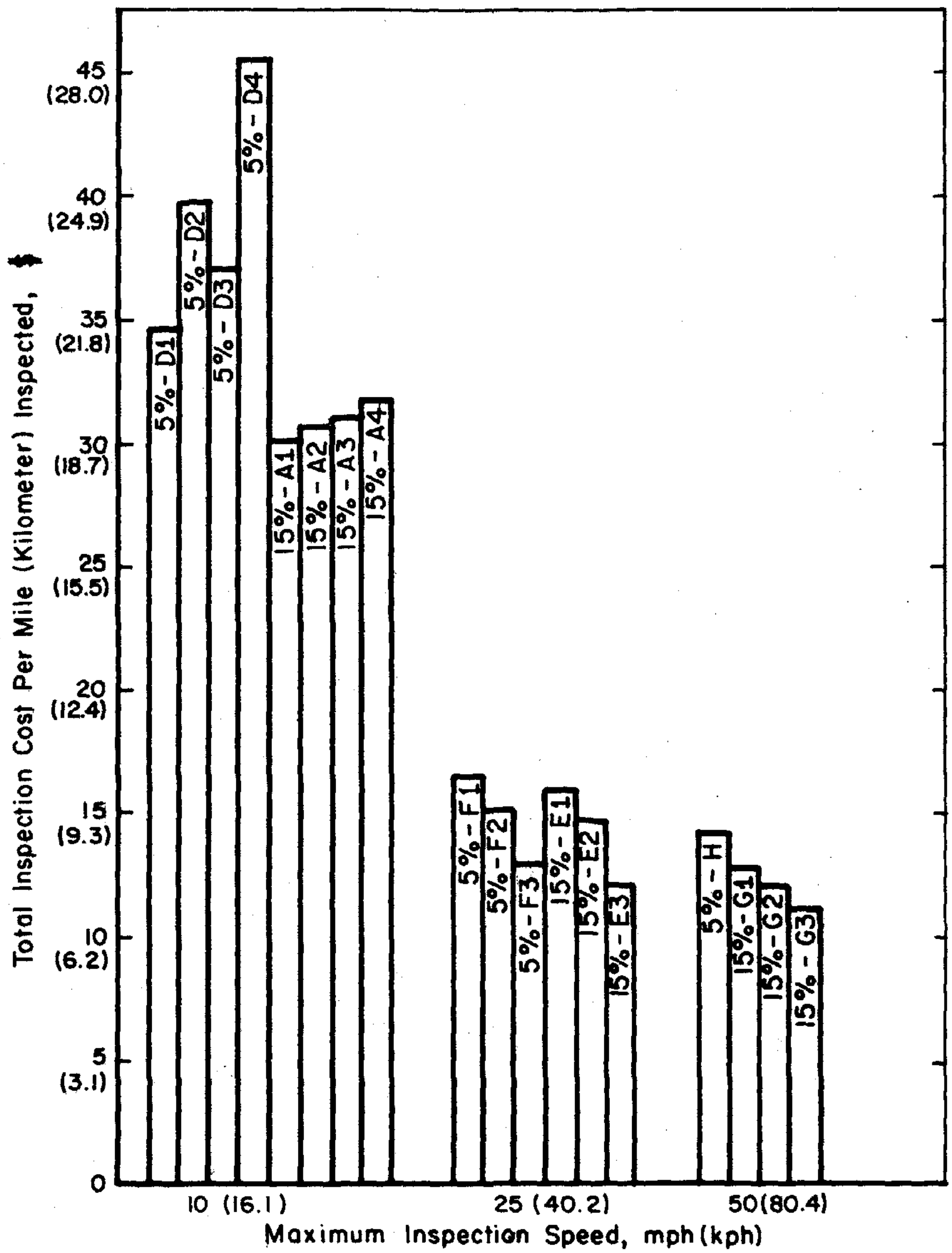


FIGURE 41. INSPECTION SPEED, COST PER MILE (KILOMETER), SENSITIVITY RELATIONSHIPS - RAILROAD B

TABLE 37. INSPECTION SYSTEM COSTS - RAILROAD C

Sensitivity, Percent	Maximum Inspection Speed[1] mph	kph	Annual Inspected Miles	Kilos.	Inspection System	Annual Develop. and Pur. Cost $ x 1000	Annual Oper. and Maintenance Cost $ x 1000	Annual Hand Test Equipment Cost $ x 1000	Annual Hand Test Oper. and Maintenance Cost $ x 1000	Total[2] Annual Cost $ x 1000	Inspection System Cost Per Mi $	Per Km $
15	10	14	25,160	40,482	A-1	195	299	-	-	791	31.50	19.55
					A-2	153	357	-	-	815	32.50	20.15
					A-3	213	299	-	-	819	32.50	20.15
					A-4	188	357	-	-	871	34.50	21.50
5	10	14	25,160	40,482	D-1	241	320	-	-	898	35.50	22.20
					D-2	247	397	-	-	1031	41.00	25.45
					D-3	277	320	-	-	955	38.00	23.60
					D-4	323	397	-	-	1152	46.00	28.45
15	25	40	25,160	40,482	E-1	95	98	4.4	62.9	416	16.50	10.25
					E-2	69	98	4.4	62.9	375	15.00	9.25
					E-3	43	83	4.4	62.9	309	12.50	7.65
5	25	40	25,160	40,482	F-1	98	101	4.4	62.9	426	17.00	10.50
					F-2	77	101	4.4	62.9	392	15.50	9.70
					F-3	53	87	4.4	62.9	332	13.00	8.20
15	50	80	25,160	40,482	G-1	78	85	3.3	62.9	366	14.50	9.05
					G-2	62	85	3.3	62.9	341	13.50	8.40
					G-3	46	82	3.3	62.9	312	12.50	7.70
5	50	80	25,160	40,482	H	96	90	3.3	62.9	403	16.00	9.95

(1) The numbers shown are vehicle limits. Assumed truck limits for medium density lines is 40 mph (64 kph) and for low density lines 20 mph (32 kph). The track limit is higher than any inspection vehicle speed considered for high density lines.

(2) Includes allowance for G&A and profits (0.6 x direct inspection costs).

