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Washington, D.C. 20590

Volume I Final Report (Including Appendices A Through E)

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16. Abstract

The results of this study substantiate the concept of using automatic track inspection vehicles as a tool in Maintenance-of-Way planning. This study is based on data collected over a period of one year on 288 miles of CONRAIL mainline track. Track geometry was measured using an FRA Track Geometry Measurement Vehicle.

The concept of a figure of merit, based on track geometry (gage, profile, alignment, crosslevel and warp) and used as a means of quantifying track condition is developed. It is shown through correlation with Federal Track Safety Standards, standard Ride Quality Indices, and derailments that these figures of merit, referred to as Track Quality Indices (TQI's), are an objective measure of track condition. An initial set of 14 candidate TQI's is reduced to a set of five which best quantify the track's ability to meet its functional requirements.

Next, eleven selected physical parameters, which affect the rate of track deterioration, are investigated. These are categorized as traffic, track structure and maintenance parameters. It is found that a subset of these is capable of accounting for at least 80 percent of the change in track condition as measured by a TQI. Predictive equations for each of the five TQI's are given for six levels and/or types of maintenance. These equations are significant above the 0.999 level. Illustrative degradation curves are derived from the predictive equations and specific observations are made for the test zone.

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METRIC CONVERSION FACTORS

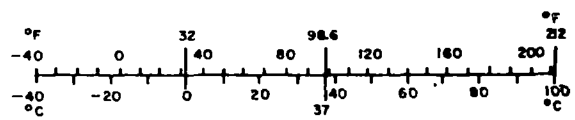
Approximate Conversions to Metric Measures

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

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

Approximate Conversions from Metric Measures

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



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LIST OF SYMBOLS

a	-	estimated intercept in regression equation
A	-	alignment
AS	-	two-foot mid-chord-offset
b	-	estimated regression coefficient
D	-	smooth curvature, degradation coefficient
e	-	error of estimate
f	-	temporal frequency (Hz)
F	-	transfer function
G	-	gage
H	-	hypothesis
m	-	moment of probability density function
N	-	number of samples
P	-	profile
PS	-	three-foot profile mid-chord-offset
r	-	correlation coefficient
R^2	-	coefficient of determination
$R^{2'}$	-	adjusted coefficient of determination
s	-	standard error of estimate
S	-	spectral density
SE	-	balanced superelevation
v	-	speed
W	-	warp
x	-	physical parameter as independent variable
XL	-	crosslevel
y	-	TQI as independent variable
z	-	arbitrary independent variable
Z	-	measured displacement
α	-	intercept in linear regression equation
β	-	regression coefficient
λ	-	wavelength
σ	-	standard deviation
ϕ	-	spatial frequency (cycles/ft)

SUPERSCRIPTS

$\hat{}$	-	present value
$'$	-	arbitrary value
$\bar{}$	-	mean value

LIST OF ABBREVIATIONS

AAR	-	Association of American Railroads
ANOVA	-	Analysis of Variance
AREA	-	American Railway Engineering Association
ATIP	-	Automated Track Inspection Program
BM	-	Basic Maintenance
B&LE	-	Bessemer and Lake Erie Railroad
C&O	-	Chesapeake and Ohio Railroad
CONRAIL	-	Consolidated Rail Corporation
CRT	-	Cathode Ray Terminal
DBMS	-	Data Base Management System
D&H	-	Delaware and Hudson Railroad
DOT	-	Department of Transportation
D&RGW	-	Denver and Rio Grande Western Railroad
FCS	-	File Control System
FRA	-	Federal Railroad Administration
ISO	-	International Standards Organization
JSSA	-	J.S. Shaffer, Jr., Associates
MCO	-	Mid-Chord Offset
MGT	-	Million Gross Tons
MOW	-	Maintenance-of-Way
MSSR	-	Mean regression Sum of Squares
MP	-	Milepost
OFS	-	Office of Freight Systems
OR&D	-	Office of Research and Development
ORSR	-	Office of Rail Safety Research
PDF	-	Probability Density Function
PSD	-	Power Spectral Density
RASP	-	Regression Analysis Software Package
RDS	-	Raytheon Data Systems
RMS	-	Root Mean Square
RQI	-	Ride Quality Index
SE	-	High Speed Surfacing Operation
SL	-	Sealand Train
ST	-	Surfacing Portion of a Tie and Surface Gang
SSE	-	Error Sum of Squares
SSR	-	Regression Sum of Squares
SST	-	Total Sum of Squares
TK	-	Kershaw Tie Injector
TQI	-	Track Quality Index
TQI's	-	Track Quality Indices
TQISP	-	Track Quality Indices Software Paackage
TRAMP	-	Track Measurement Program

EXECUTIVE SUMMARY

In order to develop methods of determining future needs of railroad Maintenance-of-Way, two things must first be accomplished. First, a means of quantifying the condition of the track must be developed. Second, the relationship between these quantifiers and those parameters which cause the track condition to change, either degrade or improve, must be established. These two basic objectives comprise the main thrust of the present work that is documented in this report.

In this study figures of merit, referred to as Track Quality Indices abbreviated TQI's, are developed. A TQI is a single number based on one of the well known track geometry parameters, gage, profile, alignment, crosslevel and warp. The data used were obtained from the FRA Automatic Track Inspection Vehicles which typically generate in excess of 36,000 data points per mile. The first objective of a TQI is then to summarize some part of this information. However, this summarization must be done in such a manner as to retain the overall information. That is, each TQI must quantify the ability of a section of track to carry out its design function. Specifically the track must guide and support rolling stock in a safe and economic manner.

For this study of a total of 288 miles of CONRAIL mainline track was selected as the test zone. Of this, 176 miles were double track (posted class 3 and 4) in the Fort Wayne Division, and the remainder, 112 miles, were double and single track (posted class 2 and 3) in the Lehigh Division. Track in the Fort Wayne Division is primarily level and tangent while track in the Lehigh Division consists of numerous curves, with high grade. Traffic in the two divisions was similarly differentiated. Fort Wayne traffic was typically high, up to 25 MGT annually, at speeds averaging over 40 mph. In contrast, the Lehigh Division traffic was lower in both tonnage and speed with 7 to 14 MGT annually at speeds averaging just over 30 mph. Further, the Lehigh Division showed consistently higher axle loads than did the Fort Wayne Division due to ore, coal, and steel movements in the region. Finally, it should be pointed out that 70 percent of the entire test zone underwent some form of maintenance during this year-long study.

For the purposes of this study the 288 mile test zone was partitioned into 676 variable length homogeneous segments. In this context the term homogeneous is used to indicate that each segment is uniformly or consistently described by eleven selected physical parameters which affect the rate of degradation. There are three categories of physical parameters, traffic (tonnage, percent heavy wheels, and speed), structure (rail weight, ballast, drainage, surface bent rails, and curvature) and maintenance (by level and type). Thus, a segment did not have any mixture of these parameters, e.g., tangent and curves in the same segment. The maximum segment length was by definition one mile and the minimum length was one-tenth mile. The average segment length was just over four tenths of a mile.

The relationship between TQI's and the Federal Track Safety Standards, ride quality (lading damage), and safety (derailments) are first developed. Following this a set of five TQI's are selected from a candidate set of 14 which best quantify track condition and degradation due to such things as traffic and track-structure parameters. It was found that there are three basic families of indices; gage, line, and surface. The final set contains one line index, two gage indices (gage roughness and wide gage), and two surface indices (surface and superelevation). The reason for the selection of two indices from the gage and surface families was due to the need to better represent safety considerations. The surface index is based on a warp measurement similar but not identical to an index developed by Souther Railroad.

Following the selection of the best five indices, predictive equations or degradation relations are developed for unmaintained track and each of six levels or types of maintenance. Basic maintenance is subdivided into three levels, up to 10 percent maintained, up to 30 percent maintained and over 30 percent maintained. Production maintenance (100 percent mainmained) is subdivided as surface, tie and surface, and rail renewal operations. The predictive equations developed are found to account for at least 80 percent of the change observed in the track over a period of one year with better than 99.9 percent confidence.

What this means to railroad personnel responsible for Maintenance-of-Way planning is rather simple yet powerful. Making use of these predictive equations it will be possible to project the condition of track one to two years into the future with 80-percent accuracy knowing that less than one mile in every thousand will be in some condition (better or worse) other than anticipated. This has a number of obvious potential applications, such as budgetary justification of MOW expenditures and quality assurance of production maintenance. These and other potential uses are discussed in detail in the conclusion and recommendation section.

A limited number of specific observations are made based on the test zone under study. It was found that the amount or rate of degradation depends to a large extent on the present condition of track. Other important parameters involved in the determination of track degradation are tonnage and rail type. For this test zone it was found that bolted rail deteriorates approximately four times as fast as welded rail. This conclusion, however, must be tempered with the fact that the bolted rail considered within the framework of this study was much older than the welded.

This report is organized as follows. The introduction briefly described the history and program overview. The introduction also describes the salient features of the technical approach. The second section of this report describes the track geometry measurement system and lays out the test zone. Section 3 presents the Track Quality Indices. This section begins with a discussion of the functional requirement of railroad track and from this are derived a set of 14 candidate TQI's. The fourth section deals with the physical parameters and segmentation of the test zone. Here are described the mechanics of data acquisition and reduction. In the fifth section the software is described which consists basically of three components, a specialized data base management system for track inventory, a software package for the extraction of TQI's from track geometry data, and a set of programs which is used to develop the relationship or predictive equations between TQI's and physical parameters (regression analysis).

Before presenting the results, a road map of the overall methodology is presented in section 6 to aid in section 7. Section 7 is the presentation and discussion of results. Finally, the findings and observations are summarized in section 8 along with recommendations for future work.

1.0 INTRODUCTION

1.1 HISTORY

In 1886, the Chesapeake and Ohio Railroad (C&O) operated the first domestic track inspection vehicle. The vehicle utilized mechanical, sliding-contact sensors to measure track geometry parameters. Mechanical linkages transmitted the signals from the sensors to recorders in the carbody. The leaf-spring, finger-type sensors required a relatively low operating speed to ensure continuous mechanical contact through track geometry aberations. Many of today's railroads operate automatic track inspection cars that are updated versions of the C&O vehicle. These cars are utilized primarily to support spot maintenance programs by detecting track problems that could potentially cause derailments.

The Federal Railroad Administration (FRA) started its Automated Track Inspection Program (ATIP) in 1967 by outfitting two Budd Silverliners with noncontact track measurement sensors and automatic data collection systems. These cars, in combination with support vehicles were used to inspect track at high speeds for compliance with FRA Track Safety Standards.

In 1971, the FRA Office of Research and Development (OR&D)/Office of Rail Safety Research (ORSR) started a joint government/industry program to provide maintenance-of-way (MOW) planning techniques based on automatically acquired track-geometry data. This program has been a cooperative effort by FRA, the Bessemer and Lake Erie Railroad (B&LE) and the Denver and Rio Grande Western Railroad (D&RGW). Track geometry surveys have been conducted every fall on the D&RGW and every spring and fall on the B&LE, and reports of these surveys have been delivered to the railroads. The final track-geometry surveys on both railroads were conducted in the fall of 1978.

The joint FRA/B&LE/D&RGW Program has witnessed an evolutionary change in measurement systems, progressing from primarily capacitive type proximity sensors (whose drawbacks were non-linearity and weather sensitivity) to an all-weather system with state-of-the-art electromagnetic, inertial and gyroscopic instrumentation.

The Office of Rail Safety Research concluded its program of providing Standards Reports and Track Quality Indices Reports by pubishing a final report (DOT/FRA-79/12) covering the task in September 1979. The ORSR program demonstrated the usefulness of the Track Quality Indices and the Standards reports. These reports are being used effectively by the D&RGW and B&LE Railroads.

1.2 PROGRAM OVERVIEW

In 1978, the OR&D Office of Freight Systems (OFS) signed a Memorandum of Understanding with the Consolidated Rail Corporation (CONRAIL) to start another joint government/industry program intended to provide long-range, track-maintenance-planning assistance utilizing Automated Track-Geometry-Inspection Vehicles. The planning system developed is based on the premise that the condition of the track is a function of a finite set of physical parameters. Track condition or quality is quantified using an FRA track-geometry-survey car. The work with D&RGW and B&LE, as well as other research, served as a base of information to be used in the CONRAIL study.

The CONRAIL study is a three phase program; the first was planning, the second is development and definition, and the third is implementation. The planning phase was completed in November 1978 and included: selection of a track geometry measurement system; selection of potential track quality indices; determination of data sources on the physical parameters that affect track degradation or improvement; outlining a methodology that will relate changes in physical parameters to changes in track quality indices; and determination of the requirements of a Data Base Management System.

The development phase of the program was completed in June 1980 by the publication of this report and included: development of the Data Base Management System (DBMS); development of the predictive procedures or methodology; collection of data on the physical parameters and the track quality indices; utilization of the predictive procedures to determine the equations that relate the track quality indices and the physical parameters; and determination of the limitations of the equations. The planning techniques were developed for a test zone of approximately 288 track miles of CONRAIL main line in the Fort Wayne and Lehigh Divisions.

The development of the MOW system is the subject of this report. The third phase of this program is planned to be the subject of a future FRA program.

1.3 DEFINITION OF THE MAINTENANCE PLANNING SYSTEM

The goal of this program is the implementation of a maintenance planning system whose functional concept is shown in Figure 1-1. The data files shown are of two types. The first file contains figures of merit computed from track geometry measurements, referred to as Track Quality Indices, which reflect the ability of the track to carry out its design mission. The second file contains the physical parameters that affect the geometric track condition or quality.

The data in both files are accessed by the Data Base Management System which will sort, edit and merge the records as necessary. Once the required data are retrieved from the files, interaction takes place with the analysis methodology to provide future values of track quality indices (Sections 5.0 and 6.0), which constitute the MOW planning information.

1.4 DESCRIPTION OF TECHNICAL APPROACH

The technical approach used to develop the track maintenance planning system was as follows:

- The functional requirements of the track in the test zone were determined.
- A geometric description of the track in the test zone was developed, in terms that can be measured by a track geometry car.
- Based on the above, a list of 14 candidate Track Quality Indices (TQI's) was selected.

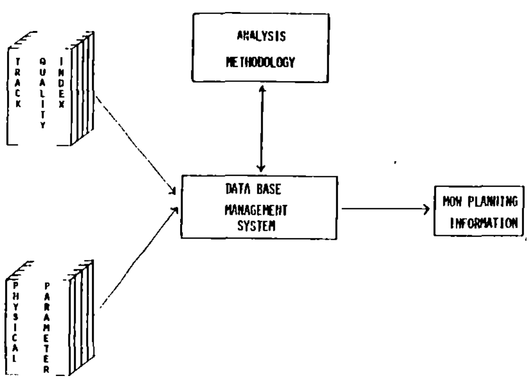


Figure 1-1. Functional Concept

- Track structure and traffic parameters and the level of maintenance were quantified for the test zone.
- The test zone was segmented with respect to physical and traffic parameters as well as maintenance history.
- Two track-geometry surveys were conducted over the test zones in the Fort Wayne Division and the Lehigh Division.
- Computer software was developed to perform data processing and regression analysis on track segments grouped by levels of basic maintenance or programmed maintenance.
- From the list of candidate indices, a final set of five TQI's was determined.
- Predictive equations that account for at least 80 percent of track degradation (as measured by TQI's) were generated.
- Analysis also included the relationship of TQI's to maintenance level, Federal Track Safety Standards, vehicle ride quality, and derailment potential.

1.5 ORGANIZATION OF THE REPORT

This report documents the development of the long-range track maintenance planning system. It includes a discussion of the predictive equation of track degradation, an evaluation of the development procedure, and techniques for further refinement.

The selected track geometry parameters are discussed in Section 2.0 along with a description of the T-6 measurement system. Section 3.0 describes the general track functional requirement and the selection of the candidate indices. The eleven physical parameters used in the study are listed in Section 4.0 as well as the track segmentation procedure and results. A general description of the MOW software is included in Section 5.0. Section 6.0 discusses the analysis methodology utilized in the program.

The results and discussion of this study are presented in Section 7.0. The final TQI's are selected along with a discussion of the predictive equations of track degradation. Conclusions and recommendations are listed in Section 8.0.

2.0 MEASUREMENT SYSTEM

2.1 GENERAL

In selecting a system that could measure the track geometry parameters specified in the track functional requirement (Section 3.0), the capabilities of the FRA survey vehicles T-6, T-2/T-4, T-1/T-3; and commercial track geometry measurement vehicles were investigated. In addition, an accuracy study was conducted for the FRA survey vehicles. The high-speed measurement system selected for the track maintenance planning program is the T-6 vehicle (Figure 2-1). A comparitive study of the different track-geometry-measurement vehicles is included in Appendix A along with a detailed description of the T-6 measurement system.

The T-6 survey car is owned by the FRA and operated under contract by ENSCO, Inc. This vehicle incorporates features such as the alignment system and the low-speed profile system. T-6 is specially equipped with electro-mechanical sensors for measurement of track characteristics and contains onboard a computer system to control the measurement and recording of these characteristics. The car is also equipped with monitoring equipment so that measurements can be checked on data display strip charts during the survey and afterward from the tape on which they were recorded.

Track surveys were conducted by T-6 over two main line test zones designated by CONRAIL in October 1978 and October 1979. The Lehigh Division and Fort Wayne Division were selected to cover a full spectrum of track conditions. The following paragraphs describe the track geometry parameters measured by T-6 and the designated test zones. Track charts for these test zones are included in Appendix B.

2.2 TRACK GEOMETRY PARAMETERS

The T-6 survey car measures the following track geometry and reference parameters:

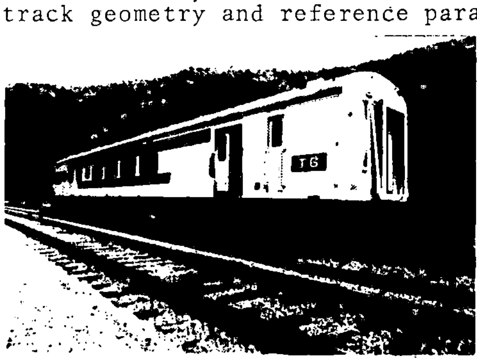


Figure 2-1. T-6 Track-Geometry-Survey Vehicle

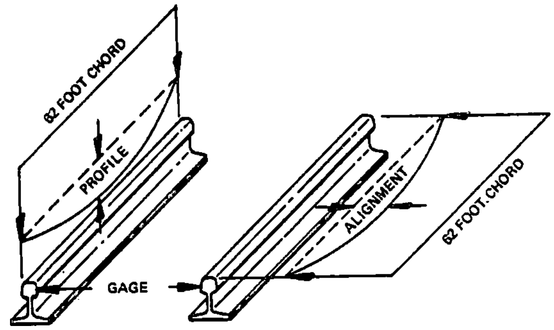


Figure 2-2. Profile, Alignment and Gage

- Profile is a measure of the vertical position of each railhead in a track structure. It is defined as the midpoint of a 62-foot chord (Figure 2-2).
- Alignment is a measure of the lateral position of each railhead in a track structure. It is defined as the midpoint of a 62-foot chord (Figure 2-2).
- Gage is the distance between the two rails in a track structure at a position five-eights of an inch below the top of the railhead (Figure 2-2).
- Crosslevel is the different in elevation between the left and right rails (Figure 2-3).
- Curvature is a measure of the angular rate of change in track condition. It is defined as the central angle subtended by a 100-foot chord (Figure 2-4).
- Location is defined as the detection of features which are random and known in the track structure (turnouts, road crossings, mileposts, etc.).

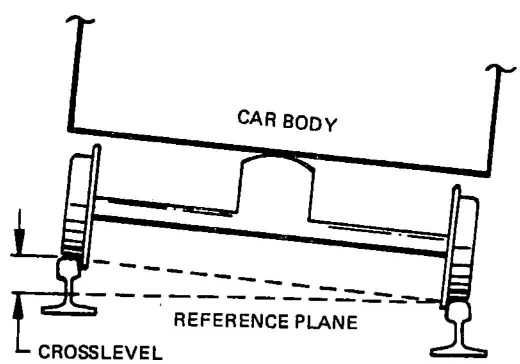


Figure 2-3. Crosslevel

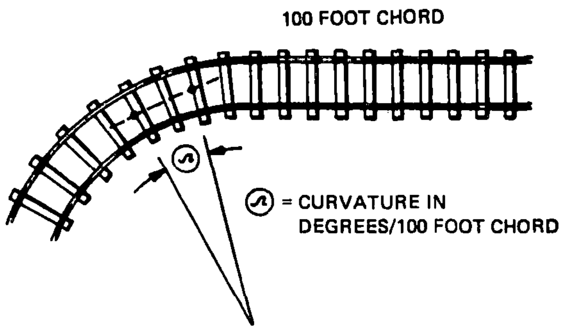


Figure 2-4. Curvature

The track geometry parameters defined in the preceding paragraphs were computed on-line and displayed on strip charts. A sample display is shown in Figure 2-5.

The digital processing and recording system on T-6 records raw signals (proportional to the track geometry parameters) on magnetic tapes for off-line processing. Warp, which is the spatial rate of change in crosslevel, is calculated during the off-line processing.

The off-line processing algorithms for this study convert the raw signals to track geometry parameters suitable for use in the computation of Track Quality Indices (Section 3.0). For example, the profile and alignment measurements are processed as short mid-chord offsets (MCO) and space curves, instead of 62-foot MCO's.

2.3 TEST ZONES

Track geometry parameters were measured on two designated zones during the Fall 1978 and the Fall 1979. The zones consisted of approximately 288 miles of CONRAIL main line in the Fort Wayne and Lehigh Divisions located in Ohio, New Jersey, and Pennsylvania. The test zones consisted of:

Fort Wayne Division

From - Bucyrus, OH (Milepost 200.6)
To - Van Wert, OH (Milepost 288.0)

Lehigh Division

From - Boundbrook, NJ (Milepost 35.8)
To - Bethlehem, PA (Milepost 86.0)

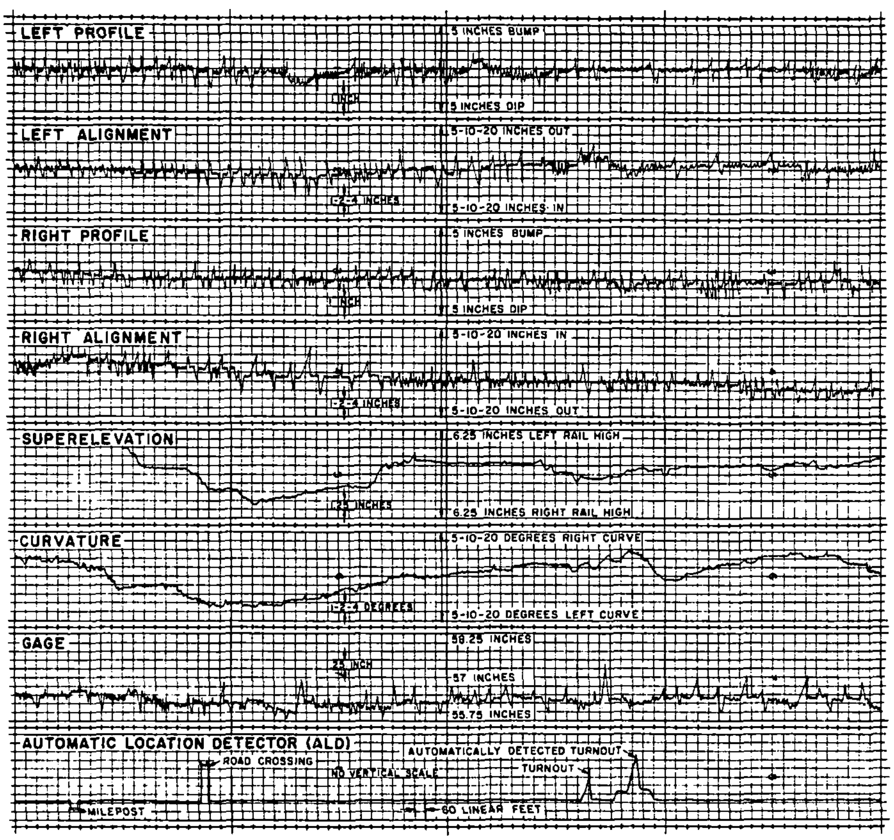


Figure 2-5. T-6 Strip Chart

From - Allentown, PA (Milepost 88.0)
To - Lehighton, PA (Milepost 114.7)

From - Lehighton, PA (Milepost 119.4)
To - Penn Haven Junction, PA (Milepost 131.0)

The Fort Wayne test zone is essentially a double-main-track, bridge line between Pittsburgh, PA and Chicago, IL. No large classification yards exist within the test zone and most of the line is tangent, low gradient track. The Lehigh test zone is divided by a major yard in Allentown, PA and contains 55 miles of single track. A significant portion of main line is comprised of high gradient, curved track. Track charts for the zones are included in Appendix B.

3.0 TRACK QUALITY INDICES

For the purpose of this study, Track Quality Indices (TQI's) are defined as figures of merit that effectively quantify the ability of a track segment to meet some part of its functional requirements. The indices are computed from data collected by an automated track geometry measurement vehicle. Track geometry parameters (gage, profile, alignment, crosslevel, and warp) are processed at one-foot intervals for the T-6 vehicle, resulting in 36,960 individual pieces of information for each mile of track surveyed. A TQI effectively summarizes the large number of measurements of each parameter for a given track segment.

Figure 3-1 illustrates the use of a TQI in rating the condition of a track segment in a relative manner. In this example, the track geometry **parameter** profile is used; however, all track geometry parameters can be applied in a similar fashion. The dashed line represents the ideal track condition. The solid line represents the actual measurement and the shaded regions represent the area between the actual line and the ideal line. By taking the square root of the average area, a figure of merit (TQI) can be calculated (having units in inches). A TQI with a high relative value, for example, 0.5 inches, depicts poor track condition, while a TQI with a low relative value, for example, 0.2 inches, indicates good track condition. In this example the profile TQI is a roughness measurement or the standard deviation in a statistical sense.

The following section deals with the selection of TQI's based on the functional requirements of railroad track. First, the general functional requirements or design mission of railroad track will be discussed. Secondly, a candidate set of TQI's will be presented based on the functional requirements of the track as well as considerations of physics. Finally, five means of qualifying the TQI's will be reviewed.

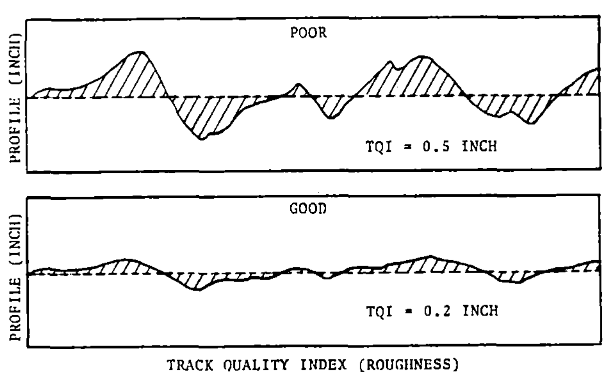


Figure 3-1. Use of TQI to Rate Relative Track Condition

3.1 FUNCTIONAL REQUIREMENTS OF RAILROAD TRACK

In the most general sense, a description of the functional requirements of track can be stated as follows: To guide and support the rolling stock under prescribed operational conditions in a safe and economic manner.

The elements of this statement must be defined in this context. Guidance and support relate to the safe and economic operation of a rail system of a general nature. The prescribed operational conditions must be qualified in terms of a specific rail system operation.

Specific functional requirements for a segment of track or a rail system operation depends on the quantification of the prescribed operation conditions. The prescribed operating conditions consist of the type of service, maximum axle load, train speed and traffic density.

The maintenance-of-way study for the FRA Office of Freight Systems will deal with track having service requirements typified by the CONRAIL test zones and which is representative of a large portion of main line track in the United States. The operational conditions for this program are:

- Mixed freight service.
- Maximum axle load of 76,000 pounds, as determined from the maximum AAR interchange weight.
- Traffic not to exceed 50 mph.
- Tonnage not to exceed 30 mgt annually.

3.2 CANDIDATE TRACK QUALITY INDICES

Based on the selection criteria contained in Appendix C, five track geometry parameters have been processed into 14 candidate track quality indices (Table 3-1). This section will describe each of these indices.

Figures 3-2 and 3-3 show each of the indices and indicate how they are computed. Appendix C discusses the

TABLE 3-1

TRACK QUALITY INDICES

Operation \ Parameter	Gage	Profile	Alignment	Crosslevel	Warp
Mean	X				
Standard Deviation (Space Curve)	X	X	X	XX*	X
Standard Deviation (Short MCO)		X	X		
99th Percentile	X	X			X
3rd Moment	X				
4th Moment	X				

*This is the Crosslevel deviations from balanced superelevation.

reasoning for selecting the descriptive statistics used in the MOW TQI's.

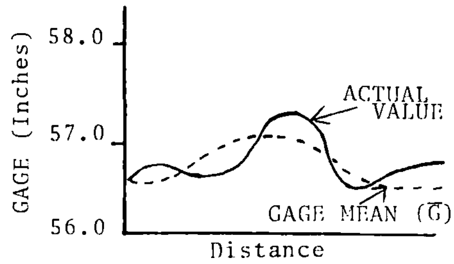
3.2.1 GAGE

Gage measurements have been processed into five indices (Figure 3-2).

- Mean value - This is the arithmetic mean of the gage measurements for a track segment. It provides a measure of the average gage condition of the track.
- Standard Deviation - This is the square root of the variance of the gage measurements for a track segment. It represents the track roughness or variability of the gage measurements.
- 99th Percentile Value - This is the gage measurement below which 99 percent of the samples lie. For a quarter-mile track segment, with a one-foot sampling interval, 1307 samples will have smaller gage measurements; while 13 samples will have larger gage measurements. This is a measure of the worst gage spots in a track segment.
- Third Moment of Probability Function - This is a measure of the symmetry of the gage distribution.
- Fourth Moment of Probability Function - This is a measure of the broadness of the gage data distribution.

3.2.2 PROFILE

Profile measurements (Figure 3-3) have been processed into three indices:



$$(\bar{G}) = \frac{\Sigma G_i}{N}$$

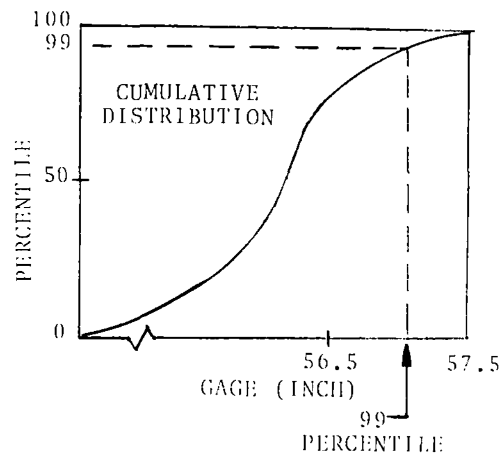
where

G = Actual Gage Value
N = Number of Samples

a) Gage Mean Value

$$\sigma = \sqrt{\frac{\Sigma (G_i - \bar{G})^2}{N - 1}}$$

b) Gage Standard Deviation (σ)



c) Gage 99 Percentile Value

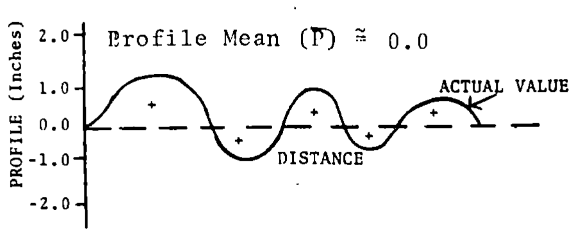
$$\text{3rd Moment of PDF} = \Sigma \frac{(G_i - \bar{G})^3}{N}$$

d) Gage Third Moment of Probability Density Function (PDF)

$$\text{4th Moment of PDF} = \Sigma \frac{(G_i - \bar{G})^4}{N}$$

f) Gage Fourth Moment of PDF

Figure 3-2. TQI's Processed from Gage Measurements



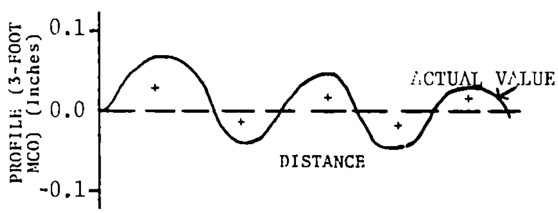
$$\text{Standard Deviation} = \sqrt{\frac{\Sigma(P_i - \overline{P})^2}{N - 1}}$$

where

P_i = Profile (left or right)

N = Number of Profile Samples (left and right)

a) Profile Standard Deviation (Space Curve)



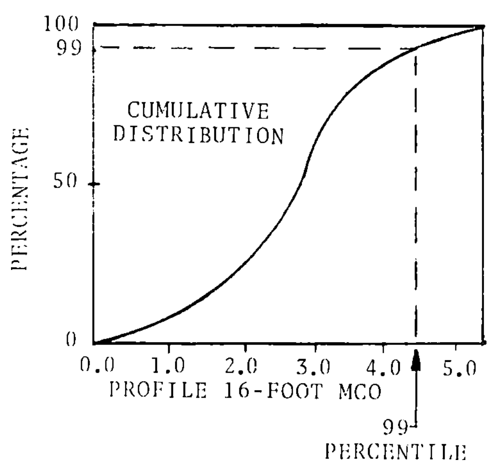
$$\text{Standard Deviation} = \sqrt{\frac{(PS_i - \overline{PS})^2}{N-1}}$$

where

PS_i = Profile 3-foot MCO (left or right

N = Number of Profile Samples (left and right)

b) Profile Standard Deviation (3-foot MCO)



c) Ninety-Ninth Percentile of Intermediate Mid-Chord Offset

Figure 3-3. TQI Processed from Profile Measurements

- Standard Deviation - This is the square root of the variance of the profile space curve* measurements for a track segment. It represents track surface roughness or variability.
- Standard Deviation of Short Mid-Chord Offset (three feet) - This is the statistical standard deviation of profile three-foot mid-chord offset measurements. It represents vertical acceleration levels for surface roughness.
- Ninety-ninth Percentile of Intermediate Mid-Chord Offset (16 feet) - This is the measurement below which 99 percent of the 16-foot mid-chord offset measurements of profile lie. It represents the severity of the low joints in a track segment.

3.2.3 ALIGNMENT

Alignment measurements (Figure 3-4) have been processed into two indices.

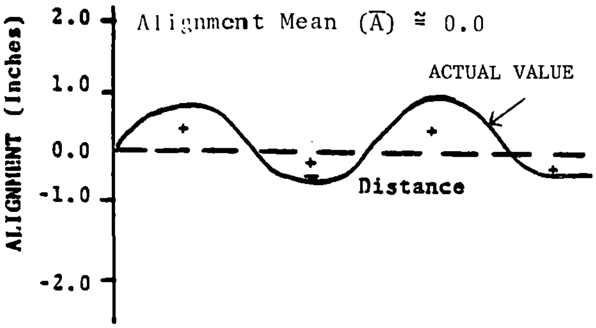
- Standard Deviation - This is the statistical standard deviation of alignment space curve measurements for a track segment. It represents line roughness.
- Standard Deviation of Short Mid-Chord Offset (two feet) - This is the statistical standard deviation of two-foot mid-chord offset measurements of alignment for a track segment. It represents track-line roughness accelerations.

3.2.4 CROSSLEVEL

Crosslevel measurements (Figure 3-5) have been processed into two indices.

- Standard Deviation - This is the statistical standard deviation of the crosslevel measurements for a track segment. It represents track surface roughness.
- Standard Deviation of Deviations from Balanced Superelevation - This is the statistical standard deviation of the difference in crosslevel measurements and the balanced superelevation (computed from smooth curvature) for a track segment. This represents the adequacy of track elevation in curves.

*Space curve is a pseudo reconstruction of track geometry without the effects of local terrain.



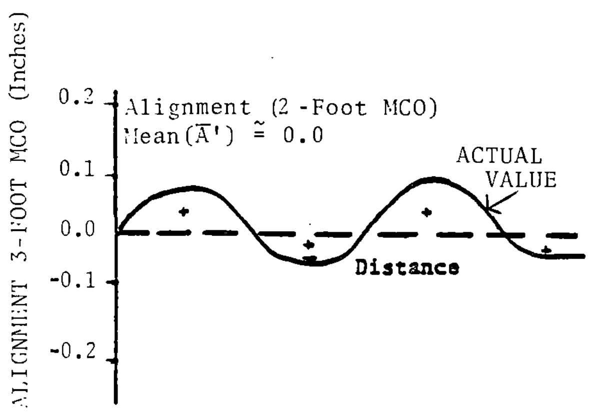
$$\text{Standard Deviation} = \sqrt{\frac{\Sigma(A_i - \bar{A})^2}{N - 1}}$$

where

A_i = Alignment Value

N = Number of Samples (left and right)

a) Alignment Standard Deviation



$$\text{Standard Deviation} = \sqrt{\frac{\Sigma(AS_i - \bar{A}')^2}{N - 1}}$$

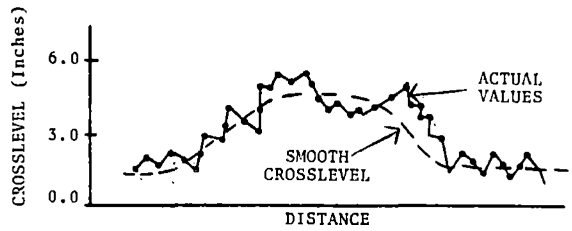
where

AS_i = Alignment Value 2-foot MCO

N = Number of Samples (left and right)

b) Alignment Standard Deviation (2-Foot MCO)

Figure 3-4. TQI's Processed from Alignment Measurements



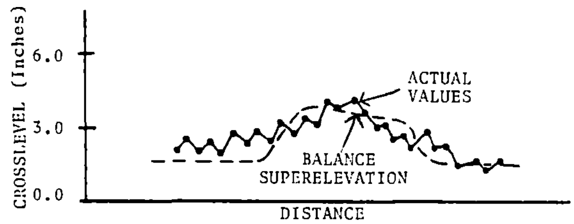
$$\text{Standard Deviation} = \sqrt{\frac{\Sigma D_i^2}{N-1}}$$

where

D_i = Actual crosslevel-smoothed crosslevel

N = Number of D_i's

a) Crosslevel Standard Deviation



$$\text{Standard Deviation} = \sqrt{\frac{\Sigma SE_i^2}{N - 1}}$$

Where

SE_i = Actual Crosslevel-balance superelevation

N = Number of Samples

Balance superelevation equals

$$0.00066V^2D$$

where

V = Nominal posted speed (mph)

D = Smooth curvature (degrees) (Section 5.3.1)

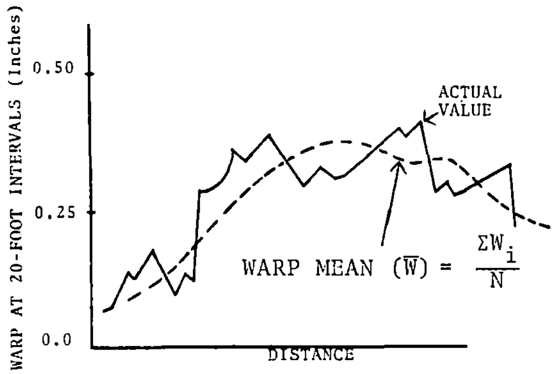
b) Balance Crosslevel Standard Deviation

Figure 3-5. TQI's Processed from Crosslevel Measurements

3.2.5 WARP

Warp measurements (Figure 3-6) have been processed into two indices:

- Standard Deviation - This is the statistical standard deviation of warp measurements for 20-foot intervals of a track segment. It represents the surface condition and vehicle rock and roll potential from staggered, 39-foot rail.



$$\text{Standard Deviation} = \sqrt{\frac{(W_i - \overline{W})^2}{N - 1}}$$

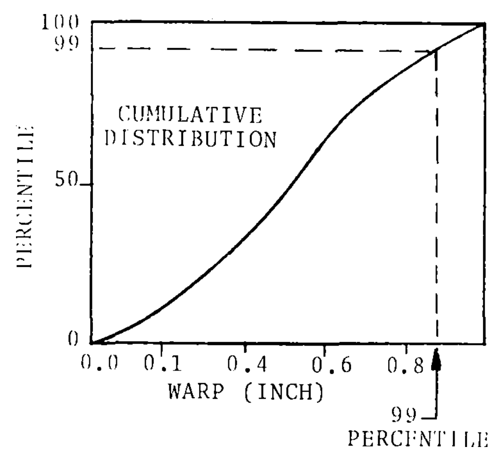
Where

W_i = Warp Value $|XL_{i+20} - XL_i|$

XL_i = Crosslevel (ith sample)

N = Number of Warp Samples

a) Warp Standard Deviation



b) Warp 99th Percentile

Figure 3-6. TQI's Processed from Warp Measurements

- Ninety-ninth Percentile - This is the measurement below which 99 percent of the 20-foot, warp-measurement samples lie in a track segment. It represents the amplitude or severity of consecutive low joints in a track segment.

3.3 QUALIFICATION OF TRACK QUALITY INDICES

The primary means of qualifying the candidate Track Quality Indices was the track functional requirement (Section 3.1) The fourteen candidate TQI's were selected to provide an objective measure of track condition to meet some part of its functional requirement.

In order to assure that the proposed candidate TQI's are good indicators of the condition of track, five empirical methods of track quality estimation were selected for comparison purposes. Results using the following empirical methods are included in Section 7.0.

One method of TQI qualification tests whether the indices are sensitive to degradation of track condition. A degradation coefficient was computed from the 1978 and 1979 TQI observations for the same track segments. Another method of qualification was to compare the 1978 and 1979 TQI's according to the amount of maintenance performed. This determined whether the candidate indices could measure the effects of track maintenance.

The third method consisted of comparing the TQI's with derailments. Rail related derailment information was screened to determine if there was any relation between the derailments and the values of the candidate indices. In addition, the reported causes of the derailments were compared with specific indices. For example, if a derailment was reported due to wide gage then the gage indices were studied. The fourth method of TQI qualification involved the relationship of various indices to the Federal Track Safety Standards. Data from an ENSCO study* were used to generate roughness indices for alignment, gage, profile, and crosslevel typical of all six FRA track classes. These results were verified using the data base of the MOW program.

Finally, the candidate TQI's were related to ride quality. Using a simple vehicle model, RMS accelerations were computed leading to the calculation of the common ride quality standards (ISO and Wz Rating). Various TQI's were compared with the ride quality standards.

*ENSCO Report, "Statistical Representation of Track Geometry," June 1979.

4.0 PHYSICAL PARAMETER STUDY

4.1 GENERAL

Many parameters influence the rate-of-deterioration of track condition. Initially in the program, representatives of FRA, CONRAIL, and ENSCO selected the most feasible set of physical parameters based on previous studies and ease of data acquisition. These eleven parameters are categorized in three areas; track structure, traffic, and maintenance, as shown in Table 4-1. The track structure parameters are quantified for each period of observation and the traffic and maintenance parameters are quantified between observations to divide the test zone into track segments of homogeneous physical make-up. An objective of the selected physical parameters is to account for at least 80-90 percent of the rate of track degradation.

Table 4-1 summarizes the category, type of physical parameter, and units of quantification. The following sections discuss the methods for physical parameter quantification and procedures for track segmentation.

4.2 TRAFFIC DATA QUANTIFICATION

Three traffic parameters were considered during this study. These are annual tonnage, heavy wheel loads and train speed. Annual tonnage and heavy wheel loads are quantified for the test zone by a seasonal sampling method. Per Stanford Research Institute reporting procedures, one week was selected that is representative of each season. Train speed information was obtained from track charts and CONRAIL time tables.

On review of historical CONRAIL freight car movement information for each division, it was determined that the spring and summer seasons contain approximately the same volume of train car movements. Hence, three seasons were sampled for this study; winter, spring/summer, and fall. It should be noted that all traffic data apply only to the time of this study. Extrapolation for different time periods could be very inaccurate due to fluctuations in traffic patterns.

The two high-volume commodities shipped in the Fort Wayne Division are grain and paper. Other common types of freight movement include coal, automotive parts, automobiles, and postal goods. Two passenger trains traverse the Fort Wayne test zone on a daily basis, one eastbound and one westbound.

TABLE 4-1

PHYSICAL PARAMETERS

Category	Type	Units
Track Structure	Curvature	Degrees
	Rail Weight	Pounds/Yard
	Rail Type	Jointed/Welded
	Ballast Condition	Clean, Dirty, Pumping, Fouled
	Rail Profile	Percent Bent
	Drainage Ability	Adequate/Inadequate
Traffic	Track Speed	Miles per Hour
	Cumulative Tonnage	Million Gross Tons
	Heavy Loads	Percent Bent
Maintenance	Basic Maintenance	Levels 0, 10%, 30%, >30%
	Production Maintenance	Surface, Tie and Surface, Rail Renewal

```
AHO BTM BMT DSF VPT NEC.ACY
ØØØ DH87   ALLENTOWNPA PHIPARJCTPA DHCR 1 Ø319 Ø415 Ø6ØØ
3*** ELAPSED TIME FROM ACTIVITY TO MSG RECD   ØØØHRS ØØMIN
3***  DH87    Ø57 LOADS   Ø6Ø EMPTIES   117 TOTAL   Ø5859 GROSS TONS
3***                                     HORSEPOWER Ø75ØØ
1IH    7413CEØØ ØØØ
1IH    76Ø6XEØØXØØØ
1IH    Ø31ØXEØØXØØØ
ØØØ AØØØ   ALLENTOWNPA PHIPARJCTPA                              BMT
3***  DH87    Ø57 LOADS   Ø6Ø EMPTIES   117 TOTAL   Ø5859 GROSS TONS
3    BO GROUP CLASS
9BM    ØØ79LB49 ØØ8KNIT BALTIMOREMDLONDONTOWPARJBO         GDH19 DH87Ø419
9IM    3122LDØUXØØØPAPPDROCKVILLEMDFAWPRINTIPARJBO         GDH19 DH87Ø419
9SAL   Ø781EFØSXØØØLUMBRPHIPARJCTPAAGENT    PARJBO         GDH19 DH87Ø419
9CUR   Ø226LB57 Ø67PAPPDGLEFURNIEMDSFAROEBUCPARJBO         GDH19 DH87Ø419
9NSL 1ØØ045LB57 Ø67PAPPDGLEFURNIEMDSFAROEBUCPARJBO         GDH19 DH87Ø419
9FAR   4Ø35LB48 Ø67PAPPDGLEFURNIEMDSFAROEBUCPARJBO         GDH19 DH87Ø419
9RFOX 71ØØ3LB5ØCØ67PAPPDGLEFURNIEMDSFAROEBUCPARJBO         GDH19 DH87Ø419
9BM    3129LD6UXØ31PAPPDROCKVILLEMDFAWPRINTIPARJBO         GDH19 DH87Ø419
9IN  ØØØ4ØØLBB1CØ62LUMBRBALTIMOREMDFURLUMBERPARJBO         GJ242 DH87Ø419
9CO  3ØØ54ØØCØ9XØØØSTEELSPAPT    MDAGENT    PARJBO         GDH19 DH87Ø419
9MEC   93ØØLB59 Ø46PAPPIELKRIDGE MDFELGRODISPARJBO         GDH19 DH87Ø419
9CE  71Ø334EF51 ØØØSTEELPHIPARJCTPAAGENT    PARJBO         GDH19 DH87Ø419
9FM    76Ø59LB48 Ø75TALC BALTIMOREMDGAF     PARJBO         GLH19 DH87Ø419
9LH    Ø4Ø31LDØAXØ65NEWSPPHILADELPPAABLPRINTIPARJBO        GDH19 DH87Ø419
9CP  ØØØ9Ø3LB46 ØØ6FURNTBELTSVILLMDCOLCOLONIPARJBO         GDH19 DH87Ø419
9CN  5Ø2714LB41 ØØØASPESBALTIMOREMDCONGOLEUMPARJBO         GDH19 DH87Ø419
```

Figure 4-1. Portion of a Typical Mechanized Machine Consist (Lehigh Division)

The Lehigh Division experiences a wider variety of lading due to the high number of industrial plants served. Coal, ore, and zinc are the most frequently shipped commodities. Grain and salt are also year-round freight commodities; however, no passenger trains traverse this portion of the test zone. In general, grain, ore, and coal tend to be heavier in volume during the summer and fall seasons, and salt heavier in the summer. Other freight is shipped year round.

