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MEASUREMENT PLAN FOR THE CHARACTERIZATION OF THE LOAD ENVIRONMENT FOR CROSS TIES AND FASTENERS

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16. Abstract

This report was prepared as part of the Improved Track Structures Research Program sponsored by the Office of Rail Safety Research of the Federal Railroad Administration. The report is a planning document for a track measurement program to obtain data on the service loads and reactions of cross ties and rail fasteners. These data will be used to validate analytical models for predicting track response and to provide a statistical description of track loading for design and testing improved cross ties and fastener assemblies. The report includes criteria for site selection, an evaluation of measurement parameters, instrumentation and data analysis techniques, and the development of statistical criteria for planning the measurement program.

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PREFACE

This report was prepared by Battelle's Columbus Laboratories (BCL) and Bechtel Incorporated under Contract No. DOT-TSC-1044 sponsored by the Office of Rail Safety Research, Improved Track Structures Research Division, of the Federal Railroad Administration, Washington, D.C.

The overall objective of this contract, which is part of the Improved Track Structures Research Program managed by the Transportation Systems Center (TSC), is to improve the safety and serviceability of cross tie track. This includes an evaluation of the technical and economic feasibility of using synthetic cross ties and rail fastener assemblies to obtain improved component life and long-term performance of railroad track for North American service. This report is a planning document for a measurement program to obtain data on the service loads and reactions of ties and fasteners in support of the program objective.

Dr. Andrew Kish and Mr. Donald McConnell of TSC were the technical monitor and alternate technical monitor, respectively, for the work reported herein. Their cooperation and suggestions are gratefully acknowledged. Donald Ahlbeck of BCL also deserves recognition for his contributions to this measurement plan.

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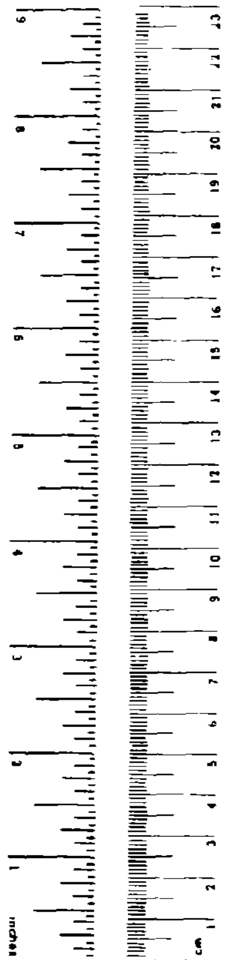
METRIC CONVERSION FACTORS

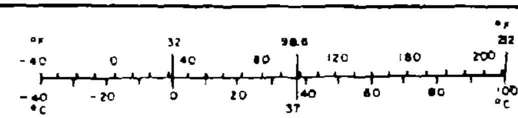
Approximate Conversions to Metric Measures

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



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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1. OBJECTIVES

The objectives of this measurement program are to obtain data on the service loads and reactions of cross ties and fasteners and the load transfer between track components which are needed to:

a. validate analytical models for predicting track response for a range of track design parameters, and

b. provide a statistical description of the loading environment for a typical track section to be used as a basis for design evaluation and laboratory testing of improved cross ties and fastener assemblies.

2. BACKGROUND

This measurement program is part of an on-going research effort to improve the safety and serviceability of cross tie track. This includes an evaluation of the technical and economic feasibility of using synthetic cross ties and rail fastener assemblies to obtain improved component life and long-term performance of railroad track for North American service. Analytical models have been assembled to predict track response to train loads and to evaluate a wide range of track and fastener design parameters. However, it is necessary to validate the analytical procedures by comparison with field data before proceeding with extensive parametric design studies. It is also desirable to obtain statistical data on the loading environment of cross ties and fasteners under typical service conditions to relate track response to component failures, and to assess long-term degradation.

The emphasis in this research effort is on the performance of cross ties made from "synthetic" materials such as concrete, plastic, or steel, rather than wood. Concrete is currently the major synthetic material which has been used for ties in Europe, Japan, and the U.S. Available information on the service performance of wood and concrete tie track has been reviewed to determine the major tie and fastener failure modes. This review was used to identify the parameters (i.e., tie bending stress, rail-seat load, rail displacement, etc.) which govern track performance and component degradation. While the long-term performance of track is the major concern, the proposed measurement program is only intended to record response data for typical service during a short time period of about one week. The predictive methodology will be utilized to relate this measurement of short-term track response to long-term performance.

The original intent of this measurement program was to utilize an existing instrumented section of concrete and wood tie track such as the Kansas Test Track (KTT). However, the premature failure of the KTT has required the selection of a new test site location and the instrumentation needed to satisfy the objectives of this program. The selection of a test site and instrumentation for characterizing the load environment for crossties and fastners are discussed in this measurement plan.

3. SITE SELECTION CRITERIA

The criteria for selecting a track test site must reflect the overall objectives of the program and the practical aspects of conducting track measurements under traffic. The test site selection includes the type of tie and fastener; the desired traffic conditions and track construction; track geometry such as a tangent, curve, or grade; weather conditions; and the particular operating property.

3.1 TRACK CONSTRUCTION

Concrete tie track is a natural choice for evaluating synthetic ties since it currently is the only non-wood tie with significant use. There are several types of concrete ties and fasteners available, including some which meet the most recent American Railway Engineering Association (AREA) specifications and several which do not, but appear to perform adequately in service. For purposes of validating analytical models, the type of tie and the type of fastener are not critical because their characteristics, such as bending stiffness, length and bearing area of the tie, and the fastener stiffness can be included in the analysis to provide a direct comparison with measured results. The type of rail fastener, rigid or flexible, may have some effect on tie loading. However, the stiffness of most current fasteners is high relative to the total stiffness of the roadbed. Therefore, large differences in fastener stiffness may be a significant factor in attenuating high-frequency response from impact loading caused by wheel flats.

The inclusion of a significant variation (20 percent minimum) in tie spacing is recommended for the measurement program to provide a critical validation check for the analytical model since tie spacing is a major track design parameter. This requires a track section with uniform subgrade and ballast conditions and a high standard of track geometry (surface, alinement, and gage) over the entire test length to minimize variations in response from causes other than a variation in tie spacing. Estimations of the expected accuracy for determining statistical descriptions indicate that variations in tie loads which are less than about 20% for two different track sites could not be detected at a high confidence level, see Section 7.3. Therefore, a minimum tie spacing variation of 20% is recommended based on the nearly linear relationship between tie loads and tie spacing predicted by conventional track design equations.

3.2 TRAFFIC CONDITIONS

A test location having typical freight traffic with a minimum of 20 million gross tons (MGT) annual traffic is recommended for this program. A specification of at least 20 MGT is based on a requirement to obtain data for a statistically significant number of axles in a reasonable period of test time. These data requirements will be discussed in greater detail in another section.

3.3 TRAFFIC LAYOUT

The test section should permit operating trains near the maximum design speed for the track. The selection of a maximum speed zone will provide data for maximum dynamic loads. On tangent track, hunting freight car trucks are recognized as a major contributor to high lateral forces, and speeds of 60 mph will ensure that loads from hunting trucks are included. Mixed freight traffic, which includes some 100-ton cars, is recommended to provide statistical data on a broad range of car types for typical North American traffic. It is recommended that the test site selected for validating the analysis models for vertical loading be a section of flat, tangent track. Measurements of track response over a selected length of nominally uniform track construction will be needed to identify the effect of spatial variations in roadbed characteristics, track geometry, and variations in track loading from low-frequency carbody dynamics. There are no established procedures for selecting an appropriate track length. However, a reasonable approach is to select the minimum instrumented track length L using the relation $L \geq V/f_o$, where V is the maximum train speed, and f_o is the lowest natural frequency of the vehicle suspension. This provides data over one cycle of carbody oscillations. An example calculation using 0.8 Hz for the lowest natural frequency and a train speed of 60 mph indicates a minimum instrumented section length of 110 ft would be required. A lead-in section of about 4 times this length, or 440 ft is recommended to separate track sections with different construction. This gives a minimum test section length of about 1000 ft with a 110 ft instrumented section in the middle to record data for trains moving in both directions on a single track.

While it is believed that the loads which determine the most severe loading of cross ties are about the same on tangent and curved track, it is recommended that a test site be located on a curve to determine the most severe lateral loading effects on the rail fastener. The combined vertical and lateral loading on the fasteners in curves represents a critical fastener design condition. The test site should be located on a curve where the maximum normal operating speed gives an unbalanced superelevation approaching 3 in., which is the maximum permissible for today's operating conditions. A curvature greater than 2 deg is preferrable to develop significant lateral loads. The minimum test section length of 1000 ft developed previously for a tangent track represents a minimum length of steady-state curve for the curve test section.

Operational requirements will also have an important influence on site selection. Easy and safe accessibility of the site for personnel and equipment is a necessity, and this may conflict with other requirements. The location should include an access road for locating an instrumentation van. It should also allow for train traffic to be diverted conveniently to another track during installation and checkout of the instrumentation.

3.4 OPERATING PROPERTY

In addition to the technical factors discussed previously, the interest and cooperation of the staff of the operating railroad are a critical factor in selecting a particular test site. It will be necessary for the operating property to provide a track maintenance crew and equipment to assist in the installation of the track instrumentation. Communications with the train dispatcher are needed to provide lead times for train passage and to control train operating speeds when necessary. It is also expected that the test crew will have to work closely with the operating property to establish guidelines for personnel safety when working near the track, to insure security for the track instrumentation and recording equipment during the time when test crews are not present, and to assist in many other aspects of program logistics.

3.5 WEATHER CONDITIONS

It is recognized that weather conditions play a significant role in track performance. Temperature extremes can produce high lateral loads on curves from thermal stresses in the rails. Frozen roadbed conditions can increase tie and fastener loads, and this can cause severe wide-gage problems on wood tie track. Freeze-thaw cycles increase the maintenance of track surface and alinement, and heavy spring rains and thawing are responsible for much of the lining and tamping operations required in the northern part of the U.S. Freeze-thaw cycles may also be quite detrimental to the life of a concrete tie which cracks sufficiently to allow the accumulation of water. The evaluation of these different weather conditions is important for long-term performance evaluation, but it is not an important factor for the objectives of this test program which require data for only a brief period of time. The weather requirements for this test program are to have relatively uniform temperatures and minimal rainfall during the 3- or 4-week test period to eliminate variations in roadbed conditons and to permit completion of the program in the shortest period of time.

3.6 SUMMARY AND RECOMMENDATIONS

Table 3-1 summarizes the site selection criteria which have been recommended, and describes some recent installations of concrete ties which have been evaluated for this measurement program. Only two of the candidate test locations have concrete ties installed at variable tie spacing, which has been identified as a key parameter for the test program. The Florida East Coast (FEC) Railway is the only candidate location which has the variable tie spacing and also has concrete tie track installed on both tangent and curve sections. The major disadvantage of the FEC test site is that the Railroad Concrete Crosstie Corporation(RCCC) ties, a modification of the MR-2 design, do not meet current AREA specifications although they do appear to perform satisfactorily with the 24-in. tie spacing and high-quality granite ballast used as standard construction. Also, the temperate climate in Florida is not a typical environment for much of North America. However as discussed previously, the effect of weather conditions is not a critical factor for the objectives of this program. Consequently, the Florida East Coast Railway is recommended as the test site for this program.

4. MEASUREMENT PARAMETERS

This section discusses the measurement parameters and data requirements which are recommended for meeting the objectives of this measurement program. A detailed review of the major track degradation modes was made to determine the critical response parameters for evaluating track performance, and for selecting specific analytical models for the different modes of degradation. Table 4-1 summarizes the critical parameters and analysis model requirements.

This discussion of measurement parameters will include separate sections for the two different program objectives of model validation and load characterization even though there is a great deal of commonality in the requirements. This will permit the identification of specific differences in the recommendations for the different objectives.

TABLE 3-1. SUMMARY OF SITE SELECTION CRITERIA AND DESCRIPTION OF CANDIDATE TEST LOCATIONS

Site Parameters	Criteria	Sante Fe Streator, IL	Chessie Lorraine, VA	Norfolk & Western Kumis, VA	FL East Coast, Jupiter, FL
Tie/Fastener Type	Unspecified	RT-7S/Pandrol RT-7S/CS-5 RT-7S/DE(10) CC 244C/Pandrol	RT-7S/Pandrol (18) RT-7S/CS-5 (100) CC 244C/Pandrol (100)	RT-7S/Pandrol (400) CC 244C/Pandrol (400)	RCCC(1)/True Temper Cliploc
Ballast	Uniform depth crushed granite or rock	24 in. crushed granite	24 in. crushed granite	18 in. crushed granite	24 in. crushed granite
Tie Spacing, in.	Variable(20% minimum)	24	24	24, 26	20,22,24 tangent 24 curve
Tangent	Required for variable tie spacing	Yes	No	Yes	Yes
Curve	Minimum 2 deg curve, operate at 3 in. unbalance	None	3 deg	None	Several (3 deg curve, 5 in. elevation (convenient)
Test Section Length	≥ 1000 ft (0.2 mile)	400 ft RT-7S 400 ft CC 244C	200 ft RT-7S 200 ft CC 244C	400 ft each configuration	2640 ft (0.5 mile) tangent, 1560 ft (0.3 mile) 3 deg curve
Traffic Type	Mixed freight (some 100-ton cars)	Mixed freight and passenger (100-ton cars)	Mixed freight	Mixed freight and coal	Mixed freight (100-ton cars)
Traffic Density, MGT	≥ 20	18-20	35 (4:1 eastbound).	40-60 (heavy eastbound)	20
Train Speed, mph	≥ 60	79	45-50	45-50	60-65
Available Instrumentation	—	8 strain-gaged ties measure bending moment	None	None	None
No. of Tracks	Double	Double	Single	Double	Double

Note
(1) Railroad Concrete Crosstie Corporation (RCCC), Modified MR-2 design

TABLE 4-1. SUMMARY OF TRACK DEGRADATION MODE ANALYSIS REQUIREMENTS

Degradation Mode	Performance Index	Critical Parameters	Analysis Model Requirements	Load Requirements	Frequency Range, Hz
1. Tie failure from bending and torsion	Number of expected tie failures per mile per MGT based on probability of fracture or exceeding fatigue life	Tie bending and torsion moment probability density for specified traffic. Tie strength probability density for static load failure. Fatigue statistics for tie bending and torsion moments and statistical description of tie fatigue strength in torsion and bending	Single vertical tie finite element model with rail seat loads and moments and variable stiffness ballast support to predict tie bending moments. Estimate of maximum torsional moment based on predicted statistical tie plate loads	Probability distributions of peak vertical rail seat loads and rollover moment for the specified traffic, speeds, and track condition	0-50
2. Rail fastener failure a) Pull-out of tie inserts b) Failure of rail clips	Number of expected fastener component failures per mile per MGT based on probability of fracture or exceeding fatigue life	Probability density of maximum rail seat loads L/V & M_T/V at rail base. Probability density of fastener component strength for static load failure. Statistical description of fastener component fatigue strength	3-D finite element track model which includes non-symmetrical vertical and lateral W/R loads, fastener stiffness, rail torsion and non-linear stiffnesses for fastener and ballast	Probability density of peak vertical, lateral and L/V W/R loads and peak rail seat loads and moments	0-2000
3. Track surface deterioration (vertical profile and cross level) a) Ballast failure and flow b) Subgrade failure and settlement.	Rate of rail profile and cross level deterioration versus wavelength	Probability density of maximum and average tie ballast pressure, maximum subgrade deviator stress ($\sigma_1 - \sigma_3$), cumulative settlement data for ballast and subgrade materials	Vertical track model using Burmister's multi-layer roadbed model and load distribution program to predict ballast and subgrade pressures and tie deflections	Probability density of peak vertical W/R and rail seat loads for specified traffic	0-50
4. Track alinement deterioration	Number of occurrences per mile where critical load for track lateral shift is exceeded	Probability density of maximum lateral force ratio H/P for individual axles. Porbability density of track critical lateral force ratio H_c/P	Vertical track model using Burmister's multi-layer roadbed model and load distribution program to predict vertical tie loads. 2-D finite element lateral track model with thermal loads, rail fastener torsional resistance and nonlinear ballast resistance which is dependent on vertical tie loads	Joint probability density of peak vertical and H/P axle load ratio for specified traffic	0-10
5. Rail rollover	Probability of exceeding critical rail loading condition (L/V)	Probability density of maximum lateral force ratio (L/V) for one rail. probability density of rail critical L/V for rollover	3-D finite element track model which includes non-symmetrical vertical and lateral W/R loads, fastener stiffness, rail torsion and non-linear stiffnesses for fastener and ballast	Probability density of lateral/vertical load ratio for all wheels on one side of one truck	0-10
6. Wide gage	Probability of exceeding critical ratio for tie plate loading on wood ties. Probability of exceeding tie compressive strength on field side of tie plate. Rate of gage change per MGT.	Probability density of maximum L/V load ratio and maximum M_T/V moment ratio for tie plates. Probability density of allowable L/V and M_T/V for tie plate slip and tie crushing on wood ties	3-D finite element track model which includes non-symmetrical vertical and lateral W/R loads, fastener stiffness, rail torsion and non-linear stiffnesses for fastener and ballast	Probability density of L/V load ratio for individual wheels	0-50

H = Lateral axle force   L = Lateral wheel force M_T = Rail rollover moment
P = Vertical axle force   V = Vertical wheel force

4.1 TRACK MODEL VALIDATION

Analytical models have been formulated for predicting the transfer of loads from the wheel/rail (W/R) interface to the track components and roadbed. The principal model which has been selected for vertical load response analysis is a combination of a Burmister's multi-layer elastic roadbed model with an influence coefficient model of the rails, ties, and rail fastener load-deflection characteristics. This program, which will be designated MULTA (MUlti-Layer Track Analysis), predicts deflections and loads on each track component as well as pressures on the ballast and subgrade. A single vertical tie finite element model will be used to predict more detailed tie bending moment distributions for specified rail seat loads and moments and ballast reactions.

A three-dimensional (3-D) finite-element lateral track analysis model has been recommended for this program, but this model has not yet been developed. An alternative choice for the lateral model is a 2-D finite-element model which includes the rails and ties as a frame with flexible restraints from the fastener, but the lateral displacement of the rail head from vertical tie bending, rail torsion, and deflection of the fastener is not included. Therefore, the more complex fastener response contributing to rail rollover and wide gage would not be included.

Table 4-2 summarizes the input data requirements and the response parameters which can be predicted using these models. Considerable data describing the track characteristics are needed to validate these track models. Also, it is not necessary to measure all of the response parameters which can be predicted analytically to verify analytical results. It is important, however, to validate those response parameters which will be the key parameters in track design parameter analyses and in the loading environment needed to design and test fasteners and ties.

Table 4-3 gives a detailed listing of the measurement parameters for validating the track models listed in Table 4-2. The parameters are identified as load data, track data or response data. Load data includes W/R loads for the track models and rail seat loads for the vertical, single tie model. The evaluation of the load transfer from the rail to tie in terms of the percent load carried by each tie and the attenuation of high-frequency W/R loads is of particular interest.