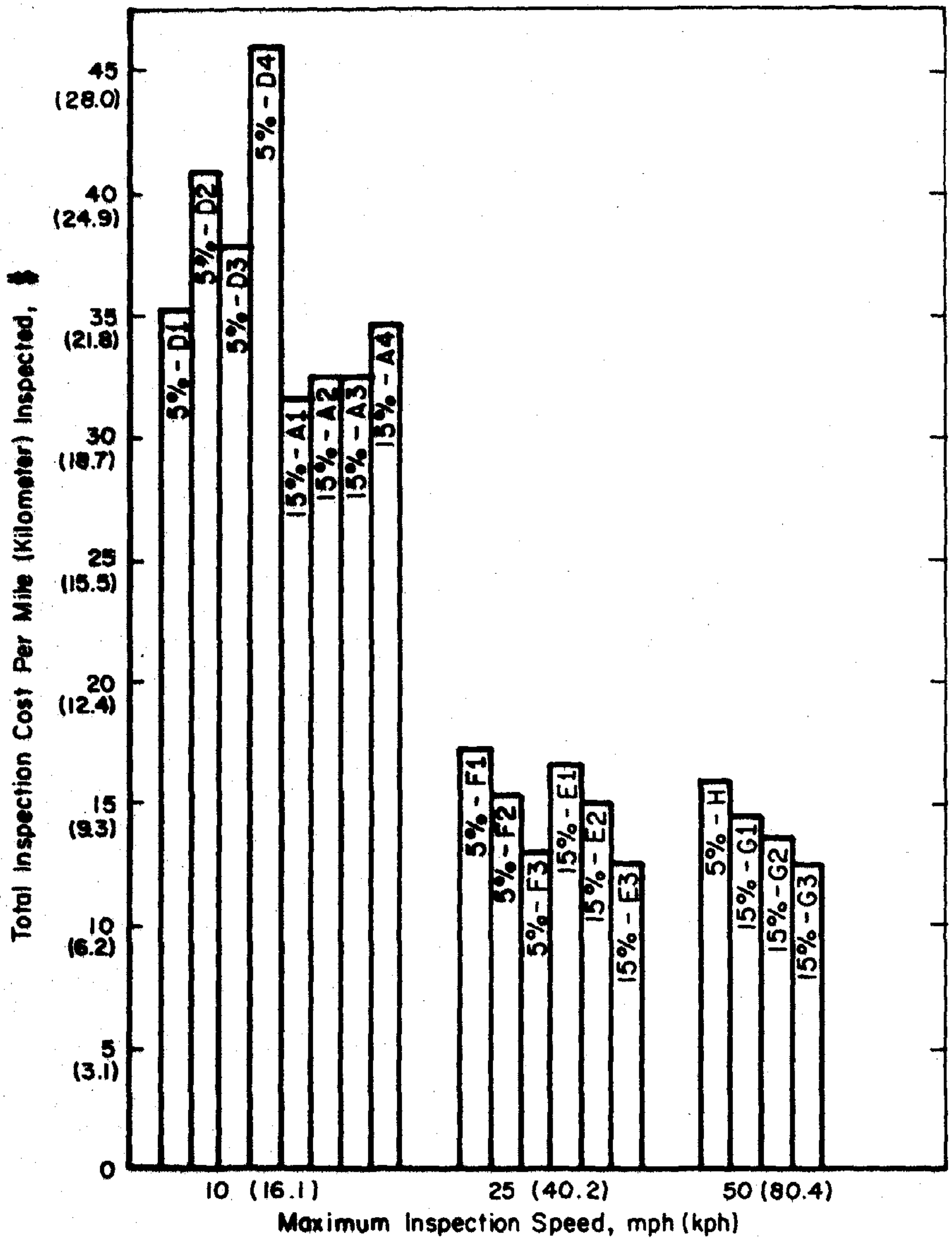


FIGURE 42. INSPECTION SPEED, COST PER MILE (KILOMETER), SENSITIVITY RELATIONSHIPS - RAILROAD C

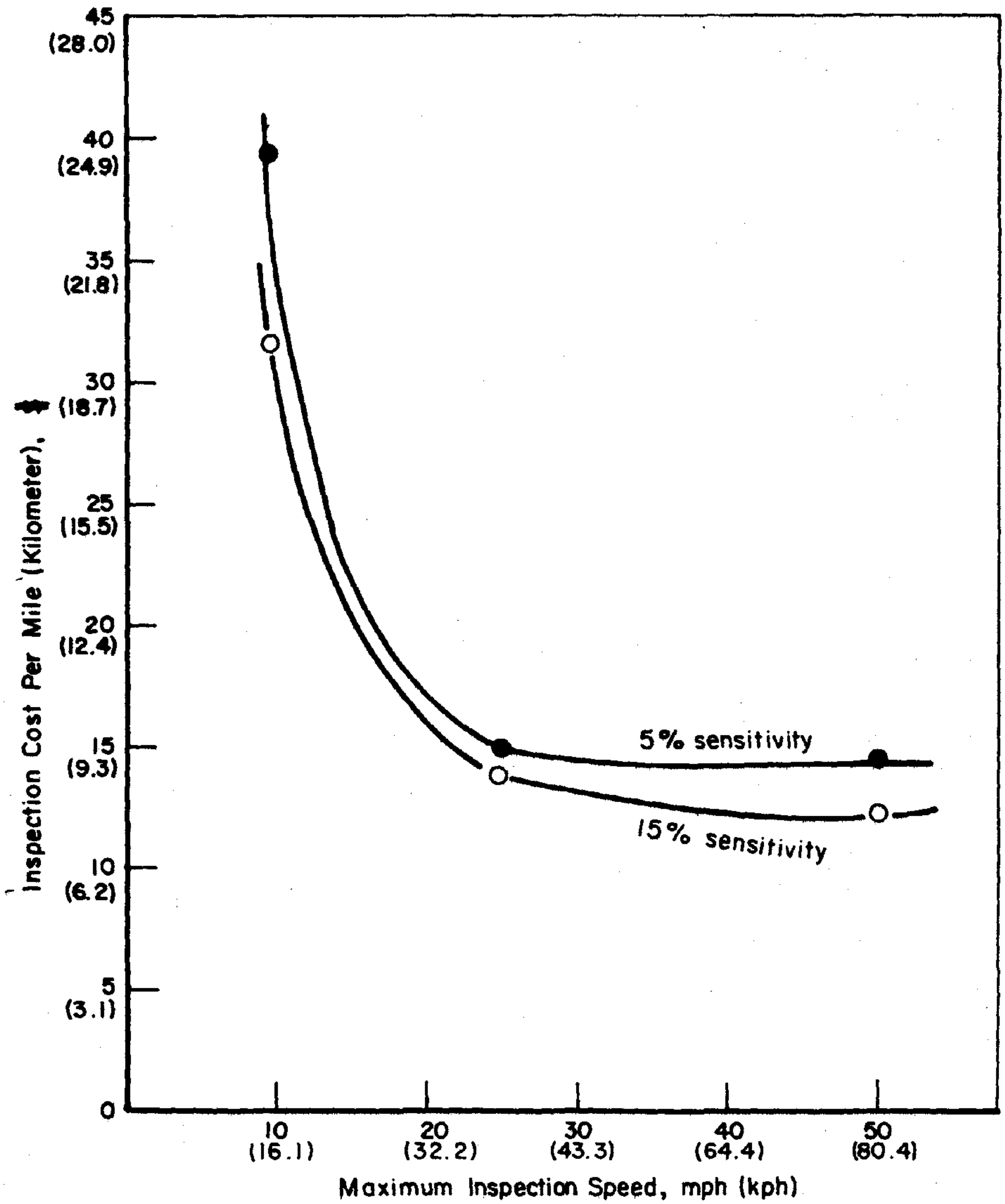


FIGURE 43. AVERAGE COST

As indicated previously, speed limits of 40 mph (64 kph) and 20 mph (32 kph) were used in this analysis for medium and low density lines. These limits are probably somewhat on the high side of the range of inspection speeds possible on these lines. Consequently, there probably is even less of a difference between the 25 mph (40.2 kph) and 50 mph (80.4 kph) systems relative to costs.

Except for the "A" and "D" system alternatives the productivities of rail and high-rail inspection vehicles are assumed to be equal. Very limited data from the test railroads indicates a somewhat lower average inspection speed for current high-rail vehicle inspection systems than for rail vehicle systems. These differences may well be attributable to the inspection system and the attendant data rates rather than to the type of vehicle used.

It should be pointed out that this analysis is based on the premise that the same inspection vehicle will be used throughout the system. For example, a system that is capable of 50 mph (80 kph) speeds will be used on branch lines (at a reduced speed) as well as on the high-speed main line tracks. In practice, it is likely that the inspection fleet will consist of both high- and low-speed vehicles to better match the requirements of the railroads. This is particularly true where the inspection is performed by a service company that can achieve high inspection vehicle utilization through the larger operating base of more than one railroad. The major drawback of using lower speed inspection vehicles for branch lines, yard tracks, and other low-speed tracks is the lost time in moving the vehicle from one point to another without performing inspection enroute. This drawback could be offset by sharing the enroute inspection task with higher speed inspection vehicles.