4.2.1 TRAFFIC SAMPLING PROCEDURES

Both Division headquarters provided the contractor with the daily Dispatcher's Train Sheets for the selected weeks of each season. These sheets record all train movements over the dispatcher's territory, including any drop-offs or pick-ups of freight cars. The Train Sheets were screened to determine which trains traverse the test zone and information was recorded according to the day of the movement, origin/destination, locomotives used, and the number of loaded and empty freight cars. The trains were then matched with the corresponding computer printout of the Mechanized Machine Consists (Figure 4-1). Machine consists are compiled by clerks at the classification yards while the train consist is built. This printout (Figure 4-2) includes train identification code, the locomotive number, freight car number and type code, consist gross tonnage, lading weight of each car in the consist, and other pertinent shipping information.

The Mechanized Machine Consists were analyzed to determine the percentage of train tonnage carried by heavily loaded cars (90 gross tons or more). In actuality, the load tonnage is only an estimate because the normal practice is to weigh one fully loaded car prior to shipping and then to apply this loading to all similar shipments made by the same customer.

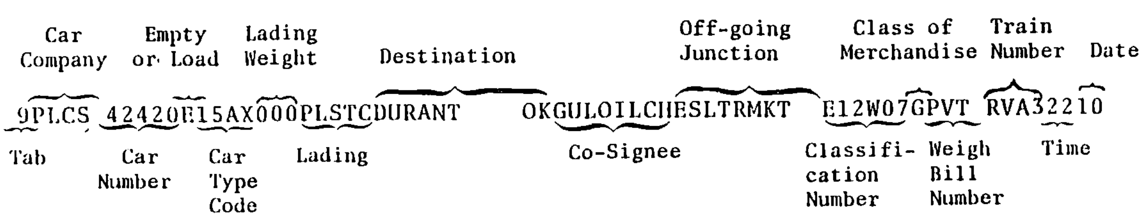


Figure 4-2. Decoding a Mechanized Machine Consist

The machine consists were also screened to determine the total tonnage of each consist, which was summed to obtain total tonnage for each sample week. The tonnage for each season was obtained by multiplying the sample week's total tonnage by 13. Summing the seasonal totals over the four seasons yields annual tonnage. In comparing consist gross tonnage of the train sheets with the machine consists, an accuracy of approximately 95 percent was achieved.

The machine consist is a more accurate source of tonnage information since it is based on the weigh bill of the consist. Train sheet gross tonnage is based on average loaded car and empty car weights. If a large difference in loads/empties or locomotive power exists between the train sheets and machine consists, the train sheet information was regarded as more reliable for the number of cars or engines.

In estimating annual tonnage and percentage of heavy loads, the following vehicle weights were assumed if tonnage data was not available for a particular consist.

- Locomotive - 150 tons
- Empty freight car - 30 tons
- Loaded freight car - 75 tons
- Passenger car - 60 tons
- Caboose - 30 tons

All freight trains include a caboose unit while passenger trains exclude the caboose. If machine consist information was missing for a particular train, at least five consist samples during or around the sample week were selected to determine the average loaded car weight and the percentage of heavy loads for the particular type of train. Then, by obtaining the number of loads and empties from the train sheets, as estimated gross tonnage for the consist can be calculated.

Due to the physical variations of the two zones, different train movements exist for each test zone. Each division requires different data sources for traffic sampling as described in the following sections.

4.2.1.1 Fort Wayne Division

Most road train, local train, passenger train, and trailer-van consists traverse the entire test zone without drop-offs or pick-ups. However, in the Lima, OH region 4-6 daily yard moves take place over the main line. For these movements the dispatcher records only the number of cars on the consist and the locomotives used. To obtain the load-empty breakdown and heavy loads information, the Field Terminal Supervisor at the Lima Yard was contacted. Gross tonnage estimates for the yard consists were calculated using the average loaded car and empty car weights. Overall, most train movements over the test zone are road trains with eastbound traffic slightly heavier than westbound traffic.

4.2.1.2 Lehigh Division

Due to the make-up of the Lehigh Division, it experiences local freight movements that are significant in the CONRAIL system. Very few trains traverse the entire test zone, however, those that do usually drop-off or pick-up cars at various yards. The Delaware and Hudson Railroad (D&H) sends two types of freight trains regularly through the test zone. The NE87 and NE84 trains are generally large, heavy consists while the Sealand (SL1, SL2, SL3, and SL4) trains are container-on-a-flatcar consists. The Sealand train, mechanized machine consists are not received at CONRAIL while a small portion of the NE87 and NE84 machine consists are received. By sampling five typical consists for each train, heavy loads were estimated. After discussion with a D&H trainmaster, it was determined that the average loaded car in a Sealand train was approximately 75 tons with two loaded containers, while the average empty car with two unloaded containers was approximately 45 tons. These loadings were used in the computations of gross tonnage for Sealand trains.

Switch movements at yards and the use of passing sidings resulted in traffic sampling modifications at the following locations.

4.2.1.2.1 Allentown Yard

The Allentown yard is being rebuilt, eliminating double thru-tracks in the center of the yard to be replaced with single track around the side of the yard. From MP-88.0 to MP-88.5 is now single track (new); MP-88.5 and west is still double track. The track up to MP-89 is used for pull backs, where the switch engine pulls a string of cars out of the yard and then backs it in onto another track during the process of blocking a train. It is estimated that 10-15 pull-backs occur in a 24-hour period. Anywhere from 30-50 cars are involved in each move resulting in an average of 500 cars being pulled back per day. Actually these cars traverse the section of track twice, once going out and once returning.

4.2.1.2.2 Easton Yard

Between Phillipsburg (MP-76.3) and Abbott (MP-77.9) the local train moves must be counted double because they are actually switch moves. These trains include the ARV, ANG, AF, AE and AM locals.

4.2.1.2.3 Musconetcong Tunnel

This tunnel is a point of concern due to the passing siding and the fact that seven-eight trains per week use this siding rather than the main track. Ordinarily, opposing trains are diverted onto Track 3. There is a daily local train which services the industries along both Track 3 and the main line track. While this train is operating, opposing trains are diverted to the siding between W. Portal (MP-66.2) and Pattenburg (MP-62.3), part of which runs under the Musconetcong Tunnel.

The general practice is to allow the westbound trains to continue thru on the main track while the opposing eastbound train is diverted to the siding. Preference is given to the westbound trains because they are usually carrying greater tonnage and are climbing a hill which reaches its peak in the vicinity of the tunnel. Generally, this same procedure is applied to the siding between MP-42.6 - MP 39.5. Approximately five eastbound trains per week are diverted to the siding.

4.2.2 TRAFFIC SAMPLING RESULTS

4.2.2.1 Fort Wayne Results

Results from the seasonal traffic samples are summarized in Table 4-2. Track 1 (eastbound) tonnage per mile for the entire test zone equals 23.95 million gross tons (MGT); and Track 2 (westbound) tonnage per mile for the entire test zone equals 18.97 MGT. Heavy wheel loads are 37 percent for Track 1 and 33 percent for Track 2.

4.2.2.2 Lehigh Results

As can be seen in Table 4-3 the Lehigh Division test zone experiences a variety of MGT and percent heavy wheel loads. Single track (7) tonnage per mile for the entire test zone equals 12.8 MGT, Track 1 (westbound) tonnage per mile for the entire test zone equals 7.2 MGT and Track 2 (eastbound) tonnage per mile for the entire test zone equals 9.3 MGT per mile. Heavy wheel loads vary from 37 percent on Truck 1 to 62 percent on Track 2.

TABLE 4-2

SUMMARY OF FORT WAYNE DIVISION TRAFFIC SAMPLING

Annual Tonnage (MGT)		Percent Heavy Wheel Loads		Distance (mi)	Location	MP
TRK 1	TRK 2	TRK 1	TRK 2			
					Bucyrus	200.6
23.9	18.6	37	32	8.7		
					Nevada	209.3
23.9	18.8	37	33	8.2		
					Upper Sandusky	217.5
24.3	18.9	37	33	1.4		
					Chess	218.9
24.3	18.9	37	33	10.6		
					Forest	229.5
24.0	18.9	37	33	6.9		
					Dunkirk	236.4
24.0	18.9	37	32	2.3		
					Dola	238.7
24.0	18.0	37	32	18.4		
					P&G	257.1
24.2	19.0	37	32	2.8		
					Sugar Street	259.9
24.8	19.8	38	33	0.4		
					Lima	260.3
24.5	20.0	37	33	1.5		
					Cole Street	261.8
23.9	19.9	37	33	1.7		
					Dug Run	263.5
23.7	19.1	37	33	9.4		
					Edge	272.9
23.7	19.1	37	33	1.6		
					Delphos	274.5
23.8	19.2	37	33	9.3		
					MP 283.8	283.8
23.8	19.3	37	33	4.0		
					Estry	287.8
23.7	19.3	37	33	0.2		
					Van Wert	288.0

TABLE 4-3

SUMMARY OF LEHIGH DIVISION TRAFFIC SAMPLING

Annual Tonnage (MGT)			Percent Heavy Wheel Loads			Distance (mi)	Location	MP
TRK 1	TRK 2	TRK 7*	TRK 1	TRK 2	TRK 7*			
6.6	6.3		40	42		.4	Penn Haven	131.0
7.7	7.2		42	48		9.6	M&H	130.6
7.6	7.3		42	47		1.6	Packerton	121.0
							Lehighton	119.4
		13.5			43	3.2	Lehighton	114.7
		13.5			43	3.1	Bomanstown	111.5
		14.1			46	3.9	Palmerton	108.4
		14.1			46	4.4	Walnutport	104.5
7.2	6.9		44	49		4.5	Treichler	100.1
7.2	6.9		44	49		1.1	Siegfried	95.6
7.4	7.0		46	49		1.5	Northhampton	94.5
7.4	6.9		46	49		5.0	Catasaugua	93.0
							Allentown	88.0
6.6	11.0		37	62		4.0	Bethlehem	86.0
6.7	11.0		37	62		1.3	Freemansburg	82.0
6.7	11.0		37	62		3.7	Richard	80.7
		12.9			43	.7	Easton	77.0
		12.6			44	6.3	Phillipsburg	76.3
		12.5			44	3.8	Musc. Branch	70.0
		12.5			44	3.9	West Portal	66.2
		12.5			44	11.3	Pattenburg	62.3
		12.4			44	2.5	Flemington Jct	51.0
		12.3			44	6.5	Three Bridges	48.5
		12.2			44	6.2	Read Valley	42.0
							Port Reading	35.8

*Single track

4.3 TRACK STRUCTURE QUANTIFICATION

Six track structure parameters were quantified using three sources. A subcontractor was selected to evaluate rail profile, ballast condition, and drainage over the test zone for each period of observation in general accordance with CONRAIL criteria. Track charts were used to determine rail type and weight and verified during the subcontractors' visual inspection. Finally, the degree of curvature was quantified using curvature data collected by T-6.

4.3.1 TRACK INSPECTION

J. S. Schaffer, Jr. Associated (JSSA) provided ENSCO with the necessary expertise (during two track inspections) to quantify:

- Rail Profile
- Ballast condition
- Drainage

The first inspection was performed in December 1978, the second in September 1979. The JSSA inspector (a former railroad Division Engineer) traversed the test zone with the aid of a high-rail car to evaluate the aforementioned parameters. On a mile-per-mile basis each parameter was assigned an integer value, as explained in the following sections, corresponding to a determined condition. If necessary, the mile section was divided into segments of varying condition. Inspection reports were generated that included summary of activity performed, completed parameter report form (Figure 4-3), observations of track, and recommendations concerning use of information

PHYSICAL AND TRAFFIC PARAMETERS -- SEGMENT #______

DATE:______________

MILEPOST - TO - MILEPOST		CUMULATIVE TONNAGE MGT	PERCENT HEAVY UNITS	AVERAGE TRAIN SPEED	DEGREE OF CURVATURE OVER 1°	RAIL WEIGHT	RAIL TYPE	RAIL PROFILE	BALLAST CONDITION	DRAINAGE	REMARKS

Figure 4-3. Physical Parameter Report Form

for maintenance-of-way planning. The following procedures were used to assign integer values.

4.3.1.1 Rail Profile

Rail profile was classified according to the percentage of surface-bent rail in a bolted track segment. A given piece of rail is considered "surface bent" according to the following definition:

- Surface Bent is a condition best illustrated in the field; it results from permanent deformation of the rail, usually at the end, after long periods of inadequate support from poor ties or ballast condition. It is a condition that cannot be corrected by surfacing alone and requires rail straightening or rail replacement.
- Rail irregularities such as corrugated rail or engine burns were noted in the remarks column of the parameter report form.

4.3.1.2 Ballast

Ballast condition was classified as clean, mildly dirty, pumping, or fouled. A given track segment was quantified for ballast condition using the following definitions:

- Clean - Any well drained ballast (except dirt) that is not supporting vegetation, does not have signs of impounded water, does not have any pumping ties, and does not show evidence of fouling of the shoulder or crib.
- Mildly Dirty - Ballast that is relatively clean in the crib area but may have some fouling of the shoulder and may be showing mild evidence of vegetation creeping into the shoulder, but which does not have impounded water in the cribs or show signs of pumping.
- Pumping - Track that has medium to heavy fouled shoulders so that water is becoming entrapped and ties particularly at joints are showing signs of pumping. More vegetation is evident.
- Fouled - Track that is generally fouled in the crib area and on the shoulders. Many ties are pumping and water is entrapped in the ballast. Restoration of good drainage would require removal of the ballast.

The conditions; clean, mildly dirty, pumping, and fouled were denoted 0, 1, 2, and 3, respectively, and tabulated as previously described. Contamination of ballast generally results from subgrade that infiltrates upward and disintegration of the ballast itself. Anything other than standard ballast contamination was reported in the remarks column of the report as to type and source.

4.3.1.3 Drainage

Drainage condition was classified as either adequate or inadequate. A given track section was quantified for drainage ability by complying with the following definition of drainage provided by the subcontractor.*

- Longitudinal Drainage Clogged - Evidence of accumulation of debris, i.e., branches, etc., that prohibit the free flow of water through the ditch. In a symptomatic condition, ponding moves right into the ballast of the track.

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*Interim Inspection Report No. 1 Engineering Evaluation for ENSCO/FRA/CONRAIL-MOW Planning, J.S. Shaffer, Jr. Associates, January 1979.

- Cross Lateral Drains Clogged - If headwall is visible, the pipe will show an accumulation of debris at the head of the pipe including earth or soil, slippage, branches, twigs, or other debris and possibly vegetation overgrowth preventing optimum drainage; in a heavy-rain condition ponding will develop at the head end of the drain. Sometimes, in the cases of a corrugated pipe culvert and concrete masonry box culverts, the pipe is crushed and the roof of the box culvert fails.

- Fills Clogged - Side ditches have debris, slippages of soil, dirt, etc.

- Cut Clogged - (Refer to longitudinal drainage.)

- Road Crossing Clogged - Longitudinal pipes underneath the road accumulate a significant amount of debris producing puddling on the track and ponding beside the track.

- Bridges (Clogged Longitudinal Drainage) - Longitudinal drainage becomes clogged by improperly diverted drainage from overhead (road or other railroad) bridges.

- Station Platforms Clogged - Longitudinal pipes in the six-foot (space between track) are clogged producing puddling. In dry weather, mud accumulation appears in the ballast because of clogged longitudinal pipes.

A given track segment is evaluated as inadequate drainage if at least three of the seven conditions exists, and is denoted "1". Otherwise the segment is denoted "0" for adequate drainage.

4.3.1.4 Rail Type and Weight

Rail type and weight was obtained from the most recent CONRAIL track charts. During the track inspection these two parameters were verified by the subcontractor and from input supplied by CONRAIL field personnel. Rail type was denoted "0" for welded rail and "1" for jointed rail. Rail weight was quantified according to the weight in pounds per yard.

4.3.2 CURVATURE

Originally, curvature was quantified from the track charts and checked during track inspection. On comparison of track chart curvature with T-6 curvature data, it was determined that the January 1979 track charts were not accurate for curve location and size. Therefore, curvature was quantified from T-6 data for the physical parameter master file. The maximum degree of curvature in the curve was used for reporting purposes. Any curvature less than two degrees was classified as tangent track.

4.4 MAINTENANCE QUANTIFICATION

Maintenance related practices are those that affect the quality of the track. Maintenance-of-way can be divided into two broad categories according to CONRAIL practices. First is basic maintenance; this is spot non-discretionary maintenance accomplished by small maintenance crews as a result of weekly track inspections. Secondly, there is production maintenance which is planned discretionary maintenance accomplished by large mechanized production gangs.

4.4.1 BASIC MAINTENANCE

The basic maintenance operations; regage, tie renewal, hand smoothing, machine smoothing, and surfacing are quantified according to the level of effort (Table 4-4). In general, basic maintenance will not affect track quality for a segment of track. The replacement of a few ties in a track segment will not influence indices which indicate average track quality for that segment. However, for some segments the indices may be affected depending on the extent of the maintenance in relation to the length of the segment.

Quantification of basic maintenance is accomplished by determining the percentage of the segment that has received maintenance. Daily Basic Maintenance Reports were screened for these five maintenance operations and the data were collected for the entire test zone in a cumulative fashion from the first period of observation.

The percentages representing the five maintenance operations were added resulting in an indication of the total percent of a segment which received maintenance. These overall percentages were stored in the Data Base Management System. A maintenenace level of "0" indicates that no maintenance was performed. Level "1" indicates that up to 10 percent of a segment received maintenance and level "2" was assigned to any segment in which 10-30 percent had been maintained. A level "3" indicates that more than 30 percent of the segment received maintenance. The extent of maintenance performed at level "3" is considered equivalent to that of Programmed Maintenance.

The five basic maintenance operations quantified in this study are described in the following paragraphs.

TABLE 4-4

MAINTENANCE QUANTIFICATION

Parameter	Description				Source	Frequency
Basic Maintenance	Level 0 0 Percent	Level 1 0 < BM ≤ 10 Percent	Level 2 10 < BM ≤ 30 Percent	Level 3 30 Percent < BM		
Regage (Track Feet)	0	0 - 528	528 -1584	1584	Basic Main-tenance Reports	Daily
Hand Smoothing (Joints)	0	0 - 27	27 - 81	81		
Machine Smoothing (Joints)	0	0 - 27	27 - 81	81		
Tie Renewal (Each)	0	0 - 300	300 - 900	900		
Surfacing (Track Feet)	0	0 - 528	528 -1584	1584		
Programmed Maintenance	Level 0 - No Maintenance Level 4, 5, 6 - Maintenance Performed				Monthly Produc-tion Reports	Monthly
Surfacing and Lining	Accomplishments of surfacing and Lining gangs					
Tie Renewal	Accomplishments of tie and surface gangs.					
Rail Renewal	Accomplishments of rail gangs					

4.4.1.1 Renew Crossties

This operation requires a minimum of a four-man gang and a foreman. First, the tie to be removed is located and the ballast is cleared from around the tie using forks and picks. Then the spikes are pulled. A track jack is used to raise the track and then the anchors are removed, freeing the tie from the rails. In the installation operation, the tie is placed under the rails, the track is lowered, the gage is determined, spikes are driven, anchors are secured, and the ballast is replaced. This operation was recorded on a per tie basis.

4.4.1.2 Surfacing

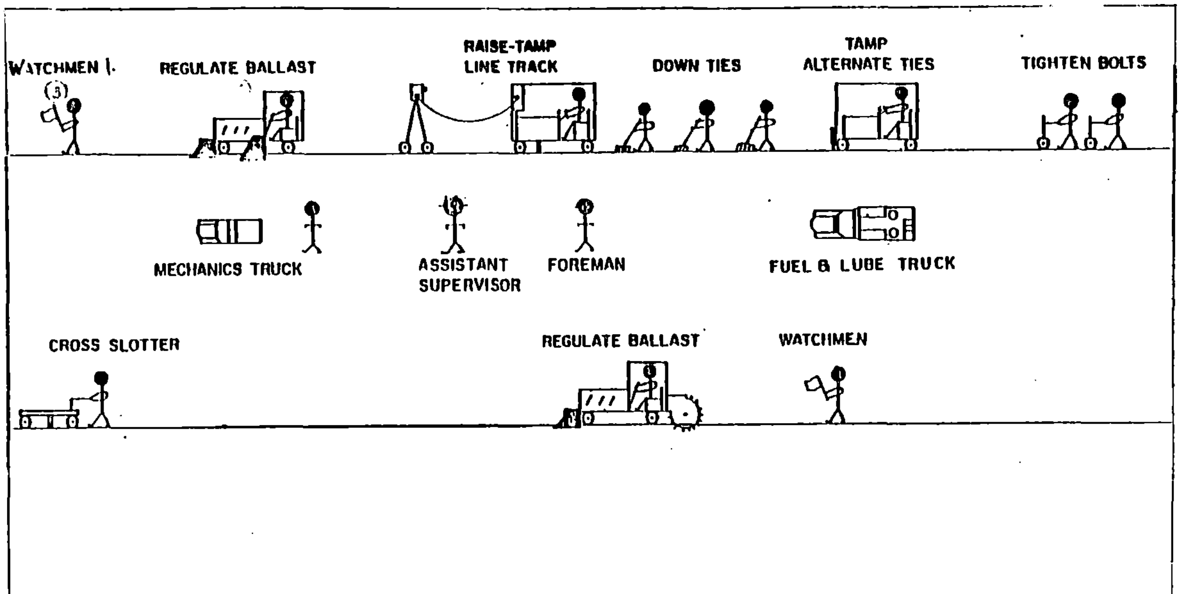
This operation is used to bring the ballast section to the AREA recommended standards. The ballast should extend 12 inches beyond the end of the tie, level with the top of the tie. A 2:1 slope is used for the shoulder until the ballast is at grade. While renewing the ballast section, additional maintenance is performed at joints and on curves.

Joints are raised to remove the underlying depression in the ballast. Depressions occur at joints due to decreased rail stiffness at these points. In curves, the superelevation is reset to the level dictated by the speed and the degree of the curve.

The machinery required for this operation includes: two ballast regulators, one clearing the ballast and the other replacing it; a bolt machine, for jointed rail only; a tamper; and a torsion beam which can raise, lower or laterally shift the position of the rail by up to six inches. This operation is recorded in terms of linear track feet.

4.4.1.3 Hand and Machine Smoothing

Both hand and machine smoothing are small scale versions of surfacing. Hand smoothing generally refers to a hand tamping operating restoring the ballast section in a specific area such as a single joint where full-scale maintenance is not necessary. Machine smoothing is used under the same circumstances with the exception that portable hand tampers are used. Both of these operations are recorded in terms of the number of joints which are affected by maintenance.



(Courtesy of CONRAIL)

Figure 4-4. Typical Set-Up for High-Speed Surfacing Gang (Class SEC, SET, and SER)

4.4.1.4 Regage

This maintenance operation is often required for curved sections of track. The base of the rail does not ordinarily shift, but due to increased lateral forces, the inside of the head of the high rail wears down sufficiently to affect the gage. This operation is accomplished by using a gage bar to hold the gage while the track is respiked. This operation is recorded on the basis of track feet regaged.

4.4.2 PROGRAMMED MAINTENANCE

For this study, programmed maintenance consists of three major operations: surfacing gangs, tie and surface gangs, and rail gangs. These operations are planned during the fall and winter and accomplished the following year during the spring, summer and fall. Monthly Production Reports were screened for the accomplishments of the production gangs. Each segment in which production maintenance occurred was assigned an integer value of 4, 5 or 6 as explained in the following paragraphs, and stored in the Data Base Management System (DBMS). Table 4-4 summarizes the quantification methodology for programmed maintenance. The following sections briefly describe these three maintenance operations.

4.4.2.1 High-Speed Surfacing Gang

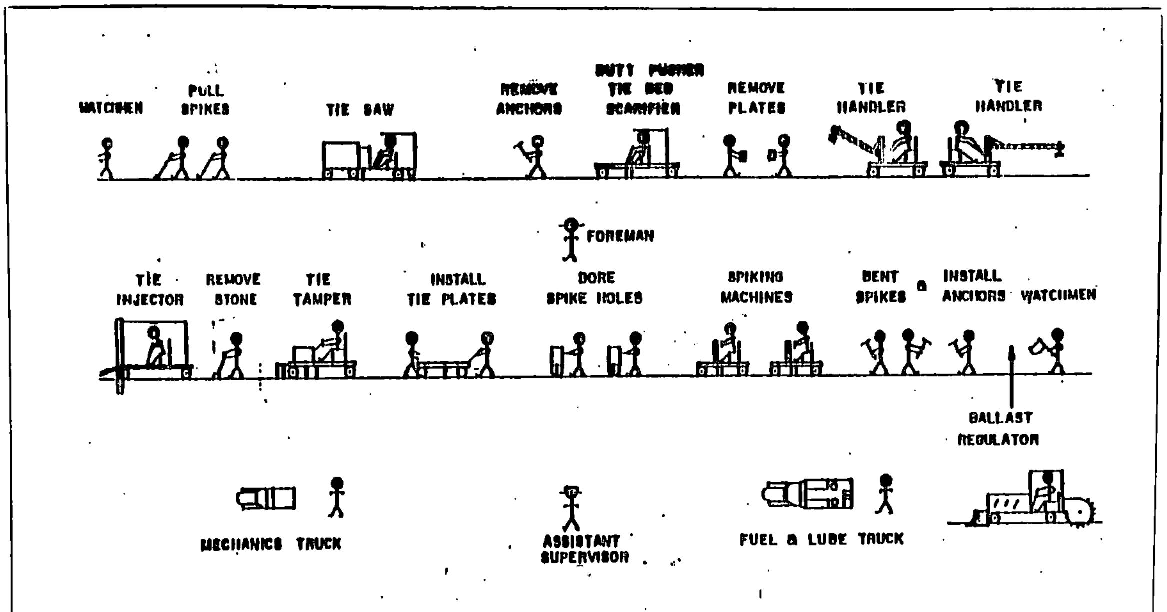
A high-speed surfacing operation is denoted 4 in the DBMS and is shown in Figure 4-4. Here ballast is pulled into the track determined by the amount of raise required. A surfacing torsion beam optically sighted device raises, tamps alternate ties, and then aligns the track. It also sets the crosslevel in curves as provided by the track supervisor. Rail anchors are then applied and gage is checked and corrected, if necessary. The remaining alternate ties and ties through switches are tamped next. Joint bolts are then tightened and the rail joints are slotted to remove clipping. The ballast is then shaped and filled where necessary. This operation* normally required 24 to 25 people.

4.4.2.2 Tie and Surface Gangs

Tie and surfacing** is denoted 5 in the DBMS. Figure 4-5 shows the tie gang portion using a Kershaw Tie Injector (TK).

*Gang Organization and Operation of a Class SEC Surfacing Gage, Penn Central Transportation Company, November 1974.

**Gang Organization and Operation of a Class TK Tie and Surfacing Gang. Penn Central Transportation Company, Nov 1974.



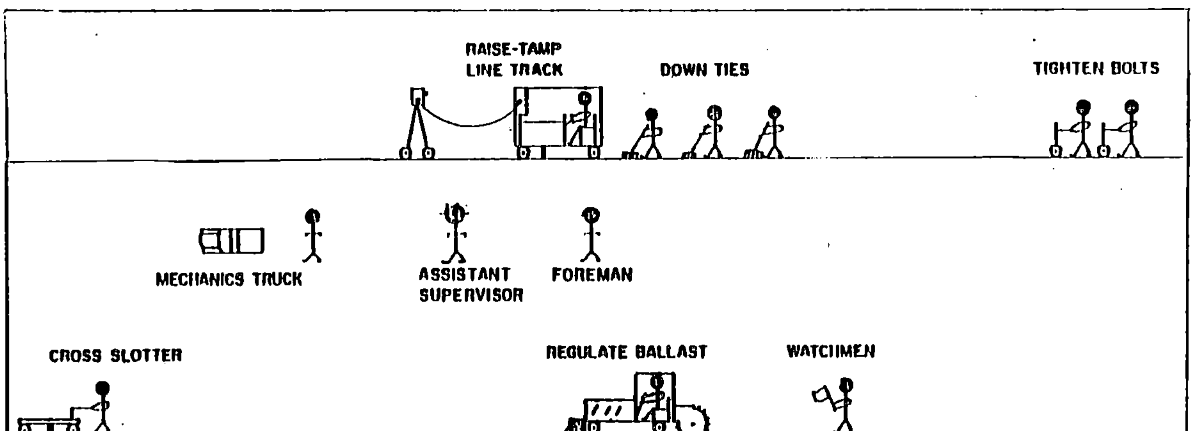
(Courtesy of CONRAIL)

Figure 4-5. Typical Set-up for Tie and Surface Gang (Tie Portion-Class TK)

Ties that require replacement are marked by an inspector ahead of the gang. Normally 30-40 percent of the ties are replaced during this type of operation.

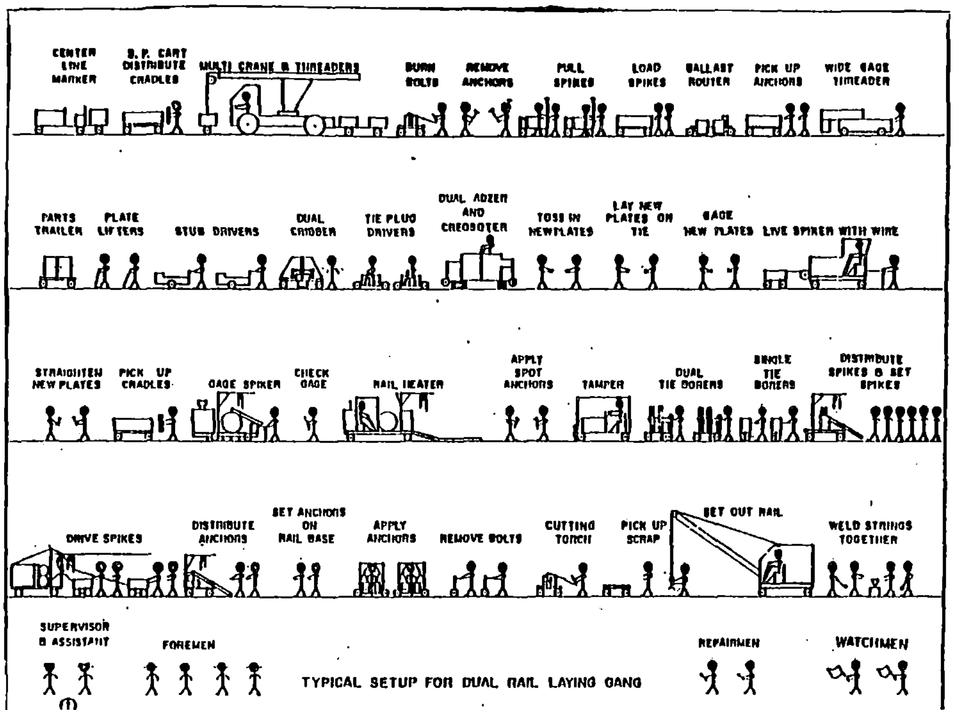
Initially the spikes are pulled and the tie is cut or sawed into three sections. The anchors are then removed from the rail. The tie ends are pushed from under the rail and the tie plates are removed. The first tie handler removes the old tie segments while the second handler places new ties on top of the rail. The tie inserter then installs the tie under the rail in the tie bed area. Stone is removed from the tie plate area and the ties are tamped. Tie plates are installed and the gage is set using a gage bar. Spike holes are bored and spikes and rail anchors are installed. The ballast regulator pushes the ballast into position for tamping.

Figure 4-6 shows the surfacing portion (ST) of this operation. The operation is similar to the high speed surfacing gang except that a second tamper is usually not needed. A Tie and Surface Gang usually requires 38 people for the tie portion and 24 people for the surfacing portion.



(Courtesy of CONRAIL)

Figure 4-6. Typical Set up for Tie and Surface Gang (Surfacing Portion - Class TN and TK)



(Courtesy of CONRAIL)

Figure 4-7. Typical Setup for Dual Rail Laying Gang

4.4.2.3 Rail Gang

Rail laying operation is denoted 6 in the DBMS. Usually a Tie and Surface Gang is sent through the track region one year prior to rail laying. In addition a high speed surfacing shortly follows the rail gang in general practice. As shown in Figure 4-7 rail laying is a labor intensive operation*, usually requiring 80 people. The ties are marked with a a centerline stripe as a reference. Cradles are centered on the line and the crane threads the welded rail into the cradles at a narrow gage. Bolts, anchors, and spikes are removed from the old rail which is then threaded to a wide gage. The ties plates are then removed and the tie plugs are installed in the spike holes. The tie plate area is then adzed and creosote is applied. New tie plates are installed and gaged. The rail is heated and spot anchored. Ties are bored, the spikes are installed and the rail is anchored. The remaining bolts are removed from the old rail and it is set aside. The strings of welded rail are then field welded (thermite) together.

4.4.3 MAINTENANCE QUANTIFICATION RESULTS

Table 4-5 summarizes the results of maintenance quantification between the periods of observation. Track segments for all maintenance levels were analyzed to obtain predictive equations for track condition. However, the main thrust of the program was directed at unmaintained track segments (level 0). Maintenance bar charts were prepared and submitted that summarized each basic and programmed maintenance operation over the test zone on a mile-per-mile basis. From these charts, histograms of cumulative

*Gang Organization and Operation of a Dual Rail Gang, Penn Central Transportation Company, November 1974.

TABLE 4-5

MAINTENANCE QUANTIFICATION RESULTS

MAINTENANCE LEVEL	
Value	Number of Segments
0	221
1	31
2	54
3	370

where:

0 - no maintenance

1 - 0 to 10 percent maintained

2 - 10 to 30 percent maintained

3 - more than 30 percent maintained (includes programmed maintenance)

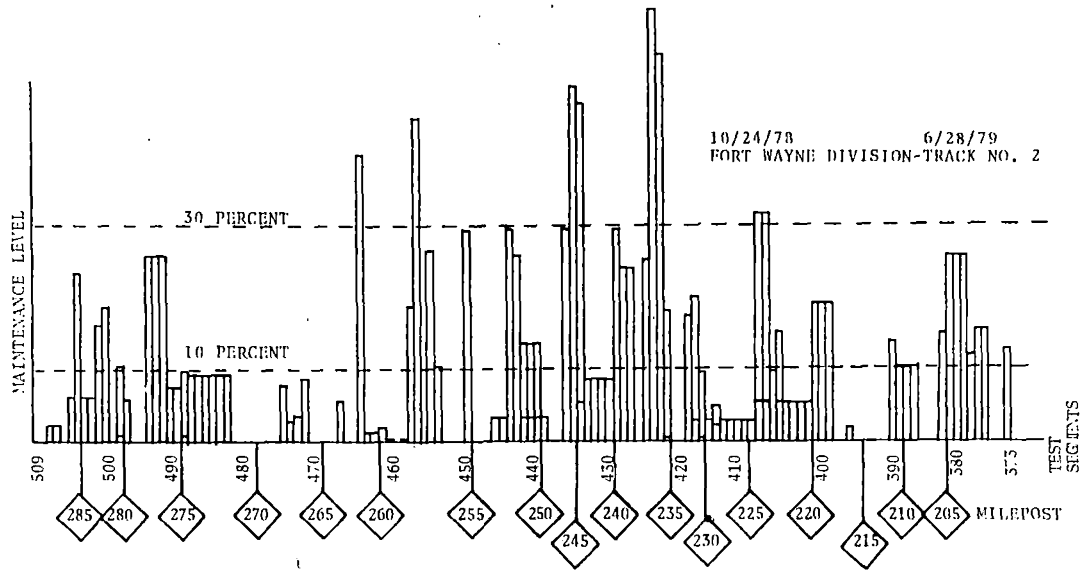


Figure 4-8. Basic Maintenance Data

basic maintenance were generated to quantify the maintenance level of each track segment. Figure 4-8 is a typical plot for track No. 2 of the Fort Wayne Division test zone as quantified through 28 June 1979. Milepost number is indicated in the diamonds along the bottom of the plot and track segment number is listed above the milepost number. As shown in Figure 4-8 most of the test segments (at this point in time) had experienced level 1 or 2 maintenance. However, segments such as 422 and 423 had received considerable basic maintenance (level 3).

4.5 TRACK SEGMENTATION

Track segentation is essential in the determination of predictive equations between track quality indices (TQI's) and physical parameters with specific track locations. A track segment in which the physical parameters are uniform is considered homogeneous. For physical parameters uniformity may be defined in two ways:

- The value of the physical parameter is constant throughout the segment, e.g., tonnage
- The parameter may vary within the track segment but the variation is consistent. For example, ballast condition may be classified as dirty for a track segment even though some joints have a pumping condition.

If all relevant physical parameters have been taken into account, the track geometry measurements within a segment should be homogeneous. It is with track segmentation that values of physical parameters can be associated with track geometry in a meaningful way. Thus, segmentation allows for the correlation of track geometry with physical parameters.

4.5.1 RESULTS

Track segmentation involves reviewing all eleven physical parameters for change in condition. After reviewing the test zone data, ground rules were set in which a minimum segment length of 0.1 mile and a maximum segment length of 1.0 mile were selected. Only for curves will the segment length be as short as 0.05 mile.

Any change in the value of a physical parameter for the minimum segment length constitutes a new segment. Curvature and ballast condition varied the most over the test zone and therefore, caused most of the segmentation. Final segmentation resulted in 676 track segments. Table 4-6 summarizes the number of track segments for classification of each physical parameter. Appendix F (Volume II) contains a listing of the physical parameters for the 676 segments.

It should be noted that at the start of the program additional physical parameters, i.e., tie condition, track modulus, and environmental conditions such as rain fall and frost heave were considered. Due to fiscal constraints and other practical considerations, the eleven most feasible physical parameters were selected by representatives of FRA, ENSCO, and CONRAIL.

TABLE 4-6

FINAL TRACK SEGMENTATION FOR 1978

1. CUM TON		2. HVY WHL		3. AVG SPEED		4. CURVE		5. RAIL WT		6. RAIL TYPE		7. RAIL PROF		8. BAL COND		9. DRAIN COND		10. MAINT LEVEL	
Range	No. of Seg.	Range	No. of Seg.	Value	No. of Seg.	Range	No. of Seg.	Value	No. of Seg.	Value	No. of Seg.	Range	No. of Seg.	Value	No. of Seg.	Value	No. of Seg.	Value	No. of Seg.
5 ≤ T<10	196	30 ≤ H<35	145	10	6	0 ≤ C<2	508	127	32	0	168	0 ≤ P<10	324	0	443	0	651	0	221
10 ≤ T<15	193	35 ≤ H<40	172	15	3	2 ≤ C<3	41	130	51	1	508	10 ≤ P<20	202	1	152	1	25	1	31
15 ≤ T<20	142	40 ≤ H<45	184	20	5	3 ≤ C<4	40	131	248	0-welded rail 1-jointed rail		20 ≤ P<30	60	2	48	0 - adequate 1 - inadequate		2	54
20 ≤ T<25	145	45 ≤ H<50	141	25	53	4 ≤ C<5	37	133	73			30 ≤ P<40	30	3	33			3	141
T-annual tonnage in MGT		50 ≤ H<55	0	30	108	5 ≤ C<6	22	136	187			40 ≤ P<50	19	0-clean 1-mildly dirty 2-pumping 3-fouled				4	94
		55 ≤ H<60	0	35	75	6 ≤ C<7	7	140	81			50 ≤ P<60	18					5	93
		60 ≤ H<65	34	40	103	7 ≤ C<8	4	155	4			60 ≤ P<70	3					6	42
		H-percent of wheel loads ≥ 90T		45	22	8 ≤ C<9	7	Weight of rail in pounds per linear yard				70 ≤ P<80	6					0- no maint. 1-0-10% maint. 2-10-30% maint 3- 30% maint. 4- production surfacing 5- tie & surfacing 6 - rail & surfacing	
				50	301	9 ≤ C<10	10					80 ≤ P<90	8						
				Speed in Posted MPH		C- Curvature of track in degrees						90 ≤ P<100	1						
												100 =P	5						
												P-percent bent rail							

5.0 SOFTWARE

5.1 GENERAL

The Maintenance-of-Way (MOW) software is an integral part of the development of predictive equations for track degradation. It provides a comprehensive approach to the storage, calculation, and analysis of the data base for given track segments. This software is used to generate Track Quality Indices (TQI's) from track geometry data collected by T-6. The accurate quantification of the condition or quality of the track provides an effective tool for the development of degradation models to aid in the planning of long range track maintenance. The following sections describe the peripheral equipment required, the structure, and the performance of the MOW software.

5.2 PERIPHERAL EQUIPMENT

The MOW software operates on a Raytheon RDS 500 mini-computer having 65K, sixteen-bit words of directly addressable memory. Figure 5-1 shows the peripheral equipment required by the MOW software. The peripherals required are a disc, two magnetic tape drives, a card reader, a line printer, a teletype or CRT terminal, and an array processor. Software is written in ANSII standard FORTRAN and is readily adaptable to other computer systems by modification of the input and output routines.

5.3 STRUCTURE

The MOW software is designed specifically for Maintenance-of-Way applications. In addition, this software was designed to meet the requirements of different user applications within the scope of track maintenance planning. The software is written from the user's perspective. It is easy to use and the results are generally self-explanatory and easy to understand. Many of the programs are interactive, with the output from one program serving as the input for another.

The MOW software consists of three major packages: The Data Base Management System (DBMS), the Track Quality Indices Software Package (TQISP), and the Regression Analysis Software Package (RASP). Each of these packages is comprised of a set of major programs and subroutines. Figure 5-2 illustrates the interface of the three software packages.

TQISP computes the 14 TQI's from the track geometry data collected by the T-6 survey car. DBMS provides a common base for operation of different software packages. DBMS stores the calculated TQI's along with the traffic, physical and maintenance parameters. This package has the ability to retrieve, sort, manipulate, and display the data which it stores. RASP is used to perform correlation and regression analysis resulting in the development of degradation models.

5.3.1 PRE-PROCESSING

The T-6 survey car measures profile, alignment, gage, crosslevel, curvature, location, speed, and distance as described in Section 2.0. The raw measurements are recorded on magnetic tapes in the form of counts proportional to the track geometry parameters. These counts must be converted to engineering units before they can be used to compute TQI's.

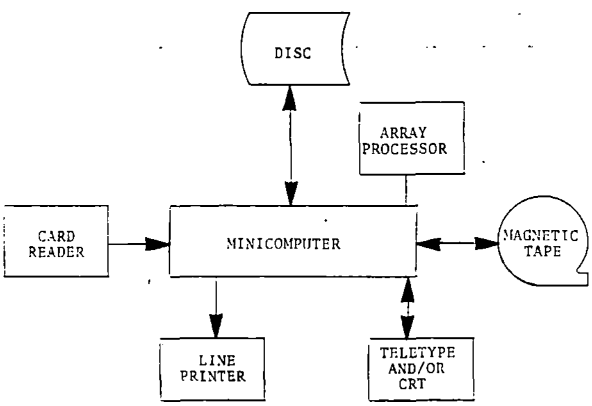


Figure 5-1. Peripherals Required by MOW Software

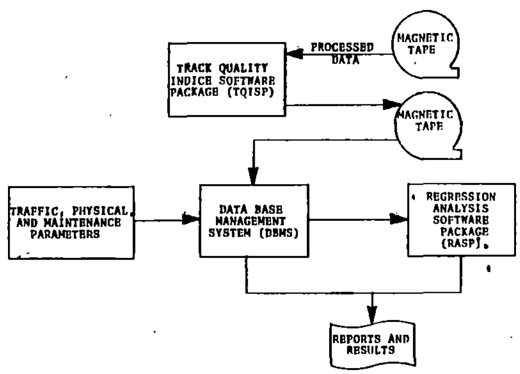


Figure 5-2. Relationship of the Software Packages

The programs used for preprocessing are a data preparation program referred to as TRAMP, and a plotting program. These two programs convert and display the track geometry data. TRAMP accepts inputs from the track-geometry, raw-data tapes and performs the conversion into track-geometry parameters in engineering units. This output is stored on additional magnetic tapes, referred to as processed tapes.

The processed track-geometry parameters are in a form acceptable for use in the calculation of TQI's (Section 3.0). Gage is recorded as the offset from a baseline of 57 inches. Both alignment and profile are calculated in the form of a short mid-chord-offset (MCO), a 62-foot MCO, and a space curve. The short MCO is two feet for alignment and three feet for profile. In addition, two MCO's of lengths selected by the user can be obtained. In the MOW application, ten-foot and 16-foot MCO's are calculated for alignment and profile. Curvature can be caluclated as raw or actual curvature and smoothed. Smoothed curvature is calculated by passing the raw curvature data through a low-pass filter having a 79-foot window. This attenuates wavelengths below 79 feet and thus smoothes the curvature measurement (Figure 5-3). Crosslevel is computed as actual crosslevel and crosslevel deviations from the designed or mean-removed crosslevel.

Once the tapes have been processed, a plotting program is used to extract any six of the track geometry parameters and to display these parameters side-by-side as a function of distance along the track. These plots enable the user to verify the quality of the track-geometry data.

5.3.2 DATA BASE MANAGEMENT SYSTEM (DBMS)

DBMS creates, maintains and manipulates data files, generates inventory reports, orders data according to various options and provides a means for interaction with other software packages.

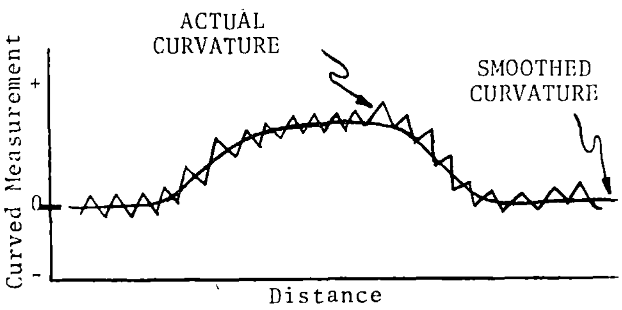


Figure 5-3. Smoothed Curvature

The MOW data base consists of raw track-geometry tapes, processed track-geometry tapes; and the collected data describing traffic, maintenance histories, and the track structure for the test zone. This data is stored in the DBMS in master files which consist of labelled segments of the test section, each including their respective TQI and physical parameter information (Appendix F).

The other types of files active within the DBMS are milepost directory files and group files. Milepost directory files are used to establish a segment-to-segment correspondence between track-geometry data, milepost information and the mileposts on track charts. This file is used to extract track geometry data in the computation of TQI's, and to determine the correct placement of the TQI's in the master file. A group file is a directory file which maintains a record of the homogeneous groups of data in a master file. The homogeneous sets of data generated within the DBMS are suitable for regression analysis.

The ten major programs of the DBMS are listed in Table 5-1, along with their functional descriptions.

TABLE 5-1

MAIN PROGRAMS IN DBMS

Name	Functions
CRTFL	Creates random files
COPYM	Copies one random file to another
FSCRESTO	Restores FCS* files on disc
FCSSAVE	Saves FCS* files on magnetic tape
GMFILE	Generates a master file from a group file
GROUPCR	Generates homogeneous groups of data
PRINTM	Prints MOW data
READP	Stores physical, traffic and maintenance data in the master file
TRANSFER	Transfers selected parameters from one file to another
UPDTF	Updates a master file

* File Control System

5.3.3 TRACK QUALITY INDICES SOFTWARE PACKAGE (TQISP)

Track Quality Indices are computed from track geometry data. TQISP is used to align the track geometry data with real-world track in the segmentation process, to compute TQI's, and to print and plot the TQI's.

The track geometry data is first segmented automatically in terms of curved and tangent sections. This segmentation and curvature information is used in conjunction with track chart and physical parameter information to construct an initial milepost directory file and the corresponding master file. Subsequent directory files are used to align track geometry data of different observation periods with the original master file segmentation.

The milepost directory file is used to locate a segment of track geometry on the data tape. The 14 TQI's are calculated and then stored in the corresponding master file segment.

TQISP plotting capabilities enable the user to obtain plots of the MOW data. Any TQI or physical parameter can be plotted against any other by segment number or by milepost. In addition, an analog representation of the data can be displayed as a function of distance along the track.

TABLE 5-2

MAIN PROGRAMS IN TQISP

Name	Functions
SEGMENTS	Segments the track geometry data based on curves and tangents
ALDSERCH	Searches the Automatic Location Detector signals for switches, road crossings, etc.
MPCOPY	Copies mileposts from the master file to the milepost directory file
LSEG	Computes the lengths of segments
TQI	Computes TQI's
PRINTY	Prints TQI's
TQIPLOT	Generates 8 x 11 plots of TQI's
TQGEN	Generates analog representation of TQI's as a function of the distance along the track
DELTAY	Computes the difference of TQI's between two operation periods

TABLE 5-3

SUBROUTINES IN RASP

Name	Functions
REGRESS	Driver routine for regression and correlation analysis
REGSET	Sets up variable names and independent and dependent variables used in regression
REGDATA	Gets data for one observation and performs the required mathematical transformation
CORREL	Computes means, standard deviations and correlation matrix for independent and dependent variables
LINEAR	Performs multiple linear regression
STEPWISE	Performs stepwise regression
MINVAD	Inverts a matrix
REGOUT1	Prints means, standard deviations and correlation matrix of the independent variables
PLOTM	Driver routine for generating various plots for regression analysis
PLOTXY	Generates an X-Y plot

Table 5-2 lists the major programs of TQISP and gives their functional description.