TABLE 4-2. TRACK ANALYSIS DATA REQUIREMENTS

Analysis Model	Load Data	Track Data	Predicted Response
I. Vertical multi-layer track analysis program (MULTA)	Vertical W/R loads Axle spacing Car spacing	Rail and tie EI Fastener vertical stiffness, Tie spacing and size Ballast and subgrade modulus, Poisson's ratio Ballast depth	Rail deflection Tie/fastener load Tie deflection Tie bending moment Ballast stresses Subgrade stresses
II. Vertical single tie model (FRAM 2)	Rail seat vertical and lateral force and rollover moment	Tie EI distribution Tie size Ballast stiffness distribution under tie	Tie bending moment Tie stresses Tie deflection Tie/ballast loads
III. Lateral 2-D track model (FRAM 2)	Lateral W/R load Axle spacing Car spacing	Rail EI Fastener lateral stiffness Fastener yaw stiffness Tie spacing Tie lateral resistance with vertical load Track gage	Rail deflection Tie/fastener lateral and yaw load Tie/ballast load
IV. Lateral 3-D track model (NASTRAN)	Vertical W/R load Lateral W/R load Axle spacing Car spacing	Rail EI_x, EI_y, GJ Fastener vertical, yaw and torsional stiffness Tie EI distribution Tie spacing Ballast vertical and lateral stiffness	Rail deflection (V&L) Tie/fastener loads and moments (V,L,M_r) Tie deflection Tie bending moment Tie/ballast loads (V&L)

TABLE 4-3. MEASUREMENT REQUIREMENTS FOR VALIDATING TRACK ANALYSIS MODELS

Measurement Parameters	Test Requirement/Purpose
I. Load Data	
a. Vertical and lateral W/R load	Measure peak load over short rail length to correlate with maximum track response
b. Rail seat vertical force	Determine vertical rail/tie load transfer and attenuation of high frequency W/R load
c. Rail seat lateral force	Determine effect on tie bending moment and rail/tie load transfer
d. Rail seat rollover moment	Determine effect on tie bending moment and rail/tie load transfer
e. Axle and car spacing	Determine from train speed and passage time to evaluate interaction from multiple wheels
II. Track Data	
a. Rail stiffness properties EI_x, EI_y, GJ	Determine from nominal size and estimated wear
b. Tie stiffness EI	Correlate laboratory measurement with tie design configuration
c. Fastener vertical, lateral, and rollover stiffness	Laboratory measurement with variable vertical load. Yaw stiffness is low priority
d. Tie spacing	Average tie spacing in ± 6-ft length from track instrumentation
e. Ballast vertical modulus and stiffness distribution	Plate bearing test on compacted ballast under tie
f. Subgrade modulus	Plate bearing test on subgrade
g. Ballast and subgrade Poisson's ratio	Estimate from literature data
h. Ballast depth	Measure at test site excavation
i. Tie lateral resistance with vertical load	Requires external lateral load applied to several ties to determine average lateral resistance. Estimate from literature and available test data

TABLE 4-3. MEASUREMENT REQUIREMENTS FOR VALIDATING TRACK ANALYSIS MODELS (Continued)

Measurement Parameters	Test Requirement/Purpose
III. Track Response	
a. Vertical rail displacement	Measured under light and heavy cars to determine vertical track modulus and validate vertical track model
b. Lateral rail/tie displacement	Measured under light and heavy cars to validate lateral track model
c. Vertical tie displacement	Can be estimated from rail displacement data and fastener stiffness
d. Lateral tie displacement	Expected to be minimal except for infrequent shifts caused by excessive lateral load. Data needed to validate lateral track model
e. Rail seat vertical load	Validate load transfer predicted by vertical track model
f. Rail seat lateral load, rollover moment, and yaw moment	Validate load transfer predicted by lateral track model and determine effect on tie bending moment. Yaw moment is a low priority parameter
g. Tie bending moment	Bending Moment at rail seat and tie center are critical tie loading conditions
h. Tie torsional moment	Torsional moment at tie center is critical tie loading condition
i. Tie/ballast pressure distribution	Measure tie/ballast pressure at 5 to 10 locations along tie length to validate model for predicting tie bending moment
j. Ballast and subgrade stresses	Requires implanting of pressure transducers in existing track. Not recommended for revenue service test. More suitably obtained from track laboratory
IV. Miscellaneous	
a. Vertical rail and tie acceleration	Determine dynamic transfer function and tie inertial forces
b. Rail bending strain	Provide data for validating rail stress analysis model

The requirements for track data listed in Table 4-3 include those parameters which represent input data for the analytical models. While determining rail section properties and tie spacing are straightforward, characterizing the roadbed is much more difficult. Vertical track modulus determined from the difference in rail deflection under light and heavy cars is a minimum requirement. However, additional detail on the variation in roadbed stiffness under a tie and the average subgrade modulus along the track are needed to fully use the capabilities of the MULTA program and the vertical single tie model. A minimum effort would include making plate bearing tests at several locations on the compacted ballast under one tie when it is removed. A plate bearing test could also be made on the subgrade between ties when a crib section is excavated to determine ballast depth. Conducting this investigation at one location on each measurement site would at least provide representative values for the selected test sites, although more than one location is needed to give credibility to the measured results.

The data required to characterize the nonlinear lateral resistance of the track for variable vertical loading are much more difficult to obtain than comparable data on track modulus for vertical loading. Vertical load characteristics can be determined using a stationary train, but a train on an adjacent track or some stationary object is needed to apply lateral loads. The difficulty of making these lateral measurements and the recognition of the fact that track response from vertical loads is a major governing factor in track design leads to the recommendation that this initial validation effort be concentrated on the vertical track models.

Fastener load-deflection data are also needed for the analytical models. They can best be done in the laboratory where the interaction between simultaneous vertical and lateral loads can be controlled. A measurement of fastener yaw stiffness has a lower priority for most fasteners which have relatively low restraint for yaw displacements of the rail relative to the tie. Yaw stiffness data are only needed for the lateral track models.

The requirements listed in Table 4-3 for the track response data include those needed to validate both vertical and lateral models. The validation of vertical track models requires measuring vertical rail deflection, vertical tie plate loads, tie bending moments, and the tie/ballast reaction pressure under the tie length. Ballast and subgrade stresses are also key parameters for long-term track degradation, but installing pressure transducers in existing track requires extensive excavation and several months of reconsolidation to obtain reliable data. It is recommended that measurements for validating the pressure distribution in the roadbed be done in a track laboratory where uniformity of the soil and ballast and the track loading can be well controlled.

The response requirements for lateral loading include the lateral displacement of the rail relative to the tie, the lateral displacement of the tie, and the lateral force, rollover moment, and yaw moment on the rail seat. It is important to realize that the lateral force and rollover moment on the rail seat contribute to tie bending in the vertical plane as well as being important factors in the track response from lateral W/R loads. Consequently, they are important for the tie loading environment even if the validation of lateral track analysis models is given a lower priority for this measurement program. The measurement of lateral tie displacement could be eliminated by this decision, but the lack of available information about lateral tie displacements with normal traffic is sufficient to justify including this measurement in the program.

Table 4-3 lists vertical rail and tie accelerations and rail bending strain under a miscellaneous heading. The acceleration measurements are recommended to determine how the dynamic response of the rail is attenuated by the rail mass. Rail fastener loads during the rail "uplift" portion of the deflection wave are also of considerable interest. Rail bending strains will be measured in the head fillet region and at the rail base to provide some typical data for the rail stress analysis being done concurrently as well as to confirm track modulus measurements.

4.2 CHARACTERIZATION OF LOAD ENVIRONMENT

The measurement parameters needed to characterize the load environment for ties and fasteners are the same as those required to validate analysis models. A comprehensive set of time history data for all measurement parameters for a few cars of a train would be adequate for validating analysis predictions, whereas data for a large number of trains is needed to characterize the statistical loading of ties and fasteners. Therefore, the major differences in the measurement requirements for the two different objectives are in the data analysis requirements rather than in the selection of measurement parameters. These data analysis requirements will be discussed in the following section.

5. INSTRUMENTATION AND DATA ANALYSIS REQUIREMENTS

The measurement and data analysis requirements recommended for validating track analysis models and obtaining statistical load data are summarized in Table 5-1. The statistical data requirements have been subdivided to show differences in the requirements for fastener performance, tie performance, and overall track performance. The requirements for the different categories of measurement parameters will be discussed separately.

5.1 WHEEL/RAIL LOADS

The measurement of W/R loads is required to characterize the input loading to the track structure. The category of W/R load data includes loads in the vertical and lateral directions and the L/V load ratio. The most important requirement for W/R load data is to provide a complete data set for validating track analytical models by correlating the wheel forces with fastener and tie loads and motions. However, the measurement of W/R loads is also recommended to evaluate overall track performance because determining the effect of tie spacing on track stiffness, and its subsequent effect on the dynamic component of W/R loads, is of considerable interest for this program.

The instrumentation for measuring W/R loads will be strain gage patterns applied to the rail. A frequency response to 2 kHz is required to record data from impacting loads such as wheel flats. Peak amplitude probability density (PAPD) data will be the major data analysis technique used to determine the effect of train speeds and vehicle type on the W/R loads through the different test sections. Joint amplitude probability

TABLE 5-1. SUMMARY OF TRANSDUCER AND DATA ANALYSIS REQUIREMENTS FOR TRACK MEASUREMENT PROGRAM

Measurement Parameter	Maximum Transducer Range	Frequency Response, Hz	Data Analysis Requirements			
			Analysis Validation	Fastener Performance	Tie Performance	Track Performance
I. W/R Loads						
a. V	60 kips	2000	TH, PAPD	-	-	PAPD
b. L & L/V	±30 kips	2000	TH, PAPD	-	-	PAPD
c. L/V vs V	-	-	-	-	-	JAPD
II. Fastener Loads						
a. V	±25 kips	50	TH, PAPD	PAPD	-	PAPD
b. L & L/V	±25 kips	50	TH, PAPD	PAPD	-	PAPD
c. M_r & M_r/V	±150 kip-in.	50	TH, PAPD	PAPD	-	PAPD
d. L/V vs V	-	-	-	JAPD	-	JAPD
e. M_r/V vs V	-	-	-	JAPD	-	JAPD
f. Bolt force	20 kips	50	-	APD, FS	-	-
III. Tie Loads						
a. Tie bending moment	±200 kip-in.	50	TH, PAPD	--	PAPD, FS	-
b. Tie torsion moment	±75 kip-in.	50	TH, PAPD	--	PAPD, FS	-
c. Tie/ballast pressure	0 - 100 psi	50	TH	--	-	-
IV. Track Deflection						
a. Vertical rail displacement	±0.10 in.	50	TH, PAPD	-	-	PAPD
b. Lateral rail/tie displacement	±0.25 in.	50	TH, PAPD	PAPD	-	-
c. Lateral tie displacement	±0.25 in.	50	TH, PAPD	-	-	PAPD, Cumulative deformation
V. Track Acceleration						
a. Vertical rail acceleration	±500 g	2000	TH, PSD	PSD	-	-
b. Vertical tie acceleration	±50 g	2000	TH, PSD	PSD	-	-
VI. Rail bending strain	1000 μin./in.	2000	TH	-	-	-

Nomenclature

PAPD - Peak Amplitude Probability Distribution and Density Analysis (mean value and standard deviation included)
JAPD - Joint Amplitude Probability Distribution and Density Analysis
FS - Fatigue Statistics
TH - Time History (Work Train and 1-2 Revenue Trains)
PSD - Power Spectral Density
APD - Amplitude Probability Density and Distribution Analysis

density (JAPD) data will be used to determine the joint occurrence of L/V ratios and vertical load. The strong dependence of the lateral response of rail fasteners and track on the vertical load dictates this requirement for evaluating the simultaneous occurrence of high lateral and vertical loading.

5.2 FASTENER LOADS

The category of fastener loads includes those highest priority forces and moments which are transmitted from the rail to the tie. They are the V, L, and L/V loads and the rollover moment and moment ratio (M_r/V) at the rail base. They are the major loads used in the current fastener specifications for which an accurate data base is needed. The vertical fastener load is used as a reference parameter for the load ratio to emphasize the need for correlating the phase relations for the various loads with the vertical load application. Fasteners typically exhibit very non-linear load-deflection characteristics which are strongly dependent on the vertical load on elastomeric elements. PAPD data will be the principal analysis format for the evaluation of fastener loads for the different types of traffic and for the different test sections. The JAPD will be used to evaluate the simultaneous occurrence of L/V and M_r/V with the vertical load. The variation of fastener loading as a function of vehicle weight, train speed, and tie spacing will be used as a key indicator for overall track performance.

The measurement of the holddown force on fastener bolts is the only fastener component load measurement recommended for this program. The bolt load environment, and particularly the variation in bolt load under traffic, is strongly dependent on the design aspects of a specific fastener. However, the rail clip used by the FEC is typical of several different fasteners which use relatively rigid support pads with a semi-rigid rail clip between the rail base and the fastener bolt. The frequent occurrence of failures of these holddown bolts has resulted in giving this measurement a high priority.

Measurement parameters which have a constant mean value independent of train passage, such as the total force in a fastener bolt, must be evaluated differently to describe the total variation of the bolt load. An amplitude probability distribution (APD) of a continuous load signal gives the probability (percent of time) that the load, rather than just the peak load for each axle pass, exceeds any selected load limit. Bolt load data will also be analyzed with regard to fatigue statistics to quantify fatigue damage potential. The fatigue statistics will describe the fluctuating bolt force by determining a mean value and a range for each separate variation. Rain-flow or range-pair cycle counting procedures are typical techniques for determining an appropriate fatigue loading spectrum. A particular technique will be selected after a detailed inspection of the bolt force data.

5.3 TIE LOADS

Tie bending moments at the rail seat and tie center and tie torsional moments at the tie center have been identified as the major loading components which are responsible for tie failures. Both amplitude statistics and fatigue statistics may be needed to characterize the tie loading environment. The question of whether concrete ties fail in service because of a single occurrence of a very high load causing fracture, or from cumulative fatigue damage from many lower-amplitude stress cycles, has been identified as one of the major concerns for this program. Data from this measurement program may or may not, give further insight on this question. Evaluation of the effect of tie spacing on the tie loading environment is also one of the major objectives.

The distribution of the support reaction between the tie and ballast is the principal unknown factor in validating the bending moments predicted by analytical models. Therefore, the simultaneous measurement of V, L, and M_r on the rail seat, the bending moments at the tie center and rail seats, and the tie/ballast pressure distribution along the length of the tie are needed to fully validate analytical predictions of these bending moments. Time history recordings of the ballast pressure distribution under the tie for a few selected train passes will be adequate to determine the shape of this distribution and to correlate the maximum pressure with the maximum rail fastener loads which occur. Therefore, there is no requirement for statistical data on the ballast pressures.

5.4 TRACK DEFLECTION

Track deflection measurements recommended for this program have been restricted to measuring the absolute vertical rail displacement, the lateral deflection of the rail head relative to the tie, and the absolute lateral tie displacement. Measurements of the vertical displacement of the rail for a work train and one or two revenue trains will be used to determine the overall track modulus for that particular section of track and to determine how displacement varies for typical traffic. Although rail fastener loads are the key factors for fastener tests, design, and model validation, the response of the fastener in terms of deflections under service loading is also important because the rail deflection is more directly related to the safety aspects such as excessive gage and rail rollover. For this reason, the measurement of lateral displacement of the railhead, relative to the tie, has been recommended. These data will be correlated with the fastener loading and used to evaluate current fastener specifications for maximum allowable displacements.

The measurement of lateral tie displacement could be neglected if the objective of validating a lateral track model is given a lower priority for this program. However, very little is known about the mechanism which governs the degradation of lateral track alinement. It is hypothesized that lateral deflections for most traffic are quite small and within the elastic range. Therefore, no significant change in alinement occurs. However, track lateral resistance exhibits a breakaway friction characteristic, so that once a critical loading condition is exceeded, a relatively large permanent deformation could occur. The questionable nature of this behavior suggests that the measurement of absolute lateral displacement of at least one tie in each test section would be desirable. This would require a PAPD analysis of the displacements under traffic and a recording of the cumulative displacement of the track before and after each train pass.

5.5 TRACK ACCELERATION

As discussed previously, vertical rail and tie accelerations will be recorded to determine the frequency response characteristics of the fastener and to evaluate tie inertial forces. A frequency range to 2kHz is recommended for the measurement system to record impact accelerations. The frequency content will be determined by an analysis of the (PSD) for a limited number of train passes. No amplitude statistics are planned for the acceleration data.

5.6 RAIL BENDING STRAIN

A recording of the bending strain time history will be made to provide some typical data for the concurrent rail stress program, as well as to verify track modulus measurements. Simultaneous recording of W/R load, tie/fastener load, and bending strain will be used to verify the accuracy of the stress analysis models.

6. EVALUATION AND SELECTION OF INSTRUMENTATION

This section includes a brief review of available instrumentation and measurement techniques for fulfilling the data requirements discussed in sections 4 and 5. The limitations of available measurement techniques are identified, and recommendations are made for new instrumentation, when necessary.

6.1 TRACK DATA

Item II in Table 4-3 lists the basic data needed to describe the track for analysis purposes and outlines the procedures for obtaining these data using laboratory and field measurements. Most of these measurements are relatively straightforward, and further detail is unnecessary. However, some additional discussion on the determination of vertical track modulus and the ballast and subgrade properties is included in this section.

Measurements of vertical track modulus made since the early 1900's have demonstrated the need for loading several ties simultaneously, rather than a single tie, to include the effect of continuity in the roadbed which is not otherwise included in the assumption of a Winkler foundation. The effect of nonlinear load-deflection characteristics of track has been recognized more recently by using the difference in deflection from a light and heavy load on the track to determine modulus. This eliminates the relatively large initial deflections representing free-play between the rail and ties and between the ties and ballast, and gives a track modulus which better represents the track response under loaded cars. This procedure is based on using the equation for track deflection,

$$(Y_h - Y_\ell) = \frac{(P_h - P_\ell)}{2U^{3/4}\ (4EI)^{1/4}} \quad , \qquad (6\text{-}1)$$

where Y_h and Y_ℓ are the maximum rail deflections under the heavy wheel P_h and the light wheel load P_ℓ, respectively, and U is the effective track modulus for this loading condition. The light wheel load should be in the range of 8 to 12 kips, and the heavy wheel load should be in the 25 to 30-kip range.