As has been shown, the line-haul rail inspection costs for a given railroad can be significantly reduced even when high-speed inspection vehicles are used for line-haul track inspection at lower speeds to match track speed limitations. The inclusion of yard tracks will increase the per mile (kilometer) costs of the higher speed inspection vehicles if these vehicles are used for this low speed task. This increase in cost is not expected to offset the cost benefits of the higher speed systems as compared to current inspection systems. It will, however, reduce the already marginal cost benefits of the 50 mph (80 kph) systems over the 25 mph (40 kph) systems.

It should be further noted that high-rail vehicle speeds of up to 50 mph (80 kph) are possible. Such speed capabilities would require redesign of the suspension system to permit safe operation. Also, no reduction in high rail system productivity is included to allow for replenishing the limited water supply that can be carried by a high-rail vehicle nor is there a specific allowance for trailer-type storage tank to provide the water for uninterrupted testing at 50 mph (80 kph). Consequently, the difference between high-rail and rail vehicle costs at the higher speeds, particularly at 50 mph (80 kph), is likely to diminish and be in favor of the rail vehicle.

Inspection System Impacts

The overriding reason for rail inspection is to control the number of in-service rail failures within acceptable limits. The result of a rail failure is,at worst,a derailment and at best, train delays until the rail can be repaired/replaced. In either case, the cost to the railroad and the safety of the public dictates the need for extensive rail-failure preventive measures, including rail inspection.

As indicated in the preceding section, inspection costs per unit length of track can be reduced by increasing inspection speed. Various alternatives for achieving increased inspection speeds are described under Item 5. Higher inspection speeds and lower per mile (kilometer) inspection costs permits more frequent rail inspection for a given cost and thus, would be expected to reduce the number of rail failures and the attendant costs. Further, increasing sensitivity would permit a reduction in the number of inspections or a reduction in the number of rail failures that occur for a given inspection frequency.