5.3.4 REGRESSION ANALYSIS SOFTWARE PACKAGE (RASP)

RASP was developed to formulate the relations between a set of independent and dependent variables. In MOW data, physical, traffic, and maintenance parameters are treated as independent variables and TQI's are treated as dependent variables. These data exist on the files in the DBMS. The DBMS allows one to identify and access the homogeneous subsets of data, called group files. RASP develops the regression equations based on these data and computes the necessary statistics to analyze these equations and to make statistical inferences for prediction purposes.

RASP provides the capability for performing correlation analysis, general multiple linear regression, stepwise regression or autoregression on either a master or group file. These correlation and regression techniques can be used to develop the degradation models for application to long-range, maintenance-of-way planning.

Table 5-3 lists the major subroutines of RASP and gives their functional description.

5.4 PERFORMANCE

The three major packages of the MOW software make up a coherent software system which is designed to meet MOW applications. Wherever precision is important, computations are performed in double precision*. The capabilities and limitations of DBMS, TQISP, and RASP are discussed in the following paragraphs.

5.4.1 DBMS

The MOW Data Base Management System provides extensive capabilities for manipulating, updating, printing and plotting MOW information. DBMS is based on the Raytheon File Control System (FCS) with various functions available by simple Fortran calls. The following limitations were imposed for efficiency and ease of operation.

- Only random and sequential files are used for the special system generated for this application. Indexed files were not used since there was no application for same.
- Both the random and sequential files consist of unblocked fixed lengths records.
- The usable record size is fixed at 159 words for random files and 160 words for sequential files.
- Data are stored in unformatted binary format to conserve storage space.

DBMS allows the user to maintain as many files as required, limited only by disc space. The maximum allowable number of files is fixed by the user at the time of Disc Initialization. The user can also fix the number of simultaneously open files. However, this number is limited by the availability of symbolic units which are used to open a file. The FCS requires that the symbolic unit used to open a file must not be greater than 11.

Grouping programs assume that a master file will not contain data for more than 1000 track segments. Furthermore, the maximum number of homogeneous groups cannot be greater than 100. These limitations are within the scope of expected applications for this study.

*Raytheon Data Systems, "RDS-500 Real-Time Fortran IV," PMD862531, November 1979

5.4.2 TQISP

The Track Quality Indices Software Package can compute TQI for one segment or a series of segments at a time. This feature allows an easy update of the master file. Track geometry data is automatically edited during TQI computation to exclude the gage and alignment data when the gage sensors are retracted. This is valuable because manual editing would be very tedious and time consuming. TQISP can compute up to 16 TQI's. A feature of TQISP enables the user to print and subsequently verify the TQI data before storage.

5.4.3 RASP

The Regression Analysis Software Package was designed to be efficient and to minimize the round-off errors. Results are displayed in an alphanumeric format that is easy to comprehend (Appendices G and H). RASP can work on either an entire file or part of a file. In addition, the program can work on up to 100 groups of homogeneous data. The following design criteria were imposed for efficiency and ease of operation.

- The number of initial independent (X) variables is limited to 15.
- The program can develop regression equations for up to 15 dependent variables at a time.
- Any dependent variable can be treated as independent. This option can be used to analyze the relations among dependent variables (cross correlation).
- A log transformation can be applied to any dependent variable.
- A log or a polynominal transformation can be applied to any independent variable. Furthermore any independent variable can be declared to consist of various levels rather than being a continuous one. A variable which consists of ℓ levels will be replaced by $(\ell - 1)$ dummy variables. Similarly $(P - 1)$ new variables will be generated for a polynominal transformation of P degrees. Thus various transformations may increase the number of independent variables. Total number of modified independent variables should not be more than 25.
- Any independent variable can be forced into the regression equation, in the case of stepwise regression. However, the number of forced variables should not exceed 10.

- An option is provided to print a table of residuals. Residuals which exceed twice the standard error of estimate will be marked with asterisks. This option can be used to detect the outliers.

- A maximum of 256 observations can be excluded from regression analysis. This option can be used to develop regression equations from data without outliers.

- Actual y's can be plotted versus predicted y's. Also the residuals can be plotted versus predicted values of y or x. These plots can be helpful in analyzing the adequacy of the regression model.

6.0 ANALYSIS METHODOLOGY

The predictive methodology for the long-range track maintenance planning system involves the establishment of a suitable data base and a number of analytical procedures. Physical parameter data were collected in 1978 and 1979 in order to determine their contribution to track condition. Track structure, traffic, and maintenance parameters were quantified for the test zone. Based on these data the test zone was divided into 676 homogeneous track segments. In addition, automated track geometry surveys were conducted in the Fall of 1978 and the Fall of 1979 by the T-6 survey car to measure and collect geometric track parameters, i.e., gage, alignment, profile, crosslevel, and curvature. From the track geometry parameters, candidate figures of merit, referred to as candidate Track Quality Indices (TQI's), were developed that effectively quantify the ability of a track segment to meet its functional requirements.

Computer software was developed to perform data processing, to compute TQI's and to perform regression and correlation analysis. This section describes the methodology used to analyze the MOW data for development of track degradation models. Section 6.1 gives the definition of certain terms which will be used throughout this section and Sections 7.0 and 8.0. The latter sections give a step-by-step procedure used to analyze MOW data. The reader is referred to Appendix D for details of regression analysis techniques which were widely used to develop the degradation models.

6.1 GLOSSARY

Dependent Variable (y): A variable which is estimated using one or more independent variables. TQI's are treated as dependent (or response) variables in this study.

Independent Variable (x): A variable which is used to estimate the dependent variable. Physical parameters such as tonnage, rail type, ballast condition, etc., are treated as independent variables in this study.

Dummy Variable: A dummy variable is used to describe a variable which has two or more distinct levels. For example, in the set of physical parameters considered in this study, ballast has four distinct levels. The effect of ballast on a TQI can be investigated by introducing three dummy variables. In general, a factor with ℓ levels will require ℓ-1 dummy variables.

Regression Analysis: Regression analysis is a technique used to develop the relationship between a dependent and one or more independent variables. The term multiple linear regression is used when the relationship involves more than one independent variable in some linear form.

Stepwise regression is the procedure whereby a subset of the independent variables is included in the regression equation. The selection criteria is based on the relative importance of the independent variables in explaining the variation of the dependent variable.

The term autoregression is used when the functional relationship for the current value of a dependent variable is based on its previous value measured sometime in the past and a set of independent variables.

Residual: A residual is the difference between the observed y and the y predicted from the estimated regression equation. By an analysis of residuals, one can test the adequacy of the predictive model and the assumptions underlying the regression analysis.

Outlier: An outlier is defined as a data point that does not appear real and results from errors in recording observations. Outliers can be traced by an analysis of residuals. If the absolute value of a residual is far greater than the rest and perhaps lies three or four standard deviations away from the mean of the residuals, the corresponding observation is most likely an outlier.

Analysis of Variance: This is an approach whereby total variation is divided into meaningful components. In regression analysis, the total variation in the response variable is divided into regression and error components. This approach is valuable in estimating the quality of a regression equation.

F Value: An F value is the statistic which measures the strength of the relationship between two quantities. In regression analysis, the F value is used to evaluate the relative magnitude of variations explained by the regression equation and those variations which could not be explained by regression. A large F value, such as 3.0 or more, indicates that the regression model explains a significant amount of variations.

Correlation Coefficient: It is a measure of the linear dependency of two variables. The correlation coefficient varies from -1 to 1. An absolute value close to unity indicates a strong linear dependency.

On the other hand, a value close to zero indicates no relationship.

Coefficient of Determination (R^2): It is the proportion of total variation explained by the regression equation. It can be used as a figure of merit for the estimated regression equation. For example an R^2 value of 0.8 means that 80 percent of the total variations are explained by the regression model.

Adjusted Coefficient of Determination ($R^{2\prime}$): This is the R^2 values adjusted for the number of independent variables. R^2 values increase with each added variable. However, $R^{2\prime}$ increases only if the added variable is significant.

T-Value: In regression analysis, a t-value provides a measure of the significance of an estimated regression coefficient. A large t-value such as 2.0 or more indicates that the corresponding regression coefficient is significant, i.e., is not zero.

Confidence Interval: A confidence interval for an estimated regression coefficient is a measure of the spread of possible values at a certain significance level. An empirical regression coefficient (b) is only an estimate of the true regression coefficient (β). A confidence interval computed, for example, at 0.95 confidence level will provide a 95 percent confidence that the population parameter (β) will fall in that interval.

Degradation Coefficient: A degradation coefficient is a measure of relative change or sensitivity in a TQI. A positive value indicates track degradation, a negative value indicates track improvement and a value of zero indicates no change in track condition.

6.2 ANALYSIS OF TQI'S AND PHYSICAL PARAMETERS

The candidate TQI's were analyzed to determine if these indices indeed quantify the track condition in terms of the functional requirements of the track. The 1978 and 1979 TQI data for unmaintained track were plotted versus distance along the track to determine if the TQI's are sensitive to track degradation. Similarly, data for maintained track were plotted to determine the effect of maintenance on TQI's.

Existing track geometry representations* were used to develop the relationships between TQI's and the Federal Track Safety Standards. The results were verified by processing the track geometry data of the MOW program and comparing this data with the posted track class as determined by the FRA Office of Safety. The relationships were also developed between the ride quality indices and TQI's. These relationships were verified with actual experimental ride quality test results*.

Data provided by CONRAIL on recent track-related derailments were reviewed to determine the correlation of TQI's with derailments. Probability density estimates were generated for 1978 TQI's to compare the magnitude of the TQI's in the derailment areas. TQI values for track segments in which a derailment occurred were also compared with expected TQI values for the posted track class.

As mentioned earlier, the test zone was divided into 676 homogeneous track segments. Track segments were grouped according to the levels of basic or production maintenance and summaries of the physical parameters were generated for each maintenance level. In addition, the correlation analysis was performed to determine the relationship among the physical parameters. This analysis effectively characterizes the test zone from which the results of this study were derived.

6.3 PREDICTIVE MODELS

Linear autoregressive techniques were used to develop the predictive models in preliminary analysis. The models tested were of the form:

$$y' = \alpha + \beta_0 \hat{y}' + \beta_1 z_1 + \beta_2 z_2 \ldots \beta_m z_m \qquad (6\text{-}1)$$

where y' is the current dependent variable, $\hat{y}'$ is the previous dependent variable, z's are independent variables, α is the constant term, and β's are regression coefficients.

It should be noted that an observed y_i value will consist of y' given by Equation 6-1 plus an error. For the purpose of this study, it is assumed that errors are random, normally distributed, independent and have a mean of zero (Appendix D).

It should be pointed out that when no transformations are involved Equation 6-1 for MOW applications can be written as

$$y = \alpha + \beta_0 \hat{y} + \beta_1 x_1 + \beta_2 x_2 \ldots \beta_m x_m \qquad (6\text{-}2)$$

where y is the current TQI, $\hat{y}$ is the previous TQI, and x's are the physical parameters.

*ENSCO report, "Statistical Representation of Track Geometry," June 1979.

*ENSCO report, "Ride Quality Test Results," November 1976.

Since Equation 6-2 is developed from experimental data which is only a sample of the entire population, the estimated regression equation should be written as:

$$y = a + b_0\hat{y} + b_1x_1 + \ldots b_mx_m \qquad (6\text{-}3)$$

where y is the current TQI, $\hat{y}$ is the previous TQI, a is the estimated constant term, and b's are the estimated regression coefficients.

Equation 6-3 can be used to make projections of track condition in the future. In this case, $\hat{y}$ is the current TQI and y is the TQI predicted for some time in the future. Therefore, the term prediction equation will be used for equations of the form 6-3.

The general model of the form given by Equation 6-1 were tested in preliminary equations. These models involved different transformations on the physical parameters and/or TQI's. Only log transformations were tested on TQI's.

Transformations tested on physical parameters were log, polynominal and cross products of certain variables. Furthermore, dummy variables were introduced to describe rail type, drainage condition and ballast condition.

Preliminary predictive equations were developed for all candidate TQI's and for all maintenance levels. The equations were examined using the criteria given in Appendix D. Residual analyses were conducted to test the adequacy of the models and the assumptions underlying regression. Residuals were also studied to determine the outliers in the data. Prediction equations were developed by eliminating the outliers. These analyses provided the basis for selection of the final TQI's and the development of final predictive equations.

6.4 SELECTION OF FINAL TQI'S

Correlation analysis was performed on all candidate TQI's for the 1978 and 1979 data for different maintenance levels. The purpose of these analyses was to determine the TQI's which duplicate each other. For example, a high correlation coefficient such as 0.9 or above would indicate a strong linear dependency of one TQI on the other.

Selection criteria for the final TQI's was mainly based on correlation coefficients among TQI's and the functional requirements of track. In addition, R^2 values, computational complexity and ease of interpretation were also considered in the selection process.

6.5 FINAL PREDICTIVE EQUATIONS

Predictive equations were developed for the final set of TQI's for unmaintained track and for maintenance levels 1 through 5. Stepwise autoregression techniques (Appendix D) were used to select an optimum subset of physical parameters to be included in the predictive equations. Analyses were performed to determine the contribution of various independent parameters to the change in a TQI. The final prediction equations were analyzed through residual analysis, analysis of variance and other test statistics as given in Appendix D. The confidence intervals for regression coefficients were computed to make inferences about the population.

The effect of different maintenance levels (0 through 6) was also evaluated in terms of change in TQI's and degradation coefficients. The effect of basic maintenance on track degradation was further investigated by comparison of regression coefficients and degradation curves.

7.0 RESULTS AND DISCUSSION

This section describes the results of the long-range Track Maintenance Planning Program. The ability of TQI's to monitor track condition is discussed first. Secondly, the characteristics of the test zone are described. Preliminary analyses were conducted on 14 candidate TQI's. Based on these analyses, a set of TQI's was selected which best describe the condition of the track. Next, track degradation is discussed in detail in terms of the final five selected indices. Finally, the results of the empirical degradation models are presented along with the effects of maintenance.

7.1 TRACK QUALITY INDICES

Track quality indices are computed from track geometry parameters and are used to quantify the condition of track in terms of its functional requirements. Section 3.0 discusses the selection of candidate TQI's based on the functional requirements of track. This section discusses the potential uses of TQI's in long-range maintenance planning. It will be shown that track quality indices provide an effective measure of track condition. This will be illustrated in terms of track degradation, effect of maintenance, safety and ride quality.

7.1.1 TRACK CONDITION

Figure 7-1 illustrates one of the important features of TQI's, i.e., their ability to summarize graphically large sections of track, in this case 84 miles. This feature is especially useful to railroad personnel charged with day-to-day, decision-making responsibility. As discussed earlier, the larger the value of a TQI, the poorer the condition of the track. Thus, Figure 7-1 suggests that the track in the vicinity of milepost 260 is in relatively poor condition in comparison with other portions of the test zone. In contrast, the track

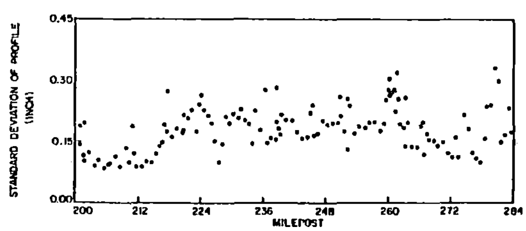


Figure 7-1. Condition of Eastbound Track of Fort Wayne Division in Terms of Profile Roughness

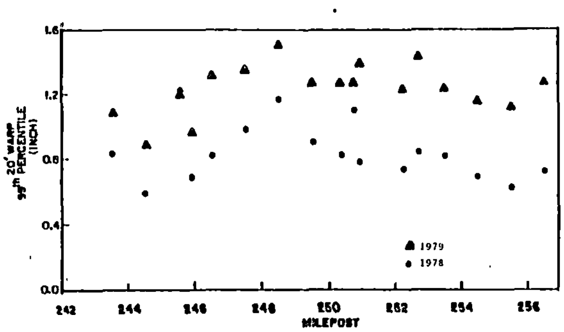


Figure 7-2. Illustration of the Ability of a TQI to Monitor Track Degradation

between mileposts 200 and 209 has relatively low values of the profile roughness TQI indicating good surface condition. This section of track was surfaced and tied shortly before the 1979 track geometry survey.

Figure 7-2 illustrates the manner in which a TQI, in this case the 99th percentile of warp, may be used to monitor track degradation. In Figure 7-2 the 99th percentile of warp for a portion of the eastbound track in the Fort Wayne Division is shown as measured in 1978 and 1979, during which time no maintenance was performed on this section. Note that all values of the TQI for 1978 lie below their respective values for 1979. Recalling that the higher value of a TQI indicates poorer track condition, Figure 7-2 clearly illustrates the ability of a TQI to quantify degradation. That is, although it comes as no surprise that in-service track which is not maintained will degrade, a TQI represents a means for actually measuring how much a given track degrades. This measurement can be used in establishing priorities for maintenance operations depending on the availability of resources.

The purpose of production maintenance is to provide a major improvement in the condition of track. Figure 7-3 illustrates the effect of production maintenance as measured by a TQI, the mean gage index. In this section of track, new rail was laid between the 1978 and 1979 surveys. In line with the established convention of low TQI values indicating better track condition, every segment shows improvement due to production maintenance. Note that the values of mean gage in this test segment are more or less uniform and very near the nominal value of 56.5 inches indicating that the work of the production gang was up to standard as measured by the gage

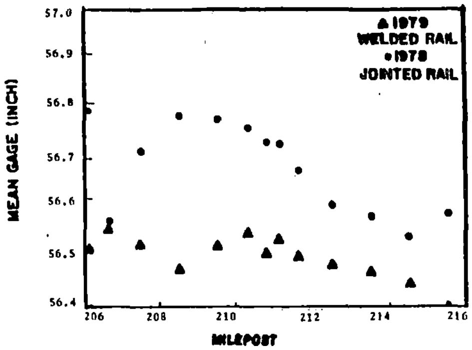


Figure 7-3. Effect of Production Maintenance on Mean Gage

index. Thus, a TQI may be used to monitor the quality of production maintenance operations.

In summary, track quality indices can be used to measure track condition objectively. A TQI can be used to summarize and display the condition of large sections of track in compact form. A TQI can also be used to monitor track degradation and to measure the effect of maintenance practices.

7.1.2 FEDERAL TRACK SAFETY STANDARDS

This section discusses the relationship of TQI's to the Federal Track Safety Standards. Four TQI's are discussed in detail for illustrative purposes. These are: gage standard deviation, crosslevel standard deviation, profile standard deviation and alignment standard deviation.

Values for the selected TQI's were derived from the track geometry characterization, of track free of anomalies.* These track geometry characterizations are based on the power spectral densities (PSD's) of track geometry parameters. The area under a PSD curve (between any two frequencies) is closely related to the dynamic energy delivered to a moving vehicle by the track. Thus, the track geometry PSD's are useful as track quality indicators. The value of a TQI can be derived from the track characterizations by calculating the area under the PSD curve in the frequency region of interest as illustrated in Appendix E. These values are derived for track free of anomalies (road crossings, switches, etc.) for each of the six FRA track classes and will be called the expected values.

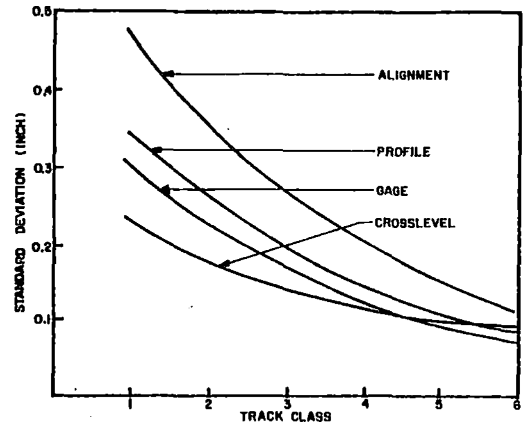


Figure 7-4. TQI Correlation with Federal Track Safety Standards

Expected values for the different track classes are plotted in Figure 7-4. The magnitude of the four TQI's consistently decrease as the track class increases. Values shown in Figure 7-4 are indicative of normal main line track which meets the criteria specified in the FRA track safety standards. Corrective measures may be required if the value of a TQI for a track segment is significantly larger than the expected value.

Figure 7-5 displays the surface condition of the eastbound track in the Fort Wayne test zone. Expected levels of the profile index for Class 3 and 4 track as previously discussed, are also indicated on the same figure. A review of the posted track class showed good agreement with the track class protrayed in Figure 7-5. Segments that did not comply were compared with the Track Standards Exception Report** generated by FRA Office of Safety. A significant number of exceptions were found for these segments.

This section illustrates the relationship of a TQI to the Federal Track Safety Standards. Thus, the value of TQI can be used to determine whether the track condition tends to meet its operating class standards on a statistical basis.

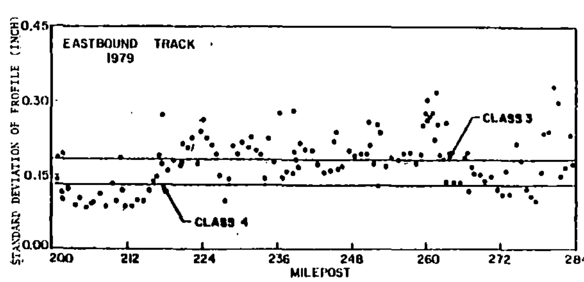


Figure 7-5. Compliance of Fort Wayne Division with Federal Track Safety Standards

*ENSCO Report, Statistical Representations of Track Geometry," June 1979.

**National Technical Information Service PB-241-196, Acquisition and Use of Track Geometry Data in Maintenance-of-Way Planning, March 1975.

TABLE 7-1

TQI'S AND DERAILMENTS

Derailment Date	Reported Cause	Track Class	TQI'S*							
			Gage		Crosslevel		Profile		Alignment	
			Expected	Actual	Expected	Actual	Expected	Actual	Expected	Actual
9/79	Profile	4	0.13	0.22	0.13	0.14	0.14	0.13	0.20	0.14
8/79	Improper Crosslevel	3	0.17	0.20	0.16	0.19	0.19	0.11	0.27	0.75
7/79	Wide Gage	4	0.13	0.14	0.13	0.22	0.14	0.16	0.20	0.20
6/79	Improper Crosslevel	4	0.13	0.20	0.13	0.28	0.14	0.27	0.20	0.21
5/79	Alignment	3	0.17	0.26	0.16	0.18	0.19	0.19	0.27	0.61
12/78	Wide Gage	3	0.17	0.18	0.16	0.26	0.19	0.22	0.27	0.20
12/78	Wide Gage	3	0.17	0.18	0.16	0.25	0.19	0.20	0.27	0.22

*Standard Deviation

This feature is especially important in making decisions regarding production maintenance.

7.1.3 DERAILMENTS

Data provided by CONRAIL on recent derailments were reviewed to determine the correlation of TQI's to derailments. Seven track-caused derailments were reported in the test zone between the track geometry surveys of 1978 and 1979. Information provided by CONRAIL was used to locate the track segments where derailments took place. A study of track charts revealed that all the derailments occurred near track appliances, such as bridges or interlockings. Three derailments occurred in regions going from tangent track to curved track and one derailment took place going from one large curve to another. All the derailments occurred on a descending grade, and in six of the derailments, the rail had been in service for more than 25 years.

Probability Density Estimates (PDE's) were obtained for all candidate TQI's to estimate the relative frequency of the index values. Figure 7-6 shows the PDE's for all TQI's measured in 1978. Peaks in these curves indicate a high frequency of occurrence for particular index values. The highest peak represents the index value at which the most data occurs. The value can be interpreted as the modal* value of a TQI for the test zone.

*Ronald E. Walpole and R. H. Myers, "Probability and Statistics for Engineers and Scientists," The MacMillan Company, New York, 1972, p. 156.

This index value for a track segment in which a derailment occured is indicated on the PDE's with vertical lines. Index values corresponding to the reported cause of a derailment are indicated with an asterisk on the PDE of the corresponding TQI. For example, values of the TQI's of crosslevel, warp and unbalanced superelevation are highlighted for the two derailments for which the reported cause was improper crosslevel.

An upward arrow on the PDE's indicates the 95th percentile value of the corresponding TQI. A study of Figure 7-6 shows that a majority of the derailments occurred at index values greater than the expected value but less than the 95th percentile value. In other words, most of the derailments occurred at relatively large index values, but not necessarily at the largest values.

Table 7-1 presents a list of the derailments by their corresponding track class. TQI values as measured in 1978 are listed along with the expected track class values discussed in the previous section. Note that most values of the crosslevel index are significantly larger than the expected values for all derailments. Values of gage index are also significantly larger than expected values for four of the derailments. Furthermore, values of TQI's related to the reported cause of derailment are significantly larger than expected values in the case of improper crosslevel and alignment.

The reported cause of the first derailment in Table 7-1 was improper profile. However, the value of the profile index measured approximately one year before the derailment was very close to its expected value. It is possible that in this case the track condition might have

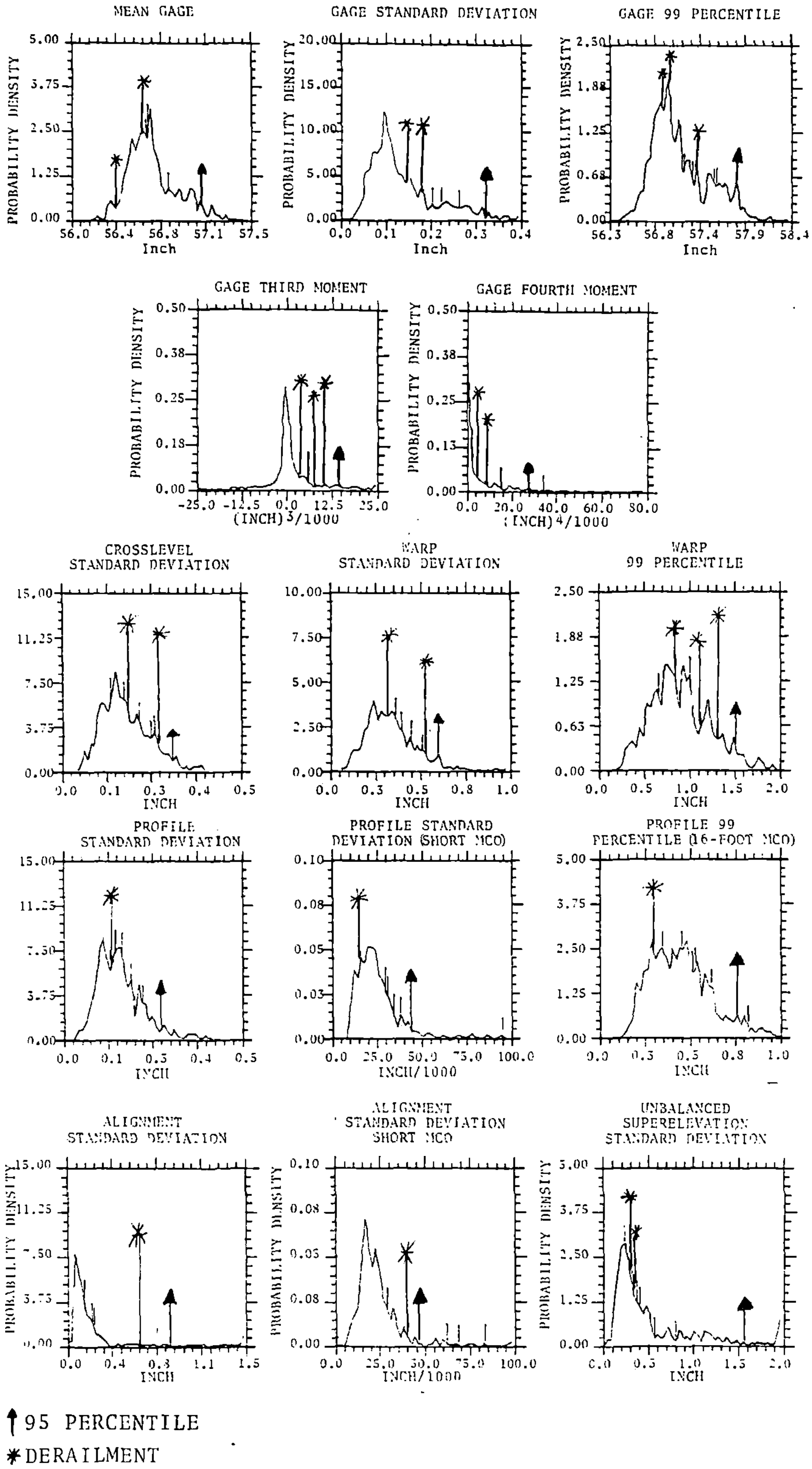


Figure 7-6. Probability Density Estimates of TQI's (1978)

deteriorated below its posted track class during the period of one year. It is also possible that the cause of the derailment might have been wide gage, as indicated by its index value, rather than improper profile or a combination of both. Similar explanations apply to derailments which were reported due to wide gage.

It should be pointed out that the candidate TQI's are designed to quantify the average relative condition of a track segment. For example, mean gage will not be affected significantly by a few exceptions having extreme values. Other TQI's also tend to mask extreme defects in track geometry. Furthermore, derailments are a complex statistical phenomenon and no definite thresholds can be established for the values of TQI's for safety purposes. Nevertheless, TQI's are related to safety in the sense that the probability of a derailment increases as the value of a TQI increases from its expected value.

7.1.4 RIDE QUALITY

For the purpose of correlating track quality with the ride quality of a vehicle two methods for measuring ride quality were used, International Standards Organization (ISO) standards and the Wz ratings. The ISO standards present three criteria in terms of exposure time for evaluating ride quality*:

- The preservation of comfort (reduced comfort boundary).
- The preservation of working efficiency (fatigue-decreased proficiency boundary).
- The preservation of health or safety (exposure limits).

TABLE 7-2

Wz RATING

Wz	Condition of Ride
1	Excellent
2	Good
3	Satisfactory (limit for passenger train)
4	Car in working order (limit for freight trains)
5	Dangerous

*ENSCO Report DOT-FR-79-22, "Wz Rating of Ride Quality-Implementation for FRA/ Amtrak Programs," January 1977.

The Wz method of rating the ride of a rail vehicle generates a single number to describe the quality of the ride. The rating scheme for the Wz method is shown in Table 7-2.

Track geometry inputs such as alignment or profile perturbations are the primary inputs for vibrations induced in the carbody. The intensity of these vibrations (acceleration levels) affect lading damage and passenger comfort. Since the Track Quality Indices are a function of the roughness of track inputs, a relationship can be found between the TQI's and the Ride Quality Indices (RQI's).

The RMS* acceleration levels induced in the carbody can be obtained from track characterizations discussed in Section 7.1.2 and the characteristics of the vehicle suspension system, speed, and the roughness of the track. Thus, the carbody acceleration levels increase with the value of a TQI, vehicle speed, and the natural frequency and the damping ratio of the vehicle suspension system. Vertical and lateral accelerations expected at different vehicle speeds for a 70-ton box car are plotted in Figures 7-7 and 7-8 for different TQI's. The RQI's for different acceleration levels are also indicated on these figures presenting a direct comparison between RQI's and TQI's.

This information may be used in a number of different ways. For example, if freight traffic is being scheduled over class 4 track and it is desirable to maintain the lading vibration environment below a RMS acceleration of 0.04g, a very practical upper limit, the maximum time table speed should be 42 mph as shown by the intersection of the broken lines in the lower left-hand corner of Figure 7-7. Conversely, if the maximum required time table speed was 35 mph over this same track, then it would not be necessary to maintain the track quality to the expected class value (0.14) but to a somewhat lower quality (approximately 0.17). Thus, maintenance allocations would not be used to over maintain this section of track at the expense of other sections requiring more work.

*Root Mean Square.

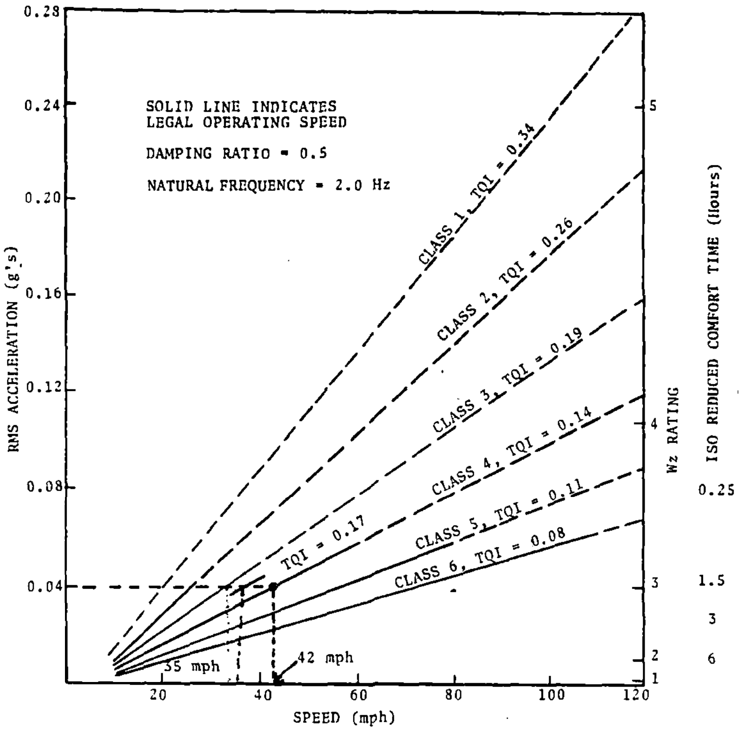


Figure 7-7. Vertical Acceleration vs. Profile Standard Deviation for a 70-Ton Box Car

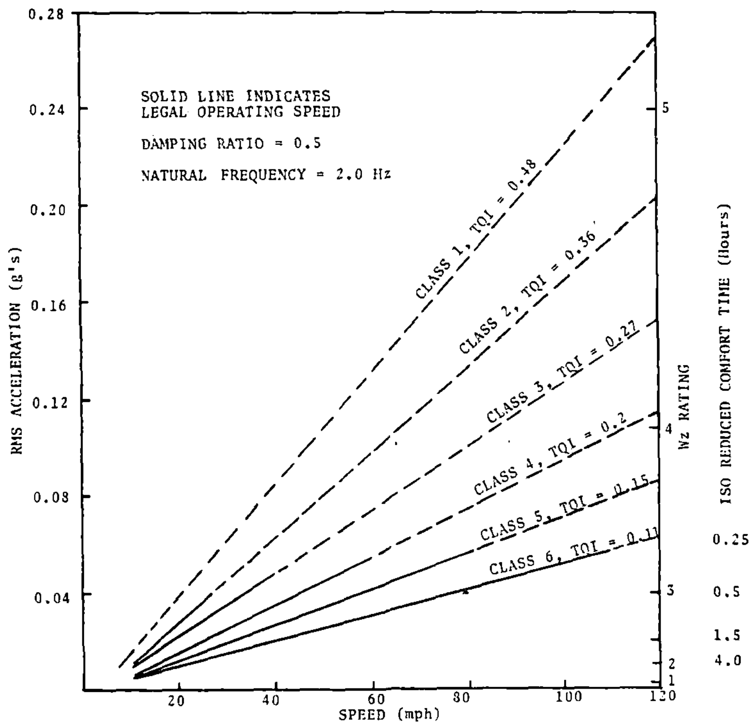


Figure 7-8. Lateral Acceleration vs. Alignment Standard Deviation for a 70-Ton Box Car

7.2 TEST ZONE CHARACTERISTICS

This section describes the characteristics of the test zone used in this study. These characteristics are described in terms of the ranges of physical parameters and the correlation among these parameters. Results presented in the following sections should be considered in light of these characteristics. The characteristics establish the type of track-regions to which the results of this study should be applied. The characteristics will also help to explain the methodology used in later analyses.

7.2.1 SUMMARY OF PHYSICAL PARAMETERS

The test zone is made up of two distinct areas, the Lehigh Division and the Fort Wayne Division. The Lehigh Division consists mainly of class 2 and 3 track and carries annual tonnage less than 14 MGT. A significant portion of the track is curved and has sharp grades. On the other hand, the Fort Wayne Division consists mainly of class 3 and 4 tangent, low-gradient track and carries heavy tonnage from 18 to 25 MGT.

The physical parameters selected to account for track degradation consist of track structure, taffic, and maintenance parameters as discussed in Section 4.0. Based on these physical parameters, the test zone was divided into homogeneous track segments. The 288-mile test zone was divided into a total of 676 homogeneous segments. Physical parameters were recorded for all 676 track segments for the 1978 and 1979 observation periods. Track geometry data were collected and processed for each observation period to compute the candidate TQI's. Due to the operational problems on T-6 during the 1978 survey of the Fort Wayne Division, data for 108 track segments were found to be invalid. These segments were subsequently deleted from the 1978 working-data file. Track geometry data were not collected for nine track segments in the Fort Wayne Division during the 1979 survey due to the presence of a CONRAIL production gang. Thus, a total of 117 segments were deleted leaving 559 segments which have one-to-one correspondence between 1978 and 1979.

TABLE 7-3

BREAKDOWN OF THE TEST ZONE ACCORDING TO THE MAINTENANCE LEVEL

Maintenance Level	Description	Number of Segments		
		Lehigh Division	Fort Wayne Division	Total
0	No maintenance	168	29	197
1	Up to 10 Percent Basic Maintenance	8	20	28
2	Up to 30 Percent Basic Maintenance	24	23	47
3	Above 30 Percent Basic Maintenance	45	74	119
4	Surfacing	63	14	77
5	Tie and Surfacing	38	31	69
6	Rail renewal	0	22	22
Total Number of Segments		346	213	559

TABLE 7-4

PHYSICAL PARAMETER SUMMARY FOR MAINTENANCE LEVEL 0*

Parameter	Range	Number of Segments		
		Lehigh Division	Fort Wayne Division	Total
Annual Tonnage (MGT)	5 to <10	97		97
	10 to <15	71		71
	15 to <20		5	5
	20 to <25		24	24
Heavy Wheels (Percent)	30 to <40	8	29	37
	40 to <50	132		132
	50 to <70	28		28
Speed (mph)	15 to 25	47		47
	30 to 40	99	1	100
	45 to 50	22	28	50
Curvature (Degrees)	0 to <2	90	29	119
	2 to <5	52		52
	5 to <8	11		11
	8 to <15	15		15
Rail Weight (lbs/yard)	127 to 130	5		5
	131 to 133	34	27	61
	136 to 140	129	2	131
Rail Type	Welded	60	1	61
	Bolted	108	28	136
Rail Profile (Percent Bent Rail)	0 to <10	132	12	144
	10 to <20	22	16	38
	20 to <50	6	1	7
	50 to <100	8		8
Ballast Condition	0	132	26	158
	1	26	2	28
	2	8	1	9
	3	2		2
Drainage Condition	Good	165	29	194
	Bad	3		3

*Total number of segments is 197.

As discussed in Section 4, maintenance data were recorded in the form of maintenance levels ranging from 0 to 6. Table 7-3 lists the breakdown of track segments in each test zone by maintenance level. It is apparent that a major portion of the test zone received basic or production maintenance; there were 197 unmaintained segments. Most of these segments were in the Lehigh Divison test zone.

A summary of the physical parameters for each maintenance level is given in Tables 7-4 through 7-10. It should be noted that the test zones consist mostly of class 2, 3 and 4 track. The traffic

TABLE 7-5

PHYSICAL PARAMETER SUMMARY FOR MAINTENANCE LEVEL 1*

Parameter	Range	Number of Segments: Lehigh Division	Fort Wayne Division	Total
Annual Tonnage (MGT)	10 to <15	8		8
	15 to <20		10	10
	20 to <25		10	10
Heavy Wheels (Percent)	30 to <40		20	20
	40 to <50	8		8
Speed (mph)	30 to 40	1	1	2
	45 to 50	7	19	26
Curvature (Degrees)	0 to <2	8	19	27
	2 to 5		1	1
Rail Weight (lbs/yard)	127 to 130			
	131 to 133		18	18
	136 to 140	8	2	10
Rail Type	Welded	3	6	9
	Bolted	5	14	19
Rail Profile (Percent Bent Rail)	0 to <10	7	12	19
	10 to <20		8	8
	20 to <30	1		1
Ballast Condition	0	8	18	26
	1		2	2
Drainage Condition	Good	7	20	27
	Bad	1		1

*Total number of segments is 28.

TABLE 7-6

PHYSICAL PARAMETER SUMMARY FOR MAINTENANCE LEVEL 2*

Parameter	Range	Number of Segments: Lehigh Division	Fort Wayne Division	Total
Annual Tonnage (MGT)	10 to <15	24		24
	15 to <20		23	23
Heavy Wheels (Percent)	30 to <40		23	25
	40 to <50	21		21
	50 to <70	3		3
Speed (mph)	15 to 25	3		3
	30 to 40	7		7
	45 to 50	14	23	37
Curvature (Degrees)	0 to <2	17	23	40
	2 to <5	5		5
	5 to <8	2		2
Rail Weight (lbs/yard)	131 to 133		20	20
	136 to 140	24	2	26
	Above 140		1	1
Rail Type	Welded	12	2	14
	Bolted	12	21	33
Rail Profile (Percent Bent Rail)	0 to <10	19	11	30
	10 to <20		12	12
	20 to <50	3		3
	50 to 100	2		2
Ballast Condition	0	15	20	35
	1	7	2	9
	2	1	1	2
	3	1		1
Drainage Condition	Good	21	23	44
	Bad	3		3

*Total number of segments is 47.

TABLE 7-7

PHYSICAL PARAMETER SUMMARY FOR MAINTENANCE LEVEL 3*

Parameter	Range	Number of Segments: Lehigh Division	Fort Wayne Division	Total
Annual Tonnage (MGT)	5 to <10	10		10
	10 to <15	35		35
	15 to <20		36	36
	20 to <25		38	38
Heavy Wheels (Percent)	30 to <40	4	74	78
	40 to <50	40		40
	50 to <70	1		1
Speed (mph)	15 to 25	3		3
	30 to 40	21	17	38
	45 to 50	21	57	78
Curvature (Degrees)	0 to <2	29	72	101
	2 to <5	11	2	13
	5 to <8	4		4
	8 to <15	1		1
Rail Weight (lbs/yard)	127 to 130	6		6
	131 to 133	36	64	100
	136 to 140	3	10	13
Rail Type	Welded	18	3	21
	Bolted	27	71	98
Rail Profile (Percent Bent Rail)	0 to <10	35	19	54
	10 to <20	2	33	35
	20 to <50	3	22	25
	50 to 100	5		5
Ballast Condition	0	26	40	66
	1	12	17	29
	2	6	7	13
	3	1	10	11
Drainage Condition	Good	38	71	109
	Bad	7	3	10

*Total number of segments is 119.

TABLE 7-8

PHYSICAL PARAMETER SUMMARY FOR MAINTENANCE LEVEL 4*

Parameter	Range	Number of Segments: Lehigh Division	Fort Wayne Division	Total
Annual Tonnage (MGT)	5 to <10	36		36
	10 to <15	27		27
	15 to <20		14	14
Heavy Wheels (Percent)	30 to <40	18	14	32
	40 to <50	43		43
	50 to <70	2		2
Speed (mph)	15 to 25	2		2
	30 to 40	61		61
	45 to 50		14	14
Curvature (Degrees)	0 to <2	28	14	42
	2 to <5	26		26
	5 to <8	6		6
	8 to <15	3		3
Rail Weight (lbs/yard)	127 to 130	15		15
	131 to 133	15	14	29
	136 to 140	33		33
Rail Type	Welded	46		46
	Bolted	17	14	31
Rail Profile (Percent Bent Rail)	0 to <10	47		47
	10 to <20	12	12	24
	20 to <50	3	2	5
	50 to 100	1		1
Ballast Condition	0	57	8	65
	1	6	1	7
	2		4	4
	3		1	1
Drainage Condition	Good	63	14	77

*Total number of segments is 77.

TABLE 7-9

PHYSICAL PARAMETER SUMMARY
FOR MAINTENANCE LEVEL 5*
(Tie Renewal and Surfacing)

Parameter	Range	Number of Segments		
		Lehigh Division	Fort Wayne Division	Total
Annual Tonnage (MGT)	5 to <10	11		11
	10 to <20	27		27
	20 to <25		31	31
Heavy Wheels (Percent)	30 to <40		31	31
	40 to <50	38		38
Speed (mph)	10 to 25	2		2
	30 to 40	33	1	34
	45 to 50	3	30	33
Curvature (Degrees)	0 to <2	25	31	56
	2 to <5	10		10
	5 to <8	3		3
Rail Weight (lbs/yard)	127 to 130	28		28
	131 to 133		31	31
	136 to 140	10		10
Rail Type	Welded	12		12
	Bolted	26	31	57
Rail Profile (Percent Bent Rail)	0 to <10	12	1	13
	10 to <20		14	14
	20 to <50	16	14	30
	50 to 100	10	2	12
Ballast Condition	0	17	3	20
	1	15	17	32
	2	3	5	8
	3	3	6	9
Drainage Condition	Good	36	29	65
	Bad	2	2	4

*Total number of segments is 69.

TABLE 7-10

PHYSICAL PARAMETER SUMMARY
FOR MAINTENANCE LEVEL 6*
(Rail Renewal)

Parameter	Range	Number of Segments		
		Lehigh Division	Fort Wayne Division	Total
Annual Tonnage (MGT)	20 to <25		22	22
Heavy Wheels (Percent)	30 to <40		22	22
Speed (mph)	40		3	3
	45 to 50		19	19
Curvature (Degrees)	0 to <2		21	21
	2 to <5		1	1
Rail Weight (lbs/yard)	131 to 133		22	22
Rail Type	Welded		1	1
	Bolted		21	21
Rail Profile (Percent Bent Rail)	0 to <10		6	6
	10 to <20		13	13
	20 to <50		3	3
Ballast Condition	0		8	8
	1		9	9
	2		5	5
Drainage Condition	Good		22	22

*Total number of segments is 22.

density on track segments is below 25 MGT. A major portion of the test zone consists of bolted rail and most of the curves are less than eight degrees. The ballast and drainage conditions are good overall. Refer to the tables for a description of each maintenance level.

7.2.2 CORRELATION AMONG PHYSICAL PARAMETERS

One of the assumptions made in regression analysis is that the independent variables are truly independent. For the purpose of this study, this would require that none of the physical parameters are a linear combination of the others.

Linear dependence of variables can be investigated through correlation analysis. Therefore, cross correlation was performed on all of the physical parameters to determine if there were any high correlations among them. Table 7-11 lists the correlation coefficients among the physical parameters for the entire test zone. None of the correlation coefficients are large enough (for example greater than 0.9) to invalidate the use of regression analysis.

However, some of the physical parameters have high correlation coefficients with others. In some cases, this is due to actual physical reasons. In other cases, it might be due to the characteristics of the particular test zone. In either case, this will affect the results obtained from regression analysis.

A study of Table 7-11 shows that tonnage is positively correlated with speed, which might not be universally true. In this case, the correlation might be due to the fact that heavy tonnage is carried in the Fort Wayne Division which operates at relatively high speeds. As expected, tonnage is shown to be negatively correlated with curvature. However, this might also be due to the fact that the Fort Wayne Division (which carries heavy tonnage) has almost all tangent track segments. Tonnage is also negatively correlated with percent heavy wheels. This should also be expected especially since the Lehigh Division experiences relatively heavy loads with low tonnage.

Heavy wheels show negative correlation with rail type. This may simply be due to the fact that most of the welded track

TABLE 7-11

CORRELATION COEFFICIENTS AMONG PHYSICAL PARAMETERS FOR ENTIRE TEST ZONE

Parameter	Tonnage	Percent Heavy Wheels	Speed	Curvature	Rail Weight	Rail Type	Rail Profile	Ballast Condition	Drainage Condition	Maintenance Level
Tonnage	1.00	-.58	.71	-.50	-.16	.37	.15	.26	0.00	.33
Percent Heavy Wheels	-.58	1.00	-.64	.38	.21	-.44	-.12	-.06	.09	-.27
Speed	.71	-.64	1.00	-.50	-.14	.35	.08	.03	0.00	.25
Curvature	-.50	.38	-.50	1.00	.11	-.18	-.10	-.18	-.04	-.19
Rail Weight	-.16	.21	-.14	.11	1.00	-.29	-.07	-.05	.07	-.28
Rail Type	.37	-.44	.35	-.18	-.29	1.00	.42	.18	.02	.04
Rail Profile	.15	-.12	.08	-.10	-.07	.42	1.00	.43	.16	.21
Ballast Condition	.26	-.06	.03	-.18	-.05	.18	.43	1.00	.28	.27
Drainage Condition	0.00	.09	0.00	-.04	.07	.02	.16	.28	1.00	.04
Mainten- ance Level	.33	-.27	.25	-.19	-.28	.04	.21	.27	.04	1.00

segments are in the Lehigh Division and these segments are associated with relatively heavy wheel loads. Speed shows negative correlation with curvature. This is believed to be due to speed restrictions and slow orders on curved track in the Lehigh Division. Rail type is positively correlated with rail profile since rail profile is defined for bolted rail only. Welded rail is considered to have no bent rail,

Table 7-12 shows cross correlation among physical parameters for the unmaintained track segments. The comments in the previous paragraphs also apply to the unmaintained track segments.