In addition to a measurement of track modulus, procedures for evaluating the separate properties of the ballast and subgrade are needed for the layered representation of the roadbed materials. The following procedure is recommended to obtain representative data for a particular section of concrete ties:

a. Remove two adjacent ties and make a load-deflection plate bearing measurement at a minimum of 5 locations on the ballast surface in the footprint of each tie. An 8-in. diameter circular loading plate is recommended for use with concrete ties which are 11 to 12 in. wide. A relatively dry mixture of plaster-of-paris should be poured on the ballast to provide a uniform, level-loading surface and to restrain motion of the top layer of ballast in contact with the loading plate. A fixed reference beam supported outside the track can be used as a displacement reference, and data from two displacement transducers should be averaged to determine plate deflection. Ballast loading to about 100 psi represents realistic track loading conditions. If a rail car is used for the reaction load, all wheels of the car should be a minimum of 6 ft from the loading point.

b. Excavate the ballast crib at the location of the two removed ties to determine the effective ballast depth. Repeat the plate bearing tests on the subgrade with maximum pressures of at least 20 psi. Data from (a) and (b) will be used in an iterative procedure with the multi-layer track analysis model to determine representative Young's modulus values for the ballast and subgrade layers.

c. Measure in situ moisture and density of the subgrade at a minimum of three locations in the excavated pit. Sufficient soil shall be removed to permit a laboratory evaluation of Atterburg limits, an optimum moisture-density curve, and a sieve analysis for soil classification. These data will indicate the type of soil used for the track subgrade and its compaction relative to optimum. It will also provide a description of the soil properties for identification purposes and for comparison with similar data from future track tests.

Vibroseismic determination of the variation of the shear and Young's modulus with depth in the subgrade is recommended as an alternative or supplemental procedure for determining subgrade properties.

6.2 WHEEL/RAIL LOADS

Because of the statistical form in which W/R load data will be presented, point sampling of vertical and lateral forces from passing trains is a satisfactory measurement technique. Of several available techniques reviewed in [6-1] and [6-2], there are two sampling circuits, one for vertical and one for lateral W/R load which are recommended for this program. Prior experience with these circuits and correlation with an instrumented wheel set has proven their reliability and accuracy. Both circuits measure the effect of shear force in the rail and have influence lengths as shown in Figure 6-1. Also shown in this figure are the longer influence lengths associated with measurements of vertical tie plate load and vertical rail deflection.

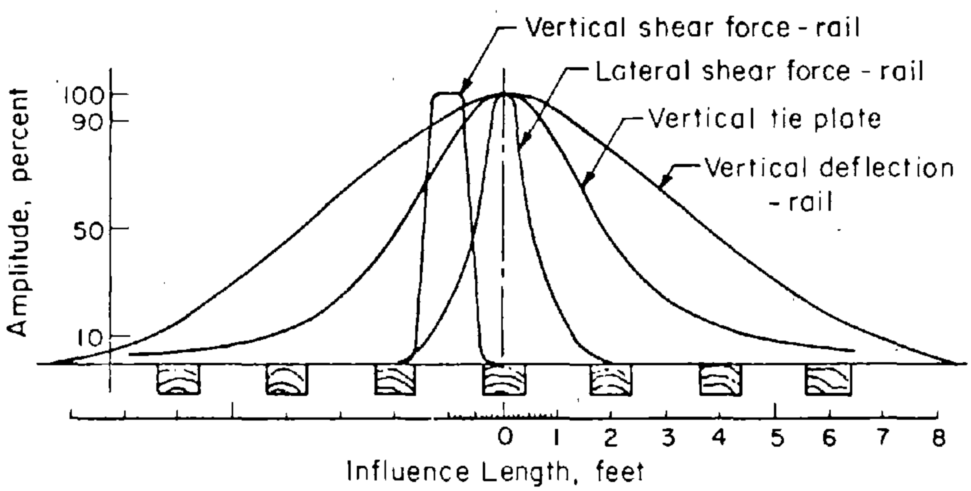


FIGURE 6-1. TYPICAL INFLUENCE LENGTHS OF WAYSIDE TRANSDUCERS

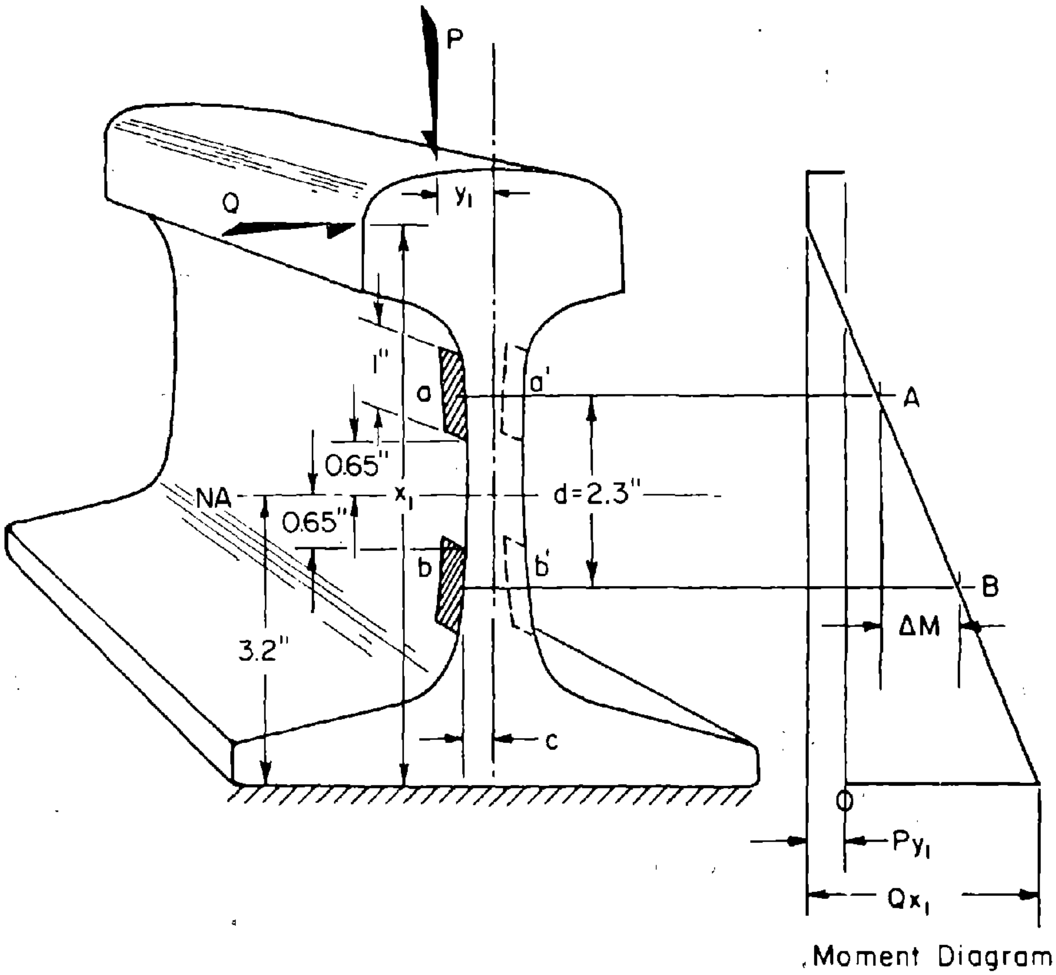
6.2.1 Lateral Shear Force Circuit

The lateral shear force circuit uses the principle that shear force in a cantilever beam is proportional to the change in bending moment. Figure 6-2 illustrates how this is applied to a rail section and schematically describes the idealized cantilever beam concept. Although there are limitations to this approach, field experience has indicated that this circuit works very effectively, with frequency response limited only by localized structural resonances of the rail. Field static calibrations have shown good circuit linearity when the rail is loaded laterally with a hydraulic ram and vertically by the axle of a test vehicle. Vertical cross talk influences the sensitivity of the circuit because of variations in rail base support with changes in vertical load. This effect can be reduced with positive hold down fasteners.

The lateral W/R load circuit installations in this country have been successfully installed in the field using weldable strain gages which require minimum preparation of the rail at the test location. This circuit has no effect on track characteristics, and it is not necessary to disturb the track structure during installation (except where accessibility is reduced around special track work such as switch points). Field calibration is necessary after installation, which requires access to the track (track time) and a test vehicle for applying vertical load. Field experiments have shown changes in sensitivity (gain) with variation in tie support. When removing the vertical wheel load, gain may vary from +10 percent with well supported rail to -30 percent with poorly supported rail. For best results, this circuit should be installed directly over the center of the tie, and it should be calibrated for sensitivity under the extreme ranges of axle loads to be measured. The measurement is not affected by changes in the location of the lateral load on the rail head.

6.2.2 Vertical Shear Force Circuit

The vertical shear force circuit measures the net shear force difference between two gaged regions. If there is no direct support under the



$Q \propto V$ (shear force)

$V = \frac{\partial M}{\partial x}$ (independent of P, x_1, y_1)

$$V = \frac{M_B - M_A}{d}$$

$$M_A = \left(\frac{EI}{c}\right)\epsilon_A$$

$$V = \frac{EI}{cd}(\epsilon_B - \epsilon_A)$$

$$Q \propto (\epsilon_B - \epsilon_A) \text{ where } \begin{cases} \epsilon_A = \epsilon_a - \epsilon_{a'} \\ \epsilon_B = \epsilon_b - \epsilon_{b'} \end{cases}$$

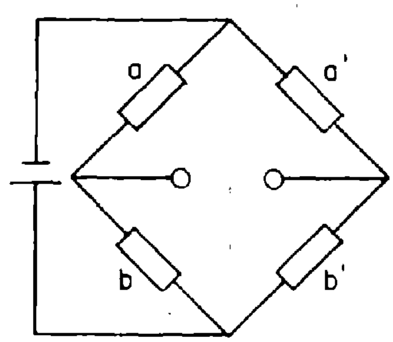


FIGURE 6-2. LATERAL RAIL LOAD MEASUREMENT USING SHEAR FORCE STRAIN GAGE CIRCUIT ON 132 LB RAIL

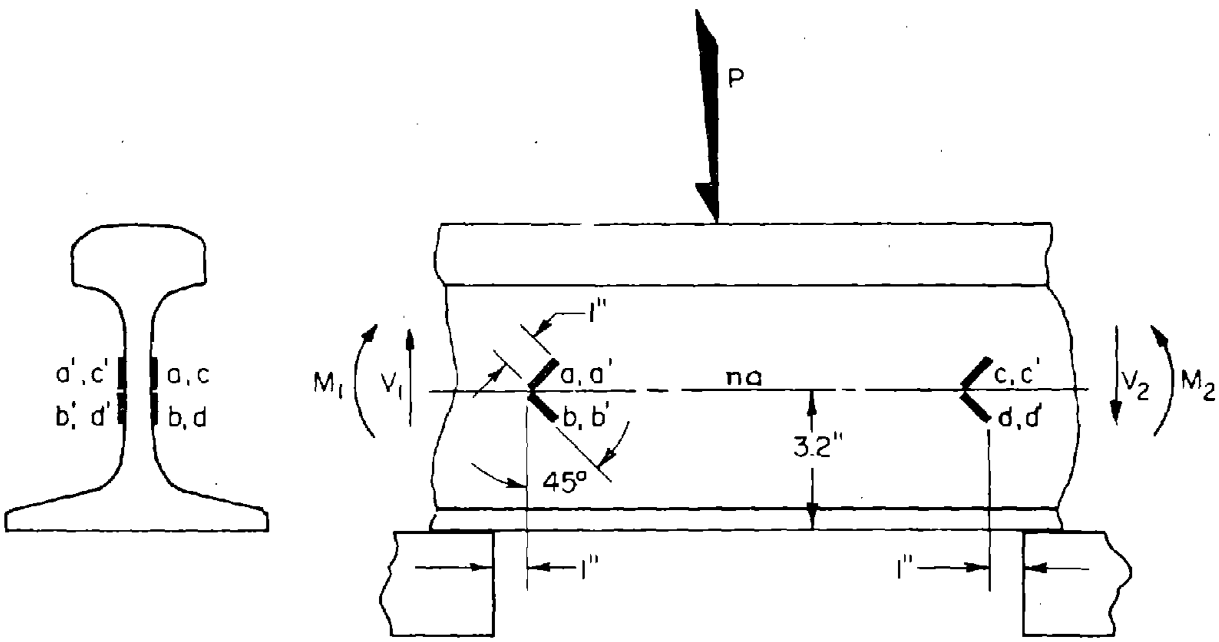
rail within this gaged region, then the output of the circuit is proportional to vertical wheel load, as shown in Figure 6-3. The gage elements at either end location are oriented at 45 degrees to measure the principal strains from the vertical shear force. The gage configurations at the two locations are identical and they could be wired independently. The outputs would then be subtracted to get the net shear force. The subtraction can also be performed within the bridge shown schematically in the lower portion of Figure 6-3.

The zone of influence of this circuit is defined primarily by the distance between the two gaged areas. This allows an influence length of approximately 7 in. at the 90-percent amplitude and 11 in. at the 50-percent amplitude, as shown in Figure 6-1. These values were taken from actual field measurements where the gage circuit was installed between ties at approximately 10 in. between gages. The Florida test site will allow for approximately 13 in. between gages on a 20-in. tie spacing, and about 17 in. between gages for the 24-in. tie spacing.

These circuits can be calibrated by observing the output amplitudes underneath several slowly moving locomotives where the total locomotive weight is known within a small percentage error or by using cars which have been weighed. The average load from several axles can then be used to adjust the sensitivity of the strain circuit.

6.3 FASTENER LOADS

The loads transmited from a rail to a tie are transmitted through the fastener via multiple load paths. Figure 6-4a illustrates the various reaction loads within the fastener. To measure these distributed loads at discrete locations, the assembly is modeled as shown in Figure 6-4b. The primary vertical load path is through the railpad (K_1 and K_2) because the pad stiffness is estimated to be 15 to 20 times greater than the rail clips (K_3 and K_4). Providing load cells at K_1 and K_2 will measure the net rail seat load, which is the parameter of major significance to this program. Total rail seat reaction can be determined by simultaneously monitoring the change in fastener bolt preload.



$$P = V_1 - V_2$$

$$V_1 \sim \epsilon_1$$
$$V_2 \sim \epsilon_2$$

$$\epsilon_1 = \epsilon_a - \epsilon_b + \epsilon_a' - \epsilon_b'$$

$$\epsilon_2 = \epsilon_c - \epsilon_d + \epsilon_c' - \epsilon_d'$$

$$P \sim (\epsilon_1 - \epsilon_2)$$

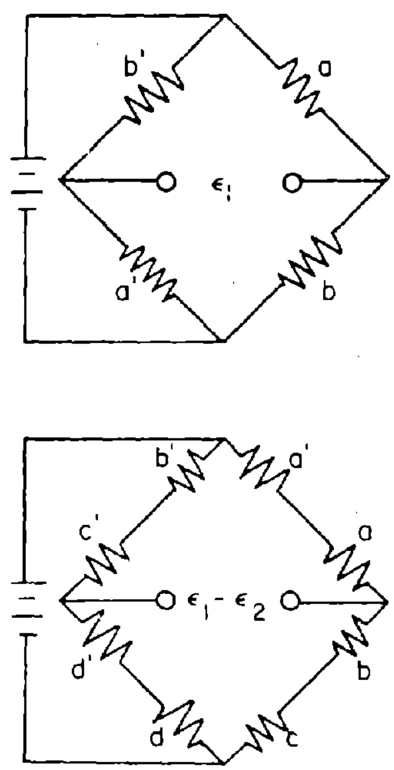


FIGURE 6-3. WHEEL/RAIL VERTICAL LOAD CIRCUITS USING RAIL SHEAR STRESS TO MEASURE LOAD ON 132 LB RAIL

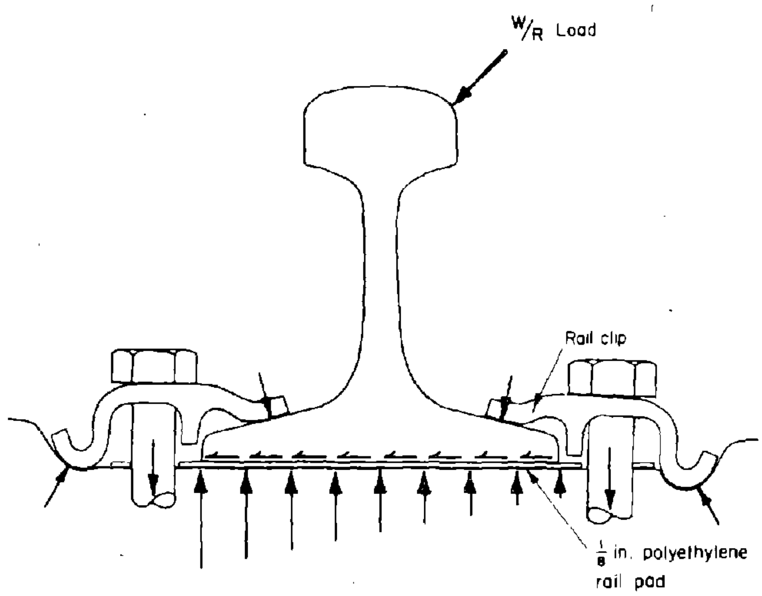


FIGURE 6-4a. FASTENER LOAD DISTRIBUTION

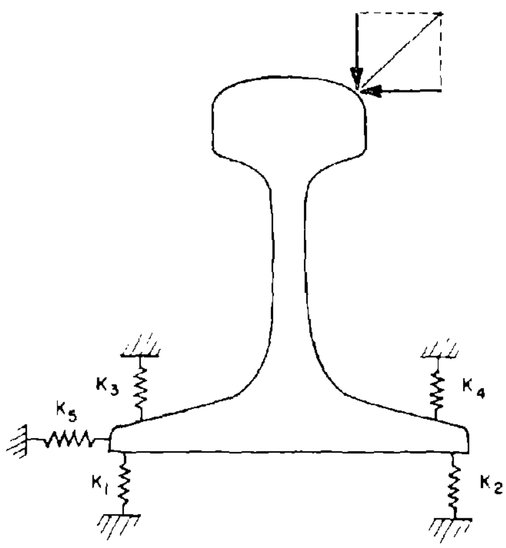


FIGURE 6-4b. RAIL FASTENER STIFFNESS MODEL

Because there are no existing rail fastener load cells capable of being used with the FEC concrete tie, a recommended new design is included in Figure 6-5. This design is capable of measuring the net vertical tie reaction and the net lateral moment from a combined lateral load and an eccentric vertical load. Vertical fastener stiffness will be reduced somewhat by the load cell, primarily because of additional bending in the rail base and by the reduction in loaded area on the rail pad. However, the effect of these changes on the total stiffness of the tie and roadbed is minimal because the roadbed stiffness is much lower than the fastener stiffness. Lateral shear force at the rail base cannot be measured with this design. However, this approach is recommended because of the significant cost and time penalty associated with the development of a full biaxial load cell design.

There are two techniques which can be used to measure hold-down force on fastener bolts: instrumented bolts or instrumented load washers. The instrumented bolt or cap screw is usually custom made for a specific application because the diameter and thread pitch as well as the length are unique to that application. On the other hand, instrumented load washers are commercially available devices which need only be selected for bolt diameter. It is recommended that load washers be used to measure fastener loads.

Two load washers will be required to simultaneously monitor the fastener bolt loads on one rail fastener assembly. It is also recommended that the load washer be mounted over a spherical washer set to reduce the edge loading from the slightly canted rail clip. Figure 6-6 illustrates the total bolt force measuring assembly. By substituting proper bolt lengths, the measurements can be made on standard ties as well as the ties having tie plate load cells installed.

6.4 TIE LOADS

6.4.1 Strain-Gaged Ties

The measurement of bending and torsional moments within the tie can be accomplished using strain gages installed directly on ties in service.