This relationship of sensitivity and inspection frequency is illustrated in Figure 44. Point 1 indicates a detected flaw prior to failure with detection levels 1, 2, or 3. Curve I illustrates the case where the flaw should have been detected at Point 2 but was missed by the detection system. With the basic inspection interval this flaw would not be detected prior to failure at Point 3. A shorter inspection interval could result in detecting at Point 4 prior to failure.

Curve II illustrates the case where the flaw is below detection Level 3 at one inspection (Point 5) and reaches a failure level, Point 6, prior to the next inspection. Such a flaw could be detected prior to failure by making the inspection system more sensitive (detected at Point 5) or by reducing the inspection interval (detected at Point 7).

Curve III illustrates the case where the flaw growth rate is sufficiently low to permit its detection with a low sensitivity (Level 3) and a relatively infrequent inspections.

Curve IV illustrates a relatively rapidly growing flaw. As shown, the detection of such a flaw requires both a sensitive detection system and frequent inspections.

Curve V illustrates a very rapidly growing flaw that could be detected only with very frequent inspections and a highly sensitive system.

The flaw curves in Figure 44 are shown to be straight lines for illustrative purposes only. Indeed, the subject of flaw initiation and growth relative to the many service and environmental variables experienced by a rail is an extremely complex one and the subject of extensive research that is not yet complete. Until such time as flaw initiation and growth is better understood, it is not possible to state with certainty what the impact of different inspection frequencies and/or sensitivities will be. However, it is possible to provide some insight into the potential for reduced rail failure costs and to make limited comparisons between railroads that use different inspection frequencies.