TABLE 7-12

CORRELATION COEFFICIENTS AMONG PHYSICAL PARAMETERS FOR UNMAINTAINED TRACK

Parameter	Tonnage	Percent Heavy Wheels	Speed	Curvature	Rail Weight	Rail Rype	Rail Profile	Ballast Condition	Drainage Condition
Tonnage	1.00	-.34	.73	-.41	-.07	.03	.06	.01	0.00
Percent Heavy Wheels	-.34	1.00	-.48	.16	.42	-.48	-.15	.11	.17
Speed	.73	-.48	1.00	-.39	-.13	.09	.17	-.08	-.04
Curvature	-.41	.16	-.39	1.00	-.01	.05	-.14	-.14	-.03
Rail Weight	-.07	.42	-.13	-.01	1.00	-.50	-.10	.03	.08
Rail Type	.03	-.48	.09	.05	-.50	1.00	.32	-.07	-.10
Rail Profile	.06	-.15	.17	-.14	-.10	.32	1.00	.36	.18
Ballast Condition	.01	.11	-.08	-.14	.03	-.07	.36	1.00	.15
Drainage Condition	0.00	.17	-.04	-.03	.08	-.10	.18	.15	1.00

7.3 PRELIMINARY ANALYSES

Preliminary analyses were conducted on the 14 candidate TQI's for all maintenance levels. The purpose of these analyses was to determine the best method for developing predictive models of track degradation and to select a final set of four or five indices. These analyses involve the regression and correlation analysis of MOW data, as described in Section 6.0. MOW data are listed in Appendix F.

Residual analyses were performed to test the assumptions used in regression analyses and to check the adequacy of the models used. Residuals were also examined to study the outliers in the data. The outliers which were three or four standard devaitions away from the mean value of the residuals were studied further. The outliers which could be traced to causes such as errors in recording data, or due to track appliances such as bridges, road crossings, interlockings, etc., were eliminated from further analysis.

Different transformations were performed on the physical parameters and/or TQI's to test different models. Transformations tested were log, polynominal and cross product of certain variables. The results of these analyses are described in the following sections.

7.3.1 TERMINOLOGY

This section describes the terminology used in describing the results. Understanding of the terminology is especially useful in interpreting the computer printouts given in Appendices G and H. This terminology was designed for efficiency and to make the computer output more readable.

Table 7-13 lists the terminology used for the physical parameter data base. Variables such as x_1, x_2 are used in equations presented in the main text of this report. The abbreviated codes are used in the computer printouts. As mentioned earlier, ballast condition was recorded in four levels for this study. Three dummy variables BLST DM1 BLST DM2 and BLST DM3 were created in regression analysis for the four levels of ballast condition. The corresponding dummy variables will be written as x_8', x_8'', and x_8'''.

Table 7-14 lists the terminology for the candidate TQI's. Variables such as y_1, y_2, etc., are used to represent each index in the regression equations. However, code names will also be used in some of the tables in the main text.

TABLE 7-13

TERMINOLOGY FOR PHYSICAL PARAMETERS

Variable	Code	Description	Unit
x_1	TONN	Annual Tonnage	MGT
x_2	HVWL	Heavy Wheels	Percent
x_3	SPED	Posted Speed	MPH
x_4	CURV	Curvature	Degrees
x_5	RWGT	Rail Weight	Lbs/Yard
x_6	RTYP	Rail Type	Bolted or Welded
x_7	PROF	Rail Profile	Percent Bent Rail
x_8	BLST	Ballast Condition	Levels
x_9	DRNG	Drainage Condition	Good and Bad

The TQI's for 1979 will be indicated as y_1, y_2, etc., and the TQI's for 1978 will be indicated as $\hat{y}_1$, $\hat{y}_2$, etc.

7.3.2 PRELIMINARY PREDICTIVE EQUATIONS

Linear autoregression was performed on all of the 197 unmaintained segments using the 1978 and 1979 TQI data. Since little change was observed in the track structure data between 1978 and 1979, the 1978 data were used in these analyses. The difference between all of the 1979 and 1978 TQI's were generated and are referred to as ΔTQI's. Residuals were

TABLE 7-14

TERMINOLOGY FOR THE TQI'S

Variable	Code	Name	Unit
y_1	GAMN	Mean Gage	Inch
y_2	GASD	Standard Deviation of Gage	Inch
y_3	GA99	99-Percentile Gage	Inch
y_4	GA3M	Third Moment of Gage	$(\text{Inch})^3/1000$
y_5	GA4M	Fourth Moment of Gage	$(\text{Inch})^4/1000$
y_6	XLDV	Standard Deviation of Crosslevel	Inch
y_7	WASD	Standard Deviation of Warp	Inch
y_8	WA99	99-Percentile of Warp	Inch
y_9	PRSD	Standard Deviation of Profile Space Curve	Inch
y_{10}	PRSM	Standard Deviation of Short MCO of Profile	Inch/1000
y_{11}	PR99	99-Percentile of Intermediate MCO of Profile	Inch
y_{12}	ALSD	Standard Deviation of Alignment Space Curve	Inch
y_{13}	ALSM	Standard Deviation of Short MCO of Alignment	Inch/1000
y_{14}	BSEL	RMS Value of Crosslevel Deviation from Balanced Superelevation	Inch

TABLE 7-15

COEFFICENTS OF DETERMINATION (R^2) FOR UNMAINTAINED TRACK

REMARKS \ TQI'S	GAMN	GASD	GA99	GA3M	GA4M	XLDV	WASD	WA99	PRSD	PRSM	PR99	ALSD	ALSM	BSEL
All 197 Segments	0.91	0.88	0.84	0.55	0.69	0.79	0.76	0.71	0.69	0.61	0.72	0.28	0.35	0.97
18 Segments Removed	0.92	0.89	0.86	0.57	0.71	0.90	0.91	0.82	0.85	0.91	0.82	0.26	0.38	0.97
x, Log y	0.92	0.92	0.85	0.65	0.90	0.91	0.92	0.88	0.85	0.92	0.87	0.40	0.52	0.94
Log x, y	0.93	0.89	0.86	0.57	0.72	0.90	0.90	0.82	0.84	0.91	0.81	0.27	0.44	0.97
Log x, Log y	0.93	0.92	0.86	0.65	0.90	0.91	0.91	0.88	0.85	0.92	0.87	0.40	0.56	0.93

examined to study the outliers. These analyses indicated that 18 segments should be removed from the process of developing the predictive equations.

Predictive equations for track degradation (Section 6.0) were developed using linear autoregression for the remaining 179 segments. Log transformations were tested on physical parameters and/or on TQI's. In the case of physical parameters, log transformation was performed only on x_1 through x_5 and on x_7. It should be pointed out that log transformations are useful in investigating the exponential or logarithmic type of relations and the relations involving the cross products of x variables.

Coefficients of determination (R^2) for the resultant predictive models are listed in Table 7-15. As expected, a significant improvement was achieved in the R^2 values for most TQI's by eliminating the 18 previously discussed outliers. Within the family of logrithmic transformations, the log y and log x combination gives as good (or better) results as the other two transformations. In addition, predictive models using this transformation can be more easily interpreted. Therefore, the results obtained using the log x, log y transformation were compared with the ones obtained without any transformation. As is apparent from Table 7-15, no significant improvement was obtained using the logrithmic transformation except for the two alignment indices. Therefore, in order to avoid the complexity of the models based on logrithmic transformation, further investigations were performed on simple linear relationships only.

Table 7-16 shows comparisons of some models based on special combinations of physical parameters. Since the models involved a different number of physical parameters in each case, comparison is provided in terms of the adjusted coefficient of determination ($R^{2\prime}$). As discussed in Section 7.2, only three segments had poor drainage conditions.

TABLE 7-16

EFFECT OF SOME SPECIAL COMBINATIONS OF PHYSICAL PARAMETERS ON THE PREDICTIVE EQUATIONS FOR UNMAINTAINED TRACK

REMARKS \ TQI'S	GAMN	GASD	GA99	GA3M	GA4M	XLDV	WASD	WA99	PRSD	PRSM	PR99	ALSD	ALSM	BSEL
All physical parameters	0.92	0.88	0.85	0.54	0.68	0.90	0.90	0.81	0.84	0.90	0.81	0.21	0.34	0.97
Drainage Removed	0.92	0.88	0.85	0.54	0.69	0.90	0.90	0.81	0.84	0.90	0.81	0.21	0.34	0.97
Ballast Changed to 0,1,2	0.92	0.88	0.85	0.55	0.69	0.89	0.90	0.81	0.83	0.90	0.80	0.21	0.35	0.97
Velocity × (Curvature)^2	0.92	0.89	0.85	0.55	0.70	0.89	0.89	0.80	0.82	0.90	0.80	0.16	0.31	0.97
Tonnage × Velocity	0.92	0.88	0.85	0.55	0.69	0.89	0.89	0.80	0.82	0.90	0.80	0.20	0.29	0.97
Tonnage × (Velocity)^2	0.92	0.88	0.85	0.55	0.69	0.89	0.89	0.80	0.83	0.90	0.80	0.20	0.29	0.97

TABLE 7-17

COEFFICIENT OF DETERMINATION FOR DIFFERENT MAINTENANCE LEVELS

Maintenance Level \ TQI	GAMN	GASD	GA99	GA3M	GA4M	XLDV	WASD	WA99	PRSD	PRSM	PR99	ALSD	ALSM	BSEL
Maintenance Level 0	0.92	0.89	0.86	0.57	0.70	0.90	0.90	0.81	0.83	0.91	0.81	0.26	0.38	0.97
Maintenance Level 1	0.90	0.91	0.92	0.90	0.87	0.90	0.92	0.86	0.89	0.93	0.78	0.40	0.65	0.92
Maintenance Level 2	0.94	0.84	0.90	0.13	0.16	0.85	0.86	0.66	0.87	0.84	0.86	0.20	0.68	0.91
Maintenance Level 3	0.83	0.89	0.88	0.24	0.42	0.84	0.85	0.70	0.76	0.87	0.85	0.15	0.48	0.93
Maintenance Level 4	0.97	0.91	0.91	0.51	0.74	0.86	0.85	0.70	0.74	0.82	0.86	0.24	0.53	0.84
Maintenance Level 5	0.95	0.89	0.88	0.56	0.79	0.80	0.76	0.66	0.72	0.84	0.80	0.17	0.59	0.88

Therefore, predictive equations were developed by excluding the drainage condition from the set of physical parameters. Table 7-16 shows an improvement in the resultant models. Therefore, drainage was not considered further in the analyses for the unmaintained track.

Since there were only three segments with ballast condition 3, these segments were combined with ballast condition 2. Predictive models were developed using only three levels for the ballast condition. The R^{2}' values for these models do not show any decrease. Since these models involve one less variable, further investigations were performed on these models only.

Special combinations of the physical parameters were tested to determine if the predictive models could be further improved. These combinations included: curvature times square of speed which is analogous to the centripetal acceleration; tonnage times speed, which is analogous to momentum; and tonnage times square of speed, which is analogous to kinetic energy. Results presented in Table 7-16 show that no improvements were achieved in the predictive models.

Based on the discussion in the previous paragraphs and to obtain simplicity, it was decided to use the predictive models based on the simple linear equations. These models do not include the drainage condition, and the ballast condition consists of three levels. The preliminary prediction equations for all of the TQI's are presented in Appendix G. These equations are of the form:

$$y_i = a + b_0\hat{y}_i + b_1x_1 + b_2x_2 + \dots + b_8'x_8' + b_8''x_8'' \qquad (7\text{-}1)$$

where

a is the constant term

i varies from 1 to 14

x_1 to x_7 are the physical parameters as described in Table 7-13

x_8' and x_8'' are the two dummy variables corresponding to the three ballast conditions

b's are the estimated regression coefficients

$\hat{y}_i$'s are the 1978 TQI's

y_i's are the 1979 TQI's.

It should be pointed out that the empirical regression coefficients are only estimates of true regression coefficients based on the given sample of observations.

Regression analysis was also performed on the maintained track segments. Preliminary predictive equations were developed for maintenance levels 1 through 5 using the linear autoregressive models. Residual and other analyses were performed (as in the unmaintained track analysis) to improve the predictive models. The final results are presented in Appendix G. These predictive equations are of the same form as Equation (7-1). The R^2 values for the predictive models are given in Table 7-17. The R^2 values for unmaintained track are also included for comparison.

It should be pointed out that due to the nature of the data for each maintenance level, the drainage condition was not considered for maintenance levels 1 and 2. The ballast condition for these maintenance levels was either 0 or 1 which can be explained by a single variable (x_8). The track segments for level 1 were tangent except for one segment. Therefore, curvature was also excluded for this maintenance level. Maintenance levels 3 and 5 included the drainage condition and the four levels for the ballast condition. Again because of the nature of data, the drainage condition was not considered for maintenance level 4 and the ballast condition was treated as 0, 1 or 2.

7.3.3 ALTERNATE SET OF CANDIDATE TQI'S

Results presented in the previous section indicate R^2 values of 0.8 or above for most of the gage and surface TQI's. This means that at least 80 percent of the change in the gage and the vertical surface condition of the track can be explained by the given models (Section 7.3.2). On the other hand, the line TQI's show poor R^2 values for most maintenance levels. This would indicate that either additional physical parameters are required or the TQI's are not appropriate.

Correlation analysis between the 1978 and 1979 TQI data can be used to study some of the important features. A high correlation coefficient such as 0.9 or above would indicate that either a TQI did not change during the year or that it changed in a uniform pattern for all segments. On the other hand, a low value such as 0.5 or below would indicate either a non-uniform or a significant change in the TQI values during the two observation periods. This could also mean that some problems might exist with the corresponding track geometry parameters.

A study of the correlation coefficients between the 1978 and 1979 y's (Appendix G shows poor correlation values for the line TQI's. The accuracy of the inertial alignment system on T-6 is better at test speeds above 20 mph. Therefore, the regression analysis was performed on 124 segments of the unmaintained track. Test speeds for these segments were above 20 mph during both the track geometry surveys. For the alignment space curve standard deviation, the correlation coefficient between the 1978 and 1979 TQI's was 0.12. The R^2 value for the prediction equation was 0.36. For the other alignment TQI, the standard deviation of the short MCO of alignment the correlation coefficient was 0.23 and the R^2 value was 0.60.

A review of the analog reproduction of the track geometry data showed that the gage data collected during the 1978 survey was relatively noisy and had a significant amount of spikes* in many segments. The TQI software package includes a filter to remove gage spikes. Therefore, these spikes do not contaminate the gage TQI data. However, gage data are also used in the processing of alignment and hence the quality of gage data will also affect the quality of the processed alignment. The nature of the complex recursive filters required to generate the pseudo-reconstruction of alignment (the alignment space curve) is such that a single bad data point might affect the quality of up to 250 feet of data, and in some cases, much larger segments of data.

Two additional alignment TQI's were investigated to minimize these effects. The new TQI's are: the standard deviation of the 10-foot MCO of alignment, and the standard deviation of the 16-foot MCO of alignment. The new TQI's have the advantages of computational simplicity and far less sensitivity to bad data points.

Regression analysis was performed on the new line TQI's for all maintenance levels. Results are presented in Appendix G. The new TQI's show better correlation between the 1978 and 1979 values. The R^2 values for the six maintenance levels are given in Table 7-18. Values for old TQI's are also given for comparison. It can be seen that the the standard deviation of the 10-foot MCO of alignment gives much better results than other line TQI's.

Based on the results presented in this section, the alternate set of candidate TQI's were selected for further analyses. This set is constructed from the original set by replacing the short MCO with the 10-foot MCO of alignment and the space curve with the 16-foot MCO of alignment. The same terminology as given in Table 7-14 with new meanings will be used in future references.

*A spike is an impulse of very high amplitude which can be caused by system noise, hardware malfunction or the presence of certain metallic objects in the field of view of the gage sensors.

TABLE 7-18

COEFFICIENTS OF DETERMINATION
FOR NEW ALIGNMENT TQI'S

TQI / Maintenance Level	Standard Deviation of 16-Foot MCO of Alignment	Standard Deviation of 10-Foot MCO of Alignment	Standard Deviation of 2-Foot MCO of Alignment	Standard Deviation of Alignment Space Curve
Maintenance Level 0	0.51	0.83	0.38	0.26
Maintenance Level 1	0.86	0.94	0.65	0.40
Maintenance Level 2	0.39	0.84	0.68	0.20
Maintenance Level 3	0.40	0.75	0.48	0.15
Maintenance Level 4	0.52	0.77	0.53	0.24
Maintenance Level 5	0.53	0.86	0.59	0.17

7.4 SELECTION OF FINAL TQI'S

The purpose of this section is to describe the selection of a set of TQI's which best indicate changes in track condition but at the same time are not duplicates of each other. The selection criteria is mainly based on the correlation coefficients among the TQI's and the functional requirements of the track. In addition, the coefficients of determination (R^2) value for prediction equations, the computational complexity, the reliability and ease of interpretation will also be considered in the selection process. The R^2 values for the prediction equations were given in the previous section. Results of correlation and other analyses will be discussed in this section.

Correlation analysis on the 14 TQI's was performed separately for the 1978 and 1979 data for all maintenance levels. For the purpose of this study, similar results were obtained for the two sets of data. For example, the TQI's which were highly correlated in 1978 were also highly correlated in 1979. The coefficient of correlation among TQI's was slightly larger in 1979 when compared to the 1978 data. This was also true when unmaintained track was studied separately.

The correlation coefficients among the 1979 TQI's are given in Table 7-19a. Those TQI's with relatively high correlation coefficeints are listed in Table 7-19b. R^2 values for the prediction equations of the unmaintained track segments for each index are also listed at the bottom of Table 7-19b for easy reference. It should be noted that high correlation coefficient values such as 0.9 or above indicate that the two indices are duplicates of each other for all practical purposes.

A study of Table 7-19b indicates that indices in the same family, i.e., ones calculated from the same track geometry parameter, such as gage, surface, and line are generally correlated with each other. Therefore, a single TQI in each family should be sufficient to describe the geometric track condition.

7.4.1 GAGE

Mean gage (GAMN) has a correlation coefficient (r) of better than 0.9 with the 99 percentile of gage (GA99). Although the mean gage index gives better prediction equations than the 99 percentile of gage, the 99 percentile of gage is a better indicator of wide gage than is mean gage. The 99 percentile of gage gives fairly good prediction equations ($R^2 \geq 0.8$) for most maintenance levels. Therfore, the 99 percentile of gage was selected rather than mean gage.

The gage standard deviation (GASD) is highly correlated with the fourth moment of gage (r = 0.88), and generally gives higher R^2 values. Therefore, gage standard was selected as opposed to the gage fourth moment (GA4M). Although the gage standard deviation has a fairly high correlation coefficient (0.83) with the 99 percentile of gage, it has a low correlation (0.66) with mean gage. Therefore, the

TABLE 7-19a

CORRELATION COEFFICIENTS AMONG TQI'S

TQI	GAMN	GASD	GA99	GA3M	GA4M	XLDV	WASD	WA99	PRSD	PRSM	PR99	ALSD	ALSM	BSEL
GAMN	1.00	0.66	0.91	0.03	0.49	0.39	0.39	0.40	0.25	0.42	0.33	0.36	0.43	0.39
GASD	0.66	1.00	0.83	0.21	0.88	0.25	0.24	0.29	0.25	0.33	0.24	0.48	0.51	0.49
GA99	0.91	0.83	1.00	0.23	0.69	0.39	0.39	0.42	0.31	0.45	0.35	0.46	0.52	0.41
GA3M	0.03	0.21	0.23	1.00	0.28	0.08	0.06	0.07	0.21	0.14	0.07	0.04	0.03	0.03
GA4M	0.49	0.88	0.69	0.28	1.00	0.20	0.19	0.22	0.32	0.27	0.20	0.40	0.47	0.41
XLDV	0.39	0.25	0.39	0.08	0.20	1.00	0.98	0.94	0.81	0.84	0.83	0.43	0.45	0.04
WASD	0.39	0.24	0.39	0.06	0.19	0.98	1.00	0.94	0.76	0.81	0.79	0.39	0.41	0.07
WA99	0.40	0.29	0.42	0.07	0.22	0.94	0.94	1.00	0.77	0.79	0.80	0.42	0.43	0.10
PRSD	0.25	0.25	0.31	0.09	0.21	0.81	0.76	0.77	1.00	0.70	0.84	0.51	0.51	0.04
PRSM	0.42	0.33	0.45	0.14	0.27	0.84	0.81	0.79	0.70	1.00	0.84	0.44	0.53	0.00
PR99	0.33	0.24	0.35	0.07	0.20	0.84	0.79	0.80	0.84	0.84	1.00	0.42	0.46	-0.05
ALSD	0.36	0.48	0.46	0.04	0.40	0.43	0.39	0.42	0.51	0.44	0.42	1.00	0.81	0.21
ALSM	0.43	0.51	0.52	0.03	0.47	0.45	0.41	0.43	0.51	0.53	0.46	0.81	1.00	0.17
BSEL	0.39	0.49	0.41	0.03	0.41	0.04	0.07	0.10	0.04	0.00	-0.05	0.21	0.17	1.00

TABLE 7-19b

CORRELATED TQI'S

TQI	GAMN	GASD	GA99	GA3M	GA4M	XLDV	WASD	WA99	PRSD	PRSM	PR99	ALSD	ALSM	BSEL
GAMN	-	X	XXX											
GASD	X	-	XX		XX								X	
GA99	XXX	XX	-		X								X	
GA3M				-										
GA4M		XX	X		-									
XLDV						-	XXX	XXX	XX	XX	XX			
WASD						XXX	-	XXX	XX	XX	XX			
WA99						XXX	XXX	-	XX	XX	XX			
PRSD						XX	XX	XX	-	XX	XX		X	
PRSM						XX	XX	XX	XX	-	XX		X	
PR99						XX	XX	XX	XX	XX	-			
ALSD												-	XX	
ALSM		X	X						X	X		XX	-	
BSEL														-
R^2	0.92	0.89	0.85	0.50	0.70	0.89	0.90	0.81	0.83	0.90	0.80	0.51	0.83	0.97

X $\geq$ 0.5
XX $\geq$ 0.7
XXX $\geq$ 0.9

gage standard deviation was also selected along with the 99 percentile of gage. It should be pointed out that both the mean gage and 99 percentile of gage are affected by the system bias and calibration errors. Since the gage standard deviation indicates the variations from the mean gage, it is not nearly so sensitive to calibration errors. Therefore, the gage standard deviation is a more meaningful index for change in gage.

In the gage family, the third moment of gage (GA3M) is not correlated with any other TQI's. However, this index does not give good prediction equations and thus was not included in the final set of TQI's.

7.4.2 LINE

The two line TQI's (ALSD, ALSM) show a correlation coefficient of 0.81 with each other. The standard deviation of the 10-foot MCO of alignment (ALSM) gives higher R^2 values than the standard deviation of the 16-foot MCO of alignment (ALSD). Therefore, the standard deviation of the 10-foot MCO was selected to describe the line condition of the track.

7.4.3 SURFACE

Table 7-19 indicates that the crosslevel (XLDV), warp (WASD, WA99) and profile (PRSD, PRSM, PR99) TQI's are highly correlated with each other. The prediction equations for the standard deviation of the profile short MCO (PRSM) have higher R^2 values than most of the other TQI's. However, a study of different maintenance levels indicated that this index is not sensitive to the effects of production maintenance (except rail renewal). This is illustrated in Figures 7-9 through 7-12 for the profile TQI (PRSM) and one of the warp TQI's (WASD). The ΔTQI's, i.e., the difference in TQI's before and after the production maintenance ($y-\hat{y}$) are plotted for maintenance levels 4 and 5. In these figures, the ΔTQI's for warp are seen to be negative for the majority of segments which clearly indicates an improvement in the overall surface condition. In contrast, the ΔTQI's for profile short MCO index are more generally positive and indicate degradation due to the inherent sensitivity of this TQI to short wavelengths (corrugations). Therefore, the warp index was preferred to the Profile Short MCO Index.

The crosslevel, warp and profile indices represent a measure of the track surface. Crosslevel is indicative of the surface of both the right and left rails. Therefore, a single crosslevel measurement would indicate the surface variation of both rails. In other words, the crosslevel indices are computed from one-half the data points needed to compute the profile indices. Crosslevel is used as a correction in the profile and alignment computations and, therefore, is an

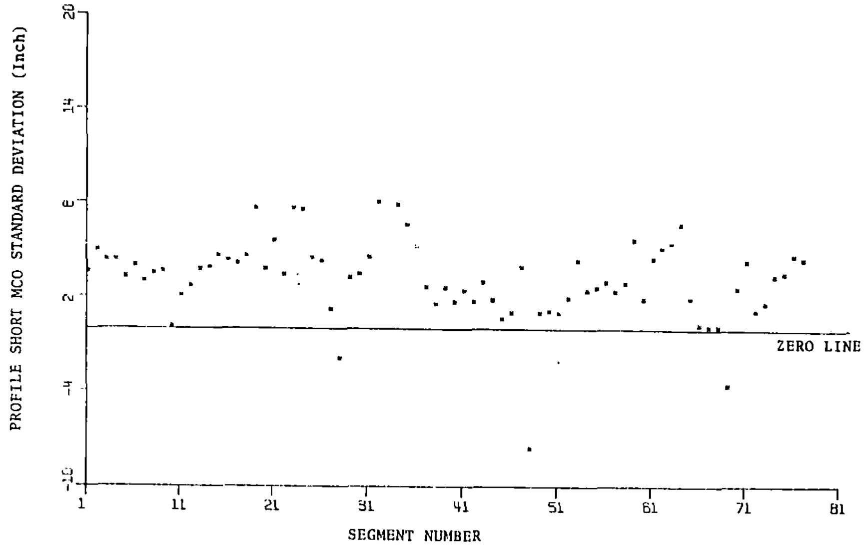


Figure 7-9. Change in Profile TQI Due to Maintenance Level 4 (ΔTQI)

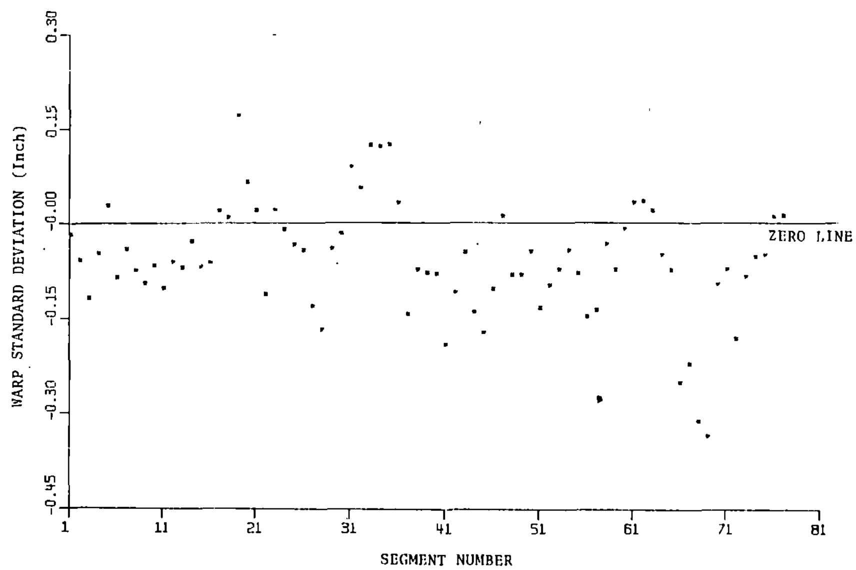


Figure 7-10. Change in Warp TQI Due to Maintenance Level 4 (ΔTQI)

integral part of the T-6 track-geometry-measurement system.* The computations required for crosslevel are simpler than the ones required for profile. Hence, the crosslevel indices are more reliable and are preferred over the profile TQI's.

The crosslevel and warp TQI's (XLDV, WASD, WA99) have correlation coefficients above 0.9 among each other. Hence, only one of them was selected. The 99 percentile of warp generally gives smaller R^2 values than the other two and thus was not selected.

The crosslevel standard deviation and the warp standard devaition have almost identical R^2 values for most maintenance levels. A study was performed to determine the sensitivity of the two TQI's. This study was conducted in terms of a Degradation Coefficient (D) which is defined as:

$$D = \frac{\bar{y} - \bar{\hat{y}}}{\bar{\hat{y}}} \qquad (7\text{-}2)$$

*ENSCO Report No. RTE-80-10, Analytical Description of Severe Track Geometry Variations, October 1979.

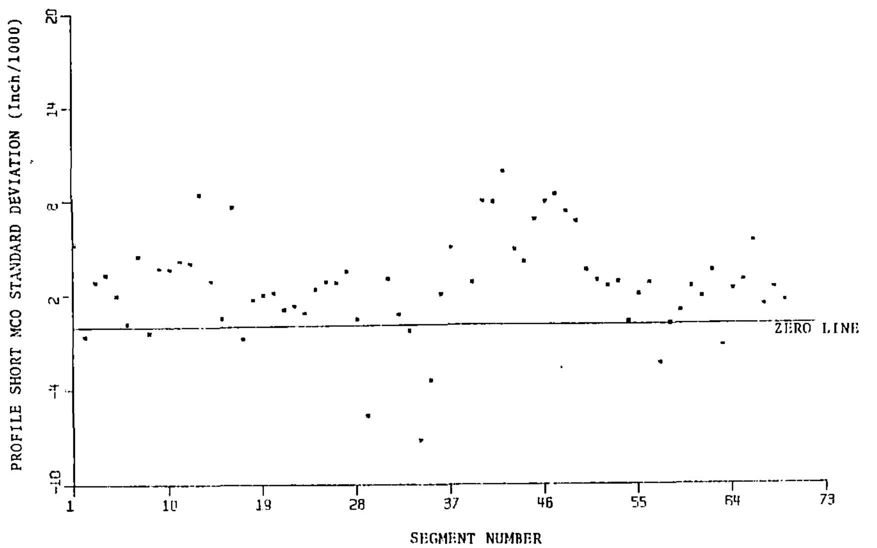


Figure 7-11. Change in Profile TQI Due to Maintenance Level 5 (ΔTQI)

where

$\bar{y}$ is the mean value of a TQI in 1979

$\hat{y}$ is the mean value of a TQI in 1978

The Degradation Coefficient, as defined above, will be positive if the track condition degrades; negative if the track condition improves; and zero if the track condition remains the same.

The values of D for the crosslevel and warp standard deviations are shown in Table 7-20 for all maintenance levels. In most cases, the absolute values of D are larger for the warp TQI than for the crosslevel TQI. In other words, warp changed more than crosslevel, the warp index is more sensitive to changes in track condition than the crosslevel index. Therefore, warp standard deviation was preferred over crosslevel standard deviation.

It should be mentioned that warp standard deviation is easier to calculate than crosslevel standard deviation. The measurement used to calculate the crosslevel TQI is the crosslevel deviation from its designed value which requires that the crosslevel data be passed through a high-pass filter. A recursive type implementation of such a filter would contaminate the computed crosslevel

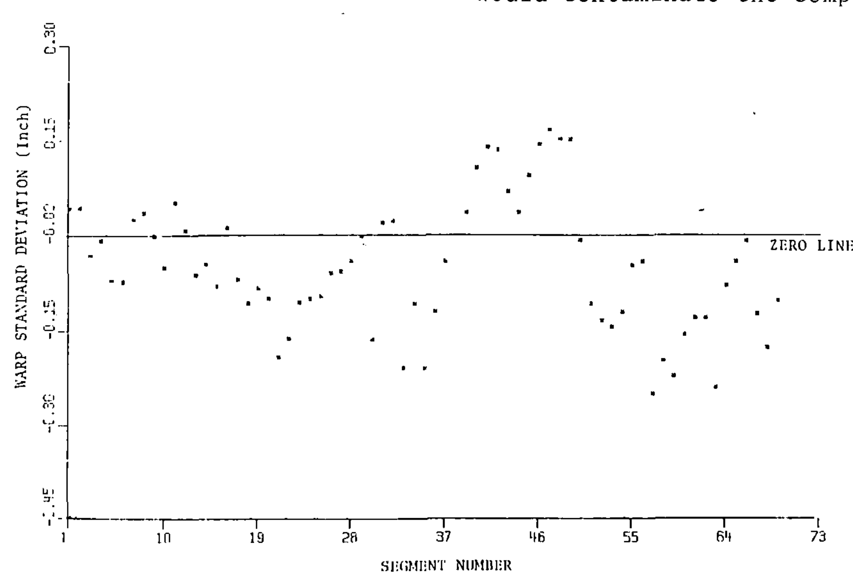


Figure 7-12. Change in Warp TQI Due to Maintenance Level 5 (ΔTQI)

TABLE 7-20

COMPARISON OF DEGRADATION COEFFICIENT FOR CROSSLEVEL AND WARP TQI

Maintenance Level \ TQI	Crosslevel Standard Deviation	Warp Standard Deviation
Maintenance Level 0	0.19	0.21
Maintenance Level 1	0.27	0.33
Maintenance Level 2	0.18	0.16
Maintenance Level 3	0.10	0.14
Maintenance Level 4	-0.16	-0.15
Maintenance Level 5	-0.08	-0.11
Maintenance Level 6	-0.39	-0.44

data for a distance equal to the filter length (79 feet) due to a single bad data point.

On the other hand, a warp measurement involves only one subtraction and thus does not suffer from the problems mentioned previously. Thus, a TQI based on warp was preferred over a crosslevel TQI. Therefore, the warp standard deviation was selected to describe the surface condition of the track.

It should be pointed out that a study* performed by Southern Railway showed that the number of occurrences of level 1 twist and level 1 alignment per mile correlated best with derailment rate. Counts of warp and alignment values falling between two thresholds are defined as level 1 in the Southern Railway Study. The Southern Railway Index depends on two thresholds and is thus limited to certain operational conditions. This points out the fundamental difference between the Southern Railway Study and the planning program documented in this report. Southern uses point-by-point exception counts while the FRA program uses statistical summarizations of data. In addition the Southern study is to predict derailments while the FRA program is to project track condition.

*Bulletin 673 - American Railway Engineering Association, W.W. Simpson, pp 37 - 391.

7.4.4 SUPERELEVATION

The standard deviation of unbalanced superelevation is not correlated with any other TQI. It is sensitive to the track degradation or improvement as a result of different maintenance operations. The prediction equations based on this TQI have relatively high R^2 values for most maintenance levels. Therefore, it was selected as one of the final set of TQI's. However, it should be mentioned that the posted speed and the instantaneous track curvature are used in the computations of this TQI. Thus the high R^2 values might be due to the fact that the posted speed and maximum curvature are also treated as physical parameters. Furthermore, a change in the posted speed will change the value of this TQI without actually changing the track condition (Section 3.0).

7.4.5 FINAL SET OF TQI'S

Based on the discussions in this section, the final set of TQI's consist of a gage roughness index, a wide gage index, a surface index, a line index, and the superelevation index. Table 7-21 lists the final set of TQI's and the terminology to be used from this point forward. Track degradation and the effect of maintenance will be discussed (in terms of the final set of TQI's) in the following sections.

TABLE 7-21

THE FINAL SET OF TQI'S

TQI	Variable	Code	Sample Statistics	Unit
Wide Gage Index	y_3	GA99	99 percentile of Gage	Inch
Gage Roughness Index	y_2	GASD	Standard Deviation of Gage	Inch
Surface Index	y_7	WASD	Standard Deviation of 20-foot Warp	Inch
Line Index	y_{13}	ALSM*	Standard Deviation of the 10-foot MCO of Alignment	Inch/1000
Superelevation Index	y_{14}	BSEL	Standard Deviation of the Unbalanced Superelevation	Inch

*From this point onward, the notation ALSM indicates the standard deviation of the 10-foot MCO of alignment and not the previous short MCO of two feet.

7.5 TRACK DEGRADATION

This section describes track degradation for unmaintained track in terms of the final set of TQI's. The equations to predict track condition are described first. This is followed by the analysis of these equations. Finally, an illustration of the prediction equations is given for both bolted and welded rail.

7.5.1 PREDICTIVE EQUATIONS

Stepwise autoregression techniques were used to develop the final predictive equations. The predictive equations contain an optimum number of physical parameters from the parameters considered in this study. The F-value both for the entry and removal of a variable was set at 3.0. This assures with 99 percent confidence that the variables included in the prediction equations are significant.

Detailed results of the prediction equations are given in Appendix H. Table 7-22 lists the equations for the final five TQI's. The coefficient of determination (R^2) for all TQI's is well above 0.8 which means that the prediction equations explain at least 80 percent of the change in the TQI's, interpreted as measures of track condition. A means to check this is to compare the actual TQI values for 1979 with the predicted

TABLE 7-22

PREDICTION EQUATIONS FOR UNMAINTAINED TRACK

TQI	Prediction Equation*	R^2
Gage Roughness	$y_2 = -0.036 + 0.84\hat{y}_2 + 0.0007x_2 + 0.0008x_3$	0.89
Wide Gage Index	$y_3 = 13.88 + 0.75\hat{y}_3 + 0.003x_1 + 0.0116x_4 + 0.0526x_6$	0.85
Surface Index	$y_7 = -0.004 + 0.92\hat{y}_7 + 0.0037x_1 - 0.0032x_4 + 0.069x_6 + 0.0005x_7 + 0.029x''_8$	0.90
Line Index	$y_{13} = 3.84 + 0.71\hat{y}_{13} + 0.429x_1 + 0.349x_4 + 6.57x_6 + 3.18x'_8$	0.83
Superelevation Index	$y_{14} = 0.043 + 0.94\hat{y}_{14} + 0.012x_4 + 0.0009x_7$	0.97

*In this table $\hat{y}_i$ is the previous value of a TQI; x_1 is the tonnage, x_2 is the percent heavy wheels, x_3 is the speed, x_4 is the curvature, x_6 is the rail type, x_7 is the percent bent rail, x'_8 is ballast level 1 and x''_8 is ballast level 2.

1979 TQI values, given the required inputs to the degradation equation. This procedure is explained in Section 7.5.2.

In studying the final prediction equations points should be made about the nature of the independent variables. Since tonnage is correlated with speed and percent heavy wheels (Section 7.2) variations associated with tonnage are explained by speed and the percent heavy wheel parameters in the case of gage roughness. None of the traffic parameters are shown to be significant for the superelevation TQI. As was discussed in Section 7.4, curvature is used in the calculation of the superelevation TQI. Therefore, curvature is a more significant physical parameter for this TQI. Because of the nature of the test zone data, curvature is correlated with tonnage (Section 7.2). This is because the Fort Wayne Division has high tonnage and low curvature while the Lehigh Division has low tonnage and high curvature. When curvature is included in the prediction equation, the tonnage is no longer significant. Thus, the prediction equation for the superelevation TQI as given in Table 7-22 could possibly be specific for the test zone under study.

The prediction equation for the superelevation TQI was developed by forcing the tonnage parameter into the equation. The prediction equation containing the tonnage parameter and the previous value of the TQI was:

$$y_{14} = 0.09 + 0.97\hat{y}_{14} - 0.0024x_1 \qquad (7\text{-}3)$$

where

y_{14} is the future value of the superelevation TQI

$\hat{y}_{14}$ is the previous value of the superelevation TQI

x_1 is the annual tonnage.

This alternate equation will predict the value of the superelevation TQI having an R^2 value of 0.97.

The contribution of each physical parameter to the track deterioration is also outlined in Appendix H. Note that the largest regression coefficient is always associated with the previous value of a TQI. This is reinforced by the fact that in the stepwise regression the previous value is the first parameter entered in every case. Tonnage and rail type are the next most important physical parameters. This is shown in Table 7-23 for the surface TQI. The prediction equations for each step of regression are listed along with the R^2 values. It should be noted that the

TABLE 7-23

CONTRIBUTIONS OF DIFFERENT PHYSICAL PARAMETERS TO THE PREDICTION EQUATION OF SURFACE TQI*

Added Variable	Equation	R^2
Previous Value	$y_7 = 0.014 + 1.16\hat{y}_7$	0.800
Rail Type	$y_7 = 0.015 + 0.99\hat{y}_7 + 0.068x_6$	0.846
Tonnage	$y_7 = -0.033 + 0.98\hat{y}_7 + 0.067x_6 + 0.0045x_1$	0.886
Percent Bent Rail	$y_7 = -0.018 + 0.92\hat{y}_7 + 0.065x_6 + 0.0044x_1 + 0.0008x_7$	0.893
Curvature	$y_7 = -0.006 + 0.93\hat{y}_7 + 0.067x_6 + 0.0037x_1 + 0.0007x_7 - 0.0031x_4$	0.897
Ballast Level 2	$y_7 = -0.004 + 0.92\hat{y}_7 + 0.069x_6 + 0.0037x_1 + 0.0005x_7 - 0.0032x_4 + 0.029x''_8$	0.899

*Warp standard deviation denoted by y_7.

addition of successive variables improves the predictability of an equation with dimishing returns. The addition of an extra variable should be evaluated in terms of economic returns since an extra variable means additional costs for data collection. For example, one might be satisfied with the following equation for the surface TQI to explain 88.6 percent of the total variations:

$$y_7 = -0.033 + 0.98\hat{y}_7 + 0.0045x_1 + 0.067x_6 \quad (7\text{-}4)$$

where

y_7 is the future value of the surface TQI,

$\hat{y}_7$ is the previous value,

x_1 is the tonnage, and

x_6 is the rail type (0 or 1).

The three additional variables, i.e., percent bent rail, curvature, and ballast level 2 improve the prediction equation to explain 90 percent of the variations. Additional physical parameters should be considered if further improvement is desired.

A study of the mean of y (1979 value) and the mean of the previous y (1978 value) in Appendix H indicates an overall degradation of approximately 0.06 inch for the surface TQI. This is roughly equivalent to a degradation of one track class over a period of one year. The same is true for the superelevation TQI. However, no degradation is observed in the case of the gage and line TQI's. This would indicate that the gage and line condition of the track did not change sufficiently over the period of one year to be measured by the present day gage and alignment instrumentation. The other explanation could lie in the fact that the quality of the track geometry data collected in 1978 is indeed doubtful as discussed earlier. Additional track geometry surveys should be conducted to verify the results presented in this report.

7.5.2 ANALYSIS OF PREDICTIVE EQUATIONS

Appendix H also gives an outline of the analysis of variance along with the prediction equations for each TQI. The total variation for each TQI is divided into the variations explained by the model and the remaining variations (to be explained possibly by additional physical parameters). The computed F-values for all TQI's are very significant; i.e., above 150. Therefore, it can be concluded with a 99.9-percent confidence level* that a significant amount of variations in the response variables (TQI's) are accounted for by the postulated models and that there is less than one chance in 1000 that the relationships are just by chance.

A residual plot** is a means for testing the adequacy of the predictive models and the assumptions underlying the regression analysis. Residuals were plotted versus the independent variables (physical parameters) and the predicted values of the TQI's. Analyses of these plots indicated that the assumptions used in regression analysis were correct and the predictive models were adequate. An example is shown in Figure 7-13. Here the residuals are plotted versus the predicted values of y for the surface TQI. The least square line drawn through the residual has a zero slope and a zero intercept. Thus the residuals are randomly distributed with a mean of zero. This means that the errors in y (ε_i) are uncorrelated and (ε_i) is a normally distributed random variable with a mean of zero. This is an important assumption in the regression methodology used in this study. Figure 7-13 also indicates that the predictive model for the surface TQI is adequate and that no transformations are required for the observations.

*Samuel N. Selby, "Standard Mathematical Tables," Chemical Rubber Co., Cleveland, OH, p. 619.

**N. R. Draper and H. Smith, "Applied Regression Analysis," John Wiley and Sons, Inc., New York, NY, 1966

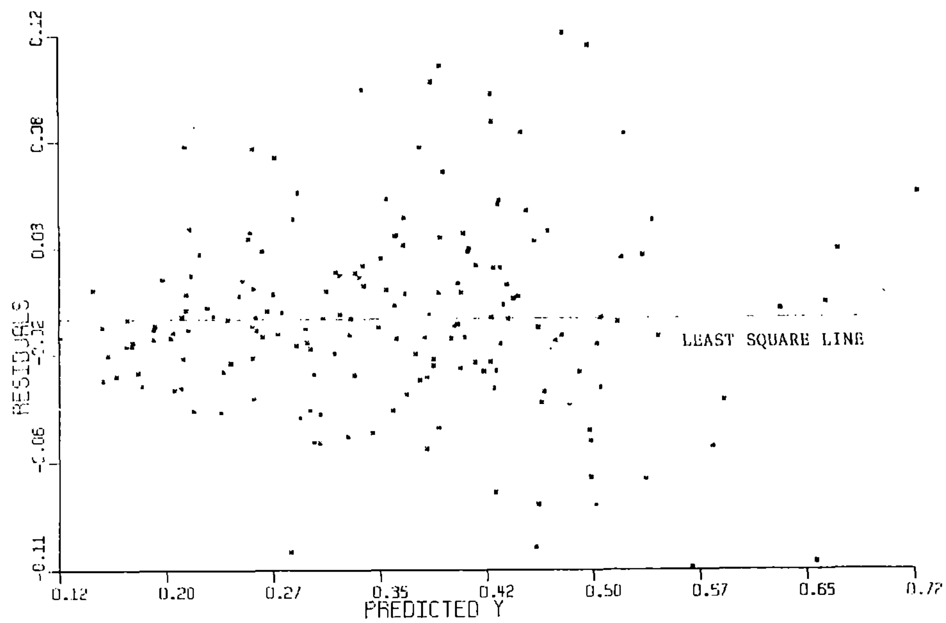


Figure 7-13. Residual Analysis for the Surface TQI

The ability of an equation to predict the y values can be evaluated by plotting the y values predicted by the equation versus the actual (observed) y values. In the case of perfect prediction, all the points will be on a 45-degree line passing through the origin. Figure 7-14 through 7-18 show plots of predicted y values versus actual y values for the final TQI's. The estimated least square lines (drawn through the points) have a slope of unity (45 degree line) and an intercept of zero except for wide gage index. The standard errors of estimate (indicated on these figures) show a measure of error with which any observed value of y could be predicted using the prediction equations. Note that it would be necessary to include additional physical parameters

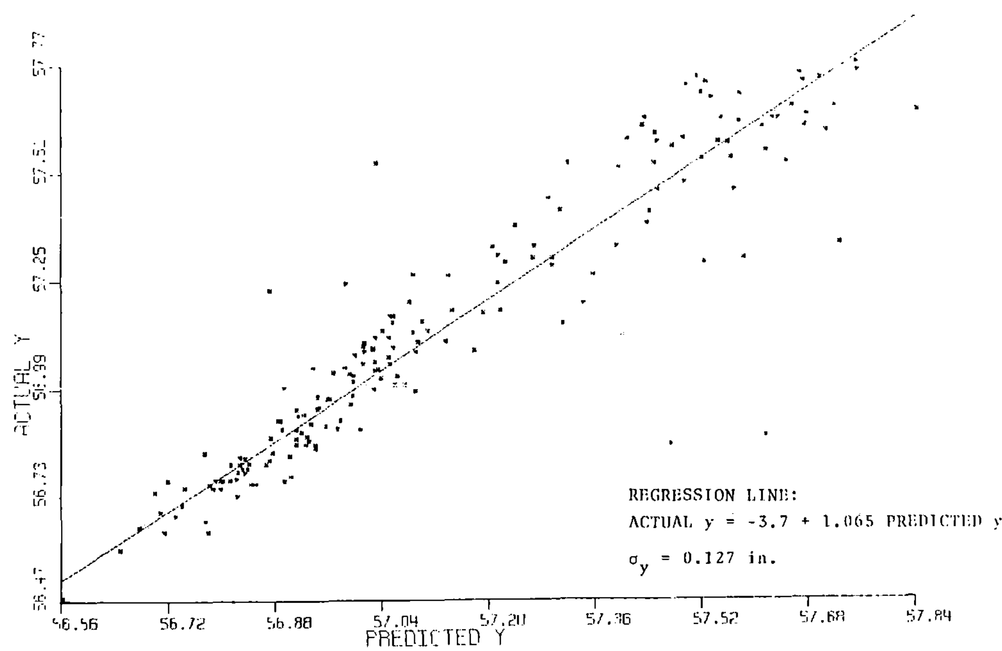


Figure 7-14. Actual vs Predicted Value for Wide Gage Index

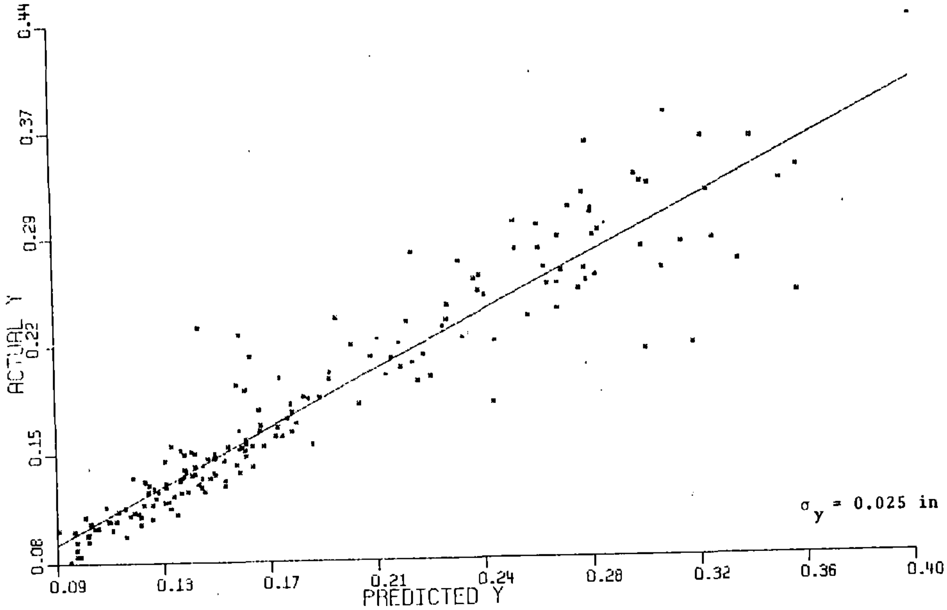


Figure 7-15. Actual vs Predicted Value of Gage Roughness

(not considered in this study) to lower the values of standard error.