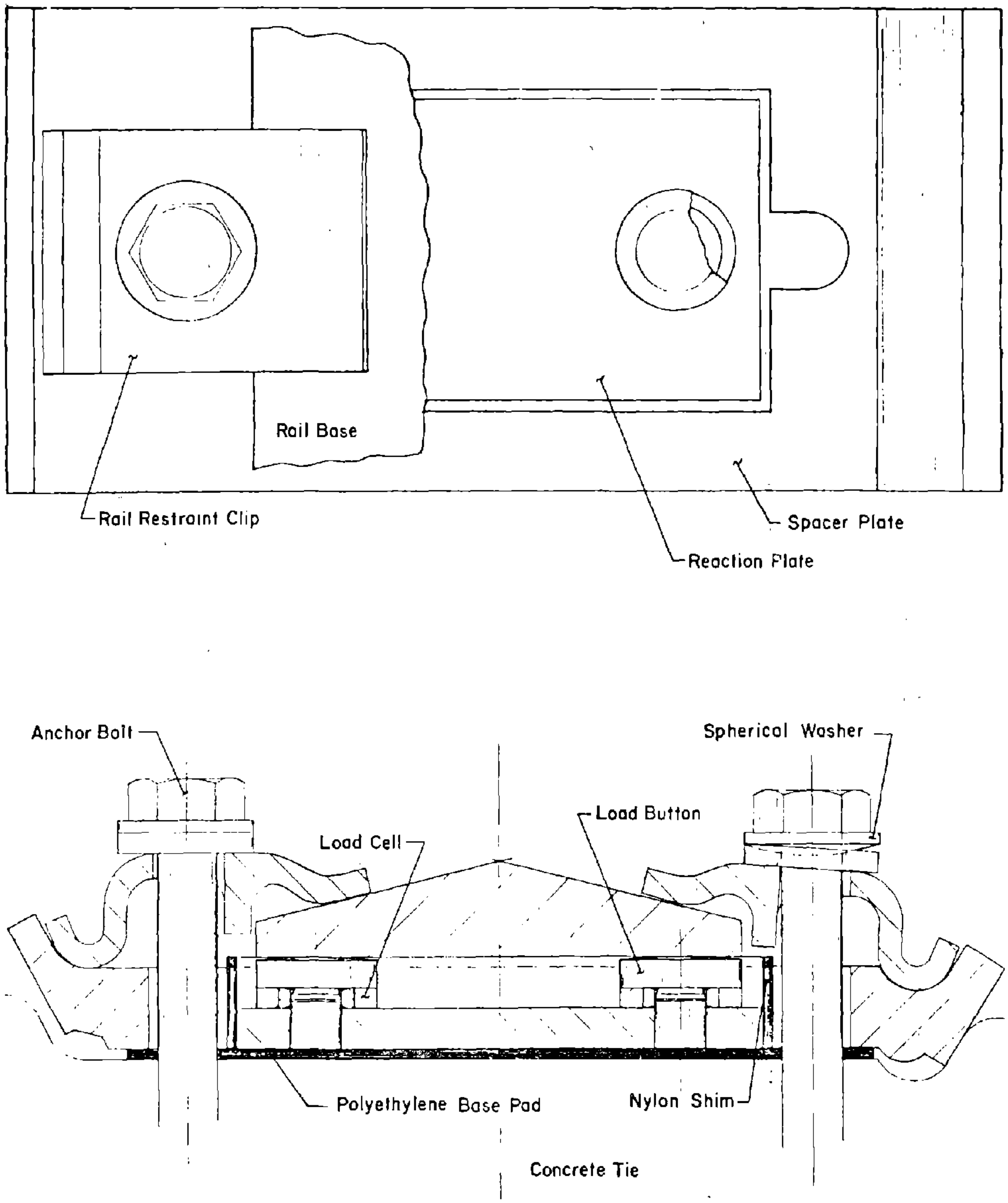


FIGURE 6-5. TIE PLATE LOAD CELL DESIGN RECOMMENDED FOR FEC TIE

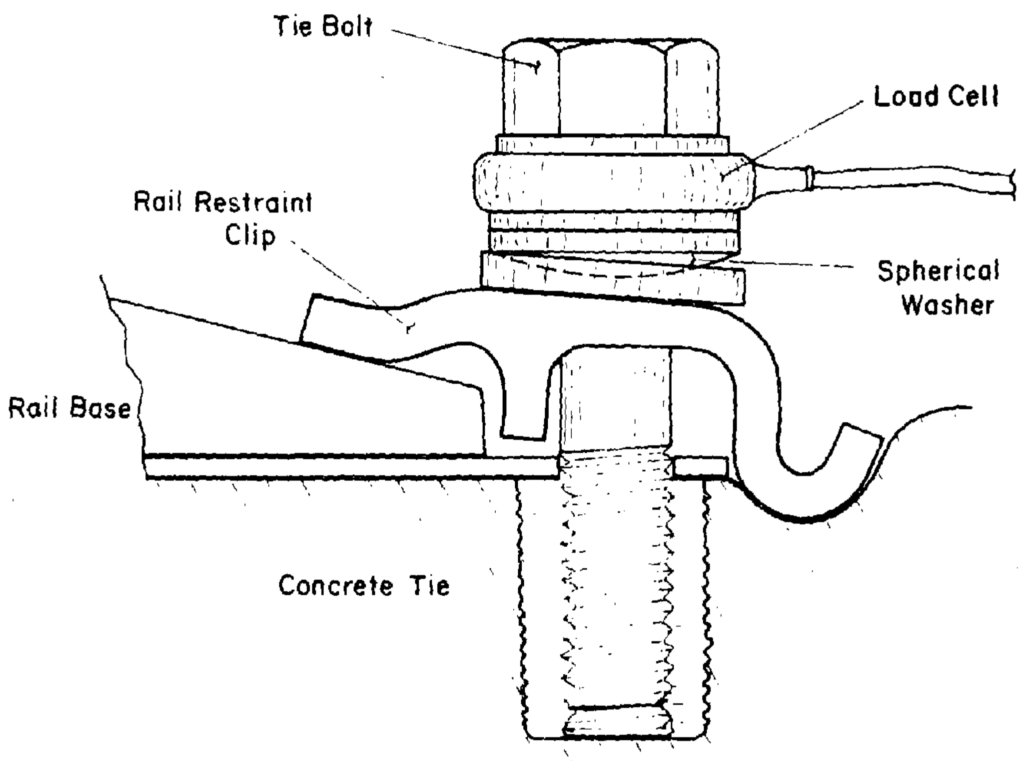


FIGURE 6-6. RAIL FASTENER BOLT LOAD MEASUREMENT

Multiple strain gages applied at a particular cross section can be wired into individual quarter-bridges, or four gages can be combined in a single full bridge. Individual gages record strain at a particular location and their output must be combined to determine a net bending moment using predetermined values for the location of the neutral axis and Young's modulus of the concrete. The output from two or more gages on one side of the tie can be used to locate the neutral axis, but material properties must be assumed or measured independently. An advantage of using independent gages is that strain data can be obtained directly and the output from each gage can be evaluated for possible anomalies caused by cracks or gage failure. However, the large number of data channels required for single gages is a major disadvantage for a large test program.

The use of a full bridge with four active gages wired to measure bending or torsional moment directly is recommended for this program to reduce the number of channels required and to provide a direct readout of the desired parameter. The output signal will be calibrated directly in in.-lb of moment using a laboratory calibration of equivalent ties to eliminate the need for knowing the neutral axis location or Young's modulus for the concrete. There will, however, be some error with this approach because of variations in the locations of the installed gages (on the order of ± 2 percent), and variations in tie geometry and Young's modulus from one tie to another (estimated at ± 10 percent). Although the total uncertainty should be acceptable considering the rather large statistical scatter expected, post-calibration of the strain-gaged ties (SGT) could be performed to further reduce these errors. Figures 6-7 shows the placement of the gages on one tie and the two circuit configurations necessary to convert the strains into bending moments at the rail seat and tie center and torsional moment at the tie center.

Considerable preparation is needed to insure efficient and reliable installation of strain gages on concrete ties. Local voids on the tie surface can be as great as 1/2 in. and the local stress concentrations from these voids must be averaged by using gages with a minimum length of about 2 in. In addition, a thin steel or aluminum shim stock substrate is recommended to permit prefabrication of the gage, and to provide a greater bonding area and a heat sink for soldering gage leads. Bonding techniques must account for

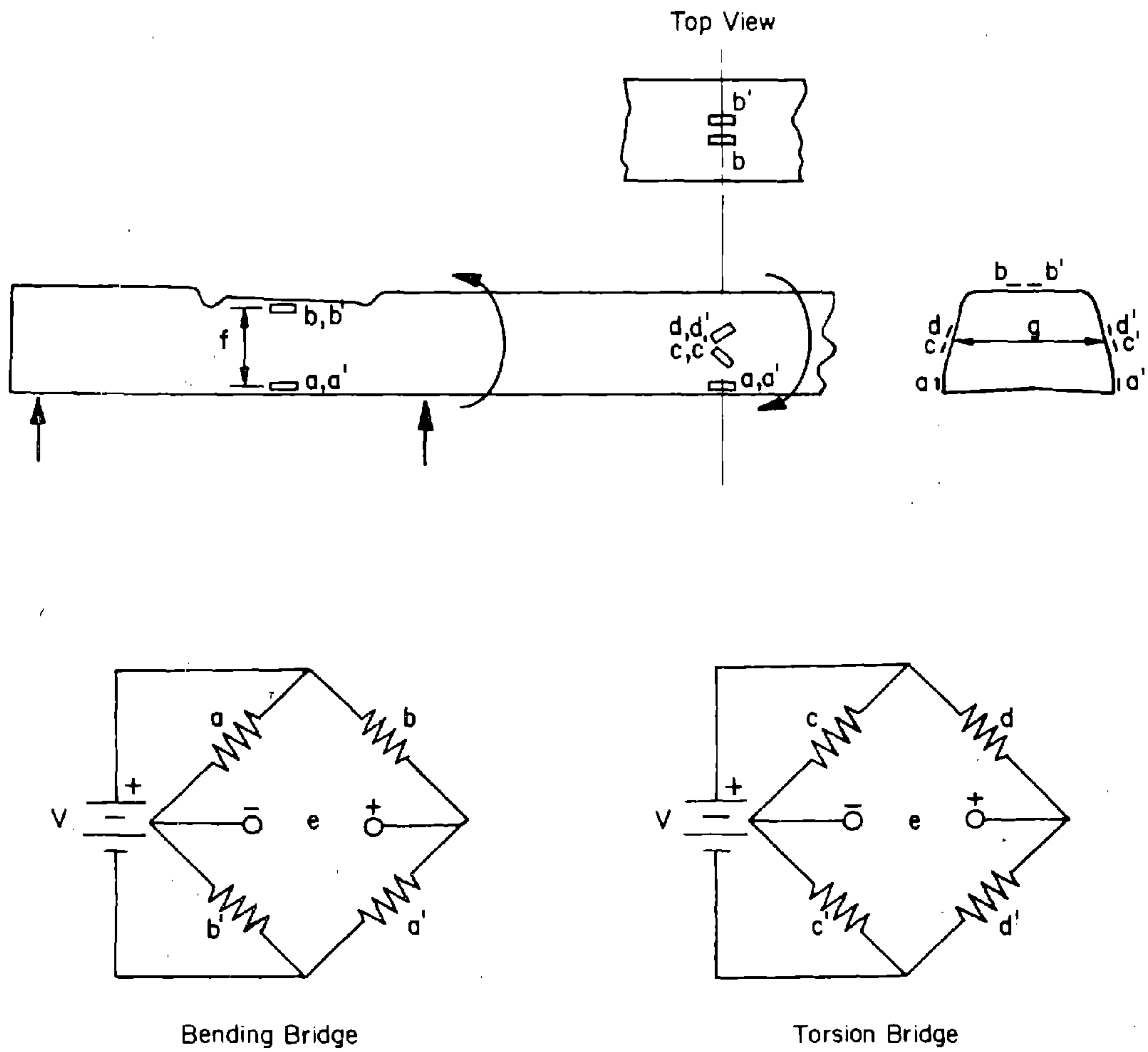


FIGURE 6-7. STRAIN GAGED TIE SCHEMATIC

moisture content and pH of the concrete as well as filling these small voids on the tie surface. Laboratory verification of gage installation techniques is needed to insure later success in the field. Gage location templates and clamping fixtures are needed to insure reliable and efficient field installation of the gages.

Temperature compensation would be required if long-term variations in tie strain were of interest. However, only the change in strain due to wheel loads from a passing train are of interest for this program. The establishment of a new zero strain reference for each train eliminates the effect of thermal strains except for any changes in temperature which occur during the approximately one minute passage time. These changes are expected to be minimal compared to the dynamic variations in the loads.

A major concern for the use of SGT is the possible presence of tie cracks in or near the gage locations. Fresh cracks in a prestressed tie cannot be detected visually unless the tie is highly loaded. The presence of a crack running through a gage location will produce a significant increase in strain when the tie is loaded sufficiently to open the crack. A crack adjacent to a gage location will limit the strain on that gage to the pre-load strain when the crack is opened. In either case, the output from the bridge will be nonlinear and different from the calibration data obtained from an uncracked tie.

The magnitude of these effects will be evaluated during the calibration phase, and barrier strips for bridge wiring will be installed on the ties to permit rewiring the bridges. Precision resistors will be used for half-bridge circuits as a contingency if calibration data show that a half-bridge using gages outside the cracked region are preferable. The application of gages to a cracked tie is clearly undesirable, and all candidate ties should be inspected carefully during tie selection.

6.4.2 Load Cell Ties

Tie support reaction at the tie/ballast interface can be determined using special-design load cell ties. The only load cell ties presently available are the FRA/PCA (Federal Railroad Administration/Portland Cement Association) ties developed for the KTT. These ties have 10 separate areas along the tie bottom to convert bearing pressures into discrete loads. The tie "backbone" is a steel channel section which has been reinforced to simulate the bending stiffness of the RT-7 tie. This backbone is the upper portion of the tie and it rests on 40 spools on which the gaging is done to measure tie/ballast pressure. Twelve additional spools support the two rail base plates for measuring vertical tie plate load. Each spool has two longitudinal and two transverse strain gages. Sets of four adjacent spools on the bottom side (and the six spools supporting each rail base) are wired into individual bridges. All wiring is routed along the length of the tie between the rows of spools and terminated in connectors at one end. The entire underside of the backbone; i.e., spools, wiring and connectors, was coated with a heavy layer of beeswax. A bottom cover is mounted on each set of four spools to provide the reaction face for that region of the tie bottom.

The combination of a low design stress limit (20 ksi) and a high design load of 80 kips at the rail seat and 40 kips per reaction face (equivalent to about 340 psi ballast pressure) produces a rather low sensitivity for each circuit. It should, however, be insensitive to off-axis loads.

The differences between the FRA/PCA load cell ties and the RCCC ties used on the FEC have been evaluated to determine their suitability for this program. The RCCC tie is 8 ft 6 in. long whereas the load cell ties are 9 ft 0 in. long. This difference of 3 in. on each end is not expected to have a significant effect on the distribution of tie/ballast pressure under the tie.

There is also a considerable weight difference in that the load cell ties weigh 875 lb compared to 575 lb for the RCCC tie. Acceleration measurements from the two ties will be compared to determine if differences in inertial forces are significant.

Laboratory measurements of the bending stiffness of both the load cell ties and the RCCC tie have been compared to evaluate these differences. The load cell ties were originally designed to simulate the stiffer RT-7 tie used in the KTT. Based strictly on theoretical calculations, Figure 6-8 shows that these stiffness curves have similar values at all stations along

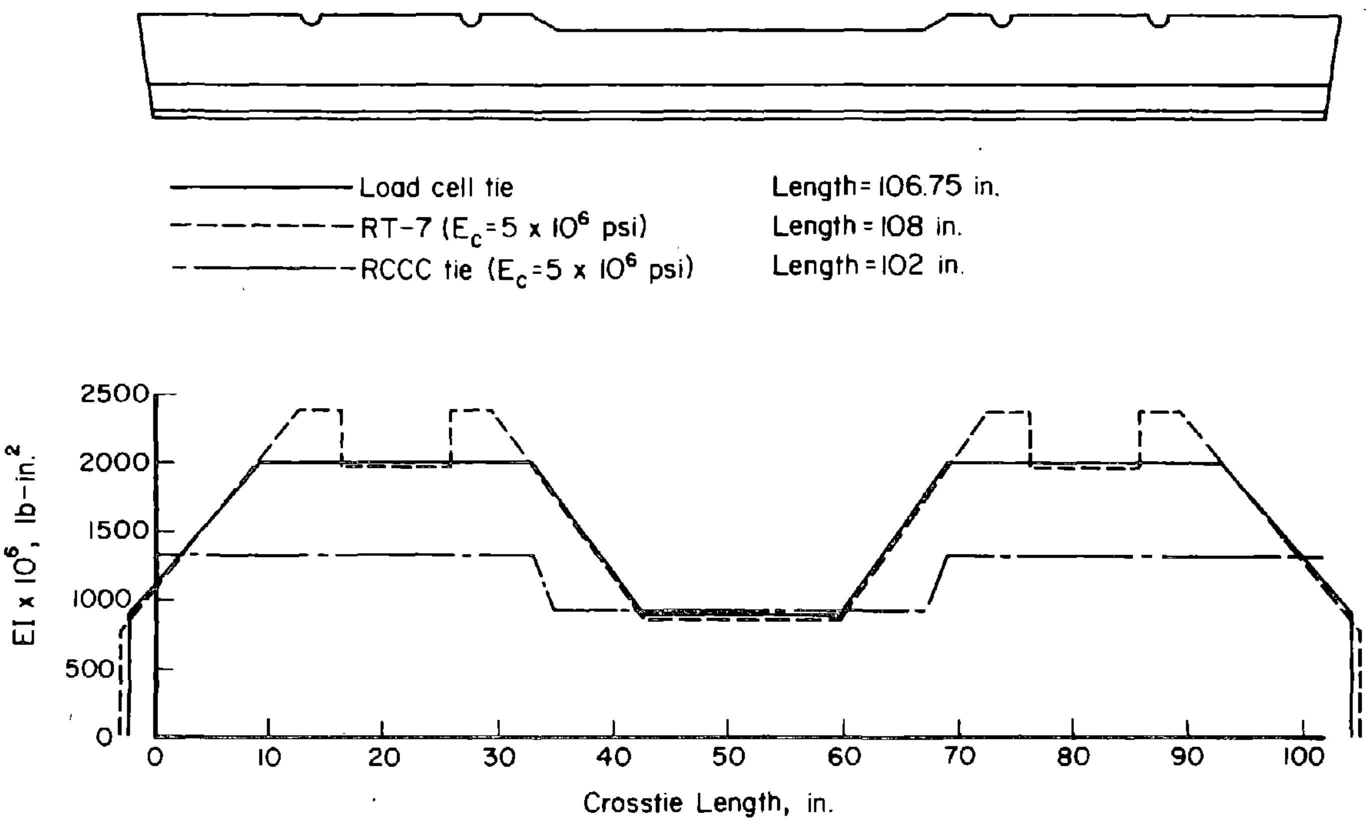


FIGURE 6-8. COMPARISON OF THEORETICAL TIE BENDING STIFFNESS

the tie length except for the stations just to the right and left of the rail seat. The stiffness of the RT-7 tie is somewhat higher at these stations. Figure 6-8 also shows the calculated stiffness for the RCCC concrete tie used by the FEC. The stiffness properties of the 3 ties agree well at their middle, but the RCCC tie is significantly less stiff at the rail seat section.