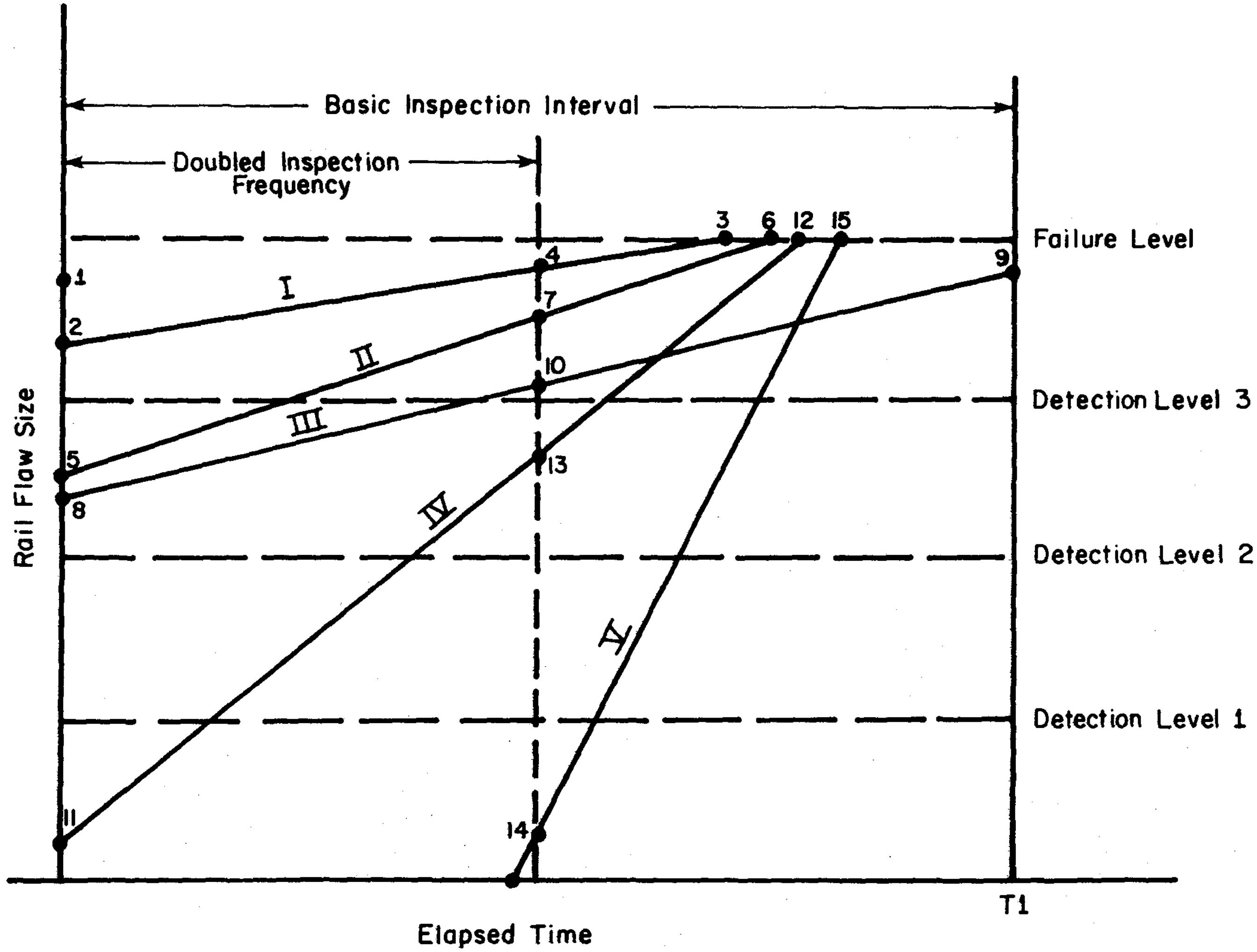


FIGURE 44. INSPECTION SENSITIVITY-FREQUENCY RELATIONSHIPS ELAPSED TIME.

The number and costs of rail-caused derailments for the 1-year study of railroads are shown in Table 38. The 1-year sample presented in Table 38 is rather small and it is not known if these are typical of the ongoing experience of the railroads. If it is assumed that these data are representative of the experience of the railroads, one can conclude that Railroad A has a higher number of rail-cause derailments than Railroads B or C but the cost of each of these derailments on Railroad A is, on the average, considerably less than on Railroad B. These observations are consistent with the facts that Railroad B operates its trains at generally higher speeds and inspects rails at more frequent intervals. Thus, one would expect fewer derailments per unit of track usage because of the more frequent inspections but perhaps a higher cost per derailment because of the higher operating speeds.

Railroad C inspects more frequently than Railroad A and at a comparable frequency with Railroad B. Railroad C's operating speed is generally less than the maximum of Railroad B. Thus, the rail-caused derailment frequency of Railroads B and C are comparable but the derailment costs are less for Railroad C.

Based on the above data and comparisons, Railroad A has a potential of reducing derailment costs by up to approximately $2.6 million annually by more frequent and/or more sensitive rail flaw inspections. Railroad B has potential savings of up to $765 thousand annually and Railroad C of up to $357 thousand. These figures apply to line-haul tracks where higher speed inspection is appropriate and do not include yard derailments which would not be appreciably impacted by increased inspection speeds.

As a practical matter, it is not likely that all of the rail-caused derailments can be eliminated even with very frequent and sensitive inspections. The reason for this is the likelihood of some very rapidly progressing defects that initiate and mature to rail failure between even the more frequent inspection passes.