Table 7-24 lists the 95-percent confidence intervals for the regression coefficients (β_i). The confidence intervals were computed using the following equation:*

$$b_i - s_i t_{\alpha/2} < \beta_i < b_i + s_i t_{\alpha/2} \quad (7\text{-}5)$$

where

b_i is the estimated value of the regression coefficeint β_i

s_i is the standard error of b_i

$t_{\alpha/2}$ is the value of t-distribution for $(1-\alpha)$ level of confidence.

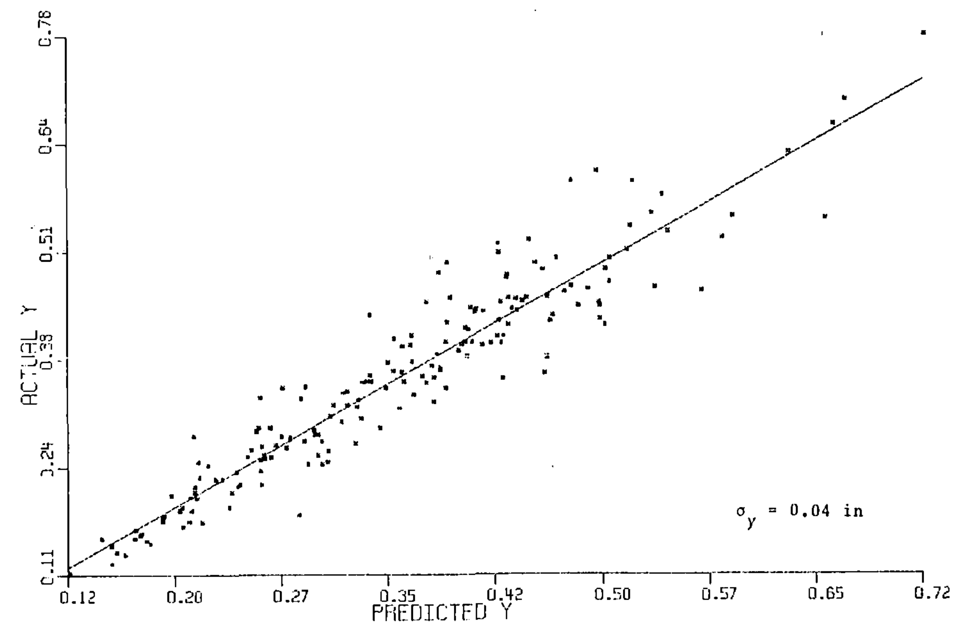


Figure 7-16. Actual vs Predicted Value of the Surface TQI

*N. R. Draper and H. Smith, "Applied Regression Analysis," John Wiley and Sons, Inc., New York, NY 1966

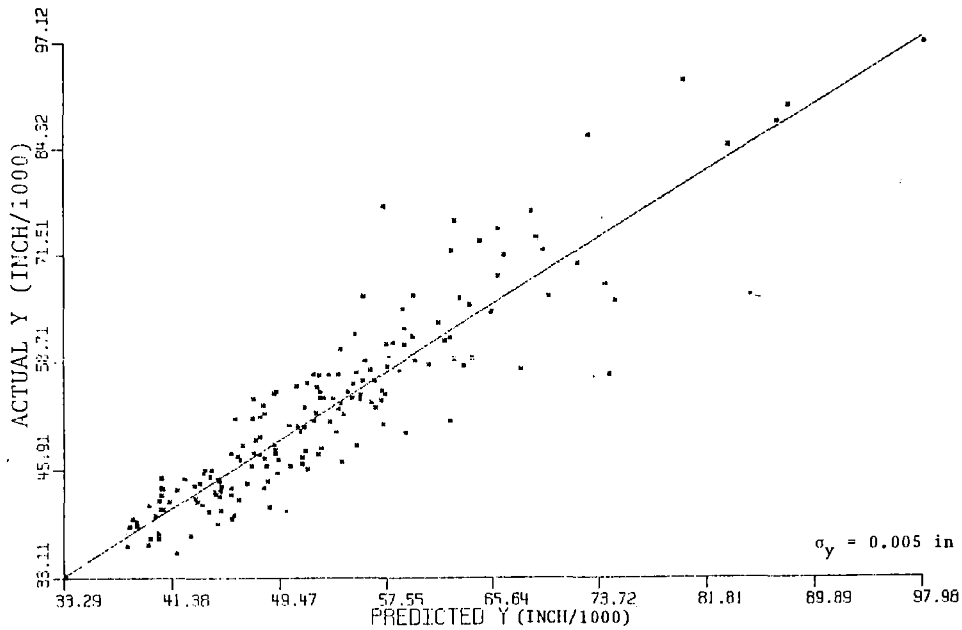


Figure 7-17. Actual vs Predicted Value of the Line TQI

It is important to remember that the empirical regression coefficients are only estimates of the true parameters based on the given sample of observations. The confidence intervals given in Table 7-24 indicate the estimated spread in the regression coefficients, which should be considered if the results are extended to other similar track regions (as characterized in Section 7.2).

7.5.3 DEGRADATION CURVES

This section gives an illustration of how the prediction equations can be used to estimate track degradation as a function of the physical parameters. For the purpose of illustration, track degradation estimation will be in terms of the Surface TQI using Equation 7-4. Before studying this particular equation, it should be noted that since all degradation

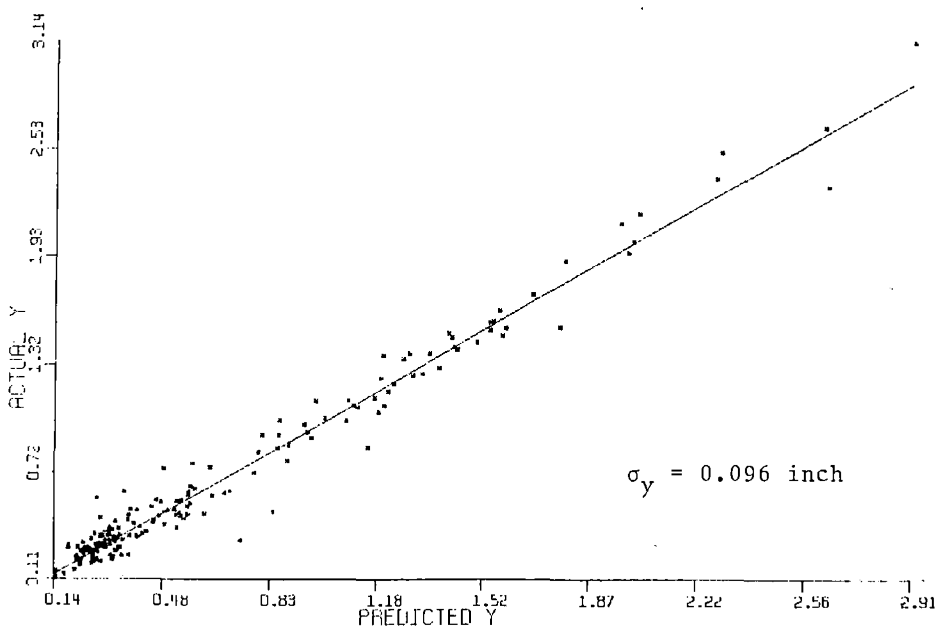


Figure 7-18. Actual vs Predicted Value for the Superelevation TQI

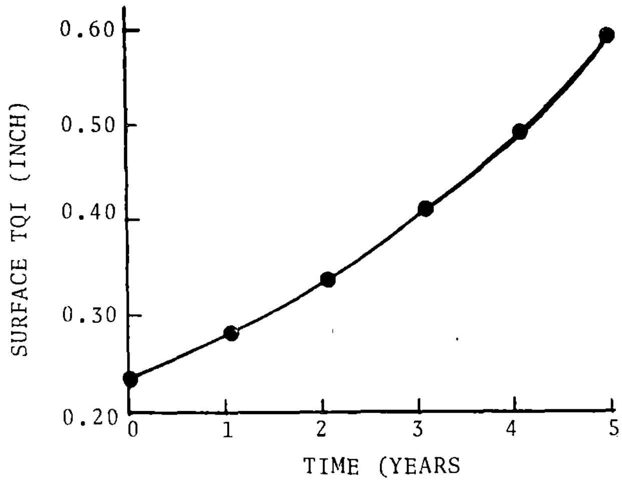


Figure 7-19. Track Degradation As a Function of the Value of the TQI

TABLE 7-24

NINETY-NINE PERCENT CONFIDENCE INTERVAL FOR THE REGRESSION COEFFICIENTS

TQI	Variable	Regression Coefficient	Confidence Interval
Wide Gage Index	Previous Value	0.75	$0.67 < \beta_0 < 0.83$
	Tonnage	0.0030	$-0.0009 < \beta_1 < 0.0069$
	Curvature	0.0116	$0.0023 < \beta_4 < 0.0208$
	Rail Type	0.0526	$0.0036 < \beta_6 < 0.1015$
Gage Roughness	Previous Value	0.84	$0.79 < \beta_0 < 0.89$
	Heavy Wheel	0.0007	$0.0001 < \beta_2 < 0.0013$
	Speed	0.0008	$0.0003 < \beta_3 < 0.0013$
Surface Index	Previous Value	0.92	$0.84 < \beta_0 < 1.00$
	Tonnage	0.0037	$0.0025 < \beta_1 < 0.0049$
	Curvature	-0.0032	$-0.0055 < \beta_4 < -0.0009$
	Rail Type	0.069	$0.054 < \beta_6 < 0.085$
	Percent Bent Rail	0.0005	$0.00001 < \beta_7 < 0.001$
	Ballast Level 2	0.029	$-0.0013 < \beta_8'' < 0.059$
Line Index	Previous Value	0.71	$0.64 < \beta_0 < 0.78$
	Tonnage	0.429	$0.278 < \beta_1 < 0.580$
	Curvature	0.349	$0.016 < \beta_4 < 0.682$
	Rail Type	6.57	$4.92 < \beta_6 < 8.22$
	Ballast Level 1	3.18	$0.89 < \beta_8' < 5.47$
Superelevation Index	Previous Value	0.94	$0.91 < \beta_0 < 0.97$
	Curvature	0.012	$0.006 < \beta_4 < 0.018$
	Percent Bent Rail	0.0009	$0.0001 < \beta_7 < 0.0018$

equations in this study are based on two observation periods; the degradation curves and extrapolations are linear. However track degradation may not be a linear process over a significant period of time, if it is not maintained. Figure 7-19 illustrates this point for the Surface TQI using just the present value of the surface index. (Equations are in Table 7-23). That is, bad track degrades faster than good track, especially after two or three years.

The prediction equations given in Section 7.5.1 can be used for both bolted and welded rail. This can be done by substituting a value of one for bolted rail and a value of zero for welded rail.

The prediction equations were developed by separating the data for the unmaintained segments according to rail type. Since there were only 61 welded segments and physical parameters did not have adequate variations, the regression equations for the welded rail were not as significant as the ones developed for the combined data. However, the regression equations for bolted rail were found to give results similar to those given by the prediction equation for the combined data.

Table 7-25 outlines the difference between bolted and welded track. The initial track condition for the welded

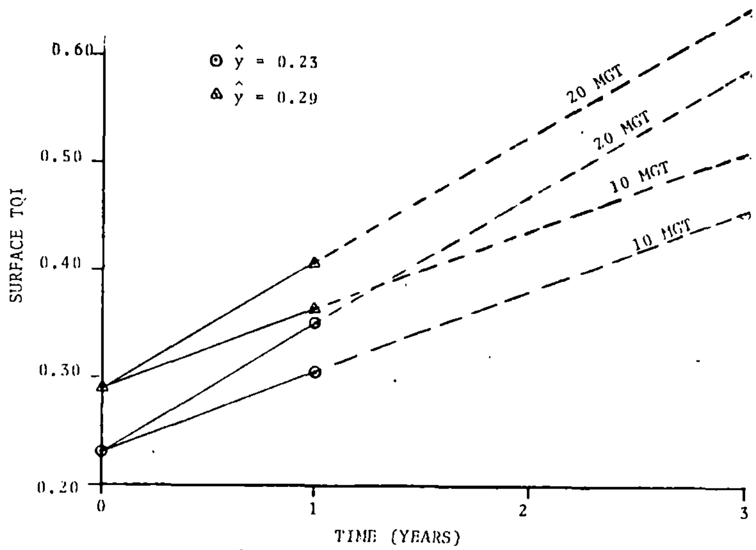


Figure 7-20. Track Degradation for Bolted Rail

track was much better than the bolted track. Over a period of one year, the bolted track shows a degradation coefficient of four times that of the welded track in terms of the surface TQI.

Figures 7-20 and 7-21 illustrate how the prediction equations can be used to estimate the future condition of track. The curves are given for an annual tonnage of 10 and 20 MGT. The initial track conditions are assumed to be that

TABLE 7-25

COMPARISON OF TRACK DEGRADATION FOR THE BOLTED AND WELDED TRACK IN TERMS OF THE SURFACE TQI

Remarks	Bolted	Welded
Mean Value for 1978 ($\hat{y}$)	0.324	0.215
Mean Value for 1979 ($\bar{y}$)	0.405	0.229
$\bar{y} - \hat{y}$	0.081	0.014
Degradation Coefficient	0.25	0.065

of class 3 and class 4 track. As is indicated in Figure 7-20, bolted rail degrades approximately one track class per year for track carrying an annual tonnage of 10 MGT. The degradation approaches almost two track classes, based on expected values (Section 7.1.2) per year for the 20 MGT track. In the case of the welded rail, Figure 7-21 indicates insignificant degradation for the 10 MGT track. However, a degradation of approximately one track class per year is observed for the 20 MGT track. It should be pointed out that the degradation models were developed using only two time observations (years 0, 1) and the results for the years 2 and 3 are extrapolated for illustrative purposes.

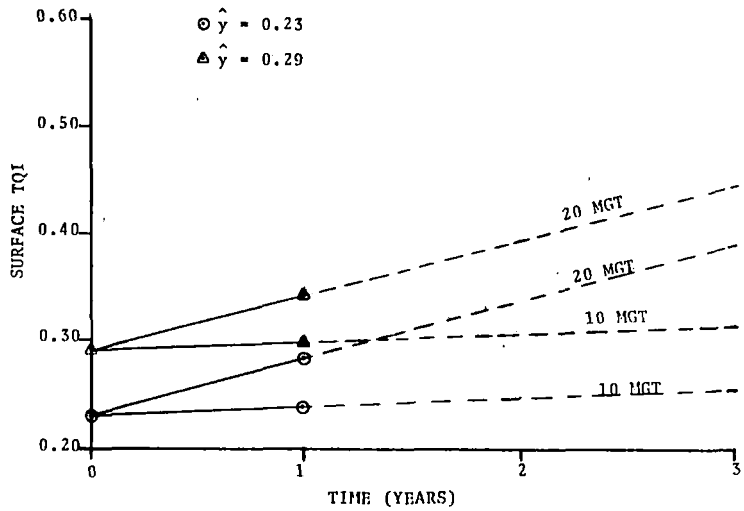


Figure 7-21. Track Degradation for Welded Rail

7.6 EFFECT OF MAINTENANCE

This section deals with the effect of maintenance on track condition. Basic and production maintenance operations are discussed separately. In general, basic maintenance operations retard the rate of track degradation while production maintenance improves track condition.

Prediction equations for the future values of TQI's were developed for maintenance levels 1 through 5. Regression was not performed on maintenance level 6 since this maintenance operation involves rail renewal. The effects of rail renewal are discussed only in terms of the change in track condition.

The prediction equations were developed using stepwise autoregression techniques as discussed for the unmaintained track. The results for the final five TQI's are presented in Appendix H. The following paragraphs discuss the important features of the effects of maintenance.

7.6.1 BASIC MAINTENANCE

Prediction equations for different levels of basic maintenance are listed in Tables 7-26 through 7-28. The R^2 values for most TQI's are well above 0.8 which implies that the predictive equations will describe at least 80 percent of

TABLE 7-26

PREDICTION EQUATIONS FOR MAINTENANCE LEVEL 1

TQI	Prediction Equation*	R^2
Gage Roughness	$y_2 = -0.332 + 0.94\hat{y}_2 + 0.0007x_1 - 0.0024x_5 - 0.0152x_6$	0.89
Wide Gage Index	$y_3 = 25.19 + 0.615\hat{y}_3 + 0.0026x_1 - 0.025x_5 + 0.1219x_8$	0.90
Surface TQI	$y_7 = -0.052 + 0.80\hat{y}_7 + 0.0049x_1 + 0.089x_6 + 0.0069x_7$	0.91
Line TQI	$y_{13} = 236.2 - 0.503x_2 - 0.661x_3 - 1.024x_5 + 0.382x_7 + 3.86x_8$	0.92
Superelevation TQI	$y_{14} = 0.681 + 0.84\hat{y}_{14} - 0.0085x_1 - 0.0109x_2 - 0.473x_8$	0.90

*Here, $\hat{y}_i$ is the previous value of a TQI, x_1 is the tonnage, x_2 is the percent heavy wheels, x_3 is the speed, x_5 is the rail weight, x_6 is the rail type, x_7 is the percent bent rail, and x_8 is the ballast condition (good or bad).

TABLE 7-27

PREDICTION EQUATIONS FOR MAINTENANCE LEVEL 2

TQI	Prediction Equation*	R^2
Gage Roughness	$y_2 = 0.036 + 0.74y_2 - 0.0004x_1 - 0.0003x_7$	0.78
Wide Gage Index	$y_3 = 9.86 + 0.82y_3 + 0.0107x_1 + 0.0384x_4$	0.89
Surface TQI	$y_7 = 0.034 + 0.82\hat{y}_7 + 0.0003x_1 + 0.091x_6$	0.83
Line TQI	$y_{13} = 89.16 + 0.72\hat{y}_{13} + 0.403x_1 - 0.873x_2 - 1.13x_3 + 0.966x_4 + 11.1x_6 - 0.068x_7$	0.84
Superelevation TQI	$y_{14} = 0.098 + 0.71\hat{y}_{14} + 0.106x_4$	0.90

*In these equations, x_4 is the curvature and other symbols are the same as in Table 7-26.

TABLE 7-28

PREDICTION EQUATIONS FOR MAINTENANCE LEVEL 3

TQI	Prediction Equation*	R^2
Gage Roughness	$y_2 = 0.005 + 0.86\hat{y}_2 + 0.0002x_1 + 0.0025x_4 - 0.017x_6 + 0.007x'_8$	0.88
Wide Gage Index	$y_3 = 7.67 + 0.86\hat{y}_3 + 0.0056x_1 + 0.0591x''_8$	0.87
Surface TQI	$y_7 = 0.227 + 0.49\hat{y}_7 + 0.0035x_1 - 0.0044x_2 + 0.010x_4 + 0.113x_6 + 0.059x''_8 - 0.038x'''_8$	0.84
Line TQI	$y_{13} = 45.50 + 0.76\hat{y}_{13} + 0.284x_1 - 0.471x_2 + 0.342x_3 - 0.250x_5 + 4.58x''_8$	0.74
Superelevation TQI	$y_{14} = 0.069 + 0.90\hat{y}_{14} - 0.0001x_1 - 0.064x_9$	0.93

*In these equations, x'_8, x''_8, and x'''_8 are the dummy variables corresponding to the ballast levels 0, 1, 2 and 3; and x_9 is the drainage condition (0 or 1). The other symbols are the same as in Tables 7-26 and 7-27.

TABLE 7-29

MEAN VALUES* OF 1978 TQI'S FOR DIFFERENT MAINTENANCE LEVELS

Maintenance Level \ TQI	Wide Gage Index	Gage Roughness	Surface TQI	Line TQI	Super-elevation TQI
Maintenance Level 0	57.19	0.19	0.29	54.0	0.64
Maintenance Level 1	57.01	0.14	0.27	48.0	0.29
Maintenance Level 2	57.04	0.15	0.31	52.0	0.54
Maintenance Level 3	57.06	0.15	0.36	52.0	0.44

*All values are in inches except for the line TQI which is in thousands of an inch.

TABLE 7-30

EFFECT OF BASIC MAINTENANCE ON CHANGE* IN TQI'S

Maintenance Level \ TQI	Wide Gage Index	Gage Roughness	Surface TQI	Line TQI	Super-elevation TQI
Maintenance Level 0	-0.06	0.00	0.06	-0.8	0.04
Maintenance Level 1	-0.01	0.01	0.08	2.8	0.05
Maintenance Level 2	-0.04	0.00	0.04	1.0	0.02
Maintenance Level 3	-0.02	0.00	0.04	2.3	0.02

*$(\bar{\bar{y}} - \bar{y})$ in inches except for line TQI which is in thousands of an inch.

the changes in TQI values. As in the case of unmaintained track, the previous value of an index is the most significant factor in predicting the new value. Tonnage is significant in most cases and rail type is important in the case of the surface TQI.

A study of Appendix H shows a poor correlation coefficient between 1978 and 1979 values of the line TQI for maintenance level 1. No obvious reason was found for this discrepancy. However, it should be pointed out that maintenance level 1 consists of tangent track segments contrary to other maintenance levels. Because of the poor correlation between the 1978 and 1979 values, the previous value of the line TQI is not included in the prediction equation for maintenance level 1. Most of the variations in this case are explained by the heavy wheel, rail-weight and percent-bent-rail parameters.

Drainage condition appears for the first time in the prediction equation of the superelevation TQI for maintenance level 3. As discussed in Section 7.2, this maintenance level has the largest number of segments with poor drainage condition. In addition, this maintenance level has a significant number of segments with ballast level 3. This ballast level is shown to be significant in the prediction equation of the surface index.

The average values of the 1978 TQI's are given in Table 7-29. No apparent relation is evident between the TQI's and the level of maintenance for the gage and line TQI's. In the case of superelevation, low values of the TQI are associated with higher maintenance levels contrary to what one would normally expect. However, as expected, the level of basic maintenance effort increased with the value of the surface TQI. As shown in Table 7-29, the value of the surface TQI for maintenance level 1 is lower than that for maintenance level 0. This is believed to be due to the nature of the data for maintenance level 1, i.e., mainly tangent segments. The nature of the data is also the cause for a very low value of the superelevation TQI for maintenance level 1.

Table 7-30 shows the change in TQI's according to maintenance level. The change in TQI's was computed by subtracting the mean value of a TQI in 1978 from the mean value in 1979. No significant change, i.e., degradation, was observed for the gage and line TQI's. The surface and superelevation TQI's show a significant change. Maintenance levels 2 and 3 appear to have retarded track degradation by approximately one-half as compared to unmaintained track.

The largest degradation is observed for maintenance level 1. The segments which receive this maintenance are probably the problem areas where track degrades relatively faster. It should be remembered that maintenance level 1 affects only up to 10 percent of a segment and this is apparently not significant in retarding the degradation rate in terms of the selected TQI's.

Table 7-31 shows the effect of basic maintenance on the degradation coefficients. Again the largest values of the degradation coefficient appear for maintenance level 1. Maintenance levels 2 and 3 have decreased the value of the degradation coefficient as compared to the values for the unmaintained track.

TABLE 7-31

DEGRADATION COEFFICIENT FOR DIFFERENT LEVELS OF BASIC MAINTENANCE

Maintenance Level \ TQI	Wide Gage Index	Gage Roughness	Surface TQI	Line TQI	Super-elevation TQI
Maintenance Level 0	0.00	-0.03	0.21	-0.02	0.06
Maintenance Level 1	0.00	0.06	0.30	0.06	0.17
Maintenance Level 2	0.00	0.0	0.14	0.02	0.03
Maintenance Level 3	0.00	0.02	0.12	0.04	0.04

TABLE 7-32

CHANGE IN REGRESSION COEFFICIENTS DUE TO DIFFERENT LEVELS OF BASIC MAINTENANCE

Maintenance Level	Prediction Equation*	R^2
0	**$y_7 = -0.033 + 0.98\hat{y}_7 + 0.0045x_1 + 0.067x_6$	0.89
1	$y_7 = -0.105 + 1.04\hat{y}_7 + 0.0054x_1 + 0.114x_6$	0.87
2	$y_7 = 0.034 + 0.82\hat{y}_7 + 0.0003x_1 + 0.091x_6$	0.83
3	$y_7 = 0.056 + 0.51\hat{y}_7 + 0.0041x_1 + 0.114x_6$	0.78

* x_1 is the tonnage and x_6 is the rail type.

** Surface TQI.

Regression coefficients provide a means of evaluating the relative contribution of a physical parameter to the change in the response variable (TQI). To compare regression coefficients, it is important to have the same physical parameters in the prediction equations. Table 7-32 provides a comparison of the regression coefficients and R^2 values for the surface index at different maintenance levels. All the equations contain the previous value of the TQI, the tonnage, and the rail type. Notice that all of the regression coefficients are larger for maintenance level 1 than for the other maintenance levels. The previous value of the TQI becomes progressively less important for maintenance levels 2 and 3. This is to be expected since the degree of correlation between the current and the previous value of a TQI will decrease with the increase in maintenance level. The other regression coefficients cannot be as easily interpreted. In addition, it should be pointed out that the R^2 values decrease as the basic maintenance level increases.

Degradation curves for different maintenance levels are shown in Figure 7-22. Values of the surface TQI were projected from the equations listed in Table 7-32 over a three-year period for bolted track carrying an annual tonnage of 15 MGT. The initial conditions were assumed to be that of class 4 track. Notice that the results for years 2 and 3 are extrapolated and actual degradation over long periods of time may not be linear as shown in Figure 7-22. From Figure 7-22, it appears that Maintenance Level 1 does not significantly retard track degradation, however, this amount of maintenance could be very important for meeting safety requirements. Also, this figure suggests that different levels of basic maintenance as defined in

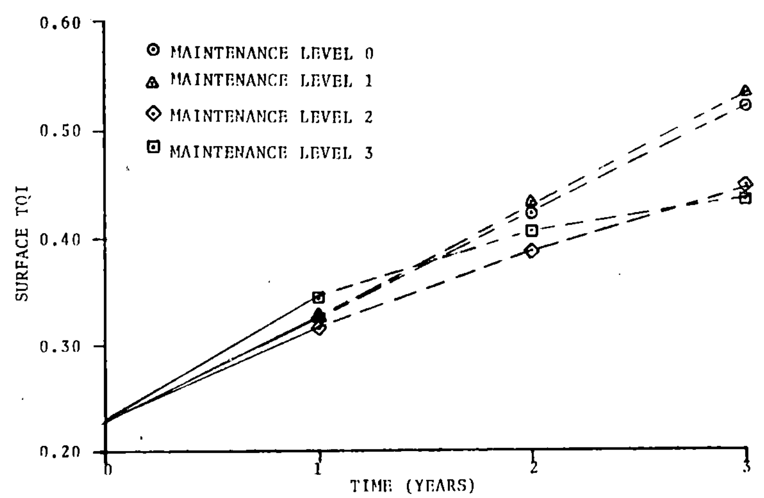


Figure 7-22. Effect of Basic Maintenance on Track Degradation (Bolted Rail)

TABLE 7-33

PREDICTION EQUATIONS FOR MAINTENANCE LEVEL 4

TQI	Prediction Equation*	R^2
Gage Roughness	$y_2 = 0.037 + 0.74\hat{y}_2 - 0.0011x_1 + 0.016x_6$	0.90
Wide Gage Index	$y_3 = 13.90 + 0.76\hat{y}_3 - 0.0129x_1 + 0.150x_6 + 0.0887x_8''$	0.91
Surface TQI	$y_7 = -0.010 + 0.50\hat{y}_7 - 0.0090x_1 + 0.0032x_2 + 0.011x_4 + 0.220x_6 - 0.0014x_7 - 0.149x_8''$	0.84
Line TQI	$y_{13} = 37.29 + 0.57\hat{y}_{13} + 0.3373x_2$ $0.268x_3 - 0.346x_5 + 6.38x_6$	0.76
Superelevation TQI	$y_{14} = 0.053 + 0.83\hat{y}_{14} - 0.0035x_1$	0.79

*$\hat{y}$ is the previous value of TQI, x_1 is the tonnage, x_2 is the percent heavy wheel, x_3 is the speed, x_4 is the curvature, x_5 is the rail weight, x_6 is the rail type, x_7 is the percent bent rail, and x_8'' is ballast level 2.

TABLE 7-34

PREDICTION EQUATIONS FOR MAINTENANCE LEVEL 5

TQI	Prediction Equation*	R^2
Gage Roughness	$y_2 = -0.494 + 0.66\hat{y}_2 + 0.0067x_1 + 0.0099x_2 + 0.0005x_7$	0.87
Wide Gage Index	$y_3 = 24.18 + 0.49\hat{y}_3 + 0.0709x_1 + 0.0895x_2 + 0.0366x_4 + 0.0024x_7 + 0.0848x_8''$	0.88
Surface TQI	$y_7 = -2.50 + 0.33\hat{y}_7 + 0.040x_1 + 0.047x_2 + 0.0026x_7 + 0.117x_8''' - 0.127x_9$	0.76
Line TQI	$y_{13} = -253.4 + 0.17\hat{y}_{13} + 5.12x_1 + 5.49x_2 - 0.701x_3 + 2.33x_4 + 0.219x_7$	0.85
Superelevation TQI	$y_{14} = -15.1 + 0.35\hat{y}_{14} + 0.080x_1 + 0.123x_2 + 0.017x_3 + 0.078x_4 + 0.063x_5 - 0.55x_6 + 0.0055x_7$	0.88

* x_8''' is the ballast level 3, x_9 is the drainage condition and other symbols are the same as in Table 7-13.

this study (Section 4.0) probably are not distinct enough for track degradation observations. Different maintenance levels should, for example, be defined as: up to 25 percent maintenance as maintenance level 1, up to 50 percent maintenance as maintenance level 2, and above 75 percent as maintenance level 3.

7.6.2 PRODUCTION MAINTENANCE

Production maintenance is performed for the purpose of improving track condition. This will have the effect of resetting the value of the TQI's. The effect of production maintenance should be evaluated in terms of the change in a TQI as a result of the maintenance operation. Ideally this would require a track geometry survey just before and another just after the production maintenance.

As discussed earlier, track geometry surveys were conducted in the Fall of 1978 and the Fall of 1979. The production maintenance was mostly performed in the summer of 1979. If it is assumed that the production gangs follow set practices, it should be possible to estimate the track condition even some time after the maintenance operation. This will be a function of the initial value of a TQI and the track operation conditions. Therefore, regression was performed on maintenance level 4 and 5 to predict the new values of TQI's. The results are shown in Appendix H.

The prediction equations for maintenance levels 4 and 5 are given in Table 7-33 and 7-34. The R^2 value for most TQI's is still above 0.80. The previous value of a TQI is also shown to be the significant parameter in the prediction equations and the same is the case for tonnage and rail type.

Table 7-35 gives the mean value of TQI's in 1978 before the production maintenance was done. Notice that mean values of TQI's are not necessarily large as compared to the values given in Table 7-29. Furthermore, TQI values for maintenance level 6 are slightly lower than the values for maintenance levels 4 and 5. Discussions with CONRAIL indicated that a tie and surfacing operation is performed one year before rail renewal. This is probably the reason for lower TQI values for maintenance level 6.

Table 7-36 lists the changes in TQI's as a result of the production maintenance. The surface and superelevation TQI's shows track improvement for all maintenance

TABLE 7-35

MEAN VALUES* OF THE 1978 TQI'S BEFORE PRODUCTION MAINTENANCE

Maintenance Level \ TQI	Wide Gage Index	Gage Roughness	Surface TQI	Line TQI	Super-elevation TQI
Maintenance Level 4	57.09	0.17	0.34	58.0	0.57
Maintenance Level 5	57.14	0.17	0.44	59.0	0.48
Maintenance Level 6	56.93	0.13	0.33	45.0	0.28

*The line TQI is in thousands of an inch. All other TQI's are in inches.

levels. The change in gage and line TQI's is less obvious for maintenance levels 4 and 5. The wide gage index shows a significant improvement for maintenance level 6. In contrast, line condition actually shows a slight deterioration. This is believed to be due to the low initial value as explained in the previous paragraph.

Table 7-37 gives a comparison of different maintenance operations in terms of the degradation coefficients. As expected, the magnitudes of degradation coefficients for maintenance level 6 are significantly larger than the ones for other maintenance levels.

Maintenance levels 4 and 5 show little difference for gage, line and superelevation TQI's. The surface TQI indicates a larger improvement for maintenance levels 4 and 5. This is believed to be due to a large mean value for

TABLE 7-36

CHANGE* IN TQI'S AS A RESULT OF PRODUCTION MAINTENANCE

Maintenance Level \ TQI	Wide Gage Index	Gage Roughness	Surface TQI	Line TQI	Super-elevation TQI
Maintenance Level 4	-0.06	-0.01	-0.06	-7	-0.08
Maintenance Level 5	-0.05	-0.01	-0.05	-5	-0.08
Maintenance Level 6	-0.13	-0.01	-0.14	10	-0.08

*Values are in inches except for ones for the line TQI which are in thousands of an inch.

TABLE 7-37

DEGRADATION COEFFICIENTS FOR DIFFERENT LEVELS OF PRODUCTION MAINTENANCE

Maintenance Level \ TQI	Wide Gage Index	Gage Roughness	Surface TQI	Line TQI	Super-elevation TQI
Maintenance Level 4	-0.0010	-0.07	-0.17	-0.12	-0.15
Maintenance Level 5	-0.0008	-0.05	-0.11	-0.09	-0.16
Maintenance Level 6	-0.0022	0.07	-0.43	0.22	-0.30

maintenance level 5 as shown in Table 7-35. It should be pointed out that both the surface, and the tie and surface operations involve the same basic surfacing equipment* which raises, tamps, lines and sets the superelevation in curves. Therefore, both operations should have the same effect on the surface, line and superelevation TQI's.

Maintenance level 4 is performed by a high-speed surfacing gang which raises the track and, in some cases, checks for wide gage. On the other hand, maintenance level 5 includes a tie gang (before the surface gang) which replaces bad ties and actually resets the gage.

As discussed earlier, regression was not performed on maintenance level 6 since this maintenance operation involves rail renewal. For the test zone under study, this maintenance operation involved replacing the bolted rail with welded rail in a section of the Fort Wayne Division. The TQI's were plotted for both 1978 and 1979 to study the effects of rail renewal in more detail.

Figure 7-23 shows the effect of rail renewal on the wide gage index. As expected, most of the segments show an improvement in the wide gage index. This improvement in some cases is as large as 0.4 inch. The wide gage index for the new rail is below 56.9 inches for all segments. Two segments near milepost 202 show a larger value of the wide-gage index for the new rail as compared to the old rail. This may be due to the fact that the wide gage index for these segments was already below 56.65 inches for the old rail.

*Discussions with CONRAIL.

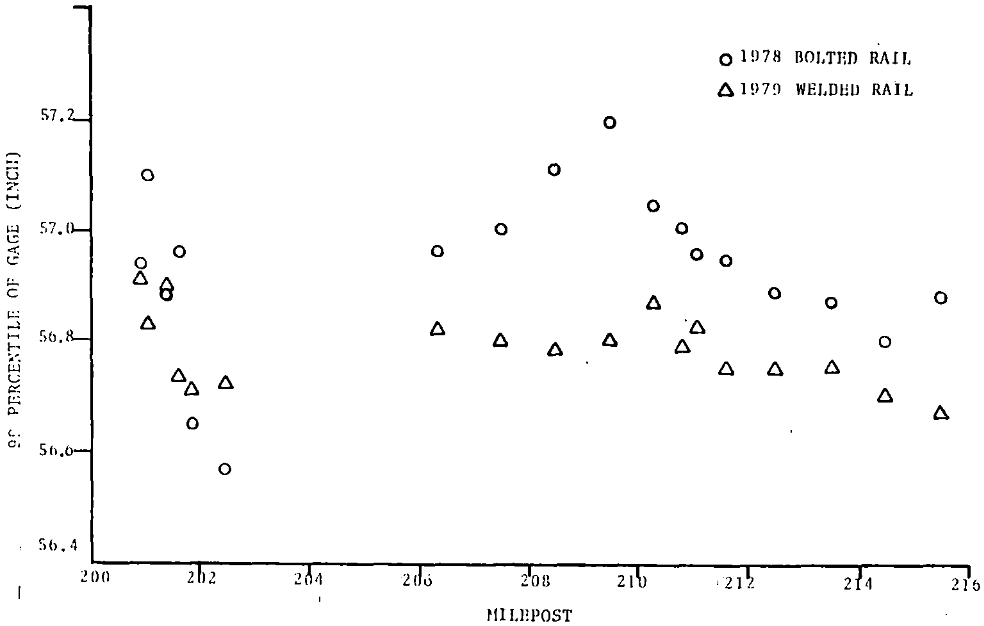


Figure 7-23. Effect of Rail Renewal on Wide Gage Index

Figure 7-24 shows the effect of rail renewal on gage roughness. The gage roughness for the new rail is mainly between 0.11 and 0.14 inch which is roughly equivalent to class 4 track. The gage roughness does not show the improvement in track condition for all the segments. This is because the gage roughness was already less than 0.14 inch for most of the segments. The gage roughness for the first three segments in Figure 7-24 is still between 0.16 and 0.20 inch, and two segments show deterioration compared to the previous values. No obvious cause could be found for this discrepancy.

The effect of rail renewal on the surface TQI is shown in Figure 7-25. The surface condition shows improvement for all track segments. The surface TQI for the new rail is mainly between 0.12

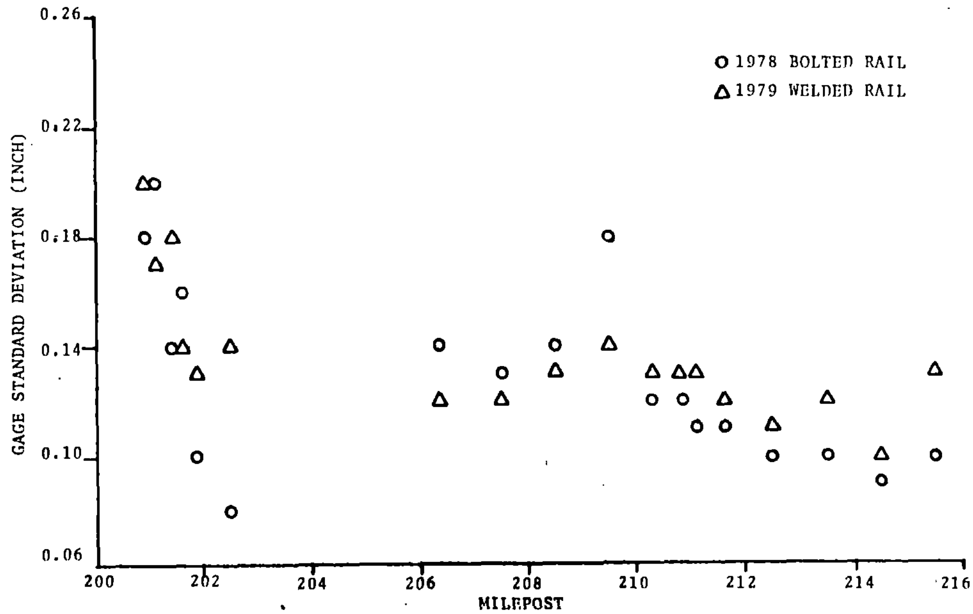


Figure 7-24. Effect of Rail Renewal on Gage Roughness

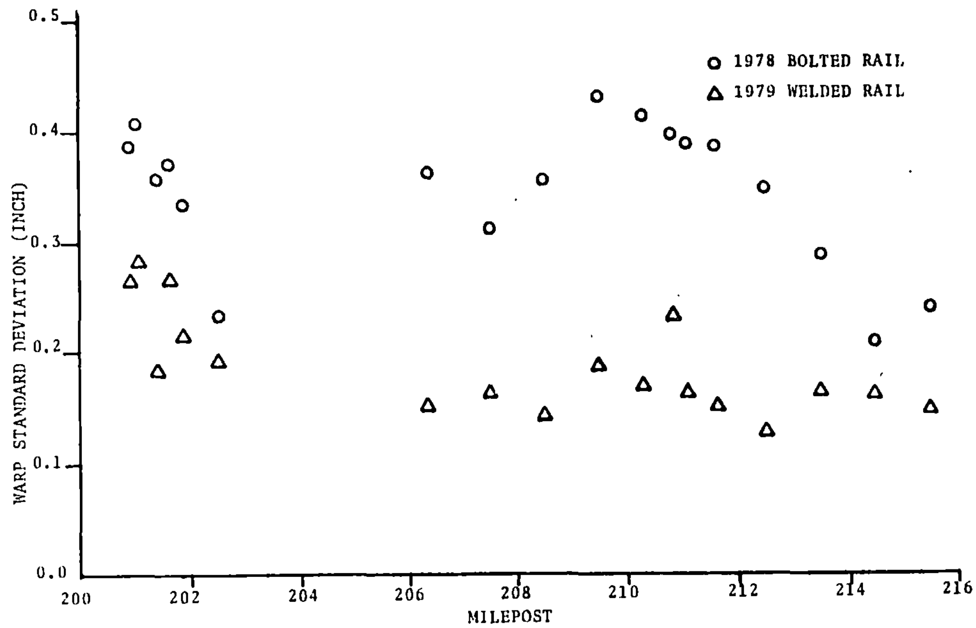


Figure 7-25. Effect of Rail Renewal on the Surface TQI

to 0.20 inch, which is approximately equivalent to class 5 or 4 track. This TQI shows an improvement of up to 0.25 inch over its previous values.

Figure 7-26 shows the effect of rail renewal on the line TQI. As discussed earlier, the line condition of the track did not show improvement as a result of the rail renewal. Figure 7-27 shows the values of the superelevation TQI for the old and the new rail. This TQI shows an improvement for all track segments and this improvement in some cases is as large as 0.21 inch.

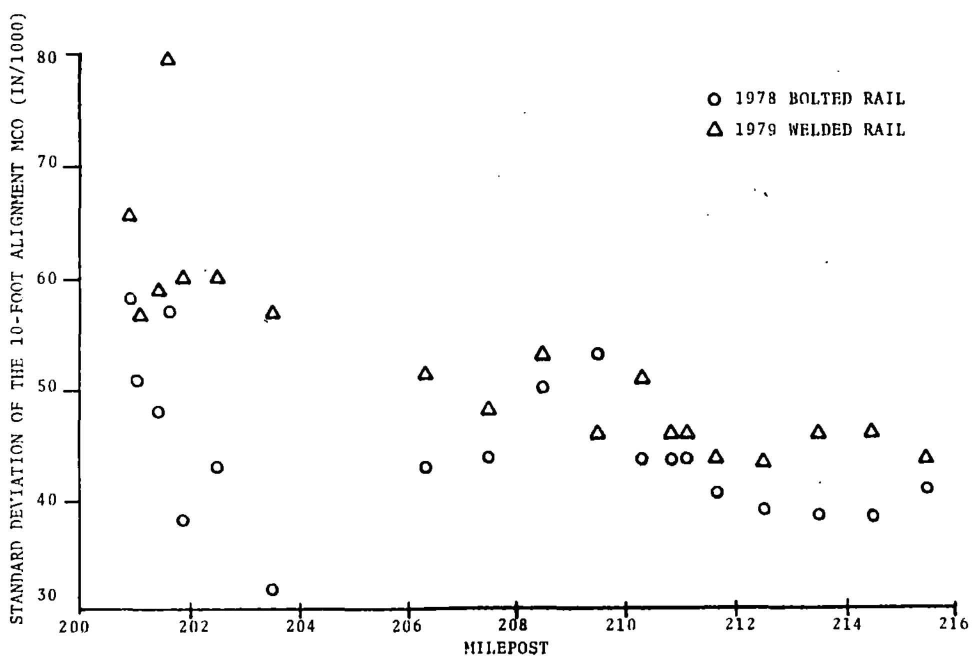


Figure 7-26. Effect of Rail Renewal on the Line TQI

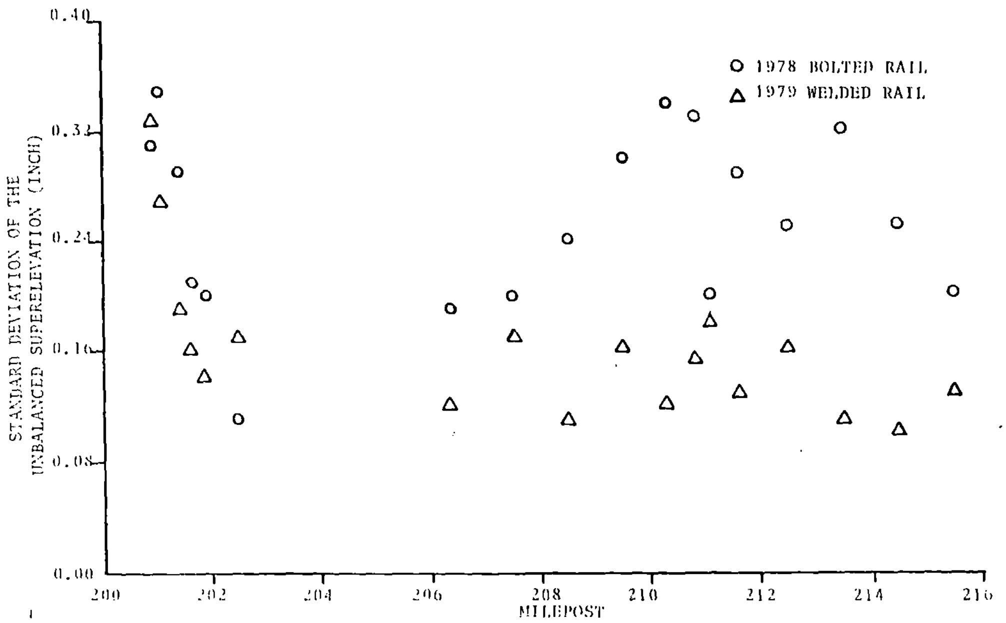


Figure 7-27. Effect of Rail Renewal on the Superelevation TQI

This section has shown the effects of basic and production maintenance on track degradation or improvement. An interesting observation was made during the analyses of different maintenance levels, i.e., the correlation coefficient between the TQI values of two observation periods (r') might be indicative of the type of the maintenance operation performed during this time. Table 7-38 lists the correlation coefficients between the 1978 and 1979 TQI values for different maintenance levels. As expected, the value of correlation coefficients decreases as the level of the production maintenance increases for all the TQI's except the line TQI. Differences in maintenance levels 4 and 5 are less obvious for the line TQI. The surface TQI shows a consistent decrease for all maintenance levels from 0 through 6. Thus the r' values for the surface TQI can differentiate between all maintenance operations performed on the track. The r' values for other TQI's can differentiate between different levels of production maintenance.