To perform comparable load measurements using the RCCC and load cell ties, the stiffness properties in critical areas (such as the middle and rail seat) should be comparable. If the theoretical calculations were accepted as giving accurate stiffness values, it would be necessary to remove some of the material which was added to the original load cell tie so that both tie stiffnesses agree. This could be easily accomplished by removing items 16 and reducing the size of items 5, as shown in Figure 6-9b. However, it was desirable to check the theoretical calculations with data obtained from load-deflection tests on the load cell and RCCC ties.

Three separate loading configurations were used by BCL on the RCCC and load cell ties. These are shown schematically in Figures 6-10a, b, and c. It was hoped that the experimental results from each of the three loading configurations would provide the stiffness properties at the critical points of each tie. However, these tests yielded somewhat inconclusive results. Table 6-1 shows inconsistency in the stiffness properties from section to section for the two ties which were tested. The theoretical calculations illustrated in Figure 6-8 show that the load cell and RCCC ties have similar stiffnesses in the center section based on an assumed modulus of 5×10^6 psi for concrete, but the bending stiffness differs considerably in the rail seat sections. It, therefore, seems reasonable to expect the data from the load configuration in Figure 6-10a, to show the average value of stiffness for the load cell tie to be higher than that of the RCCC tie. However, this was not the case.

The experimental stiffness value for the center section of the load cell tie looks respectable compared with the theoretical value. The measured value is approximately 6 percent lower than the theoretical value. This difference may be caused by shear deformation. The value determined from the experimental test for the RCCC ties is very low compared with the theoretical

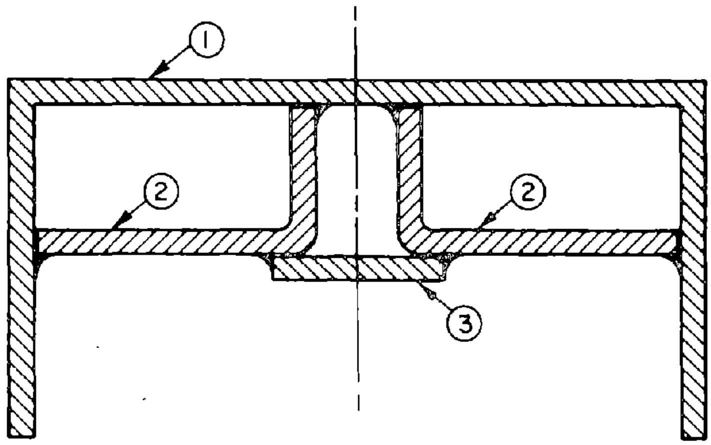


FIGURE 6-9a. BASIC LOAD CELL TIE CROSS SECTION

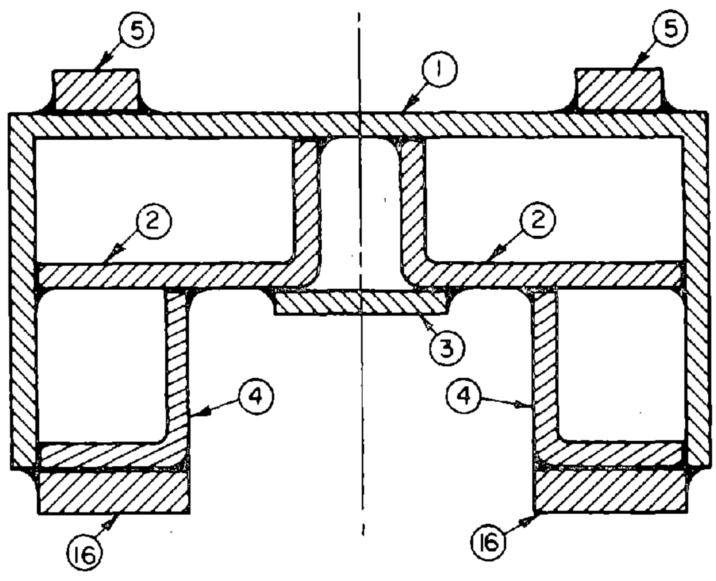


FIGURE 6-9b. LOAD CELL TIE CROSS SECTION WITH ADDED ELEMENTS

Added Elements: (4) (5) and (16)

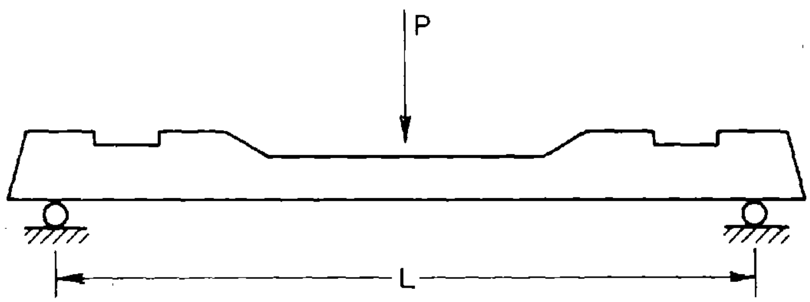


FIGURE 6-10a. LOADING CONFIGURATION TO GENERATE AVERAGE EI VALUE FOR ENTIRE SPAN

L = 86 in.

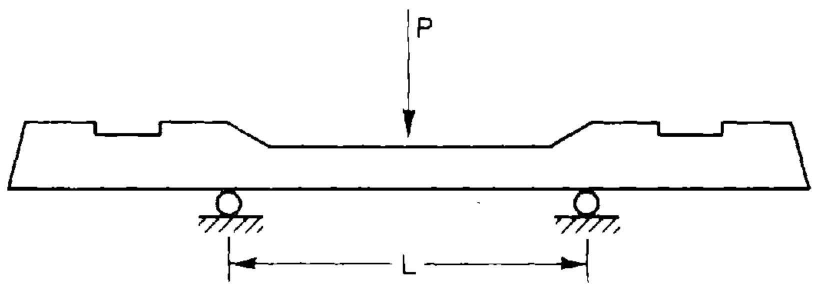


FIGURE 6-10b. LOADING CONFIGURATION TO GENERATE EI VALUE FOR CENTER SECTION

L = 36 in.

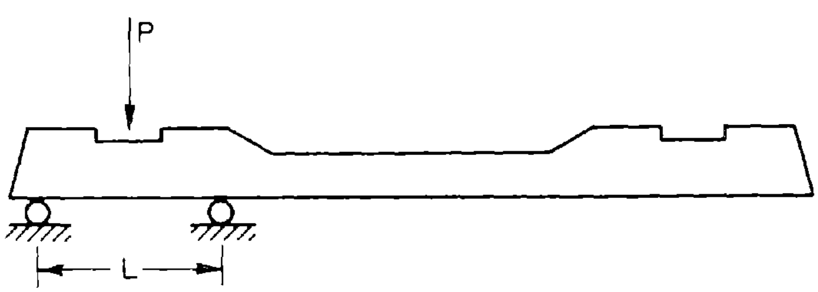


FIGURE 6-10c. LOADING CONFIGURATION TO GENERATE EI VALUE FOR RAIL SEAT SECTION

Load Cell: L = 26 in.
RCCC Tie: L = 24 in.

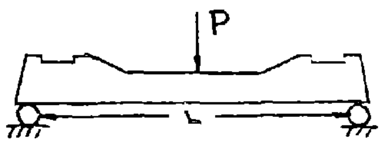
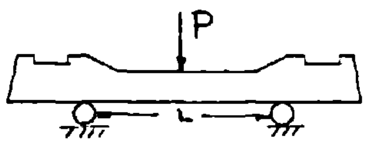
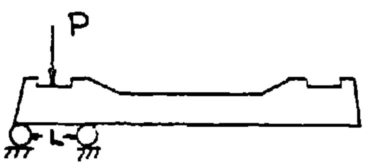
prediction at the center section. This measured value also includes shear effects. The measurement of stiffnesses for prestressed or reinforced concrete beams is quite difficult. If theoretical stiffness calculations are based strictly on gross cross-sectional properties and an assumed constant modulus E_c, these calculated values can vary considerably from the measured values, depending on the extent of cracking and variations in material properties. It is not uncommon to have ratios of calculated stiffness to measured stiffness as high as 3.4 and as low as 2 for reinforced concrete beams [6-3, 6-4]. However, cracking should not have this effect on a beam which is effectively prestressed. From Table 6-1, the theoretical stiffness for the RCCC concrete tie at the center section is slightly less than 2 times the measured value.

In conclusion, the average stiffness for the entire span for both RCCC and load cell ties were in good agreement. This is probably because of the fact that most of the bending in the ties for the test loading occurs between the rail seat sections. It is difficult to reach any definite conclusions about measured stiffness values at specific stations along the tie length. Many factors influence the measured stiffness predictions for the concrete tie. This is particularly true at the rail seat and midlength stations. Since no universally accepted method is available for determining this type of stiffness measurement in concrete beams, we can make no positive conclusion about the stiffness values at these stations from our load-deflection tests. For these reasons, it was recommended that the load cell ties should not be changed from their present configuration based on the good agreement for overall bending stiffness. The differences in stiffness values, if they actually occur, will have a second-order effect on the distribution of tie/ballast pressure which is measured under the load cell ties. For analysis purposes, the average measured bending stiffness (EI) of $764.5(10)^6$ lb-in.^{2}, listed in Table 6-1 will be used for predicting track and tie response with the RCCC tie.

6.5 TRACK DEFLECTIONS

A variety of displacement transducers are suitable for making track deflection measurements. The optimum transducer type and range may vary,

TABLE 6-1. COMPARISON OF LOAD CELL AND CONCRETE TIE BENDING STIFFNESS

Loading Configuration	Purpose of Configuration	Supported Length, L, in.	Predicted EI from Measured Data, 10^6 lb-in.^{2}	Theoretical EI (From Figure 6-8), 10^6 lb-in.^{2}
	Generate Average EI for Entire Span	RCCC: 86 Load Cell: 86	RCCC: 764.5 Load Cell: 764.5	Not Calculated
	Generate EI for Center Section	RCCC: 36 Load Cell: 36	*477.02 837.86	917.98 892.6
	Generate EI for Rail Seat Section	RCCC: 26 Load Cell: 24	*515.286 732.33 * 929.91	1320.59 2035.8

* Includes shear deformation.

depending on the specific application. Although the displacement transducer in itself does not affect track characteristics, it is usually difficult to establish an ideal point of reference from which the deflection measurements can be made. Optical tracking systems have been used in the past, without great success, to measure rail vertical absolute motions from a point well away from the track. Ground vibrations have introduced noise into these measurements. Absolute vertical and lateral displacements of the rail or tie have been referenced in past field experiments to a "ground stake," consisting of a 1-in. diameter steel rod driven through a concentric hollow casing through the ballast into the subgrade. The casing isolates the rod from ballast movements, and the displacement of a 6 to 8 ft long steel rod driven into the subgrade is low relative to the rail and tie deflections.

Relative lateral displacements measurements (rail-to-tie) may be referenced to a stable fixture which moves as a rigid body only, and is fixed to the tie at appropriate points. This method, used recently in the Association of American Railroads (AAR) Track Train Dynamics program, prevents distortion of rail displacement measurements caused by bending of wood ties in the vertical plane. However, an estimate of the effect of bending of a concrete tie indicates that this will have a negligible effect on lateral displacements at the rail head.

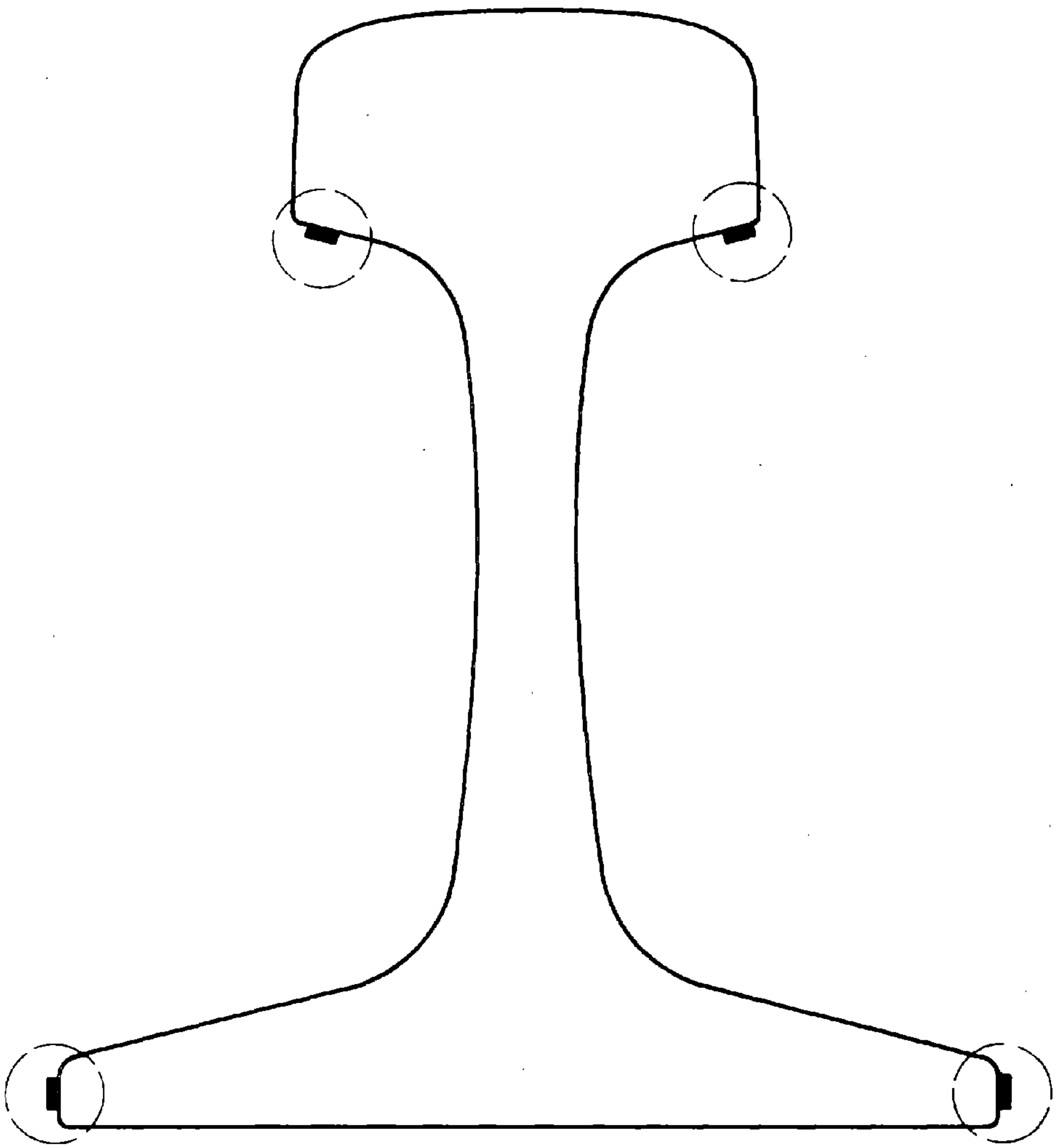
Displacement transducers have accuracies which are typically better than necessary for this particular application. However, care must be taken to insure that sufficient frequency bandwidth is available to monitor the frequencies of interest. Noncontacting displacement transducers (the magnetic reluctance type) have more than sufficient bandwidth, but these must be calibrated during installation to correct for target geometry and material properties. Contacting transducers use either direct attachment techniques or spring-loaded plungers. It is difficult to provide sufficient spring preload and stiffness to prevent contact separation in the frequency range of interest without, at the same time, causing some flexure of the reference fixture. Direct fixation of the core of displacement transducers, through nonmagnetic threaded "ready rod" to a phenolic block cemented to the rail, has proven quite successful in the past. However, this arrangement is susceptible to physical damage from ice, ballast, or dragging equipment, and distortion from longitudinal movement of the rail under reverse flow of traffic and thermal creep. Contacting displacement transducers are typically LVDT (linear variable differential transformers) or DCDT (direct-current differential transformers), which are self-contained LVDT's. Frequency bandwidth is a trade off with displacement range: a 2-in. range DCDT has a -3 dB range of 500 Hz.

For short-term tests where frequent attention can be given to the transducers, the contacting type displacement transducer is recommended because of ease in installation without the need for extensive calibration. These transducers are, however, vulnerable to contamination and wear and must be protected from the environment. Noncontacting transducers are impervious to the environment (except, perhaps, a direct hit by dragging equipment), and they are preferable for long-term installations with minimal maintenance. They require extensive calibration during installation to assure proper linearity and sensitivity, and they have been found to be sensitive to noise on electrified railroads where the rail provides a ground return.

DCDT's with a ± 0.5-in. range are recommended for this program because they have a bandwidth greater than 100 Hz and resolution (limited only by their S/N ratio) down to 0.001 to 0.002 in. with proper filtering. Vertical ground stakes will be used to provide an absolute displacement reference. Displacement transducers attached to a tie-mounted fixture will be used to measure lateral displacement of the rail head relative to the tie.

6.6 RAIL BENDING STRAIN

Figure 6-11 shows the strain gage locations which will be used to provide data on rail bending stress, for comparison with a rail stress analysis model. These gages will be oriented longitudinally and wired in separate bridges to measure strain from lateral and vertical bending. The gages will be located between two ties and between the chevron pattern for vertical W/R load measurements. The output from the two gages on the rail base will be averaged to verify vertical track modulus calculations from rail deflection measurements.



132 LB. RE RAIL SECTION

FIGURE 6-11. LOCATION OF STRAIN GAGES FOR RAIL STRESS MEASUREMENTS

6.7 TRAIN SPEED

The measurement of train speed is an important parameter for identifying the track response data. It is also required by the data analysis procedures to establish data windows for individual transducer locations based on the time delay from the beginning of the test section. Train speed can be calculated accurately from the time interval between the loading edges of vertical pulses from transducers at pre-established locations. The signals from a pair of vertical W/R load circuits spaced from 20 to 30 feet apart at either end of the instrumental track site can be used to calculate train speeds as trains enter from either direction.