TABLE 38. SUMMARY OF RAIL-CAUSED DERAILMENTS--
ONE YEAR PERIOD

Railroad	Derailments			Derailment Cost, \$ x 1000[a]			
	High Density	Medium Density	Low Density	High Density	Medium Density	Low Density	Total
A	12	39	1	600[b]	1,950[b]	50[b]	2600
B	2	1	4	372	213	180	765
C	2	4	4	157	155	45	357

(a) Derailment costs are equal to twice the costs reported on FRA Form T to account for clearing, train service, and other costs not included on Form T.

(b) Based on average rail-caused derailment cost of \$50,000.

The determination of the most economical inspection frequency is heavily dependent on the characteristics of rail flaw initiation and propagation which, in turn, is dependent on a variety of factors peculiar to a track segment. Thus, until such time as the results of research into various areas related to flaw initiation and growth are available, it is necessary to determine inspection frequency on a trial-and-error basis to achieve an acceptable level of rail-caused derailments. The relative derailment experience of Railroads A, B, and C suggest the need for further research into the economic benefits of various rail flaw inspection policies. Such research would include a longer data base time period than the 1 year used in this study. Further, the research would attempt to refine the classification of tracks in terms of the factors that affect rail flaw initiation and propagation as determined by rail studies. Knowing the characteristics of flaw development, inspection system costs, and rail failure/derailment costs, the optimum inspection frequency/sensitivity can be calculated for each track classification.

Not all rail failures result in a derailment. In 1974, Railroad B experienced approximately 60 nonderailment rail failures. Such failures result in train delays and attendant costs. These failures are impacted by inspection frequency and sensitivity in the same manner as derailments.