TABLE 7-38

CORRELATION COEFFICIENTS BETWEEN THE 1978 AND 1979 TQI VALUES FOR DIFFERENT MAINTENANCE LEVELS

Maintenance Level \ TQI	Wide Gage Index	Gage Roughness	Surface TQI	Line TQI	Superelevation TQI
0	0.95	0.94	0.89	0.85	0.98
1	0.79	0.91	0.88	0.07	0.68
2	0.94	0.86	0.85	0.57	0.94
3	0.89	0.93	0.78	0.72	0.96
4	0.97	0.94	0.68	0.67	0.83
5	0.95	0.92	0.62	0.72	0.82
6	0.58	0.66	0.20	0.42	0.86

8.0 CONCLUSIONS AND RECOMMENDATIONS

The findings and conclusions of this study are based on a one-year effort. Although these findings are accurate and consistent within this context, consideration must be given when extrapolating to other conditions. The test zone consisted of two separate sub-test zones in the Fort Wayne and Lehigh Divisions. One hundred seventy six (176) miles of double main line track (mainly Class 3 and 4) were located in the Fort Wayne Division and one hundred twelve (112) miles of single and double mainline track (mainly Class 2 and 3) were located in the Lehigh Division. Track in the Fort Wayne Division was for the most part tangent with negligible grade. In contrast, track in the Lehigh Division contained numerous curves, compound and reverse, up to 12 degrees with considerable grade. On completion of data collection it was found that the gross annual tonnage in the Fort Wayne test zone ranged between 18 and 25 MGT while in the Lehigh Division this was less than 14 MGT. Also axle loading, referred to as heavy wheels, was consistently less in the Fort Wayne Division than in the Lehigh Division. Both sub-test zones consisted primarily of bolted rail and during the period of study 70 percent of the track underwent some form of basic or production maintenance.

Before summarizing the findings concerning the relationship between TQI's and physical parameters, a brief recap of the TQI concept is useful. A TQI is based on one of the basic track geometry measurements, gage, alignment, profile and crosslevel. Warp which is derived from crosslevel was also used. These measurements are made by automatic track inspection vehicles which can generate a staggering amount of data. For example, the FRA track inspection vehicles make measurements of these seven geometry parameters at one-foot intervals at speeds up to 80 mph. In a single day one of these cars thus generate more than ten million individual data points. This is an overwhelming amount of information and, therefore, a means of condensing this data without losing too much detail is required. That is exactly what a TQI is designed to do. For example, the surface condition of a mile of track, which is made up of 10,560 individual measurements (5,280 feet times two rails) is reduced to a single number or figure of merit. If the surface is smooth the TQI is small and if the surface is rough the TQI is large.

8.1 CONCLUSIONS

This study has shown the feasibility of using automated track geometry cars along with other track related data for long-range track maintenance planning. First, it has been shown that TQI's appear to effectively quantify the ability of the track to carry out its functional requirements. Put more simply, a Track Quality Index (TQI) is an objective measure of track condition. Second, it has been found that there exist well defined relationships between TQI's and certain physical parameters (such as cumulative tonnage) which affect track condition. This is not surprising in light of the first general conclusion since track condition is dependent on such things as tonnage, rail weight and ballast condition. More specific conclusions are given below.

Track Quality Indices (TQI's) were shown to possess a certain characteristic relationship with both the six classes of track defined in the Federal Track Safety Standards and ride quality. Thus, TQI's may serve railroad engineering personnel in a number of useful ways. For example, through the use of a TQI, the condition of up to one hundred miles of track can be accurately summarized in a clear graphic format on a single 8-1/2 by 11 sheet of paper. Knowing the expected value of a given track class, engineering personnel responsible for allocating maintenance-of-way resources can easily identify those areas of track which may soon require work to remain within posted class standards. Furthermore, a TQI gives a continuous reading of track condition; whereas, the Federal track class only specifies six levels of condition. That is, two pieces of track may pass all criteria of Class 4 track, but one may be very nearly Class 3 while the other may even pass Class 5 standards. A TQI has the ability to differentiate between these two conditions and thus, resources will be directed to those areas in which they are most needed.

Knowledge of the relationship between ride quality and TQI's will be of similar value. For instance, by knowing the condition of track, timetable speeds may be determined which allow safe shipment of manufactured goods. Conversely, the cost of increasing timetable speeds may be derived knowing the cost of maintenance. This information can then be used as an aid to justify increases in freight charges in the event of rail deregulation.

TQI's offer an additional potential use in the quality assurance of production maintenance. By comparing TQI's measured before and after a certain production gang has performed a given operation, a quantitative evaluation of the quality of work may be made. This method could be used to evaluate different gangs, different approaches to a given operation, or different materials and machinery.

TQI's have been found to correlate with track related derailments. That is, those segments of track for which derailments were reported possessed values of TQI's above the expected posted class value. However, it must be kept in mind that derailments, even track related, are complex situations. Many trains pass over the derailment site even on the day of the derailment while other segements may possess equal or higher TQI values and have not as yet experienced a derailment. Thus, a TQI is not a derailment predictor. However, it is a very useful guide in assessing the overall safety environment.

A set of fourteen candidate TQI's was investigated in this study. The line TQI's in the original set of candidate TQI's did not show adequate dependence on physical parameters. Therefore, two new TQI's, the standard deviation of 10-foot MCO of alignment, and the standard deviation of 16-foot MCO of alignment were included in the candidate set. The new line TQI's showed better results than the old line TQI's.

Correlation analysis among TQI's showed that indices based on the same track geometry parameter were highly correlated. That is, the information conveyed by an index based on a given track geometry parameter is nearly identical to any other index based on the same geometry parameter.

A final set of five TQI's was selected based on (1) their correlation with safe and economic operation, and (2) the ability to account for changes in the track condition. This set of five TQI's is listed in Table 8-1. As mentioned previously, only one line index is included. However, two indices were selected from the gage family to account for both economics and safety. Two indices were included from the surface family because of the low correlation

TABLE 8-1

FINAL SET OF TRACK QUALITY INDICES

Name	Definition
Wide Gage Index	Ninety-Ninth Percentile of Gage
Gage Roughness Index	Standard Deviation of Gage
Surface Index	Standard Deviation of 20-Foot Warp
Line Index	Standard Deviation of Alignment 10-Foot MCO
Superelevation Index	Standard Deviation of Unbalanced Superelevation

between the surface indices and the superelevation index. For the unmaintained track, the physical parameters considered in this study accounted for at least 80 percent of the changes in TQI's over the study period. This was also generally true for other maintenance levels. In a number of cases, more than 90 percent of the changes in the TQI's were explained by the physical parameters.

For each maintenance level, one of the major results of this study is a set of five equations which in effect enable the projection of track condition. For example, if a railroad engineer desired to project the surface condition of a newly worked section of track which is well within the posted standard, he could do so by substituting the present value of the surface TQI (or alternatively the expected class value) and the appropriate value of anticipated gross annual tonnage, rail type, etc. The result would then tell him to within 80 to 90 percent what the surface index or condition will be like one year in the future with 99.9 percent confidence. Based on other considerations such as long-range plans, corporate operating policy, budget and resources, in addition to the projected track condition he could then make the appropriate decision as to what if any maintenance should be performed.

Another use of this ability to project condition would be in maintenance-of-way funding justification. An engineer using this method of projection would be able to demonstrate that in order to operate at a predesignated level (class, speed, tonnage, etc.) what maintenance must be performed. In other words, the projections show quantitatively in terms that an accountant should be able to understand what the consequences of deferred maintenance are.

A number of specific observations were made which should add to the overall improvement of the understanding of maintenance-of-way planning. First, it was found that the most important parameter or factor affecting the future condition of track is the present condition of track. In fact, this study has shown that the present condition of the track accounts for 50 percent or more of any change. It was further found that for the surface TQI poor track condition degrades faster than good track condition.

Additionally, it was found that tonnage and rail type are the next most important of the parameters investigated in accounting for track degradation. It was clear that bolted rail degrades faster than does welded rail. In the test zone studied bolted rail degraded approximately four times faster than welded rail. It should, however, be pointed out that the bolted rail was considerably older than was the welded. In fact, the surface index indicated that for the traffic levels studied (above 10 MGT) bolted rail degraded one track class during this one year study. Again, the rail age may have influenced this observation to some degree.

8.2 RECOMMENDATIONS

The present study has generated a great deal of insight into the use of automatic track inspection vehicles in maintenance-of-way planning and as a result a large number of positive and conclusive findings were made. However, as with any work of this nature, as many questions are raised as answers found. Therefore, the following recommendations are made.

During the period of time that this investigation was carried out the gage and line condition as measured by their respective TQI's did not degrade significantly. There is a need for further data to provide a firmer base for gage and line condition projection. For this reason it is recommendea that a track geometry survey of the test zone be conducted during calendar year 1980. This will provide much needed verfication of the present findings for all TQI's.

Also during this study a significant portion (70 percent) of the test zone underwent basic or production maintenance. Thus, there were less than 100 miles of unmaintained track from which "pure" degradation curves could be derived. Furthermore, each level and type of maintenance was similarly restricted. It is, therefore, recommended that the test zone be expanded in future studies in order to provide a broader data base from which the degradation curves can be obtained.

During this study the philosophy of partitioning the test zone into homogeneous segments resulted in variable segment lengths. In fact, each track survey resulted in a resegmenting of the test zone which meant all previous surveys had to be likewise resegmented in order to carry out the study. The concept of homogeneous segments was adopted for this program to answer such questions as what is the effect of curvature on a gage index. It would be advisable to reexamine what sort of segmenting concept should be used in future work. It should be remembered that in actual implementation segmentation must be practical as well as accurate. For this reason most studies in maintenance-of-way planning have or are using fixed length/location segments.

Even though the predictive equations established in this study were able to account for at least 80 percent of the change in track condition, some improvement in accuracy may be obtained through the use of other physical parameters known to affect track condition. These include tie condition, rail age, ballast type, rail head profile and potentially others. In particular ballast and drainage condition, which were used as a substitute for track stiffness or modulus, were not found to be entirely satisfactory. Their measure was highly subjective and their role in track degradation not well defined. Therefore, in future work it would be desirable to use either a track modulus measurement if available and practical or some other alternative parameters. In addition, it was determined that different levels of basic maintenance should be adopted for observing track degradation.

There exists fundamental differences between basic and production maintenance. Production maintenance represents a more complete reconditioning of the track which is abrupt. Basic maintenance in contrast is more localized typically affecting less than a few hundred feet of track. The effect of basic maintenance on overall track condition is less pronounced. Thus, in the future study of maintenance-of-way it would be desirable to separate these two types of operation. For the study of production maintenance, special track geometry surveys should be made immediately before and after production maintenance.

APPENDIX A

MEASUREMENT SYSTEM

A.1 GENERAL

The capabilities of the FRA track-geometry survey vehicles T-6, T-1/T-3, T-2/T-4 and two commercial track geometry survey vehicles were investigated to select an appropriate track-geometry survey vehicle for the long-range track maintenance planning program. This appendix contains the results of the survey-car comparison and a detailed description of the selected track-geometry measurement vehicle.

A.2 TRACK GEOMETRY MEASUREMENT CAR COMPARISON

Data were compiled under an FRA study on the feasibility of the National Track Inspection Program. Tables were produced that compared the capabilities of many existing track geometry measurement vehicles. Track geometry and reference parameters (gage, alignment, curvature, profile, crosslevel, superelevation, warp/twist, runoff and location detection) were reviewed as to whether or not they were measured and what type of instrumentation was used for the measurements. As a result of preliminary analysis, the T-6, T-2/T-4, T-1/T-3, the Matisa M-422 and the Plasser EM80 vehicles were selected for final comparison as to their capabilities for MOW applications.

Table A-1 summarizes the general characteristics of these five measurement vehicles. All five measurement vehicles have similar capabilities except that T-6 is the only vehicle that measures rail alignment. It should be noted that the Matisa and Plasser cars measure warp while the FRA survey cars treat warp as a parameter derived from crosslevel. Both the Matisa and the Plasser survey vehicles are self-propelled but their maximum recording speed is approximately 50 mph. T-6, T-1/T-3, and T-2/T-4 can measure track geometry at speeds up to 120 mph.

It was decided to use a FRA survey car rather than the Matisa or Plasser cars due to the following reasons. Since ENSCO operates the FRA vehicles, scheduling tests and interpreting data required much less effort if a FRA survey car was used. In addition, software had already been developed to compute track geometry parameters and to generate the Track Standards Exception Report. The T-6 survey car was selected over T-1/T-3 and T-2/T-4 because of its additional capability for measuring rail alignment and profile at low speeds. In addition, T-6 has higher system resolution as documented in ENSCO

TABLE A-1

MEASUREMENT CAR CAPABILITIES

	T_3	T_2	T_6	Matisa M-422*	Plasser EM80**
Weight	50 Tons	50 Tons	80 Tons	25 Tons	34 Tons
Maximum Speed	120 mph	120 mph	120 mph	50 mph	55 mph
Output Format	Strip Chart Mag Tape	Strip Chart Mag Tape	Strip Chart Mag Tape	Strip Chart Mag Tape	Strip Chart Mag Tape
Sample	One Foot	One Foot	One Foot	Analog 10 sec (Speed Dependent)	Analog
Profile	62-Foot Chord ≥ 20 mph	62-Foot Chord ≥ 20 mph	62-Foot Chord	28.8-Foot Chord	62-Foot Chord
Alignment			62-Foot Chord		
Crosslevel	21-Foot Warp	31-Foot Warp	31-Foot Warp	19.7-Foot Warp	8-Foot, 10-Inch
Curvature	Detection 59.5 Foot Average	Detection 59.5 Foot Average	Detection 59.5 Foot Average	32.8-Foot Versine	32.8-Foot Versine
Gage	Magnetic	Magnetic	Magnetic	Yes (Feeler Roller)	Yes (Wheel Contact)
Options				Track Analyzer Exception Count Quality Coef for Segments Magnetic Recorder	Magnetic Recorder
Other				Self-propelled Gage thru Applicances	Self-propelled Gage thru Appliances

*Technical Description, Matisa Track Recording Railcar Type M-422, June 1975.
**Plasser EM 80c/110c Track Measuring Car, Plasser American Corporation (no date).

Report DOT-FR-79-02. Results of a repeatability study on the T-6 survey car are included in Section A.3 of this appendix.

A.3 T-6 MEASUREMENT SYSTEM

Built in 1953 by the St. Louis Car Company, T-6 was obtained by FRA in 1975 along with several other surplus Army ambulance cars. It was decided to convert it to a track geometry measurement vehicle with the most up-to-date instrumentation. At this time there were two other FRA track geometry measurement consists, T-1/T-3 and T-2/T-4. T-3 and T-2 are instrumented vehicles while T-1 and T-4 provide crew support facilities and spare parts storage.

The T-6 vehicle's general specifications are as follows:

- Total length - 85 feet
- Width - 10 feet
- Height - 13-1/3 feet
- Weight - 80 tons (20 tons/axle)
- Truck spacing - 59-1/2 feet
- Axle spacing - 8 feet
- Wheel diameter - 3 feet

The advanced electronic sensing and data processing systems onboard T-6 are capable of measuring track geometry at speeds up to 120 miles per hour. The instrumentation in the consist provides raw measurements of track geometry in the form of continuous analog signals. Data processing provides real-time, onboard computation and analog strip-chart reports of computed data and, if necessary, raw data. The data tapes are processed off-line on a digital computer using software programs that compute track geometry values.

A.3.1 SYSTEM CONCEPT

The major subsystems and the signal paths of the T-6 track geometry measurement system are shown in Figure A-1. Each subsystem is configured to measure, record and display the following track geometry and reference parameters:

- Profile
- Alignment
- Gage
- Crosslevel
- Curvature
- Location
- Speed and Distance

The data acquisition system converts the signal to a digital format in real time and records the digital data on magnetic tape for off-line processing. The data acquisition system also computes track-geometry parameters from raw data

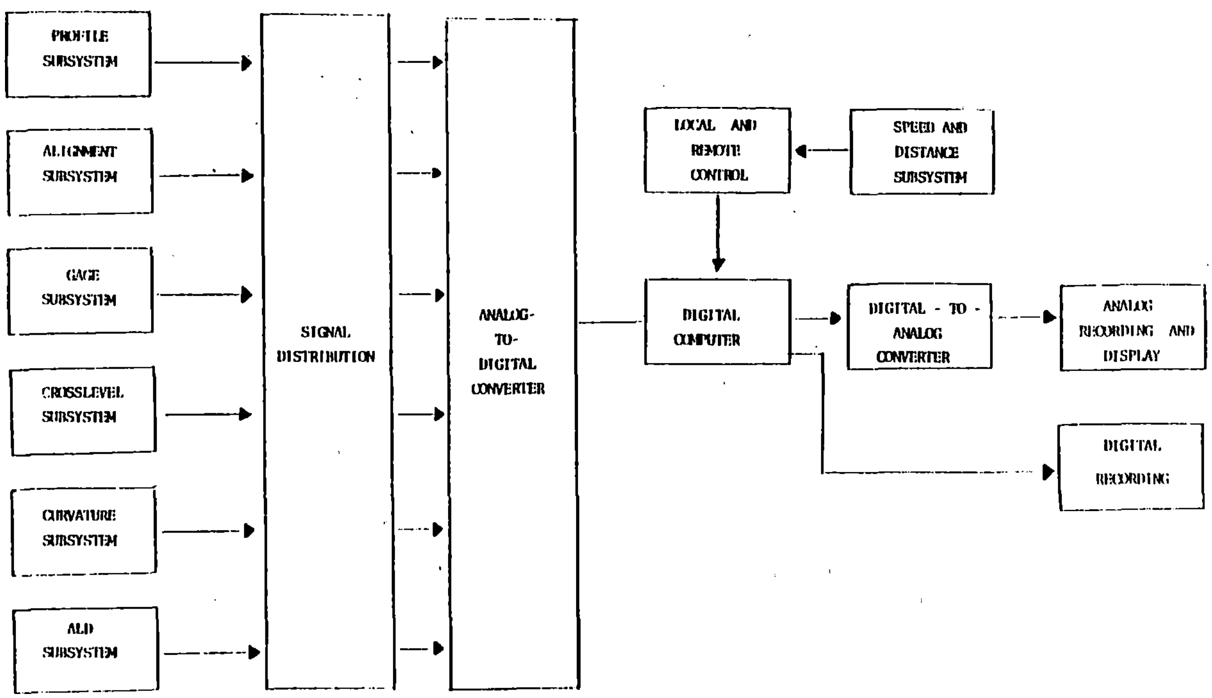


Figure A-1. Track Geometry Measurement System-Block Diagram

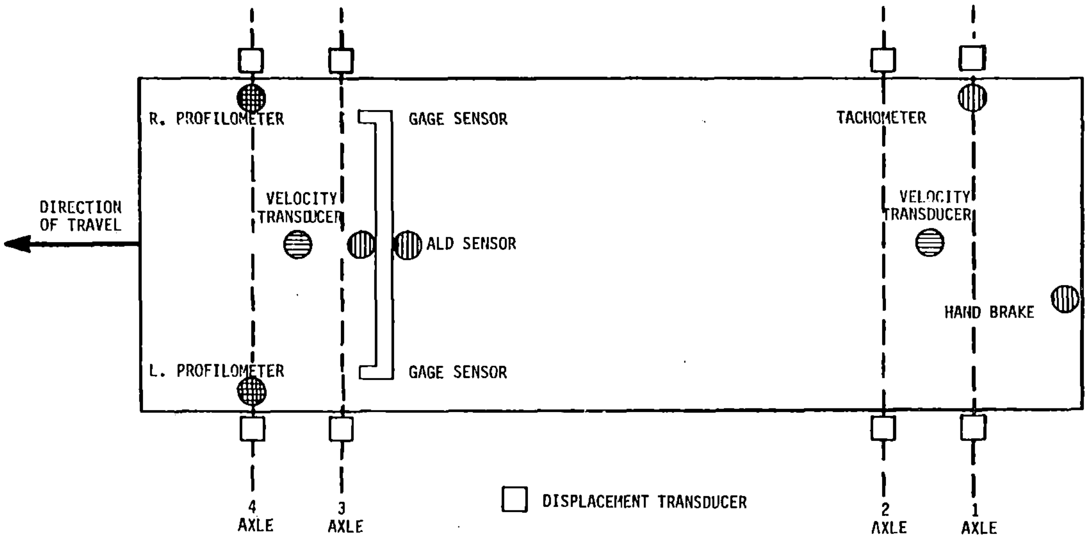


Figure A-2. T-6 Instrumentation - Block Diagram

and converts them to analog signals for real-time visual display on a strip-chart recorder. The sensors and associated electronics in the track-geometry-measurement subsystems are described in the following paragraphs. The layout of the coordinate reference system is shown in Figure A-2.

A.3.1.1 Profile Subsystem

Profile variation in each rail is measured and displayed as the vertical coordinate of a 62-foot chord, referred to as a mid-chord offset (MCO). There are two systems used to measure profile on T-6, a high-speed inertial reference system and a low-speed profile system.

The inertial reference system uses two profilometers mounted directly over axle No. 4 on each side of T-6. The profilometer consists of a mass which is attached to a wheel (axle) of the test car through a spring and damper assembly. The mass is restricted in movement to the vertical plane by low-friction guides. An accelerometer is attached to the mass and a linear-variable-differential-transformer type displacement transducer (LVDT) is connected between the mass and the wheel (axle).

As the vehicle moves along a track, the mass acts as an inertial reference in the vertical plane. Vertical displacements of the rail act as inputs to the profilometer, and are measured directly by the displacement transducer. At low speeds, low-frequency inputs (which fall below the natural frequency of the profilometer) are measured by double integration of the output of the accelerometer and added to the output of the displacement transducer.

Due to the limitations on T-6, the profilometer transducers are mounted outboard of the wheels. Thus, the points of measurement (Z_L and Z_R) are offsets from the actual locations (Z_{LT} and Z_{RT}) of the transducers (Figure A-3). The offset is corrected by compensation circuits which consist of operational amplifiers with gain characteristics which provide the required gain and signal. Either left or right profile is amplified to yield profile output from which the 62-foot mid-chord offset is computed.

In order to maintain a capability for measuring profile while stationary or traveling at very low speed (below 25 mph), a low-speed profile system is included on T-6. The carbody is used as a reference beam in this system. Vertical motions of each of the eight wheels (relative to the carbody) are measured by displacement transducers. The eight-point measurements are combined in software to form a 16-foot MCO and displayed as a 62-foot MCO.

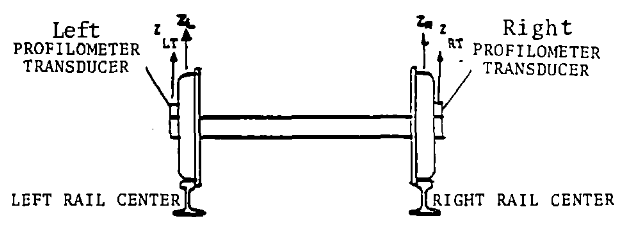


Figure A-3. Location of Profilometers

A.3.1.2 Alignment Subsystem

The alignment variation of each rail is displayed as the lateral coordinate of a 62-foot MCO. The inertial alignment system uses a servo-accelerometer (alignometer), the two sensors used to measure gage, and the crosslevel measurement system. The alignometer is soft-mounted laterally on the gage beam so that its sensitive axis is parallel to the gage direction. Soft-mounting is provided to protect the accelerometer from damaging vertical shocks.

The output from the sensor measures the inertial lateral movement of the truck. This signal is then processed in software and converted to a two-foot-chord which describes the path travelled by the truck. The signal then has the appropriate compensation signals applied and the resultant signal is referenced back to each rail using the gage sensor signals.

A.3.1.3 Gage Subsystem

Track gage is measured between the rails at right angles to the rails in a plane five-eighths of an inch below the top of the railhead. The gage measurement subsystem uses two servo-positioned magnetic sensors to detect changes in gage. These non-contact sensors are located on a cantilevered beam behind the trailing axle of the A-truck facing directly toward the gage side of the railhead.

As gage varies or the truck moves laterally, a feedback servo-control system maintains a 1/2-inch, sensor-face-to-rail gap. The position of the magnetic sensor with respect to the truck is measured using a linear displacement transducer (LDT). This position signal combined with any remaining error signal yields a relative gage signal for the respective side of the truck. Adding the outputs of the two LDT's to the known distance between them produces the gage measurements.

Since the magnetic sensor is servo-controlled, it will not always be riding within the clearance profile created by the flange of the wheel. Whenever the sensor moves away from the protection of the flange, it may be damaged by highway crossings, railroad crossings and frogs. To minimize possible damage to the sensor arm assemblies, the sensor can be retracted or moved to the protected position within the clearance profile of the flange by the operator. The sensor system has three operating modes:

- RETRACT - The sensors are in the raised position to avoid obstacles in the roadbed, to prevent damage to the sensors by contact with road crossings, frogs, or other track features or to allow sensor adjustment or replacement. This position is used for maximum sensor protection during non-operating periods.
- ACTIVATE - The sensors are in their normal operational position.
- WITHDRAW LEFT AND/OR RIGHT - The sensors are in a protected position in the shadow of the wheel flange (Figure A-4).

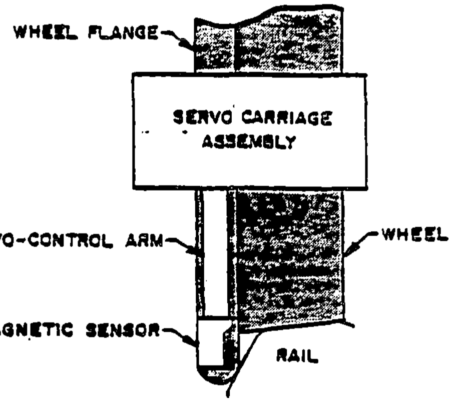


Figure A-4. Sensor Arm in Protected Position of the Wheel Flange

A.3.1.4 Crosslevel Subsystem

Crosslevel of the track is measured as the different in elevation between the rail on a line normal to the track centerline. The crosslevel measurement subsystem is composed of three sensors mounted at specific locations on T-6 (Figure A-5). These consist of a

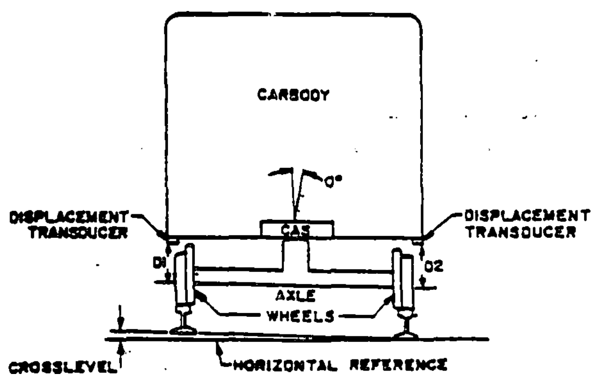


Figure A-5. Crosslevel Measurement System vertical reference sensor (CAS) and two displacement transducers. The CAS assembly consists of an inclinometer, and a roll rate gyro which is mounted on the floor of the carbody directly over the instrumented truck. This sensor is used to determine the roll angle of the carbody with respect to the vertical direction. The two displacement transducers are mounted underneath each side of the carbody over the No. 3 axle to measure the angle between the carbody and the truck. This system compensates for lateral acceleration errors by using a yaw rate gyro, two velocity transducers and a tachometer. Crosslevel is computed by adding the carbody roll angle to the carbody-to-axle angle.

A.3.1.4.1 Warp Measurement

Warp is the difference in crosslevel between any two sample points up to 62 feet apart in tangent track and curves, and not more than 31 feet apart in spirals. It is a measure of the variation of the horizontal plane of the track over these selected chord lengths. Warp, which is the spatial rate of change in crosslevel, is calculated during off-line processing.

A.3.1.5 Track Curvature Subsystem

The basis for track curvature measurement is the number of degrees of central angle subtended by a 100-foot chord. (Figure A-6). The principle elements of this subsystem include a carbody-mounted, yaw-rate gyro and two velocity transducers, one mounted on each truck. The rate gyro is placed in the center of the car and produces a signal which is proportional to the rate of carbody rotation about its vertical axis including rotation caused by track curvature. The two velocity transducers measure the yaw caused by yaw motions of the carbody relative to the tracks.

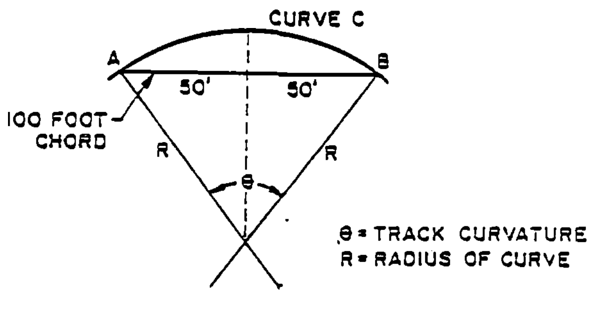


Figure A-6. Definition of Track Curvature

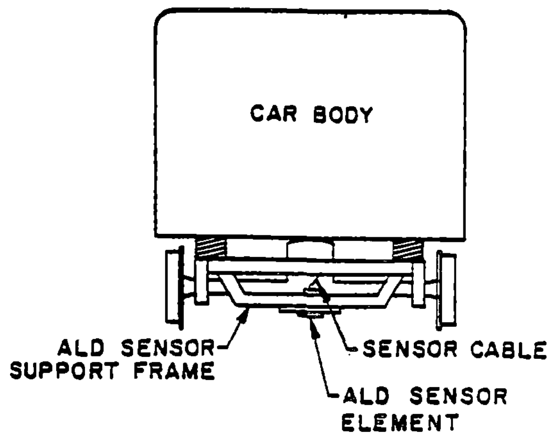


Figure A-7. Location of ALD Sensor

Curvature measurement is obtained by subtracting the velocity transducer signal from the rate gyro signal. The corrected output of the curvature system, therefore, represents a curvature measurement derived from truck paths.

A.3.1.6 Automatic Location Detection (ALD)

The ALD system detects and locates known anomalies (turnouts, road crossings, etc.) and random anomalies. A non-contact capacitive ALD sensor is mounted below the test car on the gage beam behind axle No. 3. It faces the roadbed between the rails and detects the proximity of metallic objects over which it passes (Figure A-7). The sensor consists of a 1/8 by 4 by 7-inch fiberglass board that is copper clad on the exposed side to form one plate of a capacitor. The other plate of the capacitor is the roadbed. As the train moves along a track, a metallic object causes the capacitance between the sensor and the ground to change abruptly. This change in capacitance produces a signal voltage proportional to the height, size and composition of the object.

A.3.1.7 Speed and Distance

The speed and distance subsystem provides distance-based, computer sampling, and computation and recording of track geometry data. An optical tachometer is driven off the right side of axle No. 1 through a belt and pulley assembly. During each revolution of the wheel, the tachometer produces 1000 pulses. The pulses are counted over a fixed time interval by the speed and distance processor to provide the sample rate in the computer, the drive signal to the paper feed in the data display charts, instantaneous speed, and total distance

TABLE A-2

REPEATABILITY FROM T-6 DATA
(Inches)

Speed / Parameter	15 Mph		25 Mph		35 Mph		45 Mph		55 Mph		FRA Standards	
	Mean	St.Dev	Mean	St.Dev	Mean	St.Dev	Mean	St.Dev.	Mean	St.Dev	Mean	St.Dev
Profilometer	0.000	0.084	0.000	0.049	0.000	0.060	0.000	0.030	0.000	0.030	0.26	0.52
Low-Speed Profile	0.000	0.013	0.000	0.013	0.000	0.013	0.000	0.011	0.000	0.014	0.26	0.52
Alignment	0.065	0.200	0.018	0.145	0.022	0.178	-0.003	0.063	0.027	0.045	0.26	0.57
Gage	0.008	0.014	0.005	0.012	-0.024	0.019	0.037	0.010	0.010	0.011	0.08	0.15
Crosslevel	-0.001	0.012	0.003	0.009	-0.009	0.013	-0.001	0.010	0.002	0.010	0.24	0.48
Warp*	-0.001	0.017	0.004	0.013	-0.013	0.018	-0.001	0.014	0.003	0.014		
Curvature	0.002	0.077	0.002	0.049	0.002	0.045	0.002	0.063	0.022	0.050	0.26	1.20

*Warp repeatability is equal to the rms of two crosslevel measurements.

travelled. A relative time clock is used in conjunction with the tachometer to compute the speed of the vehicle.

A.3.1.8 Digital Processing System

The digital processing and recording system is centered around a Raytheon RDS-500 central processing unit with 65K words of directly addressable memory. The peripheral units consist of a 385K-word, fixed-head disk drive, two 9-track, tape drives, an ASR-33 teletype, a 32-channel A/D converter, a 16-channel D/A converter, an electrostatic printer and a control console.

The data collection and processing functions performed by the computer are controlled through the Control Console.

The software performs the following operations during a survey:

- Records sensor data on magnetic tape.
- Displays all processed data on three distance-based strip charts.
- Handles the interfacing of operator commands and sensor operation at the computer.

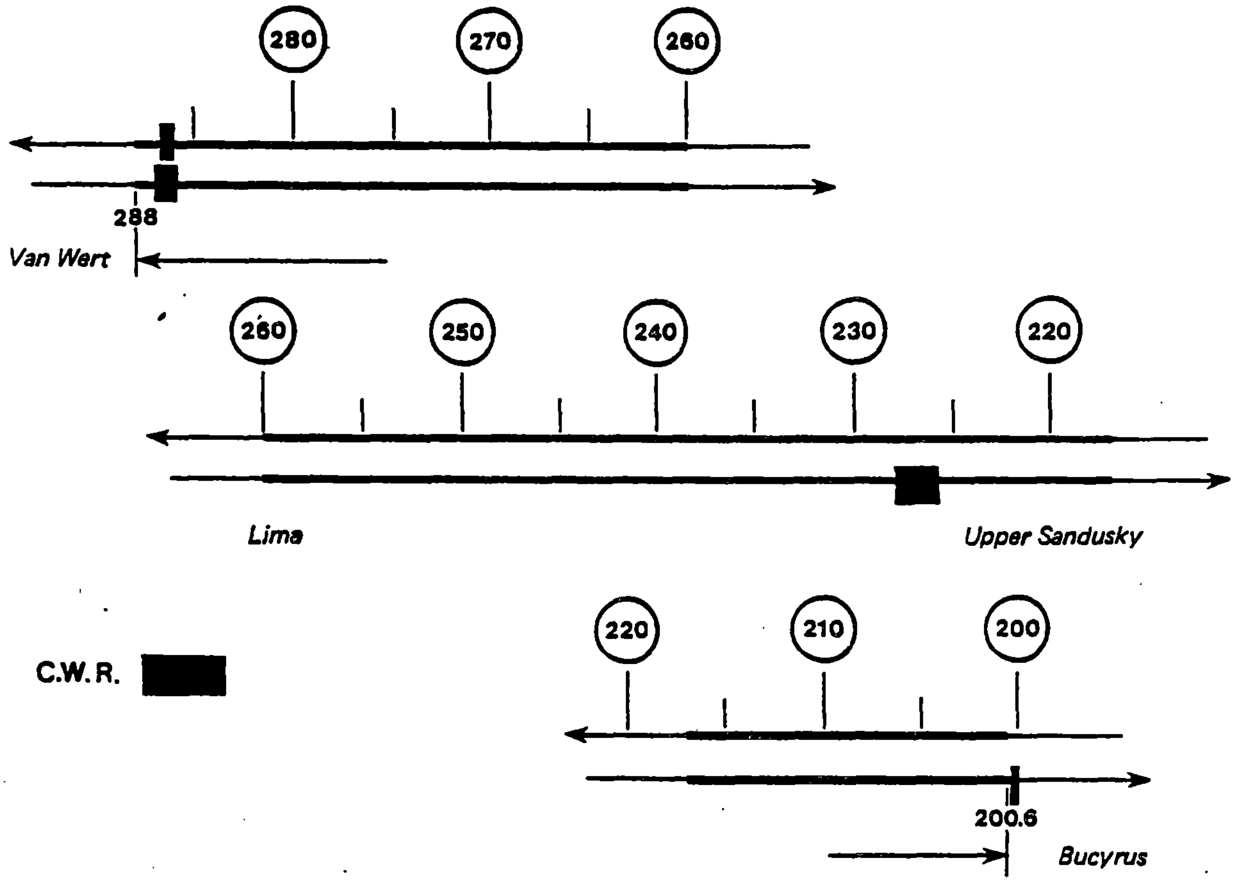
A.4 T-6 REPEATABILITY STUDY

In the study of track degradation, it is of fundamental importance that the track geometry measurement system be accurate and repeatable. In fact the requirement of repeatability is more important for this study than accuracy. This is because it is the change in track geometry, i.e. track condition, that must be measured over a period of one year. This change in track condition is relatively small. If the track geometry measurement system is sufficiently repeatable, then errors will cancel resulting in an accurate measure of the change in track condition.

A repeatability test of the T-6 measurement system was conducted in February 1978. Two surveys over the same track for various speeds were statistically processed to provide the mean or average value and the standard deviation of the measured track geometry parameters. Differences in the statistical values of the two surveys at each speed are listed in Table A-2 for 10 mph increments from 15 mph to 55 mph. The right-hand column of this table lists the FRA acceptance standards for the parameters.

A review of the table indicates that the mean and standard deviation of the parameters, in general, are not significantly effected by changes in speed. However, the profilometer and alignment systems are much more repeatable, in a relative manner, at speeds above 35 mph. This is due to the instrumentation of the profilometer and alignment inertial reference systems, as discussed in A.3. It should be emphasized that for all measurement systems at all speeds the repeatability information is well within the FRA acceptance criteria.

APPENDIX B
TRACK CHARTS



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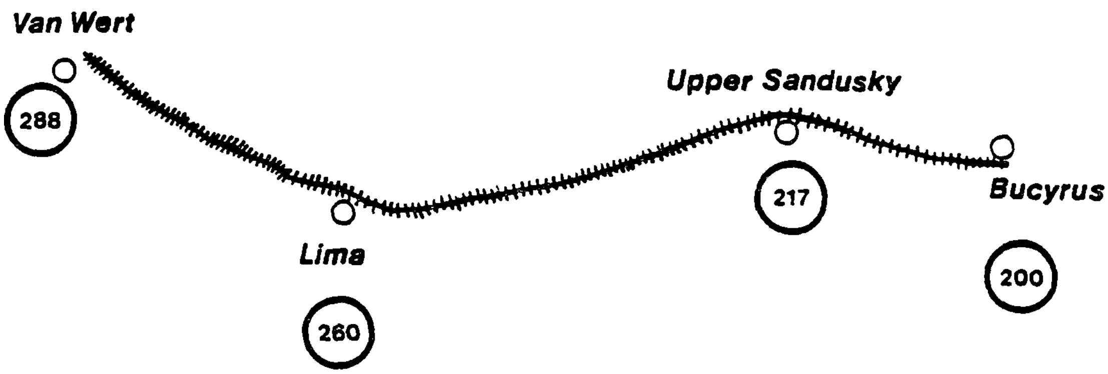
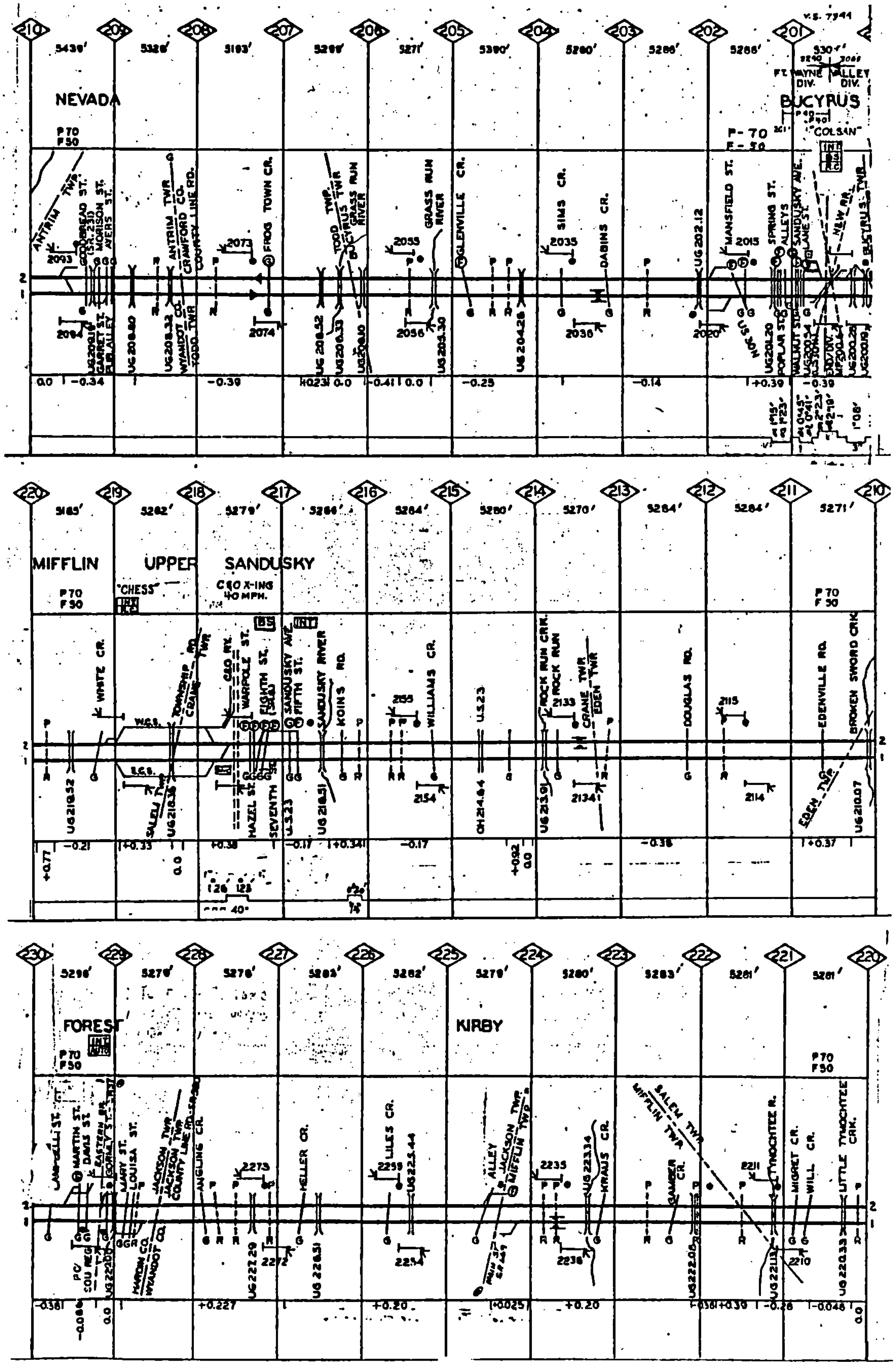