7. INSTRUMENTATION PLAN

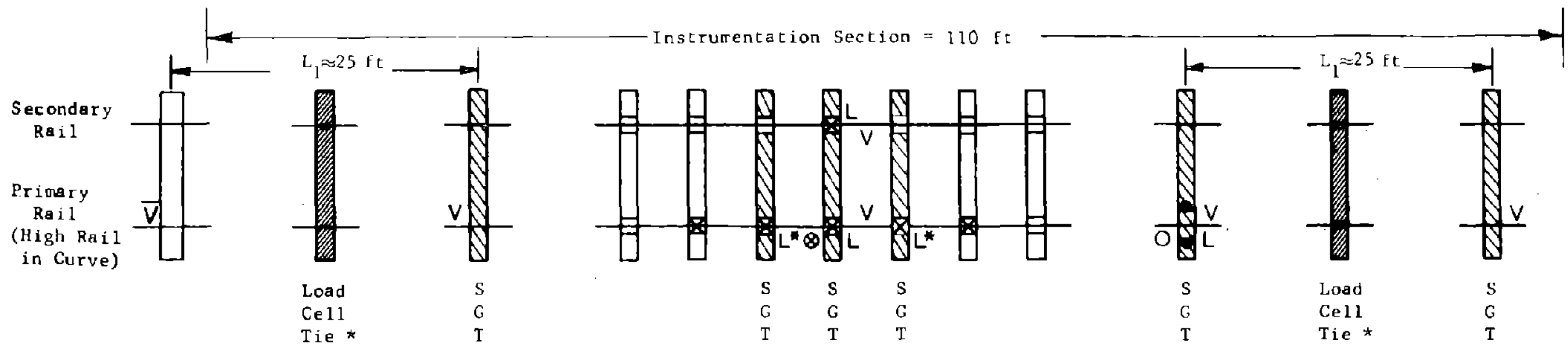
Table 7-1 summarizes the track instrumentation recommended for the FEC test sites. Two sections of tangent track having 20- and 24-in. tie spacing will be instrumented to determine the effect of tie spacing. A third test section in the body of a 3-deg curve and having 24-in. tie spacing will also be instrumented to determine the effect of curving forces on the tie and fastener load environment. During the actual conduct of the tests, minor deviations from Table 7-1 may occur to accommodate local variations in track conditions.

7.1 MAIN ARRAY DESIGN

All three test sections will have a main instrument array which extends over seven adjacent ties. The purpose of this continuous section is to obtain a complete set of track load and response data over a nominally uniform track section to validate the track analysis models. Based on track modulus measurements of 13,000 psi at Noble, IL, and similar data from other concrete tie track, a track modulus of 10,000 to 15,000 psi has been assumed for designing the test sites at the FEC.

Table 7-2 summarizes the results of some estimated track response parameters using beam-on-elastic-foundation equations for these expected track

TABLE 7-1. INSTRUMENTATION PLAN FOR CONCRETE TIE TRACK MEASUREMENTS



	Tangent Track 24-in. Tie Spacing		Tangent Track 20-in. Tie Spacing		Curve Track 24-in. Tie Spacing	
	Number Channels	Statistical Data	Number Channels	Statistical Data	Number Channels	Statistical Data
SGT (6)						
Rail Seat Bending	7	6	7	6	7	6
Center Bending	6	6	6	6	6	6
Center Torsion	6	1	6	1	6	1
Load Cell Ties						
Vertical Rail Seat Load	4	0	0	0	2	0
Tie Ballast Pressure	20	0	0	0	10	0
⊠ Instrumented Tie Plates(6)						
Vertical Rail Seat Load	6	6	6	6	6	6
Rollover Moment	6	6	6	6	6	6
☐ Tie Plate Spacers (8)	0	0	0	0	0	0
W/R Loads						
V Vertical	5	5	5	5	5	5
L Lateral	3	2	3	2	5	4
V̄ Vertical Axle Detector	1	1	1	1	1	1
● Fastener Bolt Load	2	1	2	1	2	1
Track Deflection						
○ Vertical Rail Absolute	2	0	2	0	2	0
× Lateral Rail/Tie	1	1	1	1	1	1
× Lateral Tie	1	1	1	1	1	1
Rail Bending Stress	4	0	0	0	0	0
Vertical Acceleration (2)						
Rail	1	0	1	0	1	0
Tie	1	0	1	0	1	0
Total	76	36	48	36	62	38

*Note: 2 Load cell ties in tangent track (24-in. spacing)

0 Load cell ties in tangent track (20-in. spacing)

1 Load cell tie in curve track (24-in. spacing)

2 Lateral W/R load circuits added to curve track

TABLE 7-2. SUMMARY OF ESTIMATED TRACK RESPONSE AT FEC TEST SITE

Track Parameter	Assumed Track Modulus	
	U = 10,000 psi	U = 15,000 psi
Rail Size, lb/yd	132	132
Rail EI, $lb\text{-}in^2$	$2.56(10^9)$	$2.56(10^9)$
$\beta = (U/4EI)^{1/4}$, $in.^{-1}$	0.031	0.034
$\beta = (U/4EI)^{1/4}$, ft^{-1}	0.377	0.417
Track Stiffness $K_r = 2U/\beta$, 10^3 lb/in	645	882
$X_1 = \pi/4\beta$, ft *	2.08	1.88
$X_2 = 3X_1$, ft *	6.24	5.64
Typical Heavy Wheel Load P, kips	30	30
Track Deflection $Y_o = P/K_r$, in.	0.046	0.034
Rail Seat Load $q_o = U\ l_t\ Y_o$, kips		
l_t = 20-in. tie spacing	9.2	13.8
l_t = 24-in. tie spacing	11.0	16.6
Rail Bending Moment $M = P/4\beta$, kip-in.	242	220

* Notes: X_1 = distance from wheel load to location for zero bending moment.

X_2 = distance from wheel load to location for zero deflection.

parameters. These results show that the effective reaction zone for a single wheel load is about $\pm$ 6 ft ($\pm X_2$), where X_2 is the distance from a wheel to the location of zero rail deflection. Consequently, a section of seven ties has been selected to provide a length of about $\pm$ 7 ft for the main array. This insures that the central tie is completely within the wheel influence zone at the beginning of the main array,and the instrumented ties adjacent to the center tie are within the major portion of that influence zone. The reason for the concern about this main array length is that installation of instrumented tie plates will require sinking each tie about 1 in. in the ballast to provide adequate clearance. There is concern that this may cause an atypical support condition, but that this effect will be minimized by adjusting all ties within the wheel influence length in the same way. Also, it is planned to lower these ties and install dummy spacer plates with sufficient lead time to allow about 1 to 2 MGT of traffic (one month on the FEC) to reconsolidate the ballast before recording data. Available data on track consolidation indicates this should be adequate for this relatively minor disturbance to the ballast.

7.2 WHEEL/RAIL LOADS

The instrumentation in the main array includes strain gaged rail to measure vertical and lateral W/R loads adjacent to the center tie. The emphasis in this program is on fastener and tie loads, so the W/R load instrumentation has been limited to the minimum needed to determine reference values for describing the traffic characteristics and for validating analytical models. Two additional lateral W/R load measurements will be added to the main array on the curve site to better define the lateral loading.

Additional W/R load strain gage circuits will be installed adjacent to the 3 SGT outside the main array, as shown in Table 7-1. The data from these load circuits will be compared and combined with data from the main array to evaluate spatial variations and to provide a reference for the bending and torsion moment data on the SGT. The signals from a pair of vertical W/R load circuits spaced about 25 ft at either end of the instrumentation section will be used to calculate train speed as a train enters the section from either direction. This speed calculation and accurately measured distances to the different instrumented ties will be used to establish time delays for axle identification during data analysis.

Statistical data will be recorded for the five vertical and all of the lateral W/R load circuits on the primary rail in the instrumentation section. An additional channel will be required for the vertical W/R load circuit used as an axle detector, but no statistical analysis is planned for this channel. The vertical W/R load data from both rails in the main array will be used to determine axle loads and total weight for each car to identify car weight categories.

7.3 TIE LOADS

A total of 3 SGT will be used in the main array to measure the bending moment under the rail seats and the bending and torsional moments at the tie center. The three ties span an influence length of about 6 ft where they will be subjected to maximum wheel loading. This is about 2/3 of a normal wheel revolution, so at least one of these three adjacent ties will be subjected to the flat wheel impact or other loading related to wheel revolutions for at least 2/3 of the wheel population. Three additional SGT will be located randomly within the 110-ft test section. The purpose of these additional ties is to record any spatial variations in tie loading which may be caused by vehicle dynamic effects and to serve as a comparison for data from the main array where it has been necessary to disturb the ballast during installation.

The number of locations which should be instrumented to determine spatial variations in load or response data within any one instrumented section can be selected for specified objectives. As a first example, consider the objective of establishing a mean value of tie bending moment for the tangent track site with a 24-in. tie spacing. Bending moment data will be collected for each of N ties for a large number of axles, and a mean value X_i will be computed for each tie. If the standard deviation of the variation in mean value due to spatial variations is known, then the number of measurement sites (ties) can be selected to establish a mean value tolerance band for a desired confidence level, see Figure 7-1. These results were obtained using the equation,

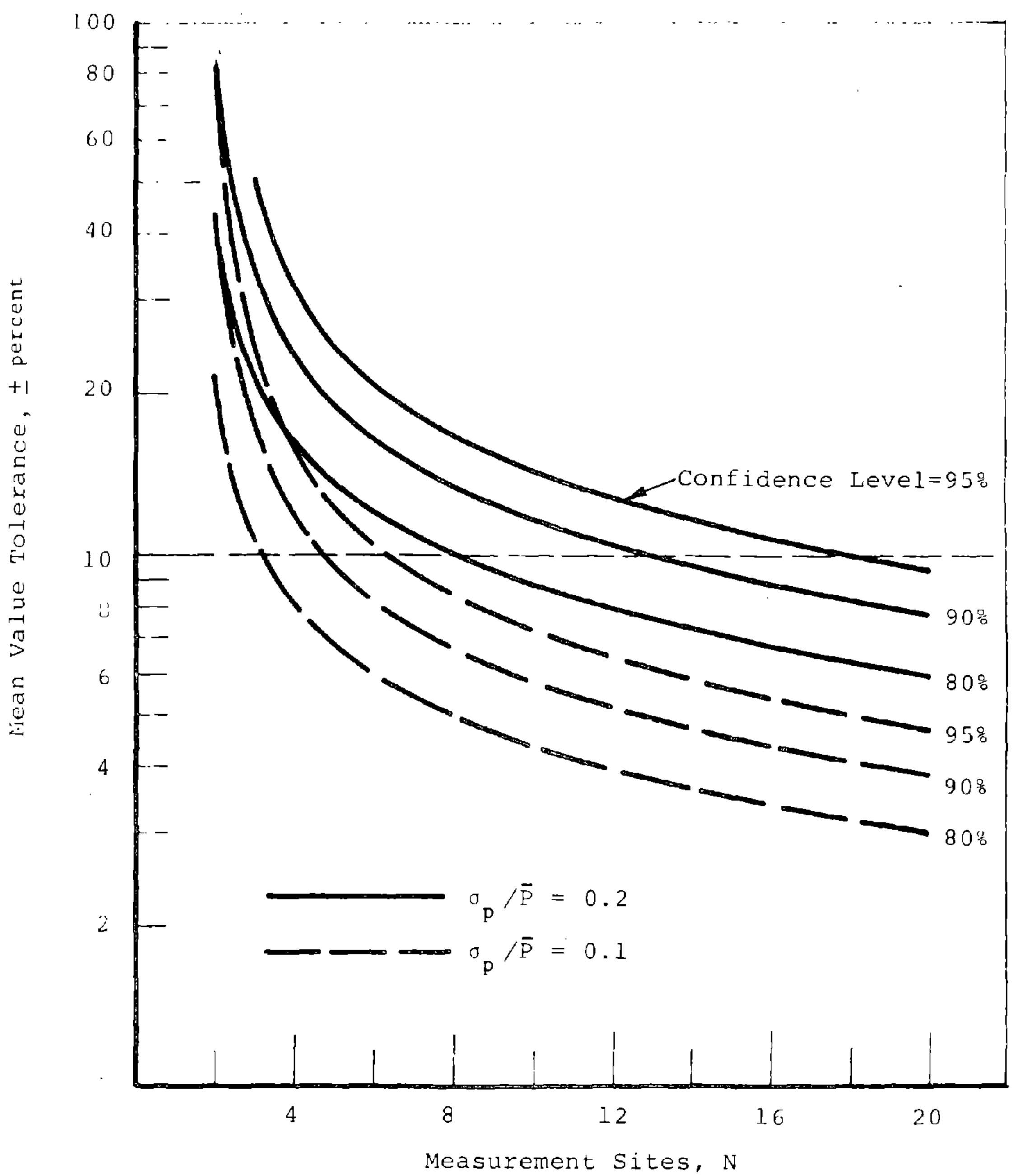


FIGURE 7-1. TOLERANCE BAND ON TRUE MEAN VALUE VERSUS NUMBER OF MEASUREMENT SITES AS A FUNCTION OF CONFIDENCE LEVEL AND RATIO OF MEASURED STANDARD DEVIATION TO MEAN VALUE

$$\bar{P}_t = \bar{P} \pm \frac{\sigma_p t_{n;\alpha/2}}{\sqrt{N}} \quad , \qquad (7\text{-}1)$$

where

$\bar{P}_t$ is the true mean value

$\bar{P}$ is the estimated mean value using N samples

σ_p is the standard deviation of the mean value from spatial variations

$t_{n;\alpha/2}$ is the student t probability distribution function for $n = N-1$ degrees of freedom.

Equation (7-1) is discussed in greater detail in most texts on statistics and has been used in previous work [7-1] on selecting instrumentation for track measurements. Typical data from wood tie track indicates the standard deviation of mean values measured at different locations in nominally identical track is about 15 percent of the mean value ($\sigma_p/\bar{P} = 0.15$). It is expected that the standard deviation for the FEC concrete tie track, which appears to be in excellent condition with minimal variations in track geometry to excite vehicle dynamic response, may be close to about 10 percent of the mean value. Figure 7-1 shows that an estimate of the mean value with a $\pm$ 10-percent tolerance band can be achieved using N = 4 to 6 measurement sites with a confidence level in the range of 80 to 95 percent. This accuracy appears quite adequate. Furthermore, increasing the number of measurement sites above six brings diminishing benefits, so this appears to be a cost-effective choice. This same approach can be used to evaluate the statistical accuracy of the measured data once the data are processed to establish the actual statistical parameters.

A second example of significance for this measurement program is to record load data at two different test sites (20- and 24-in. tie spacing) and determine if the measured differences in mean values are statistically significant. An equation for evaluating this is [7-2],

$$\overline{X}_t - \overline{Y}_t = (\overline{X}-\overline{Y}) \pm \sqrt{\frac{\sigma_x^2 + \sigma_y^2}{N}} \quad Z_{\alpha/2} \quad , \qquad (7-2)$$

where $\overline{X}_t$, $\overline{Y}_t$ are the true mean values of a variable at sites X and Y

$\overline{X}$, $\overline{Y}$ are the estimated mean values using N samples (ties)

σ_x, σ_y are the standard deviations of the mean values from spatial variations

$Z_{\alpha/2}$ is the standardized normal probability distribution function.

Figure 7-2 shows an evaluation of Equation (7-2) where a difference in mean values for two different track sites of 20 percent is expected; i.e., $(\overline{X}-\overline{Y})/\overline{X} = 0.20$. Results are shown for standard deviations ranging from 10 to 20 percent of the mean value. This standard deviation is for the effect of spatial variations only, whereas track measurements also include variations caused by the vehicle population and operating conditions. It may be necessary to evaluate the effect of spatial variations using a subcategory of vehicles such as all locomotives, or all heavy cars, operating in a narrow speed range to minimize the influence from the vehicle population.

The results in Figure 7-2 show that two to six measurement sites are required to determine a statistically significant 20-percent variation in mean value at a confidence level of 90 percent for the 10- to 20-percent range of standard deviations. Therefore, a total of 6 SGT and instrumented tie plates have been recommended for this program to identify the expected effect of variations in tie spacing on tie and fastener loads. The center tie in the main array will measure bending under both rail seats and at the center. All other ties will measure bending under the primary rail (see Table 7-1) and at the center. Statistical data will be recorded for the six rail seat bending moments under the primary rail and for the six tie center bending moments. Statistical data on tie torsional moment, a lower-priority objective, will be limited to the one tie in each section which has the highest torsional moments under the first passing train. It is expected that the torsional moments will be quite low for most ties if misalinement of the plane of the rail seats is the principal source of high moments. Therefore, the objective is to determine a maximum expected torsional moment for the random selection of six ties in each section.

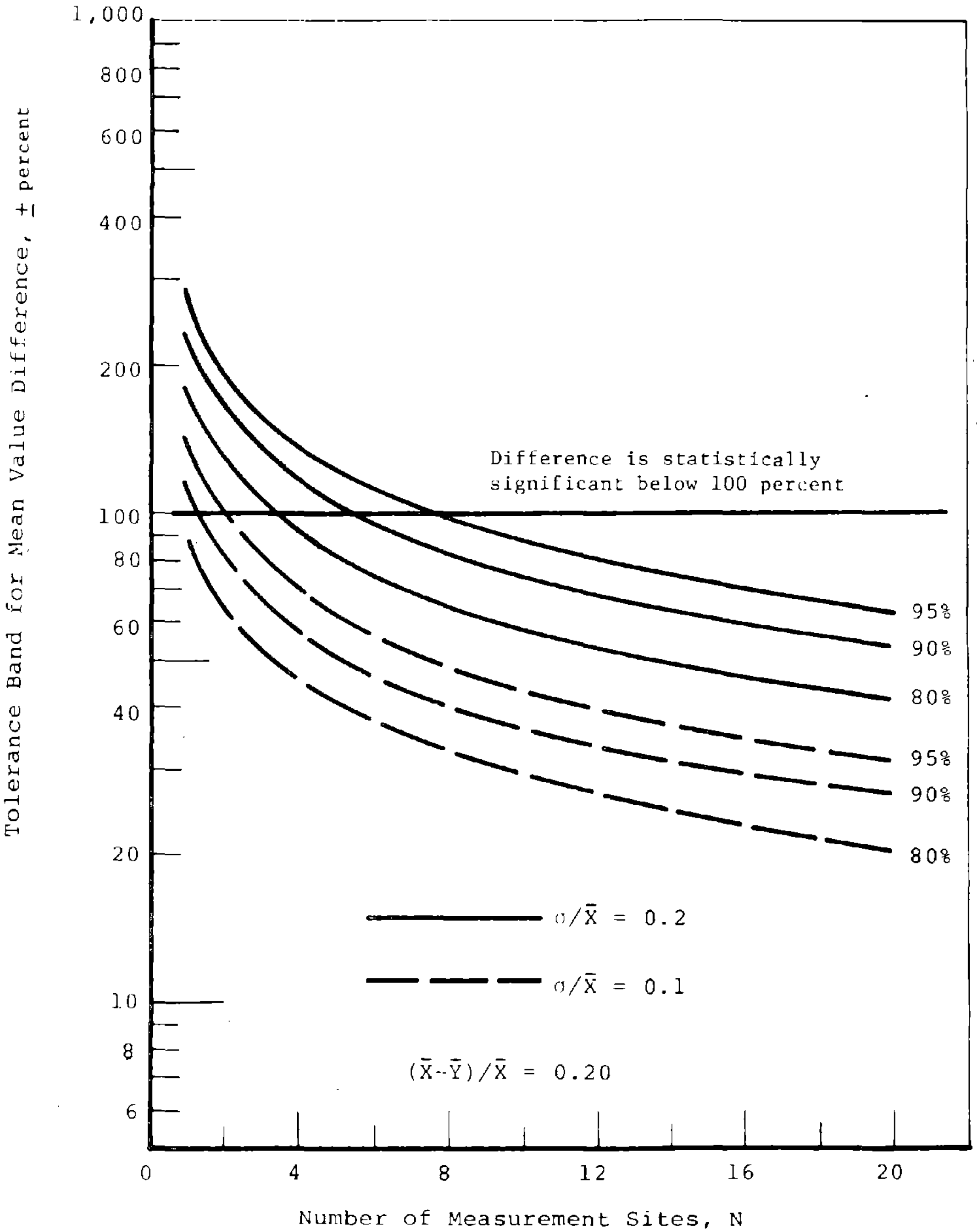


FIGURE 7-2. NUMBER OF MEASUREMENT SITES REQUIRED TO IDENTIFY A 20 PERCENT VARIATION IN MEAN VALUE FOR TWO DIFFERENT TRACK SITES

7.4 RAIL FASTENER LOADS

Table 7-1 shows that the main array also contains six instrumented tie plates, with five on one rail. The instrumented tie plates will be used to record the tie rail seat loading throughout the influence zone of the center tie for purposes of model validation. The combined statistics from the five tie plates under the primary rail will also record load variations over about one wheel revolution. No additional instrumented tie plates have been recommended outside of the main array because it was believed that disturbing a single tie to install tie plates might produce an anomaly in the track support condition which was greater than any spatial variations. Additional rail seat load data will also be obtained from the load cell ties.