The current policy of railroads is to repair rail defects as they occur, particularly in main line service. The impact of higher speed, inspection systems relative to this policy depends primarily on the number of flaws detected. In high speed main line tracks where few flaws are detected, the current sized accompanying repair crew may be able to readily keep up with the higher speed inspection vehicle. Work crew boundaries may require a change in the composition of the crew during the day as the inspection moves across the railroad, thus incurring some cost penalties because of these transitions.

On track sections where a greater number of flaws are detected than can be readily repaired by the conventional size repair crew in a day, it would be necessary to assign additional repair crews to accompany the inspection vehicle or to revert at least partially to a policy of slow orders until defective rails can be replaced. A third alternative is to reduce the inspection speed below maximum or limit the work day to the detection of the flaws that can be handled by the accompanying crew. This latter option increases inspection costs in proportion to the decreased usage of the inspection vehicle. While there could be some policy other than to repair flaws on high speed track immediately after they are found (as practiced by the test railroads), the perceived risk by railroad management, even with slow order protection, is unacceptably high. Consequently, it is likely that the current "repair as you go" policy will remain in effect on some railroads even with higher speed inspection vehicles. The possible added expense of additional accompanying crews is expected to be more than offset by the increased productivity of these crews brought about by shorter travel time periods between detected rail defects resulting from the higher inspection speeds.

As described previously, rail inspection does not alter the basic factors that combine to cause a rail flaw. Consequently, increasing the frequency and/or sensitivity of rail inspection alone will not alter the number of flaws that occur over a period of time. Inspection merely detects these flaws prior to their reaching a failure point. However, if a railroad should use an inspection vehicle that is more sensitive than current vehicles or inspect more frequently than is the current practice, there will be a transition period during which rail replacements will occur at a higher rate than normal. During this transition, a higher railroad investment would be required in rails and labor. The determination of the optimum inspection frequency/sensitivity for a given railroad will depend on the availability of railroad capital. In effect, the rail replacements resulting from increased inspection frequency and/or sensitivity produces an upgraded track system relative to the rail element of this system. The extent to which the increased cost of upgrading is offset by reduced rail failures and derailments can only be determined after a better understanding is gained of the characteristics of rail flaw initiation and propagation. Again, if the flaw growth is quite rapid in the range of flaw detection, the benefits of improved flaw detection (reduced rail failure and derailment costs) may not offset the increased rail replacement costs. Thus, the determination of the impact of increased inspection sensitivity and frequency must await the results of research into flaw initiation and growth phenomena.

Cost Analysis Conclusions

The following conclusions are derived from the cost analysis of alternative inspection systems:

(1) Significant reductions in rail inspection per mile (kilometer) costs can be derived from higher speed inspection vehicles. The greatest reduction occurs in increasing speed from the current capability (3 to 10 mph - 5 to 16 kph) to 25 mph (40 kph). Above this level, the inspection cost per mile (kilometer) continues to decrease, but at a relatively slow rate. This leveling is partially due to track speed restrictions that limit inspection speeds.

(2) Inspection systems using all ultrasonic sensors and a high-rail vehicle are generally less expensive (cost per unit length of track) than systems with magnetic systems using a rail vehicle. This assumes comparable productivities of these systems. The water carrying capacity of high-rail vehicles is marginal at higher speeds for all-day operation without refilling the

water tanks. The need to refill would reduce inspection time and, therefore, reduce productivity.

(3) At the higher inspection speed of 25 mph (40 kph) and 50 mph (80 kph) there is a rather small difference between the unit inspection costs at 5 percent and 15 percent sensitivities.

(4) The optimum rail inspection frequency and sensitivity are dependent on flaw initiation and growth characteristics. These characteristics are not sufficiently well known at this time to determine the optimum inspection frequency and sensitivity.

ITEM 9 - RECOMMENDED RAIL FLAW INSPECTION SYSTEM

The results of the cost analysis described in the preceding section clearly indicate a significant reduction in inspection costs as speeds are increased above those of the present rail inspection vehicles. Cost reductions are most significant up to a nominal maximum speed of 25 mph (40 kph) with cost reductions being rather low above this speed.