CONRAIL
ATLANTIC REGION
FORT WAYNE DIVISION
MAINLINE TEST ZONE



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NEVADA
BUCYRUS
FT. WAYNE DIV.
VALLEY DIV.
"COLSAN"
P70
F50
ANTRIM TWP.
GOODHEAD ST.
MORISON ST.
AYERS ST.
ANTRIM TWP.
WYANDOT CO.
CRAWFORD CO.
COUNTY LINE RD.
TODD TWP.
FROG TOWN CR.
TODD TWP.
CYRUS TWP.
GRASS RUN RIVER
GRASS RUN RIVER
GLENVILLE CR.
SIMS CR.
DABINS CR.
MANSFIELD ST.
SPRING ST.
ALLEYS
SANDUSKY AVE.
LANE ST.
POPLAR ST.
WALNUT ST.
BUCYRUS TWP.
220
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212
211
MIFFLIN
UPPER SANDUSKY
"CHESS"
C&O X-ING 40 MPH.
WHITE CR.
TOWNSHIP RD.
CRANE TWP.
C&O RY.
WARPOLE ST.
EIGHTH ST.
SANDUSKY AVE.
FIFTH ST.
SANDUSKY RIVER
KOINS RD.
WILLIAMS CR.
U.S.23
ROCK RUN CRK.
ROCK RUN
CRANE TWP.
EDEN TWP.
DOUGLAS RD.
EDENVILLE RD.
BROKEN SWORD CRK.
SALEM TWP.
HAZEL ST.
SEVENTH
U.S.23
EDEN TWP.
230
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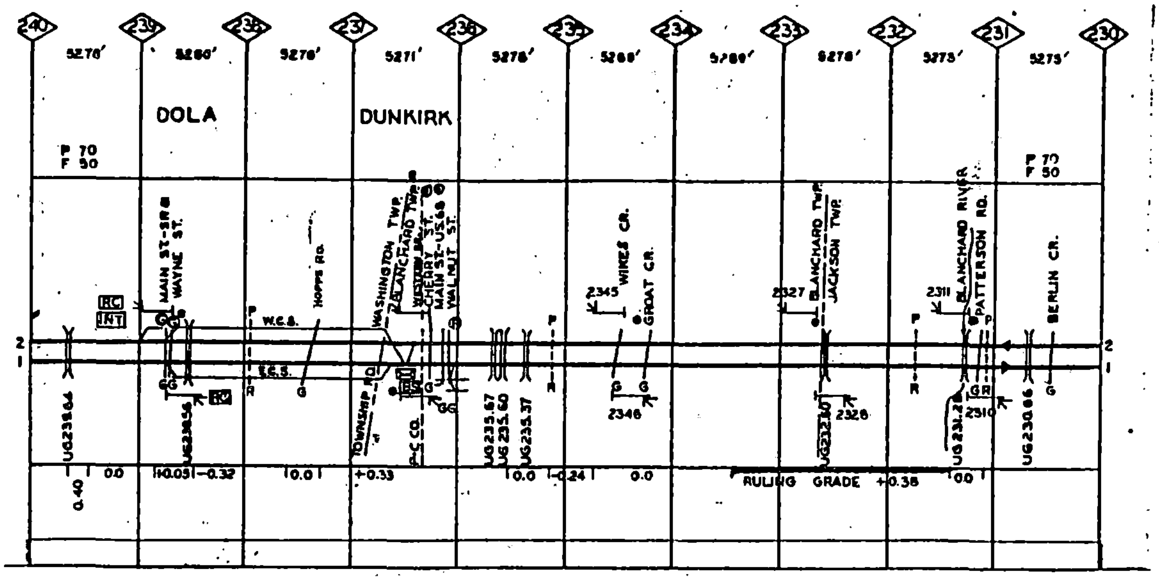
FOREST
KIRBY
MARTIN ST.
DAVIS ST.
EASTERN BR.
GORLEY ST.
MARY ST.
LOUISA ST.
JACKSON TWP.
COUNTY LINE RD.
ANGLING CR.
HELLER CR.
LILES CR.
ALLEY
JACKSON TWP.
MIFFLIN TWP.
KRAUS CR.
SALEM TWP.
MIFFLIN TWP.
GANGER CR.
TYMOCHTEE R.
MIGRET CR.
WILL CR.
LITTLE TYMOCHTEE CRK.
HARDIN CO.
WYANDOT CO.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DOLA
DUNKIRK
P 70
F 50
MAIN ST-SR
WAYNE ST.
HOPPS RD.
WASHINGTON TWP.
BLANCHARD TWP.
WALNUT ST.
WIKES CR.
GROAT CR.
BLANCHARD TWP.
JACKSON TWP.
BLANCHARD RIVER
PATTERSON RD.
BERLIN CR.
TOWNSHIP RD.
P-C CO.
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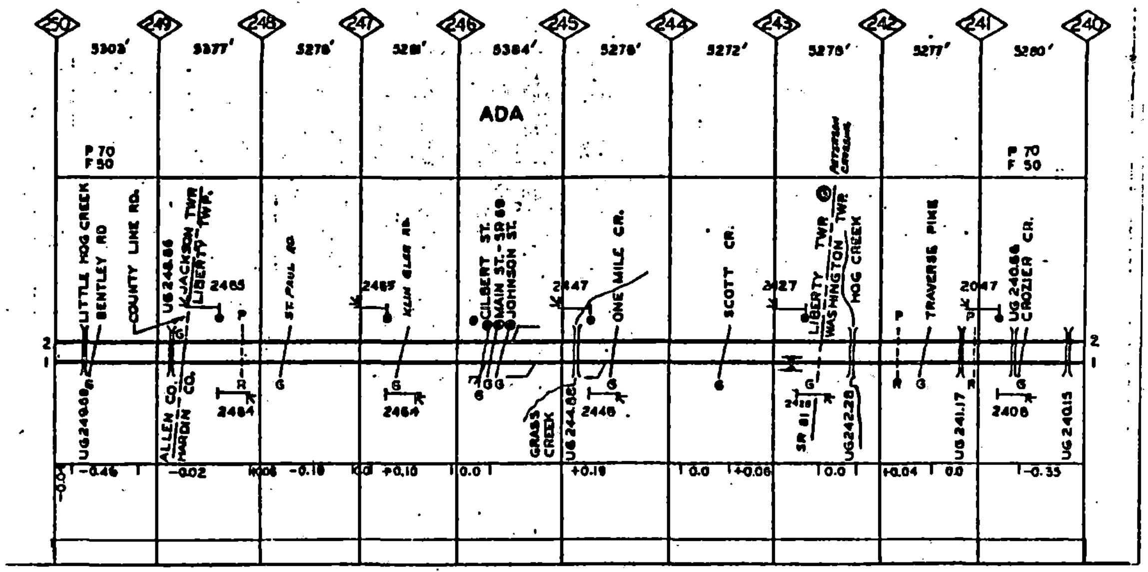
2327
2326
2311
2310
RULING GRADE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ADA
P 70
F 50
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BENTLEY RD
COUNTY LINE RD.
JACKSON TWP
LIBERTY TWP.
ALLEN CO.
HARDIN CO.
GILBERT ST.
JOHNSON ST.
ONE MILE CR.
GRASS CREEK
SCOTT CR.
LIBERTY TWP
WASHINGTON TWP
HOG CREEK
TRAVERSE PIKE
CROZIER CR.
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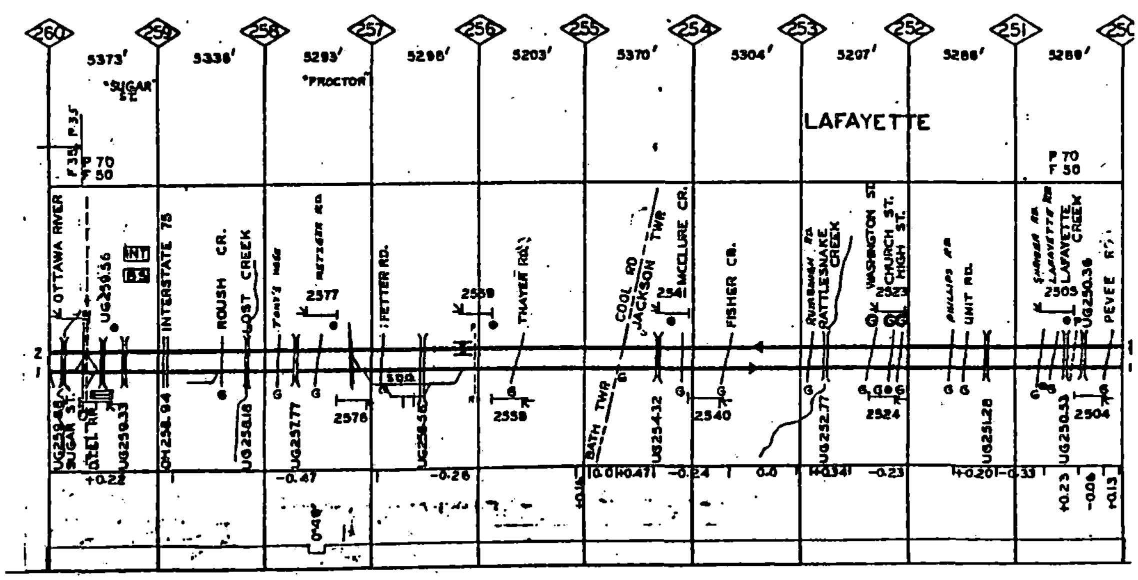
UG242.28
UG240.15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"PROCTOR"
LAFAYETTE
P 70
F 50
OTTAWA RIVER
INTERSTATE 75
ROUSH CR.
LOST CREEK
FETTER RD.
THAYER RD.
COOL RD
JACKSON TWP
MCCLURE CR.
FISHER CR.
RATTLESNAKE CREEK
WASHINGTON ST.
CHURCH ST.
HIGH ST.
UNIT RD.
LAFAYETTE CREEK
PEVEE
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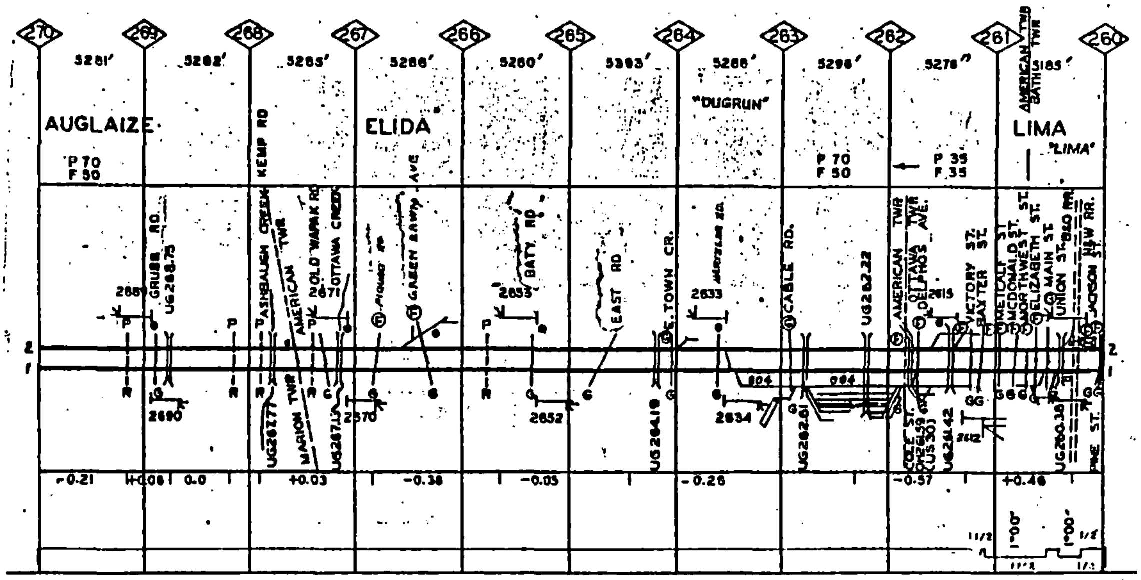
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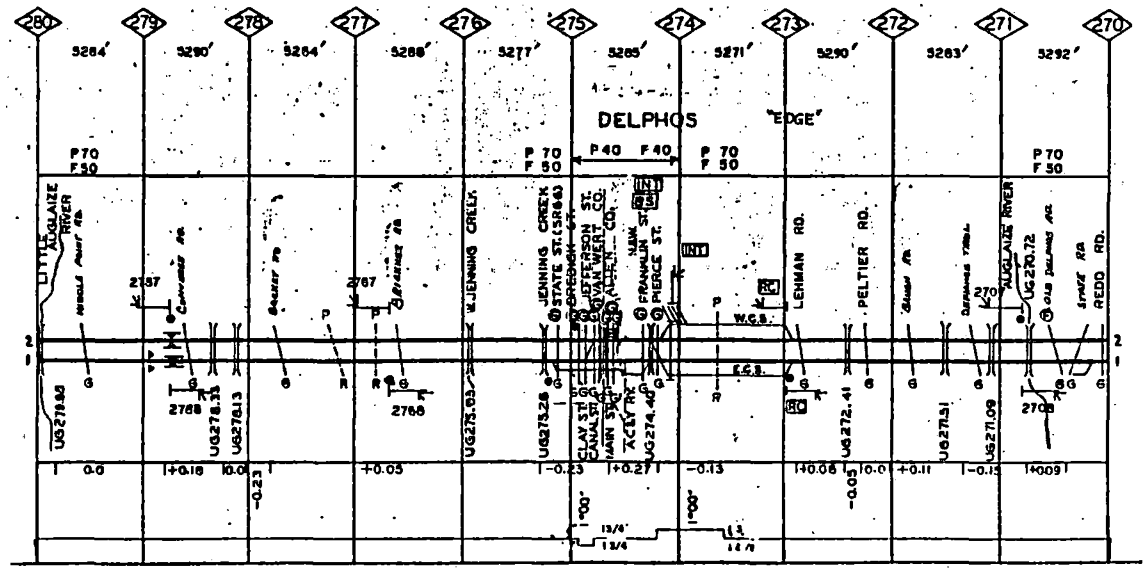
ELIDA
"DUGRUN"
LIMA
"LIMA"
P 70
F 50
P 35
F 35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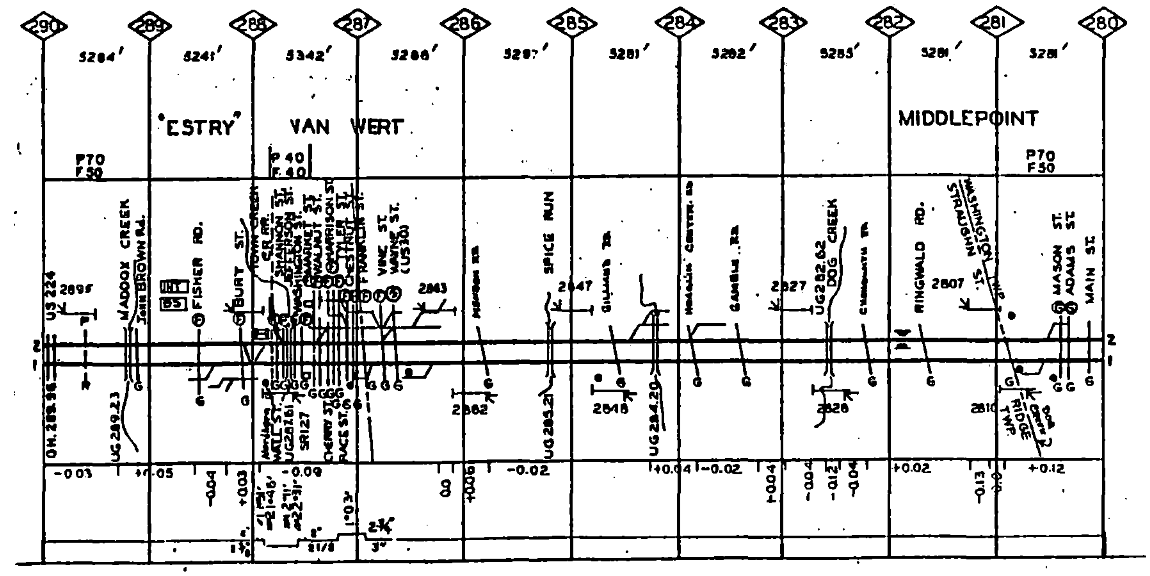
"EDGE"
P 70
F 50
P 40
F 40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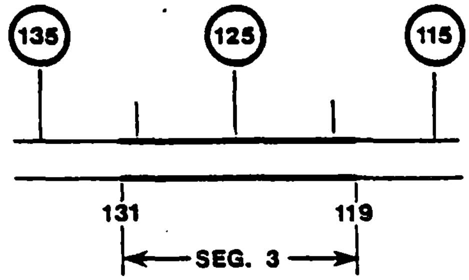
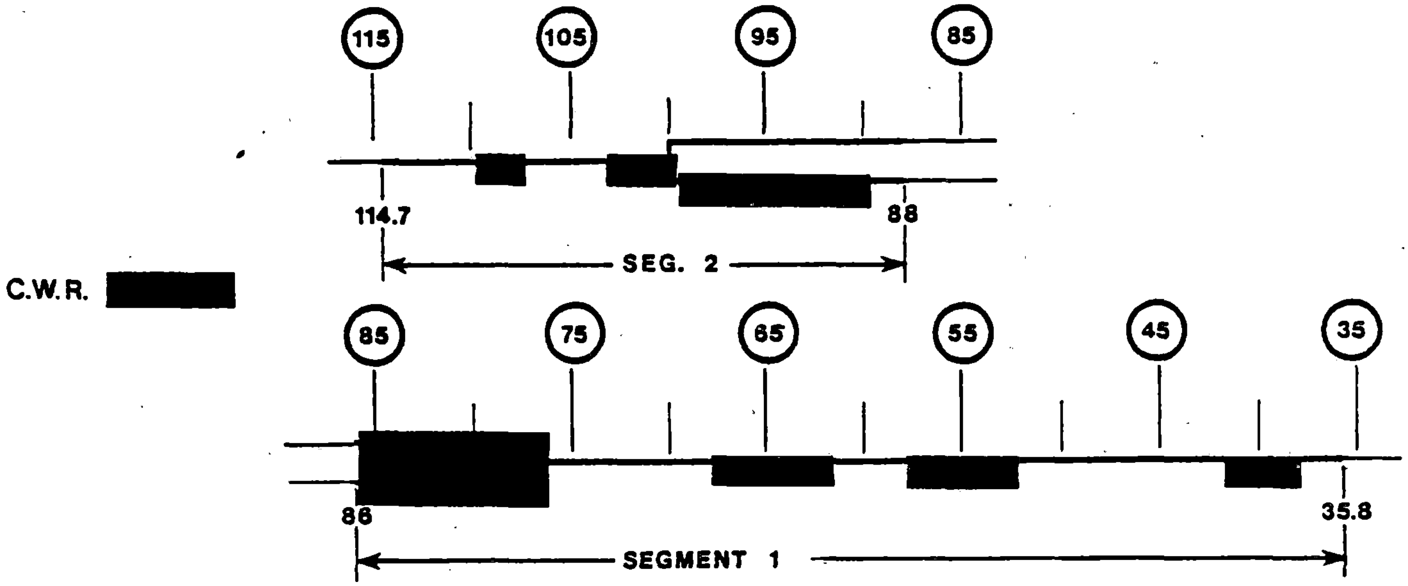
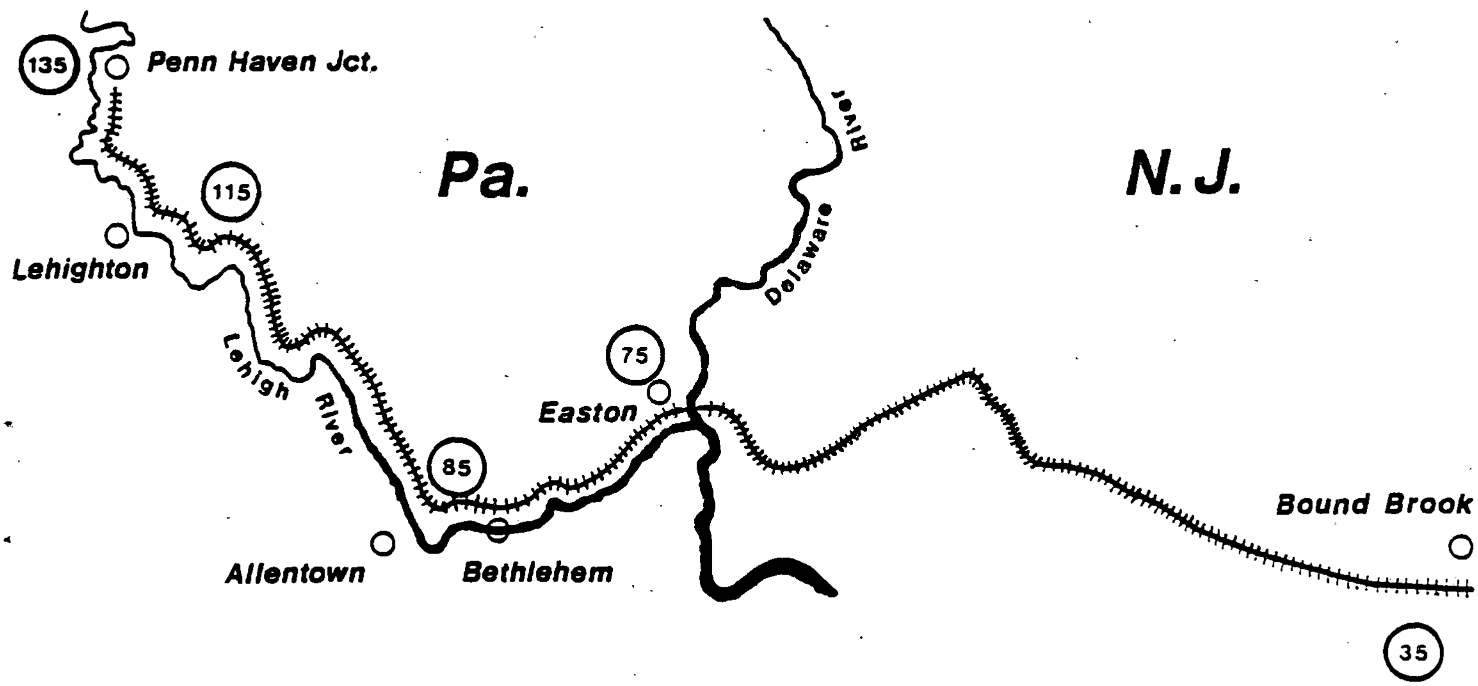
"ESTRY"
VAN WERT
MIDDLEPOINT
P 70
F 50
P 40
F 40

SEG. 1 & 3 - JC&S LINE, LINE CODE 63-0501
SEG. 2 - L & S LINE, LINE CODE 63-0521





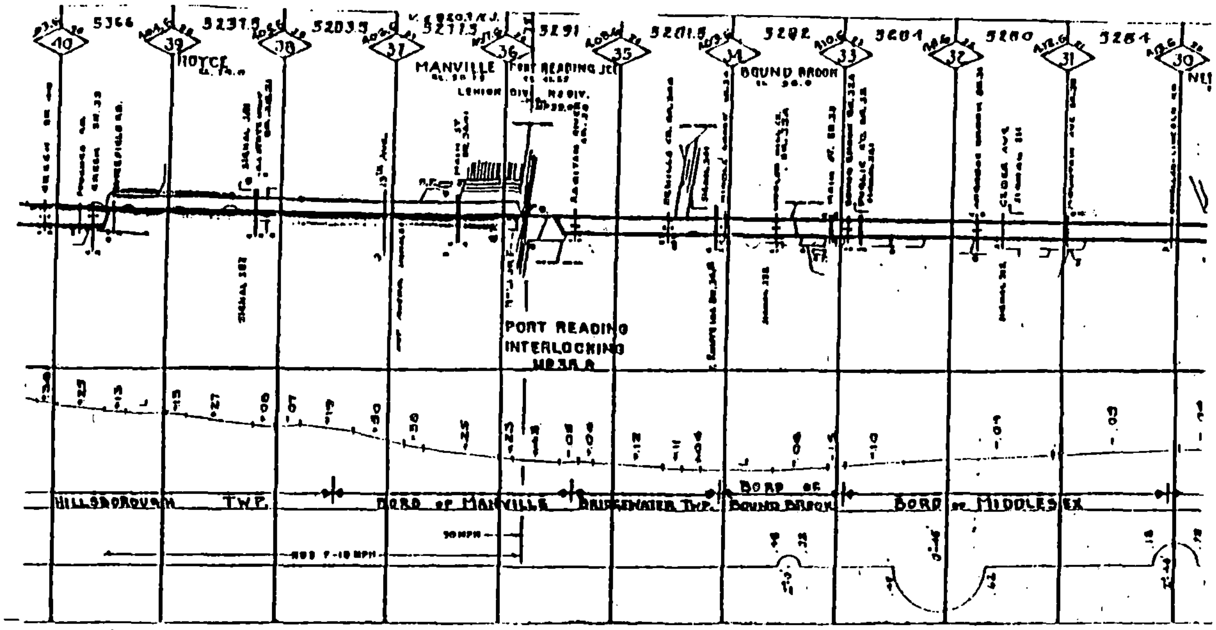


CONRAIL

ATLANTIC REGION

LEHIGH DIVISION

MAINLINE TEST ZONES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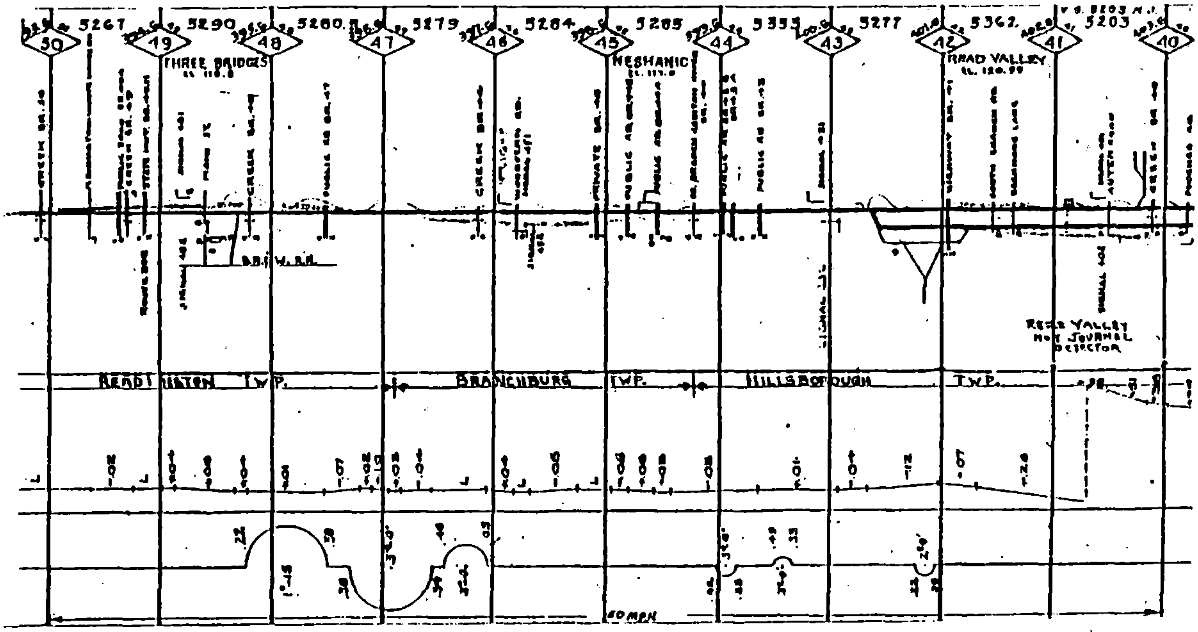
PORT READING
INTERLOCKING
HILLSBOROUGH TWP.
BORO of MANVILLE
BRIDGEWATER TWP.
BORO of BOUND BROOK
BORO of MIDDLESEX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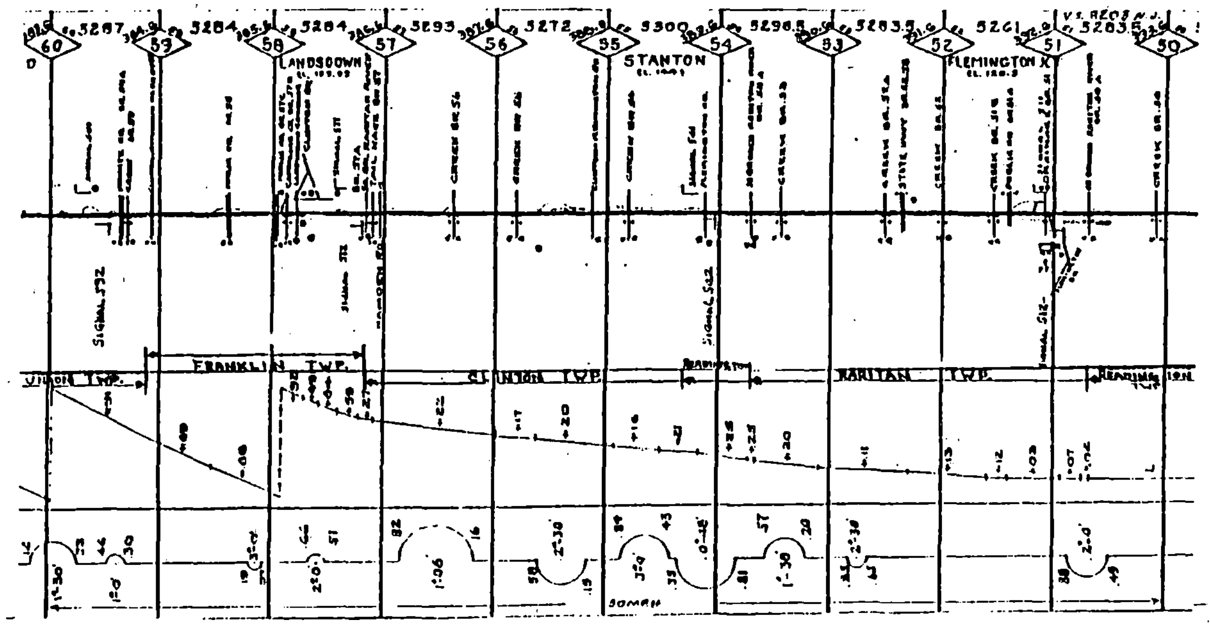
READINGTON TWP.
BRANCHBURG TWP.
HILLSBOROUGH TWP.
60 MPH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FLEMINGTON X
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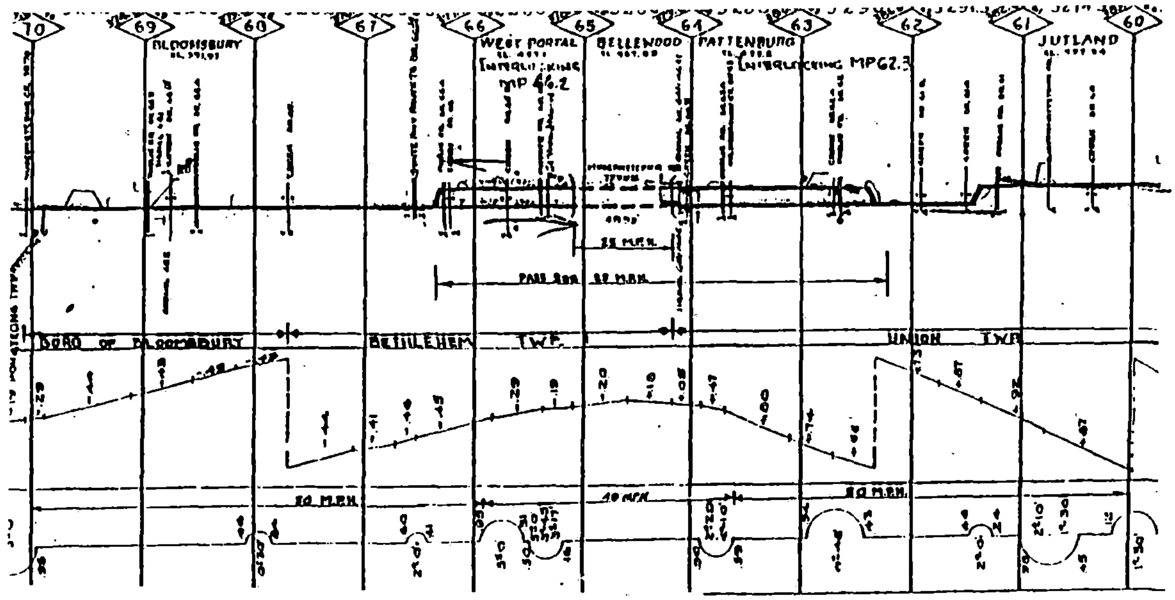
FRANKLIN TWP.
CLINTON TWP.
RARITAN TWP.
60 MPH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WEST PORTAL
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PATTENBURG
INTERLOCKING MP62.3
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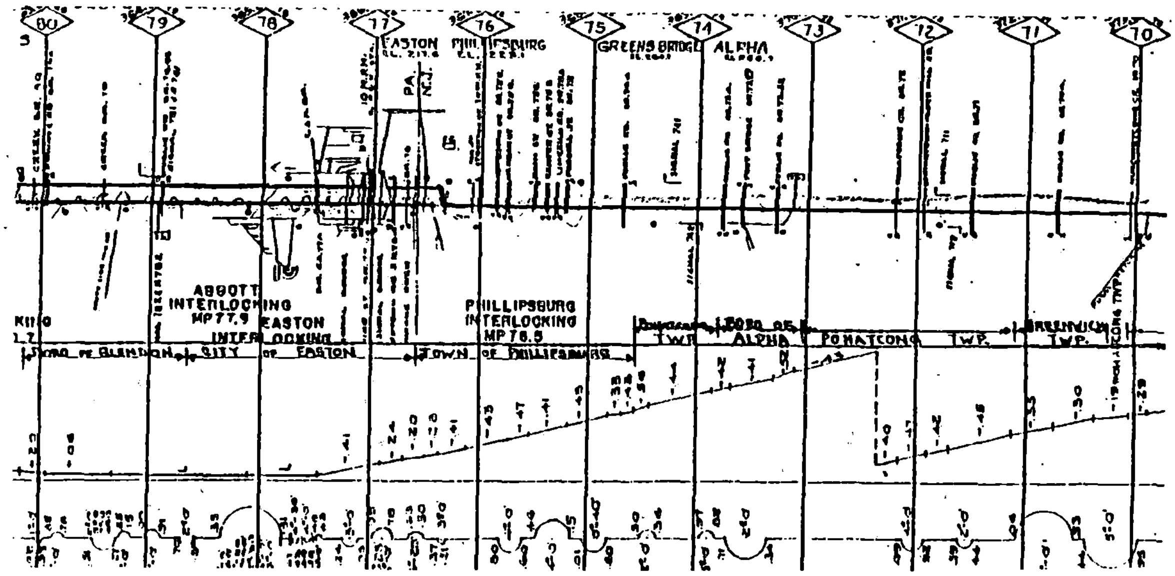
50 M.P.H.

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ABBOTT INTERLOCKING MP77.9
EASTON INTERLOCKING
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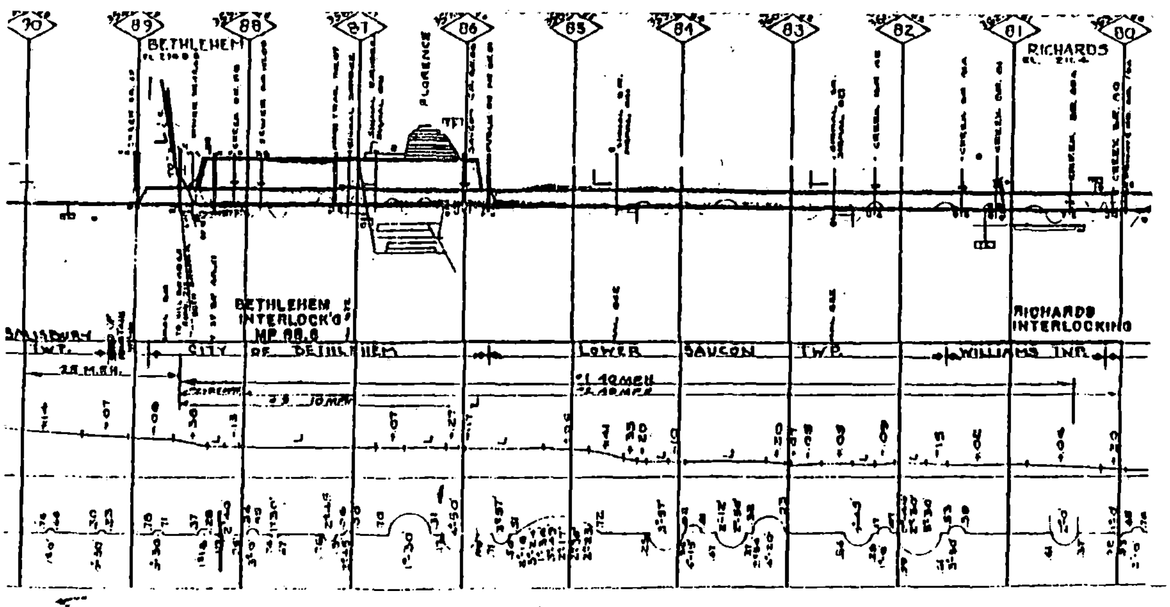
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FLORENCE
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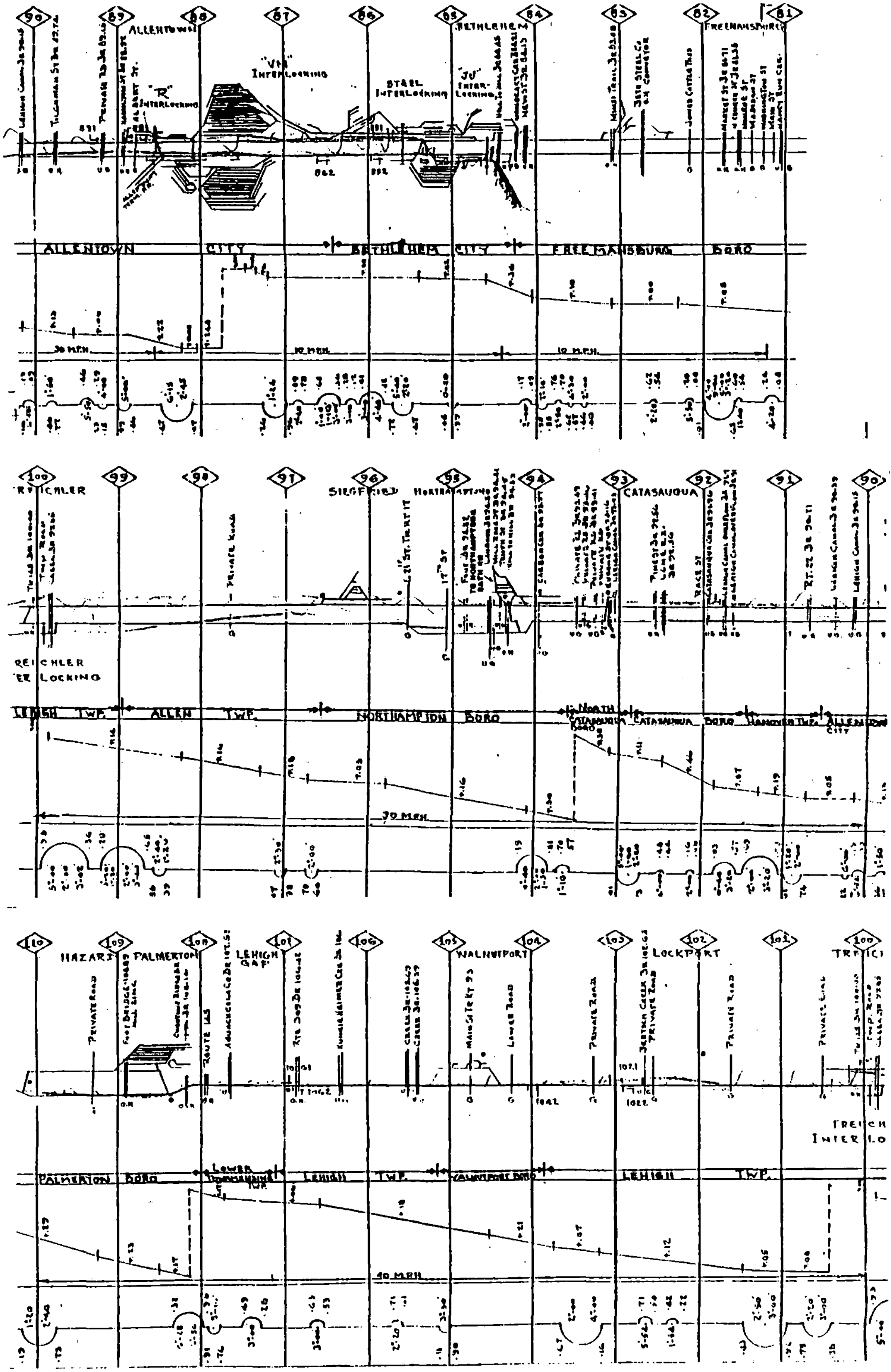
WILLIAMS TWP.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"VH" INTERLOCKING
STEEL INTERLOCKING
BETHLEHEM
"JU" INTERLOCKING
FREEMANSBURG
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BETHLEHEM CITY
FREEMANSBURG BORO
10 M.P.H.
30 M.P.H.
SIEGFRIED
NORTHAMPTON
CATASAUQUA
REICHLER INTERLOCKING
LEHIGH TWP.
ALLEN TWP.
NORTHAMPTON BORO
NORTH CATASAUQUA BORO
CATASAUQUA BORO
HANOVER TWP.
ALLENTOWN CITY
HAZARD
PALMERTON
LEHIGH GAP
WALNUTPORT
LOCKPORT
TREICHLER INTERLOCKING
PALMERTON BORO
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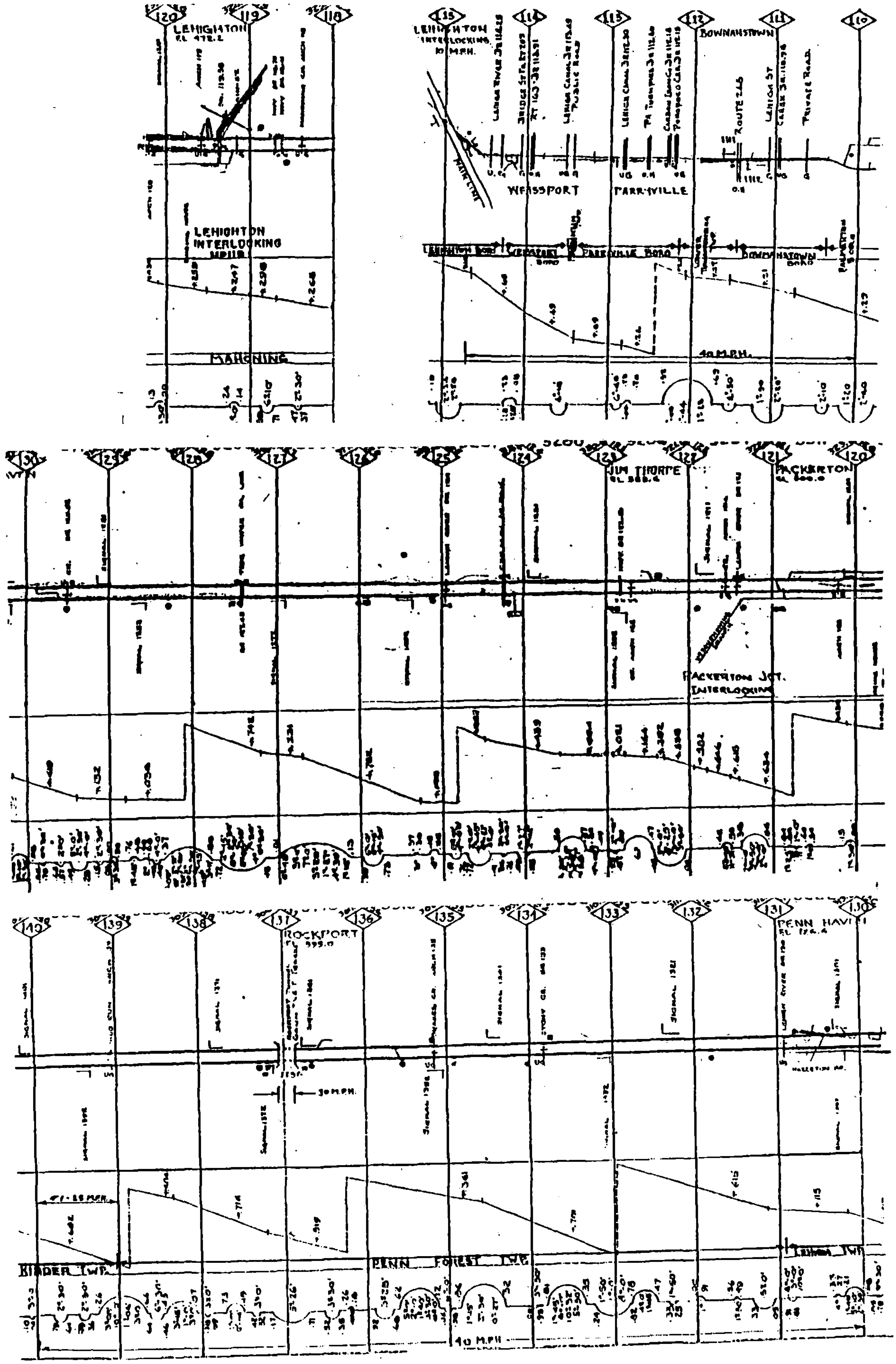
LEHIGH TWP.
WALNUTPORT BORO
LEHIGH TWP.
40 M.P.H.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BOWMANSTOWN
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JIM THORPE
PACKERTON
PACKERTON JCT. INTERLOCKING
ROCKPORT
30 M.P.H.
PENN HAVEN
KIDDER TWP.
PENN FOREST TWP.
40 M.P.H.

APPENDIX C

SELECTION OF CANDIDATE TQI'S

C.1 GENERAL

The successful development of a long-range track maintenance planning system requires the selection of appropriate quantifiers (TQI's) which indicate track condition. This appendix describes, in detail, the selection criteria for candidate TQI's based on the functional requirements of track and the laws of physics. In addition, descriptive statistics are reviewed to determine their applicability to the measurement of TQI's.

C.2 SELECTION CRITERIA

To operate a rail system safely the dynamic interaction of two subsystems must be considered. The track structure is one subsystem and the rail vehicle is the other. The interaction occurs at the wheel/rail interface. Force levels at this interface are transmitted both to the vehicle and to the track support elements. Ideally the vehicle-suspension-subsystem should interact to reduce the force at the wheel/rail interface. The force at this interface is a vector and is characterized as the ratio of lateral to vertical force (L/V). The quantity L/V has been found to be an effective indicator of derailment potential. Although the ability of track to accomplish its functional requirements (as indicated by its geometry) are discussed in the following, reference is made to L/V to tie-in the physics of the interaction between the track structure and the vehicle.

In its role as a guide, the track necessarily acts to exert force at the wheel/rail interface to cause directional changes in the momentum of the rail vehicle. This is accomplished through track alignment. When the change in alignment is too abrupt for an effective interaction between the vehicle-suspension subsystem and the track-structure subsystem, a derailment potential is produced. This may be of two basic types.

The first type of derailment potential occurs when the track-structure subsystem has adequate mechanical integrity. In this case, abrupt changes in alignment can lead to wheel climb. As the wheel-flange contacts the gage side of the rail, it tends to roll up and finally over the rail head. The second type of derailment potential occurs when the track is unable to maintain its mechanical integrity. In this case, the rail may roll over or the track may shift laterally.

In addition to its role in safe operation, alignment also plays a part in wear, which is an economic consideration. Continued excessive changes in momentum will invariably cause wear to both the track and the vehicle-subsystem. Thus, the maintenance of alignment is important in terms not only of safety but also of economics. In both cases, interest lies in the tendency of the track to change direction or, more graphically, in roughness. Anomaly-free track has been statistically modeled (as referenced in Section 3.3) as a combination of two processes. The first is a stationary random process while the second is a periodic deterministic process associated with rail lengths. The random process can be considered the roughness that is superimposed on the periodic process. One of the more promising means of producing a figure of merit, referred to as a track quality index, is to summarize the line roughness of a track segment by its standard deviation. Table C-1 shows the relationship between the type of failure mode, the track geometry parameter, and the TQI. The standard deviation with a zero mean is identical to the root-mean-square (rms), a term used widely, in particular by electrical engineers to indicate power levels in alternating current. That is, the standard deviation may be thought of as the area between a curve and its mean; thus, showing its roughness. (TQI No. 1)

In addition to the ability of alignment to impart momentum changes while guiding the vehicle, it also causes vibrations which are ultimately transmitted to the lading. The levels of acceleration generated at the wheel/rail interface are, therefore, considered an economic concern. Acceleration is proportional to the second spatial derivative, the constant of porportionality being speed squared. This strongly suggests the use of short mid-chord-offset (SMCO) as a potentially useful TQI. That is, any MCO is by definition a finite second difference which is a numerical approximation of the second derivative. The SMCO with a chord length of two feet offers a reasonable approximation since the rail head usually does not exhibit radical changes in a two-foot interval. As in the preceding paragraph, the SMCO would most likely be best summarized using a standard deviation (TQI No. 2 in Table C-1.)

Rail profile enters the area of economic consideration in much the same manner as

TABLE C-1

CANDIDATE TRACK QUALITY INDICES

Failure Mode	Cause	Track Geometry Parameter	Track Quality Index (TQI)	TQI No.
Component Wear Wheel Climb	Line Roughness	Alignment	Standard Deviation	1
Lading Damage	Lateral Acceleration	Alignment	Standard Deviation of Short Mid-chord Offset (Two Feet)	2
Component Wear	Surface Roughness	Profile	Standard Deviation	3
Lading Damage	Vertical Acceleration	Profile	Standard Deviation of Short Mid-chord Offset (Two Feet)	4
Component Wear	Low Joints	Profile	Standard Deviation of Intermediate Length Mid-chord Offset (16 Feet)	5
Component Wear	Surface Roughness	Crosslevel	Standard Deviation	6
Cant Deficiency	Inadequate Elevation	Crosslevel	Standard Deviation from Balanced Superelevation	7
Component Wear	Surface Elevation	Warp (20 Feet)	Standard Deviation	8
Rock and Roll	Low Joints	Warp (20 Feet)	99 Percentile	9
Lack of Support	Wide Gage	Gage	Mean	10
Lack of Support	Wide Gage	Gage	Standard Deviation	11
Lack of Support	Wide Gage	Gage	99 Percentile	12
Lack of Support	Wide Gage	Gage	Third Moment of Probability Function (Skewness)	13
Lack of Support	Wide Gage	Gage	Fourth Moment of Probability Function (Kurtosis)	14

alignment. The reason for this is that profile is simply the alignment of the rail in the vertical plane. There are, however, certain differences. First, gravity is acting at all times in the vertical direction creating relatively large steady-state forces. Second, long-term variation of profile or grade is generally small, usually less than two percent. Third, profile plays a singularly important role in the overall efficiency of the rail transportation system. It is, in fact, the steel-on-steel contact that provides the most efficient and practical means of transportation in terms of energy requirements. The steel-on-steel contact quite simply reduces rolling friction to the minimum practical level achievable today. However, track with a rough surface acts to force vertical motion into the vehicle suspension subsystem. The suspension subsystem, in effect, diverts energy from the direction of travel by this mechanism and this can increase fuel costs. Finally, vertical rms acceleration levels caused by variations in profile are usually larger than those caused by alignment due to the nature of the contact. Thus, two additional candidate TQI's are given in Table C-1, standard deviation of both profile and its SMCO (TQI's No. 3 and No. 4).

Profile is also an important parameter when considering the dynamic phenomena at joints between rail lengths. This aspect of track maintenance is widely known and quite costly. It would, therefore, be useful to track this phenomenon. Since the rail deflects vertically at poorly supported or weak joints, profile is a prime candidate as the track geometry parameter which can be used to quantify weak joints. A low joint can affect a length of track of about 16 feet; this is considered the zone of influence. An intermediate chord length equivalent to the zone of influence would serve well as a means to quality weak joints. Thus, joint condition would be tracked by a TQI based on the standard deviation of an MCO with a chord length of 16 feet (TQI No. 5 in Table C-1).

In addition to profile and alignment roughness, there is one other parameter which needs to be considered as an economic factor. That is variation in crosslevel which, similar to profile and alignment variations, causes changes in the angular momentum (roll) of the vehicle subsystem. Changes in angular momentum, like changes in linear momentum, impart energy to both the track structure and the vehicle subsystem, which when dissipated result in wear. Because angular momentum or rolling of the vehicle represents a significant portion of the effect of the wheel/rail interaction, the sixth candidate is the standard deviation of crosslevel (TQI No. 6 in Table C-1).

In curves, the elevation of the outer rail affects both safety and economics. The resultant vector of the gravitational and centripetal accelerations should be normal to a line drawn through the tops of the rail head. Unequal rail head wear will result if the vector is not normal and a derailment potential will exist. A filtered version of the curvature data is transposed into a balanced superelevation using the balance-speed equation and the posted speed. The standard deviation is computed for the difference of the unfiltered crosslevel and the balanced superelevation. This standard deviation is TQI No. 7 in Table C-1.

The remainder of the TQI's are directed at safety. Recalling that high L/V is an indicator of a potential derailment situation, consider the effect of periodic weak or low joints (which present a cuspid sinuosidal input to the vehicle suspension system) at a speed equivalent to the resonance phenomena, amplification of the vertical displacement of the vehicle wheels occurs creating a marked decrease in the vertical force. This off-loading has the effect of increasing the L/V so that small increases in lateral force (on the order of hundereds of pounds) can result in a critical L/V ratio which can cause derailment. This phenomenon is referred to as rock and roll and, as stated, is caused by regular or periodic low joints. Low joints are then a concern of safety.

Periodic low joints occur every one-half rail length due to the staggering of rail lengths or 19.5 feet. For this reason, warp is used to track the tendency of the track to create rock and roll. Warp is the first difference of crosslevel and in this study is calculated for a 20-foot interval to approximate the effects of 19.5-foot, low-joint spacing. In this case the 99th percentile level as well as the standard deviation (TQI No. 8 and TQI No. 9 in Table C-1) represent potentially useful TQI's. The 99th percentile level can be used to indicate the amplitude or severity of the worst joints in a track segment while the standard deviation quantifies the average condition.

The final consideration of the functional requirements of railroad track is that of support. That is, in order to support the rail vehicle subsystem statically, gage cannot exceed the width of the wheelset. In the case of a moving rail vehicle, the influence of the lateral force, generated by alignment deviations or, more importantly, the design alignment in a curve, can cause what is referred to as dynamic wide gage. Dynamic wide gage generally occurs when the tie does not adequately secure the spike and the tie plate. This, for example, is often a result of rotten or spike-killed ties in curves. Thus, there is a range of gage that is adequate for statically supporting a rail vehicle, but with increasing speed the upper boundary of that range must decrease to accommodate dynamic effects. This introduces the need to include three additional TQI's in the list of candidate indices. These are the mean and standard deviation of gage and the 99th percentile level indicating the support capability (TQI's No. 10, No. 11, and No. 12 in Table C-1).