7.5 TIE/BALLAST PRESSURE DISTRIBUTION

Two of the FRA/PCA load cell ties will be installed in the tangent section with 24-in. tie spacing, and one load cell tie will be installed on the curve. The purpose of using these load cell ties is to simultaneously measure vertical rail seat loads and the resulting distribution of tie/ballast pressure on the 10 instrumented segments along the tie length. No statistical data from revenue traffic are required for these measurements. Also, because of the limited number of available ties, variations in pressure distribution which might occur at different track locations will not be fully documented. However, it is believed that these tie-to-tie variations in pressure distribution will not be too great. Much larger variations occur during the degradation of track under traffic, which is a long-term effect that is not included within the objectives of the current program.

The installation of the load cell ties will require the removal of a standard tie. Therefore, the load cell ties have been located randomly outside the main array to avoid the effect which this disturbance to the roadbed might have on adjacent ties. The load cell ties will be installed at the same time as the tie plate spacers to allow reconsolidation under traffic.

7.6 TRACK DEFLECTION

The main array will include displacement transducers to measure the absolute vertical rail deflection, the lateral deflection of the rail head relative to the tie, and the absolute lateral displacement of the tie. All measurements will be made on the center tie so the results can be correlated with complete loading data for model validation. Vertical rail deflection will also be measured at one of the SGT located away from the main array to compare data on vertical track modulus at two locations. Statistical data will only be recorded for the two lateral deflection measurements.

7.7 FASTENER BOLT LOADS

The vertical load will be measured in the fastener bolts on the field and gage sides of one fastener for one or two revenue trains. Statistical data will then be collected for the one bolt which has the most severe fatigue load environment in terms of range of fluctuating load.

7.8 RAIL BENDING STRESS

Strain gages will be applied on both sides of the rail in the head fillet region and on the rail base directly above the center tie in the main array. Data from one or two revenue trains will be used to correlate with stress predictions for the measured W/R loads and tie reactions.

7.9 VERTICAL ACCELERATION

Accelerometers will be placed on the rail and the center tie in the main array to document the vertical dynamic response of this section. The main array has been selected for these measurements to permit correlation with the W/R and tie plate loads and rail deflection measurements. Data from one or two revenue trains will be used to compare the frequency content of the rail and tie accelerations and to determine typical tie accelerations caused by rail uplift.

8. TEST DURATION

The data requirements for this program include two separate categories. One category consists of a complete set of W/R load and track response data recorded for a slowly moving work train and 1 or 2 revenue trains. These data will be used to calibrate the instrumentation and to verify analytical predictions of load transfer through the track components. Table 7-1 shows that the total number of data channels to be recorded exceeds the 38 available channels by a considerable margin so that two or three different recording sessions will be needed to obtain the correct grouping of initial data. It is estimated that about two days will be required for calibration and to make these initial measurements at each test location.

The second data category is a statistical compilation of maximum loads, bending moments, etc., for typical revenue service. These data will be used to determine the statistical parameters listed in Table 5-1 for different ranges of train speeds and car weights. As discussed previously, data from each single transducer within a test site record the statistical variations from the revenue traffic. The combination of similar data from several transducers within the same test site is needed to document the statistics for that type of track and includes normal spatial variations in vehicle loading or track response. The data requirements which arise from this statistical characterization are discussed in the following section.

8.1 STATISTICAL DATA REQUIREMENTS

Amplitude statistics, including mean value, standard deviation, probability distribution, and probability density functions, have been recommended for analyzing many of the track loading and response parameters for this program. Statistical criteria can be used to estimate the number of data points needed for a desired accuracy and confidence level for a particular "experiment". Statistical criteria for determining the number of instrumentation locations needed for spatial variations within each test site were discussed in the previous section. This section discusses the statistical requirements related to the variation in the vehicle population passing the test site.

Previous work on the data requirements for amplitude statistics shows that the probability density function governs the number of data samples required. The statistical data for this program will consist of one data point (peak value) for each axle pass, so the number of data samples is identical to the number of axles for any particular measurement parameter of interest. To compute the peak amplitude probability density function (PAPD) for a set of load data, the load range must be established and divided into the minimum number of intervals compatible with the required resolution for the statistical description. Then the number of data values, and percentage of data, in each interval would be calculated to give a probability density, or histogram.

It is clear that the load intervals should be sufficiently small to provide good resolution of amplitude variations, and the total range must be adequate to cover the desired low-probability events. Data must be collected from a sufficient number of axles, so that each interval has several data points to provide a reliable estimate. It is recommended that each interval have at least five data values although two can be acceptable for the last interval. Figure 8-1 shows the number of data points required to have at least five values in the window at a specified number of standard deviations from the mean value, assuming a normally distributed variable. It is desirable to determine amplitude statistics over at least a $\pm$ 3-σ range for the purposes of comparing the measured distribution to a theoretical one for purposes of extrapolating to lower-probability events. Figure 8-1 shows that data from about 1000 axles are needed using a total of 12 intervals to define the $\pm$ 3-σ load range, and a total of 3000 axles are needed to resolve that load range into 24 windows. The data requirements would be reduced considerably by requiring only two data entries in the last interval or by reducing the number of standard deviations.

Table 8-1 gives some additional recommendations [8-1] for the number of intervals (windows) K required for N data points based on applying a chi-square goodness-of-fit equivalence test between a hypothetical and measured probability density function at the 5-percent level of significance. For the same number of data points, these results recommend a greater number of load intervals for a hypothesis test.

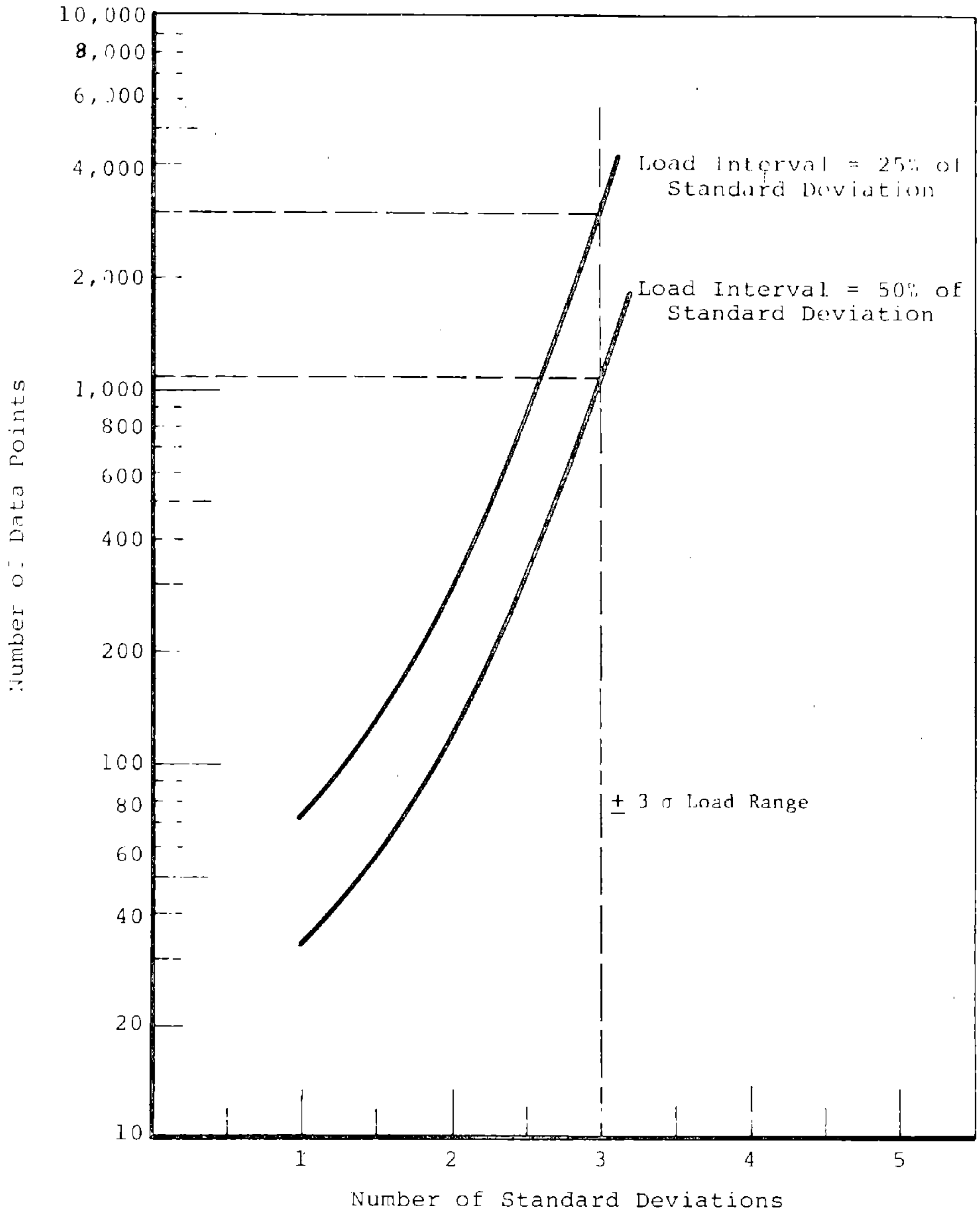


FIGURE 8-1. NUMBER OF DATA POINTS REQUIRED TO HAVE A MINIMUM OF 5 SAMPLES AT A SPECIFIED STANDARD DEVIATION

TABLE 8-1. RECOMMENDED NUMBER (K) OF INTERVALS FOR AMPLITUDE PROBABILITY DENSITY ANALYSIS OF SAMPLE SIZE N

Sample size, N	200	400	600	800	1000	1500	2000
No. of Intervals	16	20	24	27	30	35	39

Typical data from Noble, IL [8-2] shows that the mean tie bending moment for locomotives is about 100 kip-in. and the standard deviation is 14 to 17 percent of the mean value. A range of 40 to 160 kip-in. will cover a range of $\pm$ 3-σ for a normally distributed variable using an assumed standard deviation of 20 percent of the mean value. Intervals no larger than 10 percent of the mean value (12 windows) are recommended where expected variations from tie spacing are on the order of 20 percent, and 5-percent intervals (24 windows) will give an even better resolution. Based on the previous discussions, data from about 1000 axles are required for the 10-percent resolution, and data from about 3000 axles are needed for the 5-percent resolution.

Table 8-2 shows some estimated statistics for 20 MGT of annual traffic based on traffic data from Noble, IL [8-2]. This indicates a total of about 3700 axles/day can be expected at the FEC test sites. It is assumed that about 65 percent of the trains will be operating in the 55 to 65-mph speed range through the test sites. A total of four speed ranges appear adequate to identify speed effects, and the traffic has also been subdivided into categories for locomotives, cars exceeding 50 tons gross weight, and cars weighing less than 50 tons. Data in these subcategories are needed to characterize the effect of vehicle population and speed on the load data and to provide a more uniform loading case for comparing the different test sections.

Table 8-3 summarizes the data requirements for mean value and probability density statistics for different car weight and car speed categories. The number of axles required for a $\pm$ 10-percent mean value tolerance band at the 95-percent confidence level is based on data which show that the typical standard deviation for loading from all cars is 100 percent of the mean load,

TABLE 8-2. ASSUMED STATISTICS FOR 20 MGT OF ANNUAL TRAFFIC

Consist Data	No. per Day
Trains	13.7
Locomotives	41
Cars	888
Loaded	537 (60%)
Empty	351 (40%)
Axles	3,719

ESTIMATED SPEED AND WEIGHT DISTRIBUTION FOR TEST SITE

Speed Range mph	Percent	Axles/Day			
		Locomotives	Cars >50 tons	Cars <50 tons	Total
25-35	5	12	111	63	186
35-45	10	24	223	125	372
45-55	20	48	446	250	744
55-65	65	162	1450	805	2417
Total	100	246	2230	1243	3719

TABLE 8-3. SUMMARY OF DATA REQUIREMENTS

a. Mean Value Estimate (± 10 percent at 95 percent Confidence)

Car Class	No. Axles Required	Test Duration, days		
		1 Tie, All Speeds	1 Tie, 4 Speeds	6 Ties, 4 Speeds
All Cars	400	0.1	2.1	0.4
Cars >50 tons	120	0.05	1.1	0.2
Cars >50 tons	120	0.1	1.9	0.3
Locomotives	18	0.1	1.5	0.3

b. Amplitude Probability Density

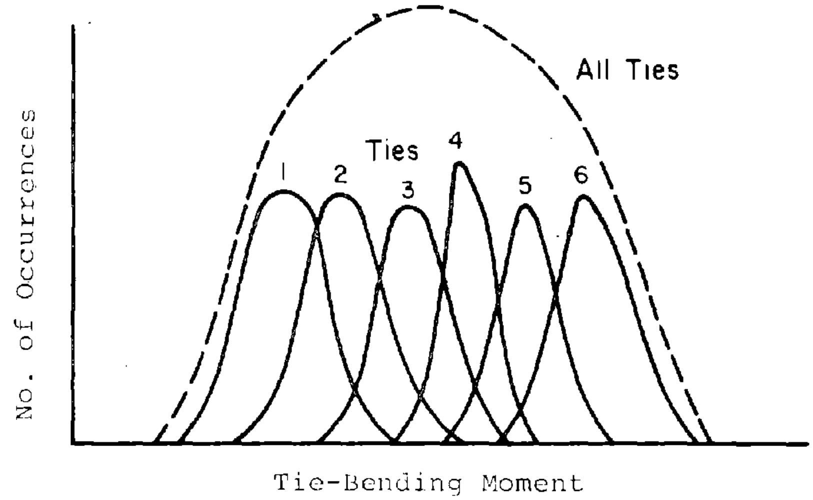
Car Class	No. Axles Required	Test Duration, days		
		1 Tie, All Speeds	1 Tie, 4 Speeds	6 Ties, 4 Speeds
All cars	3,000	0.8	16	2.7
Cars >50 tons	1,000	0.5	9	1.5
Cars <50 tons	1,000	0.8	16	2.6
Locomotives	1,000	4.0	83	14

and it is about 20 percent of the mean load for locomotives. Equation (7-1) and the results in Figure 7-1 give a requirement for 400 axles for all cars and 18 axles for locomotives. A standard deviation of 50 percent was assumed for the above and below 50-ton weight categories, and this requires 120 axles. With these requirements, the axle distributions listed in Table 8-2 were used to predict the test duration in days for data from one measurement (one tie, tieplate, etc.) using all train speeds or four speed ranges. The low estimated number of trains in the lowest speed range of 25 to 35 mph makes this the governing parameter for test duration. This could be shortened considerably by slow ordering several trains to fulfill the speed category requirements at the risk of incurring atypical data. When data from six measurements in one test location are combined to include spatial variations, the time required to obtain a mean value estimate is reduced. The duration for six ties has been estimated at 1/6 of the single tie duration with the restriction that the standard deviation from spatial variations is less than the variation caused by vehicle population.

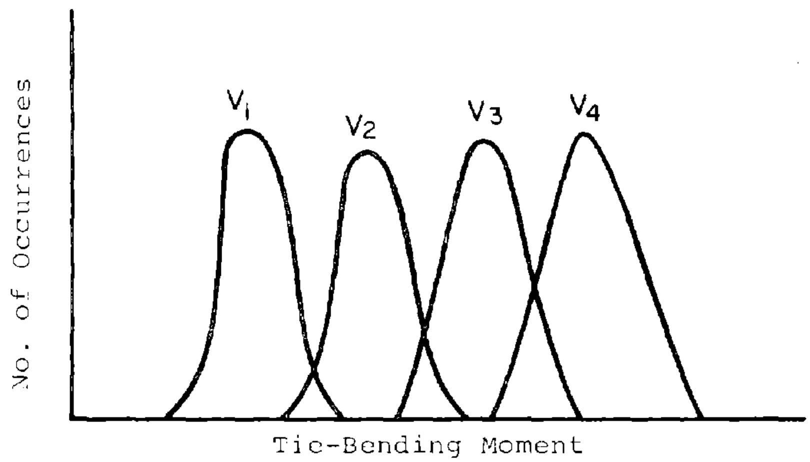
A similar procedure was followed to determine the test duration required for amplitude probability density statistics. Results in Figure 8-1 show that data from 3000 axles are needed to determine the density function with 24 load intervals over the $\pm$ 3-σ range. This is recommended for the all car data. Data from 1000 axles are recommended for the other car load categories because the reduced standard deviation gives about the same load interval resolution with only 12 load intervals to define the $\pm$ 3-σ range.

Figure 8-2 shows three sample cases which have been identified to evaluate the data requirements. The requirements for using rail seat bending moment data from six different ties will be discussed for illustration, but the requirements are the same for the other measurement parameters which require a PAPD function.

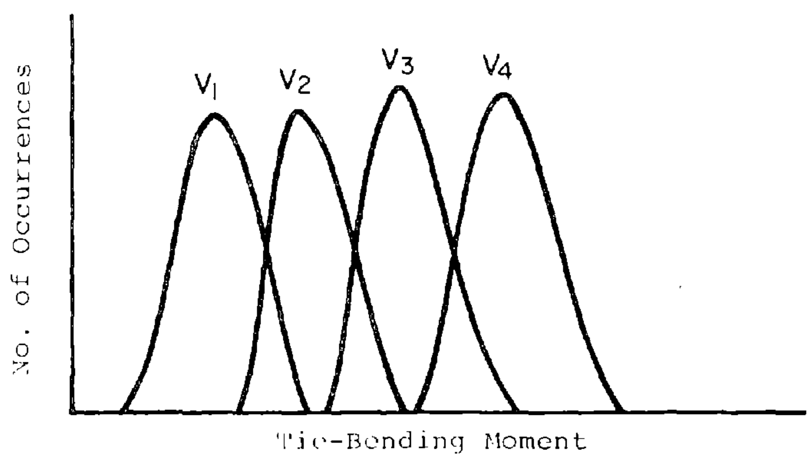
The Case I data consist of peak bending moment data for each of six ties for all of the traffic passing the test sites. This provides a statistical description of the tie loading for the traffic mix and operating speed at the test site location on the FEC. The data from individual ties can be combined to give an overall PAPD for the site, and the mean value and standard deviation from the different sites can be compared to determine the effect of tie spacing. Case I requires data for 3000 axles for each tie to cover a $\pm$ 3-σ range with 24 intervals. Table 8-3b shows this will require data from one day of revenue traffic. The combined data from all ties will be more than adequate for composite statistics.