Cost reductions for speeds above 25 mph (40 kph) are to a large extent dependent upon vehicle usage. If the vehicle is used only on a single railroad with moderately low speed limits on main line track, and a large percentage of branch lines and yards, there is little or no cost incentive for procuring an inspection vehicle with maximum speed capabilities above about 25 mph (40 kph); however, if the vehicle were to be operated primarily on main line track it would be desirable to have the capability of operating at up to the speed limit of that line. Therefore, for many railroads it is believed that in the forseeable future the most practical rail inspection vehicle will be one with a maximum inspection speed capability of about 25 mph (40 kph).

For more specialized applications, such as use by an inspection service company where the vehicle can be predominantly scheduled for use on higher speed lines, by a large railroad with a large percentage of high-speed main line, or by the Government to check main lines of many railroads, there is a stronger cost incentive for procuring a vehicle which will operate at 50 mph (80 kph) or greater speeds.

In order to best meet the needs of the smaller railroads with lower speed limits and larger railroads and agencies which can effectively use a high-speed vehicle, it is recommended that development be started of an inspection vehicle which will have an ultimate speed capability in excess of 50 mph (80 kph). In order to effectively and rapidly utilize existing technology without incurring excessive delays in developing all of the technology necessary to operate a 50 mph (80 kph) vehicle, it is recommended that the inspection vehicle be designed and developed in a modular configuration. In the initial configuration, many of the modules would be current state of the art with speed limitations of about 25 mph (40 kph); however, the basic vehicle would be capable of sustained speeds in excess of 50 mph (80 kph). To obtain sustained speeds of over 50 mph (80 kph) with current technology, it is desirable to use rail type rather than high-rail type vehicle as the basic vehicle because the suspension systems on high-rail vehicles have not been designed for high-speed operation, and because high-rail vehicle small enough to easily enter and leave track at grade crossings would have to leave the track several times a day to refill the couplant water tanks. Other factors in favor of a rail type vehicle are that with a rail type vehicle there is adequate space and load carrying capacity to easily use large numbers and/or heavy transducers and data processing systems, including geometry or other types of inspection systems, and that loading on the rail can be made high enough to produce tensile stresses in the rail head large enough to open and improve the detectability of transducer type defects which are normally too tightly close to be readily detectable.

It is recommended that an automatic data processing system be developed for the new vehicle which is also in a modular configuration so that it can also easily be modified to accept new transducer systems as they are developed. It is recommended that the configuration of the data processing system be one where there are micro- or mini-computers dedicated to processing the data from individual transducers and decides in real time if the data produced are normal or abnormal, and a central minicomputer which receives and compares abnormal data from the several dedicated computers to decide if a flaw exists. This system is described in more detail in the section on data processing. It is recommended that the data processing system should be initially developed for a minimum speed of 25 mph (40 kph), but that the configuration and components be selected and procurred which will give the system an ultimate speed capability in excess of 50 mph (80 kph).

As indicated in the cost analysis section, there is a relatively little cost per mile (kilometer) difference between systems having 15 percent and 5 percent detection capabilities. Further, the higher sensitivity (5 percent) may permit less frequent inspections (and, therefore, lower total inspection costs) depending on the nature of the flaw growth curve. Consequently, a system with 5 percent detection capabilities is recommended.

Combining the above recommendations the recommended system is either the F1 (combined magnetic and ultrasonic sensors) or the F2 (all ultrasonic sensors) configurations, as described in Table 31. The final choice between these configurations will depend, to some degree, on the outcome of current research that is directed at developing improved magnetic techniques to differentiate between surface and subsurface defects. The choice between these two approaches can be made during system design as part of the engineering trade-off studies that are an integral part of the design process.

To provide the best transducer system, it is recommended that research on both magnetic and ultrasonic transducers continue. For ultrasonic systems the emphasis should be on developing improved high-speed wheel and sled coupling systems, and on developing transducer orientations that will not miss poorly oriented flaws and will produce adequate flaw size information to allow the ability to detect small flaws to be effectively utilized. For magnetic systems, the emphasis should be on the development of systems which will distinguish between surface and subsurface defects, on systems which will operate at high speeds, and on systems which will operate close to a joint.

In summary, the recommended system is one that uses a rail vehicle, has an ultimate inspection speed capability of at least 50 mph (80 kph), with an initial speed capability of at least 25 mph (40 kph), and has an inspection sensitivity to detect flaws of 5 percent of the rail cross section or longitudinal flaws of 2 inches (10.2 cm) or less. Development of transducer systems should continue and the inspection vehicle should be constructed so that the vehicle can be readily modified to use the new transducer systems as they are developed.

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