In addition to these more conventional TQI's, two more candidate TQI's are the third and fourth moments of the probability function, they are generally termed the skewness and kurtosis, respectively. Skewness and kurtosis are always zero or give redundant information when the probability function is normal or Gaussian. These TQI's can indicate any asymmetry in the probability function and the relative thickness of the tails of the distribution. When the asymmetry and tail thickness are known, the portion of track (in a segment) that is approaching a critical gage value can also be estimated.

Each track geometry parameter can theoretcally be defined by an infinite number of statistically descriptive track quality indices, but experience indicates that the vast majority of these are either redundant with respect to the information presented or of a trivial nature in that they do not reflect the ability of a track segment to meet its functional requirements, i.e., to guide and support the rolling stock under prescribed operational conditions in a safe and economic manner.

C.3 DESCRIPTIVE STATISTICS

Table C-2 lists a set of descriptive statistics. While this set is not all inclusive, it does represent the most frequently used descriptors of data of a general nature. Each track geometry parameter is represented by a set of measurements made at equally spaced intervals. The measurement processing techniques employed are necessarily different for each parameter; some employ filtering while others do not. Profile, for example, is high-pass-filtered to remove long-term trends associated with grade. Alignment is similarly filtered. Crosslevel measurements are not filtered initially but filtering is accomplished

TABLE C-2

DESCRIPTIVE STATISTICS

Statistic	Description
Moments	The rth moment about the origin: $m'_r = \frac{1}{n}\sum_{i=1}^{n} x_i^r$ The rth moment about the mean: $m_r = \frac{1}{n}\sum_{i=1}^{n} (x_i - \bar{x})^r$ where: x_i = actual value, $\bar{x}$ = mean value
Mean	Arithmetic average of sample population (m_1)
Mode	The sample value that occurs with the greatest frequency
Median	For an odd number of samples in ascending order of magnitude, the middle value. For an even number, the mean of the two middle values
Standard Deviation	$\sqrt{m_2}$
Variance	Square of the standard deviation (m_2)
Root Mean Square	$\sqrt{m'_2}$
Quartiles	If data is arranged in ascending order of magnitude with j = 1,2 or 3, the j(n+1)/4 th value
Deciles	If data is arranged in ascending order of magnitude with j = 1,2,3...or 9, the j(n+1)/10 th value
Percentiles	If data is arranged in ascending order of magnitude with j = 1,2,3 ... or 99, the j(n+1)/100 th value
Range	Difference between largest and smallest values in the sample population

before the TQI (standard deviation) is computed. Gage measurements are not filtered.

Generally, experience indicates that the processed measurements of profile, alignment and filtered crosslevel can be adequately represented by a probability distribution which is unimodal and symmetric with respect to the mean for all types of track. This means that higher order moments are of a redundant nature for these measurements. Figures C-1 and C-2 show typical probability densities for revenue track. The vertical axis is the percent occurrence. As shown here, alignment, profile and mean removed crosslevel are unimodal (only one peak in the distribution) and have symmetric probability densities approximated by a normal distribution. Gage, however, has a probability density that is most closely approximated by a Maxwell distribution.

Moments of an order higher than four have been computed for Maxwell distributions as have non-zero odd and even higher order moments but these also prove to be redundant. The higher order moments have a significant value when non-unimodal

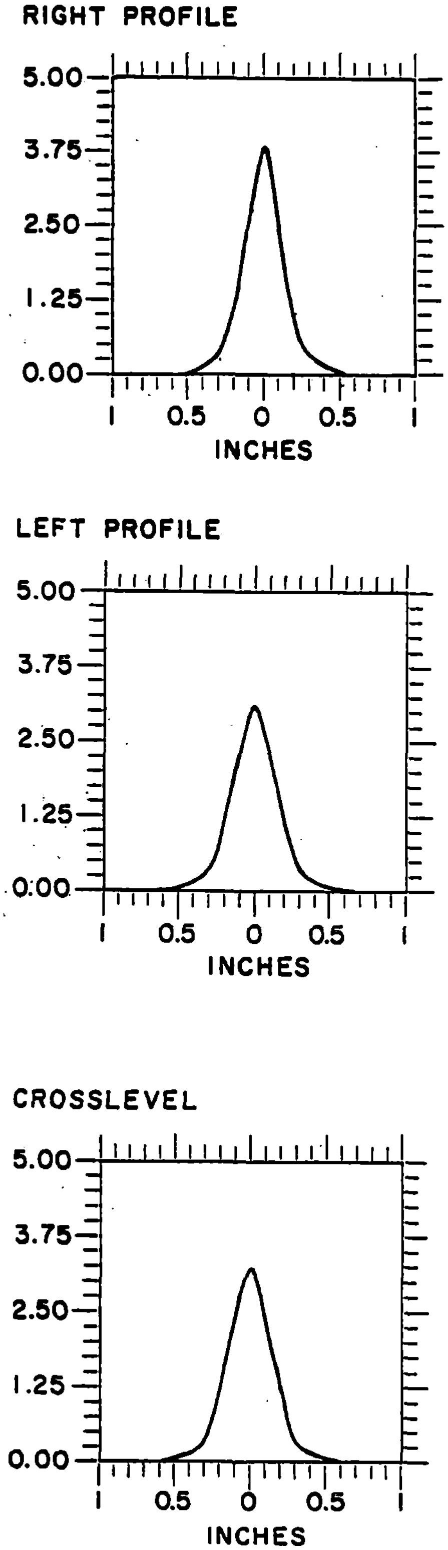

Figure C-1. Probability Density Estimate (Profile and Crosslevel)

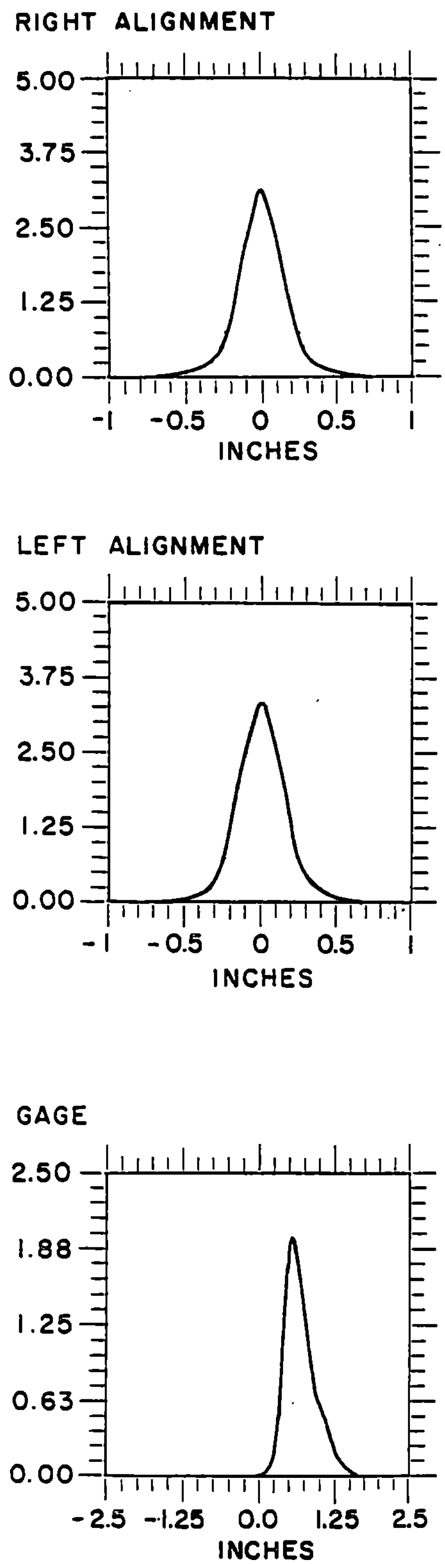

Figure C-2. Probability Density Estimate (Alignment and Gage)

distributions are expected but experience indicates that track geometry data is unimodal.

Filtering reduces to triviality the statistical descriptor mean. Generation of mid-chord-offsets also removes means or biases. Therefore, only gage can be described by the mean value. The descriptors mode and median are relevant statistics for some types of data. Unimodal, symmetrical distributions will have modes and medians that are redundant when compared to the means of those distributions. The mean is the easiest of the three to calculate. Non-normal distributions will have modes and medians that can differ from the mean but the difference is related to skewness which is a function of the third-order moment and hence would be redundant.

The standard deviation is a universally accepted statistical descriptor. When used in the context of track geometry measurements, it yields information on the variability of the parameter in the track segment. The units are in inches and, hence, it has physical significance. The variance, since it is the square of the standard deviation, is by definition redundant. The root mean square (rms) is very similar to the standard deviation. In those measurements where a mean exists, it will yield essentially redundant information since both the mean and the standard deviation will be computed.

Quartiles, deciles and percentiles are all means of representing data values in different regions of the sample population. Percentiles provide the finest resolution of the three. The magnitudes of the worst samples in a track segment are of interest and the 99th percentile would give the data value above which only one percent of the sample lie. Percentiles of 80 or 90 do not yield as much critical information as the 99th percentile. However, the closer the extreme point in the distribution is to the percentile value the more the confidence in its validity decreases because of statistical outliers. The consideration of outliers also eliminates the possibility of utilizing range. It is totally reliant on extreme values and hence is almost devoid of confidence. Unimodal, symmetrical distributions will have 99 percentile values that are directly related to the standard deviation. Therefore, the 99 percentile will be redundant for profile, alignment and crosslevel.

Indices have been used in other studies of track quality which represent the areas between the curves of theoretically perfect track and the actual track. In these studies the length of each track segment is identical which is not the case in this study. Variable length segments require normalization of the area index which means that it must be divided by the segment length. This operation yields an index that is identical to the standard deviation plus the mean. When the mean value is zero, the index is the same as the standard deviation.

APPENDIX D

REGRESSION ANALYSIS

Regression analysis techniques were used extensively to develop the degradation models for the long range Track Maintenance Planning Program. The models were used to predict the value of a TQI based on the previous value of the TQI and a set of physical parameters. Accordingly, these models treat the physical parameters as independent variables and the TQI's as dependent variables.

This appendix discusses the regression analysis in textbook format for easy reference to Sections 6.0 and 7.0. The reader is referred to any advanced text book on applied regression analysis for details.

D.1 MULTIPLE LINEAR REGRESSION

D.1.1 FUNCTIONAL RELATIONSHIP

Regression analysis may be broadly defined as the analysis of relationships among variables. It is one of the most widely used statistical tools because it provides a simple method for establishing a functional relationship among variables. The relationship is expressed in the form of an equation connecting the response or dependent variable y, and one or more independent variables $x_1, x_2, \ldots, x_m$. The equation may be written as

$$y = \alpha + \beta_1 x_1 + \beta_2 x_2 + \ldots \beta_m x_m \qquad \text{(D-1)}$$

where α is the constant term and β_i are the regression coefficients.

The estimated equation, or to be more precise, the regression equation is written as

$$\hat{y} = a + b_1 x_1 + b_2 x_2 \ldots b_m x_m \qquad \text{(D-2)}$$

where a is the estimated constant and b_i are the estimated regression coefficients.

The regression coefficients are usually estimated from an experimental set of data using the method of least squares. The method of least squares involves minimizing the sum of the squares of residuals between the observed y's and the predicted y's. This gives the least squares "best" value of these coefficients for a particular sample of observations. An important aspect of regression analysis is that it is a measure of the reliability of each of the coefficients so that inferences can be made regarding the parameters of the population from which the sample observation was taken.

D.1.2 DERIVATION OF THE METHOD

Let us assume that y_i is to be estimated by the equation

$$y_i = b_o + \sum_{j=1}^{m} b_j x_{ij} + e_i \qquad \text{(D-3)}$$

The error of estimate e_i is given by

$$e_i = y_i - b_o - \sum_{j=1}^{m} b_j x_{ij} \qquad \text{(D-4)}$$

The purpose of the regression analysis is to determine b_j in such a way that the length of the vector e_i, i = 1, n is minimized. But

$$||e||^2 = (e, e) = \sum_{j=1}^{n} \left\{ y_i - b_0 - \sum_{j=1}^{m} b_j x_{ij} \right\}^2 \qquad \text{(D-5)}$$

Taking the partial derivative with respect to $b_0, b_1 \ldots b_m$ and equating to zero, we generate the set of normal equations

$$nb_0 + \sum_{j=1}^{m} b_j \sum_{i=1}^{n} x_{ij} = \sum_{i=1}^{n} y_i$$

$$b_0 \sum_{i=1}^{n} x_{i1} + \sum_{j=1}^{m} b_j \sum_{i=1}^{n} x_{1i} x_{ji} = \sum_{i=1}^{n} x_{1i} y_i$$

$$b_0 \sum_{i=1}^{n} x_{i2} + \sum_{j=1}^{m} b_j \sum_{i=1}^{n} x_{2i} x_{ji} = \sum_{i=1}^{n} x_{2i} y_i \qquad \text{(D-6)}$$

$$b_0 \sum_{i=1}^{n} x_{im} + \sum_{j=1}^{m} b_j \sum_{i=1}^{n} x_{mi} x_{ji} = \sum_{i=1}^{n} x_{mi} y_i$$

The solution of regression can be simplified using the matrix approach. First consider the matrix:

$$X = \begin{bmatrix} 1 & x_{11} & x_{12} & \ldots x_{1m} \\ 1 & x_{21} & x_{22} & \ldots x_{2m} \\ 1 & x_{n1} & x_{n2} & \ldots x_{nm} \end{bmatrix}$$

where the i^{th} row, apart from the initial element, represents the x values that given rise to the response y_i. One will note that the normal equations can be written as

$$(X'X)b = X'Y \tag{D-7}$$

where X' is the m x n matrix which is the transpose of X, b is a column vector of length m which is given by

$$b = \begin{bmatrix} b_0 \\ b_1 \\ \vdots \\ b_m \end{bmatrix}$$

and y is the column vector of length n given by

$$Y = \begin{bmatrix} y_1 \\ y_2 \\ \vdots \\ y_n \end{bmatrix}$$

If the matrix X'X is non-singular, the solution of regression coefficients can be written as

$$b = (X'X)^{-1} X'Y \tag{D-8}$$

The regression coefficients can be calculated using the relation given by Equation D-8 when the regression model contains only a few (two or three) independent variables. However, results can be entirely invalidated due to round-off errors in problems with several independent variables. The round-off errors can be minimized by replacing the X'X and X'Y matrices by the respective correlation matrices. Furthermore, if the number of independent variables exceeds 7, the computations should be performed in double precision. The regression analysis algorithms for MOW applications were implemented in this form. The reader is referred to Volume III of this report for details.

D.1.3 ASSUMPTIONS

The regression coefficients given by Equation D-8 are an unbiased estimate of b which minimizes the error sum of the squares irrespective of any distribution properties of the errors. However, for tests listed in later sections such as t- or F-tests and for obtaining confidence intervals, it is assumed that errors are normally distributed. Furthermore, simple least square analysis (as opposed to weighted least squares) assumes that errors are random with a mean of zero. It is also assumed that errors are independent and thus b are the maximum likelihood estimate of β.

D.1.4 TRANSFORMATION OF VARIABLES

Discussions in the previous paragraphs were limited to simple linear models. However, several other models can be made linear by appropriate transformations. Then the method of linear least squares can be applied to estimate the parameters of the regression model. Some of the important linearizable curves are shown in Figures D-1, D-2 and D-3 and the transformations to make them linear are listed in Table D-1.

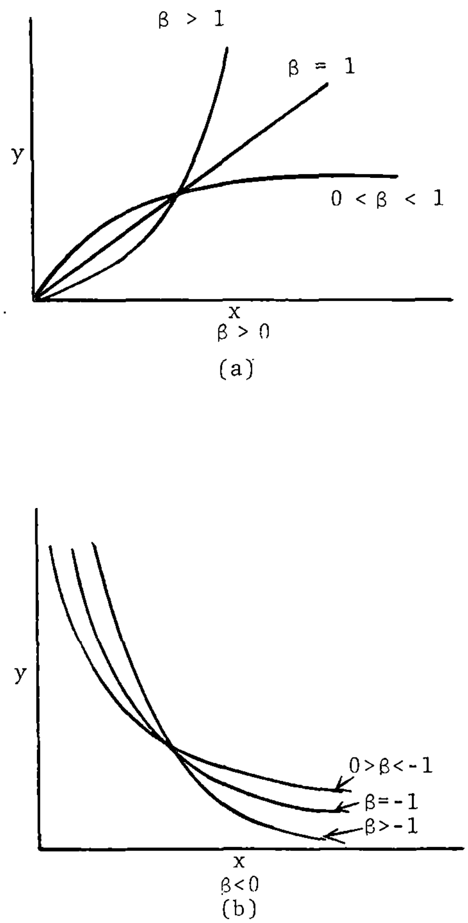

Figure D-1. Graph of $y = \beta_o x^\beta$

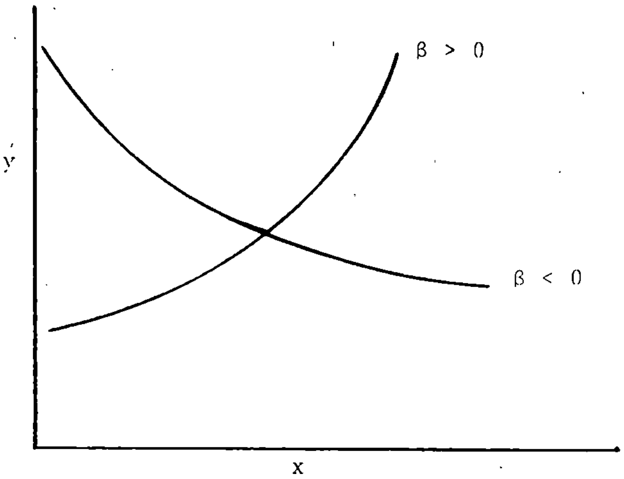

Figure D-2. Graph of $y = \beta_o + \beta \log x$

D.1.5 DUMMY VARIABLES

The variables in the regression equation may not always be continuous. Occasionally, some of the variables may take two or more distinct levels. In regression analysis, this situation may be handled by using dummy variables. We can deal with ℓ levels by the introduction of $(\ell - 1)$ dummy variables. Suppose a variable, such as ballast condition, takes the values of 0, 1, 2 and 3. The effect of ballast condition may be analyzed by the introduction of three dummy variables (z_1, z_2, and z_3). Then we can assign the values as follows:

Ballast Condition	z_1	z_2	z_3
0	0	0	0
1	1	0	0
2	0	1	0
3	0	0	1

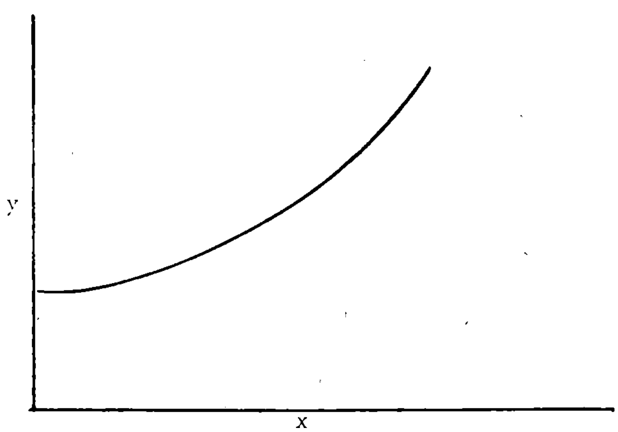

Figure D-3. Graph of $y = \beta_o + \beta x^2$

TABLE D-1
LINEARIZABLE FUNCTIONS

Function	Transformations
$y = \beta_0 x^\beta$	$y' = \log y$, $x' = \log x$
$y = \beta_0 + \beta \log x$	$x' = \log x$
$y = \beta_0 + \beta x^2$	$x' = x^2$

The model developed will then include extra terms $\beta_1 z_1$, $\beta_2 z_2$ and $\beta_3 z_3$.

D.1.6 ANALYSIS OF VARIANCE

The quality of the estimated regression line is usually analyzed through an analysis of variance approach. This is a procedure in which the total variation in the dependent variable is subdivided into meaningful components. As shown in Figure D-4, the deviation of the i^{th} observation of y can be expressed as

$$y_i - \bar{y} = (y_i - \hat{y}_i) + (\hat{y}_i - \bar{y}) \qquad \text{(D-9)}$$

It can be shown* that

$$\sum_{i=1}^{n} (y_i - \bar{y})^2 = \sum_{i=1}^{n} (y_i - \hat{y}_i)^2 + \sum_{i=1}^{n} (\hat{y}_i - \bar{y})^2 \qquad \text{(D-10)}$$

where the term on the left is the total sum of the squares, the first term on the right is the sum of the squares about regression called the error sum of the squares, and the second term on the right

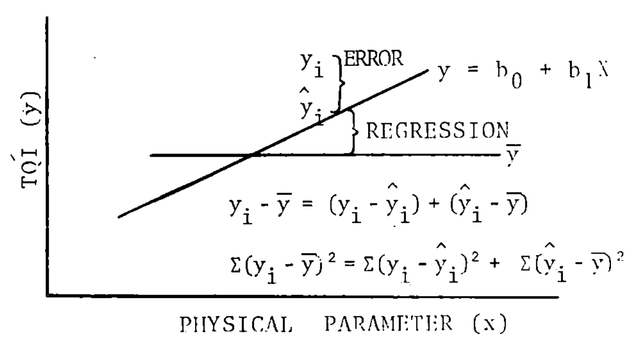

Figure D-4. Partitioning the Total Variation of y

*N. Draper and H. Smith, "Applied Regression Analysis," J. Wiley & Sons, New York, 1966, p. 14.

is the sum of squares due to regression called the regression sum of the squares.

This shows that the total corrected sum of the squares of y (SST) can be partitioned into two components. We shall indicate this partitioning symbolically as

$$SST = SSE + SSR \qquad \text{(D-11)}$$

SSR is called the regression sum of the squares and it reflects the amount of variation in the y values explained by the model. The second component (SSE) is the error sum of the squares which reflects the variation about the regression line.

Partitioning the total sum of the squares into two components gives a way of assessing how useful the regression line is. SSR and SSE are values of independent chi-square variables with m and n-m-1 degrees of freedom, respectively. for m independent variables. To test the null hypothesis that the variation in y is not explained by the regression but rather by chance, i.e.,

$$H_0: \ \beta_1 = \beta_2 \ldots \beta_m = 0$$

$$H_1: \ \text{At least one } \beta \neq 0$$

we compute the F value as follows:

$$F = \frac{SSR/m}{SSE/(n-m-1)} = \frac{MSSR}{s^2} \qquad \text{(D-12)}$$

and reject H_0 at the α level of significance when $F > F_\alpha\ (m, n-m-1)$. This is illustrated in Figure D-5.

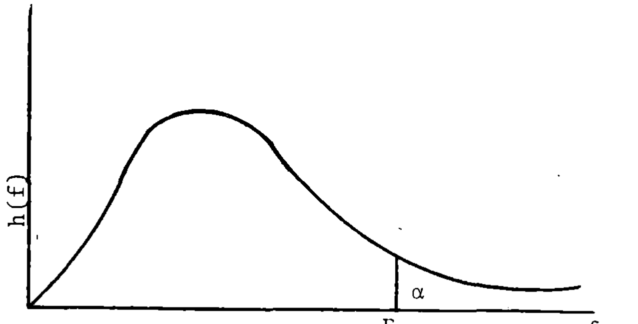

Figure D-5. Test of the Significance of Regression Equation

The computations are usually summarized as an analysis of variance (ANOVA) table shown in Table D-2.

When the null hypothesis is rejected, we conclude that there is a significant amount of variation in the response accounted for by the postualted model. If the F statistic is in the acceptance region, we conclude that the data did not reflect sufficient evidence to support the model postulated.

D.1.7 STANDARD ERROR OF ESTIMATE

The mean squares about regression (s^2) provide an estimate of the variance about the regression (σ^2). If the regression equation was estimated from a large number of observations, the variance about regression would represent a measure of error with which any observed value of y could be predicted using the regression equation. The quantity (s) is called the

TABLE D-2

ANALYSIS OF VARIANCE TABLE

Source of Variation	Sum of Squares	Degrees of Freedom	Mean Square	F
Regression	SSR	m*	MSSR	$MSSR/s^2$
Error	SSE	m - n** - 1	s^2	
Total	SST	n - 1		

* Number of independent variables.
** Number of observations.

standard error of estimate and a relatively small value of (s) would indicate a relatively better prediction power for a regression equation.

D.1.8 CORRELATION COEFFICIENT

The measure of the linear relationship between two variables x and y is estimated by the sample correlation coefficient (r) which is defined as

$$r = \frac{S_{xy}}{\sqrt{S_{xx}\ S_{yy}}} \qquad \text{(D-13)}$$

where

$$S_{xy} = \sum_{i=1}^{n} (x_i - \bar{x})(y_i - \bar{y})$$

$$S_{xx} = \sum_{i=1}^{n} (x_i - \bar{x})^2$$

$$S_{yy} = \sum_{i=1}^{n} (y_i - \bar{y})^2 = SST$$

From equation (D-13),

$$r^2 = \frac{S_{xy}^2}{S_{xx}S_{yy}} \qquad \text{(D-14)}$$

It can be shown* that S^2_{xy}/S_{xx} is the regression sum of the squares (SSR). Thus

$$r^2 = \frac{SSR}{SST} \qquad \text{(D-15)}$$

or

$$r^2 = 1 - \frac{SSE}{SST} \qquad \text{(D-16)}$$

Since SSE $\leq$ SST, we conclude that r^2 must lie between zero and 1. Consequently r must range from -1 to 1. A value of -1 or +1 will occur when SSE = 0, but this is the case when all points lie in a straight line. Hence, a perfect relationship exists between x and y when $r = \pm 1$. On the other hand, a value of r=0 occurs when SSE = SST or SSR = 0, and this is the case when no linear relationship exists between x and y. The relationship for these extreme values of r is shown in Figure D-6. Intermediate values of r are not so easily interpreted However, if we consider r^2, it is evident from equation D-15 that (100 x r^2) percent of the variation in the values of y may be accounted for by the linar relationship with the variable x.

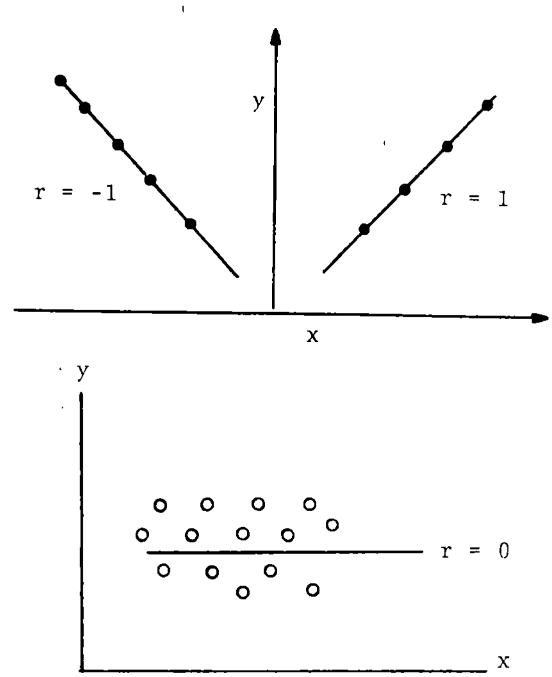

Figure D-6. Interpretation of Extreme Values of Correlation Coefficients

D.1.9 COEFFICIENT OF DETERMINATION

Although the concept of the correlation coefficient is strictly applicable to a single independent variable, we can define a similar criterion to illustrate the adequacy of a fitted regression model in the case of multiple linear regression, i.e.,

$$R^2 = \frac{SSR}{SST} \qquad \text{(D-17)}$$

R^2 is called the Coefficient of Determination and indicates the proportion of the total variation in the response y that is explained by the fitted model. A value of R^2 close to unity would indicate a good regression model.

The nature of the computation for R^2 is such that an addition of a variable would always increase the value of R^2 whether or not the contribution due to the additional variable was significant. This problem can be overcome by adjusting the R^2 value for the degrees of freedom. This modified quantity is called the Adjusted Coefficient of Determination and is defined as follows:

*R. E. Walpole and R. H. Myers, "Probability and Statistics for Engineers and Scientists," The MacMillan Co., New York, 1972, p. 286.

$$R^{2'} = 1 - (1 - R^2)(n - 1)/(n - m) \qquad (D\text{-}18)$$

where m is the number of independent variables in regression, and (n - 1) is the degrees of freedom of SST.

D.1.10 TESTING THE INDIVIDUAL REGRESSION COEFFICIENTS

In the previous paragraphs, it was shown how the overall regression model can be tested to see whether a relationship exists between the response variable and a set of independent variables. The individual regression coefficients can be tested by computing the t values.

$$T = b_i/s_{b_i} \qquad (D\text{-}19)$$

where b_i is an estimated regression coefficient, and s_{b_i} is the estimated standard error of b_i.

The statistics given by Equation D-19 have a t distribution with (n - m - 1) degrees of freedom and can be used to test the null hypothesis:

$$H_0: \beta_i = 0$$

$$H_1: \beta_i \neq 0$$

If the magnitude of the computed t value is greater than $t_{(n-m-1),\alpha/2}$, we can reject the null hypothesis at α level of significance. As a rule of thumb, if $|T| > 2$, we can conclude that β_i is not zero. This is illustrated in Figure D-7.

D.1.11 CONFIDENCE INTERVALS FOR REGRESSION COEFFICIENTS

As indicated in the previous paragraphs, the regression coefficients are computed from a sample of observations from a certain population. Inferences for the entire population can be made by constructing the confidence intervals for regression coefficients. A $(1 - \alpha)$ a 100-percent confidence interval for the parameter β_i is given by:

$$b - t_{\alpha/2}s_{b_i} < \beta_i < b + t_{\alpha/2}s_{b_i} \qquad (D\text{-}20)$$

where $t_{\alpha/2}$ is a value of the t distribution with (n - m - 1) degrees of freedom.

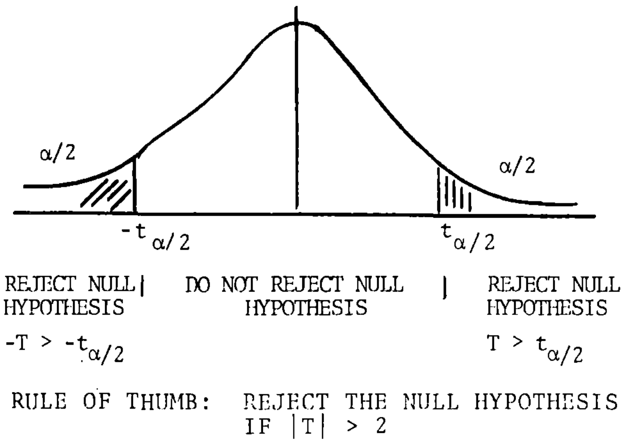

Figure D-7. Test of Individual Regression Coefficients for Null Hypothesis

D.2 STEPWISE REGRESSION

In many applications of regression analysis, the set of variables to be included in the regression model is not pre-determined, and it is often the first part of the analysis to select these variables. In the situation where there is no clear-cut theory as to which variables should be included, the problem of selecting variables for a regression equation becomes an important one.

To make the equation useful for predictive purposes, it is necessary to include as many x's as possible so that a reliable estimate can be made for the reponse variable. However, due to the cost involved in obtaining information on a large number of x's and subsequently monitoring them, we would like the equation to include as few x's as necessary. The compromise between these extremes is what is usually called selecting the best regression equation. Stepwise regression is one of the tools used to arrive at such an equation.

In stepwise regression, the regression equation is developed by adding one independent variable at a time. The variable added is the one that has the highest partial correlation coefficient with y at each step and is significant according to the F test. A significance test is also made on the variables already in the model. This procedure is continued until an additional variable would not significantly improve the model.

D.3 AUTOREGRESSION

Autoregression is used to investigate the effects of previous values of the response variable on the current values. In this case, the response variable can be treated as an independent variable and the regression equation takes the form

$$y_t = \alpha + b_o y_{t-1} + b_i x_1, \ldots b_m x_m \qquad \text{(D-21)}$$

where y_t is the current value of y, y_{t-1} is the previous values of y, and b_i's are the estimated regression coefficients.

For all practical purposes Equation D-21 can be treated as a general linear model. The parameters of the model can be estimated by the usual procedures such as multiple linear regression or stepwise regression.

APPENDIX E

RELATIONSHIP OF TQI'S TO FEDERAL TRACK SAFETY STANDARDS AND RIDE QUALITY

E.1 FEDERAL TRACK SAFETY STANDARDS

Track quality indices are computed from track geometry parameters using mathematical operations. An estimate of a TQI value for an FRA track class can be obtained from existing track geometry models*. These models were developed for homogeneous track (free of anomalies) and are based on the Power Spectral Density (PSD). A PSD is an estimate of the frequency content of a track geometry parameter. Figure E-1 shows an example of a typical PSD processed for the profile measurement.

The value of a TQI can be derived from a PSD by calculating the area under the PSD curve in the frequency-region of interest. In the following paragraphs, the procedure is illustrated for a profile index. The same procedure applies for the other TQIs.

The profile spectrum $S(\phi)$, is given by:

$$S(\phi) = \frac{A\phi_4^2(\phi^2 + \phi_3^2)}{\phi^4(\phi^2 + \phi_4^2)} \qquad \text{(E-1)}$$

where

ϕ = Spatial frequency in cycles/foot

A = Roughness parameter* in inch^2-cycles/foot

ϕ_3, ϕ_4 = Break frequencies* in cycles/foot

The variance (σ^2) of profile is calculated by integrating $S(\phi)$ in the desired frequency band. Thus

$$\sigma^2 = \int_{\phi_1}^{\phi_2} S(\phi)\,d\phi \qquad \text{(E-2)}$$

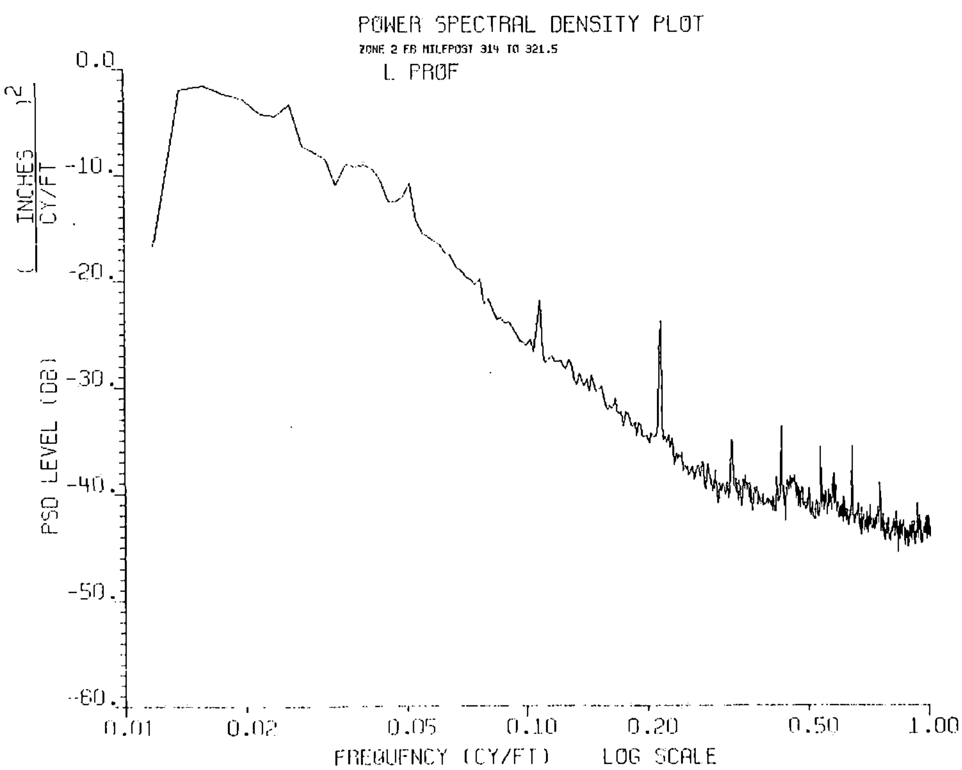

Figure E-1. Typical PSD Curve

*ENSCO Report, "Statistical Representations of Track Geometry," June 1979.

TABLE E-1

TQI'S FOR DIFFERENT TRACK CLASSES

Track Class	Standard Deviation (inch)							
	Profile		Alignment		Crosslevel		Gage	
	Theoretical	Empirical	Theoretical	Empirical	Theoretical	Empirical	Theoretical	Empirical
1	0.34	0.50	0.48	1.11	0.23	0.40	0.30	0.23
2	0.26	0.22	0.36	0.37	0.20	0.19	0.22	0.21
3	0.19	0.27	0.27	0.39	0.16	0.15	0.17	0.19
4	0.14	0.11	0.20	0.30	0.13	0.10	0.13	0.17
5	0.11	0.08	0.15	0.08	0.11	*	0.09	*
6	0.08	0.09	0.11	0.14	0.09	*	0.07	*

*Data not available.

Let $\phi_4^2 = a$, $\phi_3^2 = b$, then the variance may be written as:

$$\sigma^2 = \int_{\phi_1}^{\phi_2} \frac{Aa(\phi^2 + b)}{\phi^4(\phi^2 + a)} d\phi \qquad \text{(E-3)}$$

The integration can be performed by the method of partial fractions. Factoring the expression under the integral:

$$\sigma^2 = \frac{A}{a} \int_{\phi_1}^{\phi_2} \left(\frac{a-b}{\phi^2} + \frac{ab}{\phi^4} - \frac{a-b}{\phi^2 + a} \right) d\phi \qquad \text{(E-4)}$$

Evaluting the integral

$$\sigma^2 = \frac{A}{a} \left[\frac{b-a}{\phi} - \frac{ab}{3\phi^3} + \frac{b-a}{\sqrt{a}} \tan^{-1}\left(\frac{\phi}{\sqrt{a}}\right) \right]_{\phi_1}^{\phi_2} \qquad \text{(E-5)}$$

The upper integration limit ϕ_2 is a function of sample rate and is 0.5 cycle/foot for a one-foot sample interval. The lower integration limit ϕ_1 depends on the lowest frequency content of the data. Note that the expression given in equation (E-5) is undefined for $\phi_1 = 0$. However, the lowest frequency of interest is 1/300 cycle/foot* Furthermore, profile data is high-pass filtered and most of the information is above approximately 1/141 cycle/foot. The alignment accelerometer data is also high-pass filtered with a similar filter. However, gage also enters into the alignment calculation as a correction and gage data is not filtered. The integration for alignment can be carried down to approximately 1/205 cycle/foot. The expression for gage and crosslevel can be integrated down to 1/300 cycle/foot

Values of selected TQI's were computed for the six FRA track classes from track geometry models. Empirical values of TQI's were obtained by processing 20 miles of test data for each track class. A comparison of theoretical and empirical values is given in Table E-1. The empirical values in general are in good agreement with the theoretical values.

E.2 RIDE QUALITY

Track geometry inputs such as alignment or profile perturbations are the primary causes of vibrations induced in the carbody. The intensity of these vibrations (acceleration levels) can cause lading damage or passenger discomfort. Since track quality indices (TQI's) are a function of the roughness of track inputs, a relationship exists between the TQI's and the Ride Quality Indices (RQI's).

The ride quality of a vehicle can be evaluated either in terms of International Standards Organization (ISO) standards or by using a Wz rating. Figure E-2 shows the relationship between acceleration levels and the RQI's**. The ISO rating is given in terms of reduced comfort exposure time. A factor of 6.31 (16 dB) should be applied to obtain times for exposure limits and a factor

*ENSCO Report No. RTE-80-10, "Analytical Description of Severe Track Geometry Variations," October 1979.

**ENSCO Report No. DOT-FR-79-22, "Wz Rating of Ride Quality-Implementation for FRA/Amtrak Programs," January 1977.

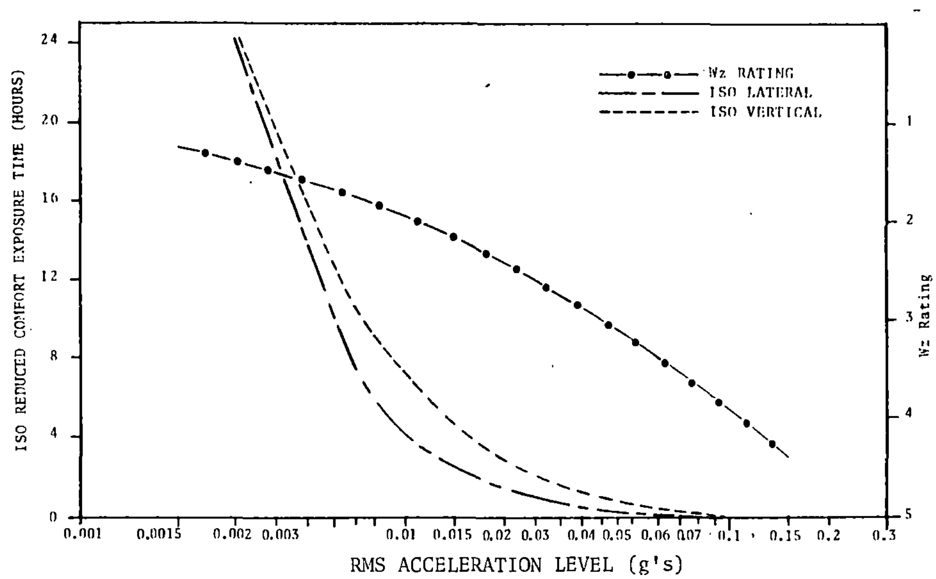

Figure E-2. RQI's as a Function of Acceleration Levels

of 3.16 (10 dB) should be applied to obtain the values for decreasing proficiency*.

Accleration levels induced in the vehicle can be obtained by operating on the track inputs through a transfer function of the vehicle suspension system. A simple vehicle model, as shown in Figure E-3, can be used to approximate the transfer function of the vehicle suspension system. The transfer function $F_1(f)$ for this model is given by**:

$$\left[F_1(f)\right]^2 = \frac{1 + 4\beta^2 \frac{f^2}{f_0^2}}{\left(1 - \frac{f^2}{f_0^2}\right)^2 + 4\beta^2 \frac{f^2}{f_0^2}} \qquad \text{(E-6)}$$

where

f = frequency, in Hz
β = damping ratio

Track goemetry models based on PSD's are represented by a roughness parameter (A) and a set of break frequencies***. Table E-2 lists the relationships between the TQI's and the parameters of the track geometry models for alignment and profile. Once an index is converted to A, mean square power of acceleration can be found by:

$$\sigma^2 = \int_{f_1}^{f_2} (2\pi f)^4\, S(f)\, [F_1(f)]^2 df \qquad \text{(E-7)}$$

The function in the integral is multiplied by $(2\pi f)^4$ to convert the displacement type motion to acceleration power. The distance domain PSD $[S(\phi)]$ can be

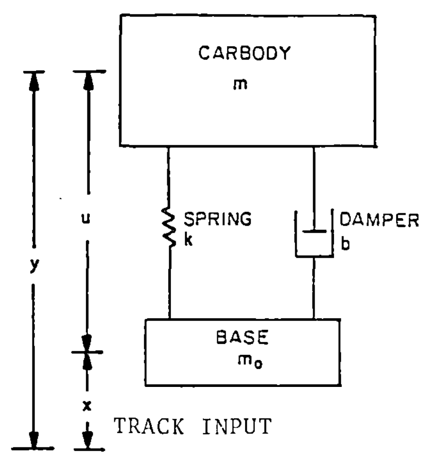

Figure E-3. Simple Vehicle Model

*ENSCO Report No. DOT-FR-75-9, "Computer Implementation of ISO Standard 2631 for Processing Ride Vibration Data," Jul 1975.

**ENSCO Report No. RTE-80-10, "Analytical Description of Severe Track Geometry Variations," October 1979.

***ENSCO Report, "Statistical Representations of Track Geometry," June 1979.

TABLE E-2

RELATIONSHIP BETWEEN TQI'S AND PARAMETERS OF THE TRACK GOEMETRY MODELS

Track Class	Profile				Alignment			
	TQI (inch)	$A \times 10^4$ (in^2-cy/ft)	Break Frequencies (cy/ft) $\phi_3 x10^3$	$\phi_4 x10^2$	TQI (inch)	$Ax10^4$ (in^2 - cy/ft)	Break Frequencies (cy/ft) $\phi_3 x10^3$	ϕ_4 $x10^2$
1	0.34	7.9	7.1	4.0	0.48	5.0	10.0	5.6
2	0.26	4.5	7.1	4.0	0.36	2.8	10.0	5.6
3	0.19	2.5	7.1	4.0	0.27	1.6	10.0	5.6
4	0.14	1.4	7.1	4.0	0.20	0.89	10.0	5.6
5	0.11	0.79	7.1	4.0	0.15	0.50	10.0	5.6
6	0.08	0.45	7.1	4.0	0.11	0.28	10.0	5.6

converted to the time domain PSD [S(f)] by substituting $\phi = f/v$ where v is the speed of the vehicle in feet/second.

The integration limits f_1, f_2 can be determined by:

$$f = v/\lambda \qquad \text{(E-8)}$$

where

v = speed in feet/second

λ = wavelength in feet

It has been shown that the wavelength region important in vehicle dynamics lies between 3 and 300 feet*. For a top speed of 110 mph, a wavelength of three feet will correspond to $f_2 \cong 54$ Hz. On the other hand, at a speed of 10 mph, a wavelength of 300 feet will correspond to $f_1 \cong 0.05$ Hz.

Note that the mean square acceleration levels given by equation (E-7) are a function of vehicle speed, vehicle suspension system (f_0,β) and the value of the TQI. The expression in equation (E-7) was evaluated numerically for different values of f_0, β, v and TQI. The vertical and lateral rms accelerations were computed by taking the square root of the resultant quantity. RMS acceleration levels induced by TQI's corresponding to different track classes are listed in Tables E-3 and E-4. Note that the acceleration levels increase with the resonant frequency and the damping ratio. Results presented in Tables E-3 and E-4 are in good agreement with the actual ride quality tests**.

*ENSCO Report No. RTE-80-10, "Analytical Description of Severe Track Geometry Variations," October 1979.

**ENSCO Report, "Ride Quality Test Results," November 1976.

TABLE E-3

VERTICAL ACCELERATIONS INDUCED BY A PROFILE TQI CORRESPONDING TO DIFFERENT TRACK CLASSES

Track* Class	TQI** (inch)	RMS Acceleration (g's)					
		f_0 = 1 Hz		f_0 = 2 Hz		f_0 = 3 Hz	
		β = 0.5	β = 0.7	β = 0.5	β = 0.7	β = 0.5	β = 0.7
1	0.34	0.0094	0.0099	0.0147	0.0152	0.0186	0.0190
2	0.26	0.0212	0.0238	0.0376	0.0400	0.0500	0.0513
3	0.19	0.0264	0.0306	0.0490	0.0536	0.0678	0.0720
4	0.14	0.0304	0.0361	0.0576	0.0650	0.0820	0.0893
5	0.11	0.0309	0.0373	0.0588	0.0678	0.0849	0.0945
6	0.08	0.0329	0.0399	0.0619	0.0728	0.0901	0.1027

* Freight, ** Profile space curve standard deviation.

TABLE E-4

LATERAL ACCELERATION INDUCED BY AN ALIGNMENT TQI CORRESPONDING TO DIFFERENT TRACK CLASSES

Track* Class	TQI** (inch)	RMS Acceleration (g's)					
		f_0 = 1 Hz		f_0 = 2 Hz		f_0 = 3 Hz	
		β = 0.5	β = 0.7	β = 0.5	β = 0.7	β = 0.5	β = 0.7
1	0.48	0.0097	0.0104	0.0157	0.0163	0.0201	0.0207
2	0.36	0.0205	0.0236	0.0375	0.0408	0.0514	0.0545
3	0.27	0.0255	0.0302	0.0483	0.0542	0.0684	0.0742
4	0.20	0.0293	0.0353	0.0555	0.0642	0.0804	0.0898
5	0.15	0.0300	0.0363	0.0562	0.0662	0.0818	0.0934
6	0.11	0.0320	0.0386	0.0586	0.0700	0.0852	0.0993

* Freight, **Alignment space curve standard deviation.

A Prototype Maintenance-of-Way Planning System, volume I: Final Report (Including Appendices A through E), 1980
US DOT, FRA, A Hamid, D Sawyer, MA Kenworthy, K Rasmussen