(a) Case I - Data for Individual Ties with All Cars at All Speeds



(b) Case II - Data for Single Tie at Different Speeds with All Cars



(c) Case III - Data for All Ties at Different Speeds

FIGURE 8-2. SAMPLE CASES FOR DATA REQUIREMENTS

Case II data will be used to identify a speed effect on the bending moment for one tie. This requires separate subsets of data for the four speed ranges. Table 8-3b shows that the small number of trains (5 percent) expected in the low-speed range requires collecting data for a longer time. If data for 3000 axles of all cars were required in the lowest speed range, this would require data for 16 days of normal traffic. However, the evaluation of speed effects does not require probability density statistics as long as sufficient data are obtained to provide accurate estimates of the mean and standard deviation for each speed range. Table 8-3a shows this will require about 2 days of revenue data for all cars or 1.5 days for locomotives. However, it is possible that speed data for all cars could contain atypical load bias (trains with light cars run fast and loaded trains run slow), so it is preferable to evaluate speed effects using nearly identical cars, such as all locomotives, or all cars with weight >50 tons.

Case III data show the speed effect for the total Case I data; i.e., all cars and all ties. These data would show the effect of changing train speeds for the typical FEC traffic mix. The number of data samples in the different speed ranges would be increased by the number of ties (six in this case), so Table 8-3b shows that a complete PAPD could be obtained for each speed range with data from three days of revenue traffic. Any load bias could be evaluated by using data for cars >50 tons, which would only require about 1-1/2 days of data.

8.2 DATA COLLECTION SUMMARY

Table 8-4 summarizes the estimated maximum duration recommended for collecting revenue traffic data at the three test sites. Table 8-3 can be used to determine what data analysis can be accomplished for each test site for a specified duration. However, Table 8-4 lists the principal analyses and respective speed and car weight categories which have the highest priority.

The tangent track with 24-in. spacing will be used as the principal test section. A complete statistical description using data from all ties in the section to include spatial variations will include probability density distributions for the four speed ranges and for all car weight classes except for locomotives. Available data on locomotives can be processed, but an excessive

TABLE 8-4. SUMMARY OF RECOMMENDED DURATION FOR TRACK MEASUREMENT PROGRAM

Test Site Description	Revenue Data Collection (1)	Objectives
I. Tangent Track, 24-in. tie spacing	3 days (11,000 axles)	a. Determine PAPD statistics and mean values for speed effect with all ties (Case III) and all cars, cars >50 tons, cars <50 tons. b. Determine mean value for speed effect on one tie with all cars, cars >50 tons, cars <50 tons, locomotives.
II. Tangent Track, 20-in. tie spacing	1-1/2 days (5,500 axles)	a. Determine PAPD statistics and mean values for speed effect with all ties (Case III) and cars >50 tons for comparison with Location I.
III. Curve Track, 24-in. tie spacing	3 days (11,000 axles)	a. Same as Test Site I. b. Same as Test Site I.

Note:
(1) An additional two days will be required for instrumentation calibration and recording complete data sets for a work train and one or two revenue trains.

time period would be required to obtain 1000 axles in each speed range. Mean value and standard deviations will also be computed for load data from single locations (ties) to demonstrate speed effects for all different car classes.

Data from the tangent track section with 20-in. spacing will be used to evaluate tie spacing effects on track loading (W/R loads) and on the transfer of loads to the fastener and ties. The comparison between the two tangent test sections will be made using data from all ties to average the spatial variations. The basic comparison will be based on the mean values for loads in the different speed ranges using data for cars >50 tons. Data from a particular car class rather than all cars will be used to minimize differences which might occur from a shift in the car population during the time period when data are recorded at the two sites. The recommended duration of 1-1/2 days is based on a desire to obtain sufficient data to compute PAPD statistics for cars >50 tons in addition to the mean values and standard deviations which will be used for basic comparisons.

Data from the curve track section with a 24-in. tie spacing will be used to demonstrate the differences in track loading for curved and tangent sections of identical construction. The same data requirements are recommended for both sections with 24-in. tie spacing to obtain a complete statistical data base for tie and fastener loads on curved and tangent track.

The test duration and number of axles recommended in Table 8-4 are estimated based on recording data for all revenue trains passing the site in that time period. Fulfilling the data requirements in the lowest speed range is the limiting factor based on the assumed distribution in Table 8-2. The test period could be shortened by recording normal revenue service, and then slowing a few trains to complete the data in the speed ranges where additional data are needed. The only disadvantage of altering normal speeds is that the overall statistical load data for all cars at all speeds could be changed somewhat by this change in speed distribution. However, it can be argued that this statistical description is only pertinent to the specific test site location on the FEC, so minor variations would be acceptable. It is planned that an axle count versus speed range will be maintained during the test program and some limited speed control will be used if a significant time saving can be achieved. This would also reduce the total amount of recorded data and the costs for subsequent data analysis.

9. INSTRUMENTATION INSTALLATION AND CALIBRATION

9.1 INSTRUMENTATION INSTALLATION

The initial instrumentation task is to select the specific locations for the main instrument arrays. Locations having similar roadbed construction and located a minimum distance of 400 feet from track anomalies, such as switches, grade crossings, and culverts should be inspected. Track geometry charts should be compared to avoid having a discrete perturbation close to the instrumentation of one test site which would bias the recorded data. A clear and level area adjacent to the track is needed for the instrumented van.

The ties in the candidate locations for the main arrays should be inspected closely for any visible cracks in the rail seat or the tie center regions. Noticeably cracked ties should be avoided in the selection of SGT, see section 6.4.

The load cell ties and tie plate spacer blocks should be installed with sufficient lead time to permit reconsolidation of the disturbed ballast under about 1 MGT of revenue traffic. Track surface and alinement should be checked to insure that the disturbed section of the test site has retained acceptable geometry after consolidation.

The application of rail strain gages requires that the rail be prepared by grinding smooth patches on both sides of the rail web at each gage pattern location. A scribing template should be used to simultaneously mark the gage locations on both sides of the rail. Weldable strain gages will then be installed using a special electric-discharge spot welder. Integral leads from the gages will be routed to terminal boards.

Installation of the instrumented tie plates will require the use of a track jack to lift the rail a sufficient amount to install the instrumented plate in place of the spacer block. The rail fastener bolts and insulated rail clips should be reinstalled using a torque wrench to set the design preload.

Rail displacement transducers will be attached using phenolic blocks cemented with epoxy to a clean patch on the rail. The core rods for the DCDT transducers will be threaded into the phenolic blocks, and the cores will be attached to either the ground stakes or the tie reference base. All elements of the displacement measurement systems must be below the rail running surface and on the field side. Protective coverings are needed as shields for dragging equipment.

9.2 CALIBRATION AND CHECKOUT

An end-to-end calibration from the transducer to the recorder output will be made for each transducer in the measurement system. The SGT, the load cell ties, and the instrumented tie plates will be calibrated in the laboratory using a hydraulic loading ram. As described in section 6.4.1, the SGT will be calibrated using both full and half-bridge circuits, and these results will be compared for new and cracked ties. The instrumented tie plates will be calibrated to determine the output of the individual load cells and the total response to combined vertical and lateral loading as an assembled unit on a concrete tie. Shunt resistor calibration factors will be established at this time for use during the test. A post-test calibration will be run on the tie plates after the field measurements are completed.

Other transducers will be calibrated in the field. Physical calibration of the lateral strain gage circuits will be done with a lateral load applied between the rail heads with a laboratory-calibrated hydraulic jack. Recent field experiments have shown that when the rail base is well supported by the tie, there is negligible difference in circuit sensitivity, with or without vertical wheel load. These results will be verified by a combined lateral and vertical load calibration. Lateral load/deflection curves will be established for three conditions: vertically unloaded, under light axle load, and under heavy axle load using the work train. A sprayed coating of molybdenum disulphide powder will be used at the W/R interface to limit the lateral frictional force component. Previous results show that about 10 percent of the lateral load is shunted through the wheelset, and this must be considered in the calibration.

Pairs of vertical strain gage patterns between ties will be calibrated under known vertical wheel loads. For all of the strain gage circuits, a shunt calibration will be run after each test run to provide a functional check of the transducer and to establish correct end-to-end gain. Physical calibration of the DCDT displacement transducers will be done by moving the DCDT body a measured distance relative to the core, which is fixed to the rail. A voltage-insertion calibration from a stable oscillator voltage source will be used to establish system gains after each test run. Calibration of the accelerometers will be done by using a vibration calibrator to establish a 1-g rms signal at 100 Hz.

A complete checkout of the measurement system will be made using repeated passes of the work train, and data will be recorded for several speeds over the 0 to 60-mph speed range.

10. RAILROAD SUPPORT REQUIREMENTS

The host railroad will provide support in terms of track crews, coordination of the use of a work train, communications regarding train operations, and liaison with a local agency to provide security for the track instrumentation during off-hours.

10.1 TRACK CREWS

Track crews will be needed to clear the ballast cribs for the initial inspection of candidate ties for strain gaging, and for the installation of the tie plate spacers and the FRA/PCA load cell ties. These tasks would be done about one month before the measurement program started.

Minimal assistance will be required during the measurement program to install the instrumented tie plates and the ground stakes used for a displacement reference. Approximately one day will also be needed for the ballast and soil plate bearing measurements which requires the removal of two ties and an excavation to the subgrade level adjacent to each of the three test sites.

10.2 WORK TRAIN

A minimum work train consists of a locomotive, one car having axle loads in the range of 16,000 to 24,000 lb, and one loaded car having axle loads greater than 60,000 lb is needed for calibrating the load transducers, for the measurement of track modulus, and as a reaction mass for the plate bearing tests. The train should be accurately weighed, and the cars should be retained for the duration of the test program, if possible, so the same cars can be used at all test sites.

It is estimated that the work train will be needed for four to six hours for calibration on separate days at each of the three test sites and for one entire day for the ballast and soil plate bearing measurements.

10.3 WAYSIDE COMMUNICATION

Railroad personnel will be needed for communications with the dispatcher throughout the measurement program. Track time will be needed during the day for a continuous period of two weeks for installation of strain gages on the concrete tie and for installation of the rail strain gages. The wood tie track adjacent to the two tangent track test sites can be used for the minimal traffic during the day and traffic can be returned to the concrete tie track during each night. Installation of instrumentation on the curved track test site in single-track territory will require good communication with the train dispatcher.

After the instrumentation is installed, all traffic can resume normal operations. Communications with the dispatcher will be needed to provide sufficient lead time for activating recorders for each train pass and to identify each train. A high-power mobile radio installed in the instrument van may be the most efficient way to prov. le this communication. This would allow the test crew to maintain communications without a railroad supervisor being occupied during periods of low traffic.

10.4 SECURITY

It will be necessary to leave the instrument van and all instrumentation at the track for the duration of the test program. Security personnel will be needed for protection during the time that test crews are away from the track. This will include nights while the instrumentation is being installed, and during some days when measurements are being made only during the high-traffic periods at night. Twenty-four-hour surveillance will be needed for one or two weekends. Because of the need for flexibility in scheduling security guards, it is recommended that the host railroad make these arrangements using either railroad personnel or a local security agency.

10.5 TRAIN CONSISTS

A copy of train consist sheets will be needed for each train which passes the test site during the test period. This information is used to identify car types and car loads if load data are included.

10.6 TRACK HISTORY

A record of construction dates, construction standards, traffic history, and maintenance history will be needed for each of the test sites.

11. DATA ACQUISITION AND RECORDING

A block diagram of the track measurement and recording system is shown in Figure 11-1. This diagram shows the specific instrumentation and recording equipment recommended for this program.

The recording system consists of two 14-channel Frequency Division Multiplexors (FDM) and a 14-channel FM tape recorder (Wide Band Group I). The 28 data channels from the multiplexors will be recorded on two FM tape channels; and an additional 10 data channels will be recorded directly on FM tape. The remaining two channels will be used for the time code signal and tape synchronization.

A demodulator and oscillograph will be used to monitor data at the site while it is being recorded on FM tape. Some channels will be combined at this stage (individual tie plate load cell signals, for example, to give vertical load), and signals will be filtered as appropriate for oscillograph time-history recordings. A real-time analyzer will be used to obtain frequency spectra of rail and tie acceleration in the field. In addition to the equipment shown

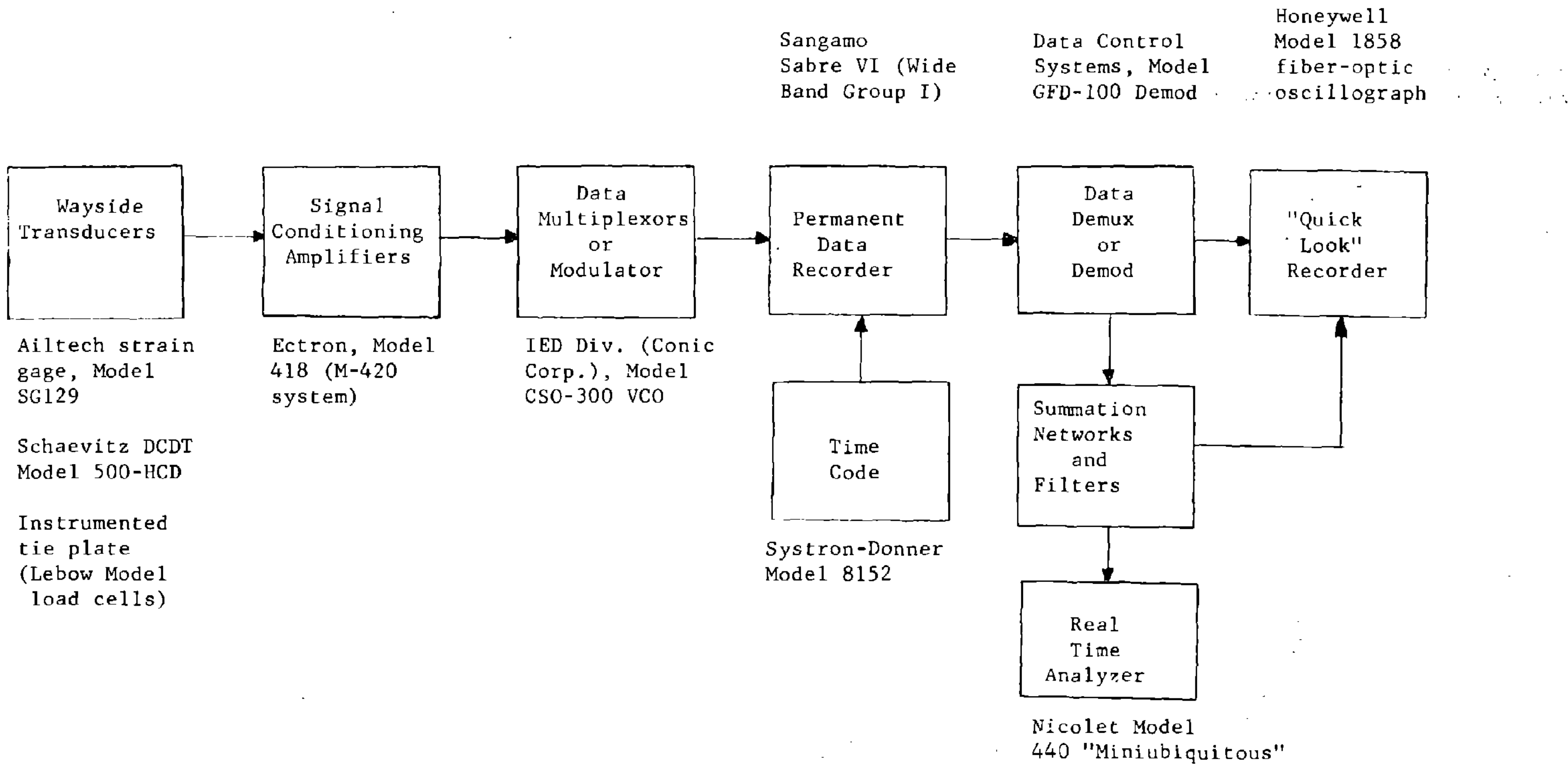


FIGURE 11-1. BASIC RECORDING SYSTEM COMPONENTS

in Figure 11-1, standard electronic diagnostic instruments will include a portable oscilloscope and a digital voltmeter.

The recording system will be operated continuously in the "ready" state when trains are approaching the test site, and functional checks will be made shortly before a train passes. After recording the track response, shunt and voltage insertion calibrations will be made on FM tape and checked on the oscillograph recordings. Run number, time and date, train identification, and other information will be recorded on the tape edge track (voice) and on the log sheet. A sample of the log sheet is shown in Figure 11-2.

12. DATA ANALYSIS PROCEDURES

The data analysis requirements are summarized in Table 5-1 for the measurement parameters which have been selected for this program. The key data channels will be processed after completion of the field-test program to generate peak amplitude probability distribution and density curves. All data from these channels will be monitored in the field on the oscillograph to verify data quality. Since the oscillograph can record "comfortably" 10 to 14 maximum channels at a time, other channels of data will be recorded on second and third passes through the tape. A switching manifold will be fabricated to facilitate this task. Time histories of work train runs and a few samples of revenue traffic will be reproduced for their entire length. Otherwise, just short samples plus calibrations will be recorded on the oscillograph to check measurement system operation. These data time histories will be used to check the quality of recorded data, to establish load and deflection characteristics through the test site, and to provide preliminary estimates of track response for both the work train and revenue traffic.

The first step in the detailed statistical analyses (see Fig. 12-1) includes an analog/digital conversion of data, calculation of peak values within the data "window" for each axle, and storage of these data points on a digital tape. This step will use a Honeywell DDP-516 mini-computer. This digital tape of "raw" data, digitized voltages blocked as sequential axles

PAGE ________

TEST SITE ____

MILE POST ______________ DATE __________ TEST SETUP ______________

REEL ____________ TAPE RECORDER SETUP ________________________

TRAIN ID NO. ______________ HEAD UNIT NO. ____________________

TIME: START RUN ____/____/____ START TRAIN ____/____/____

END RUN ____/____/____ END TRAIN ____/____/____

TAPE COUNT: START RUN ____________________ START TRAIN ______________

END RUN ____________________ END TRAIN ______________

NUMBER OF AXLES: LOCO __________ CAR __________ TOTAL __________

SPEED: IN ________ MPH OUT ________ MPH DIRECTION ______________

COMMENTS: ____

____

____

____

FIGURE 11-2. EXAMPLE OF WAYSIDE TEST LOG

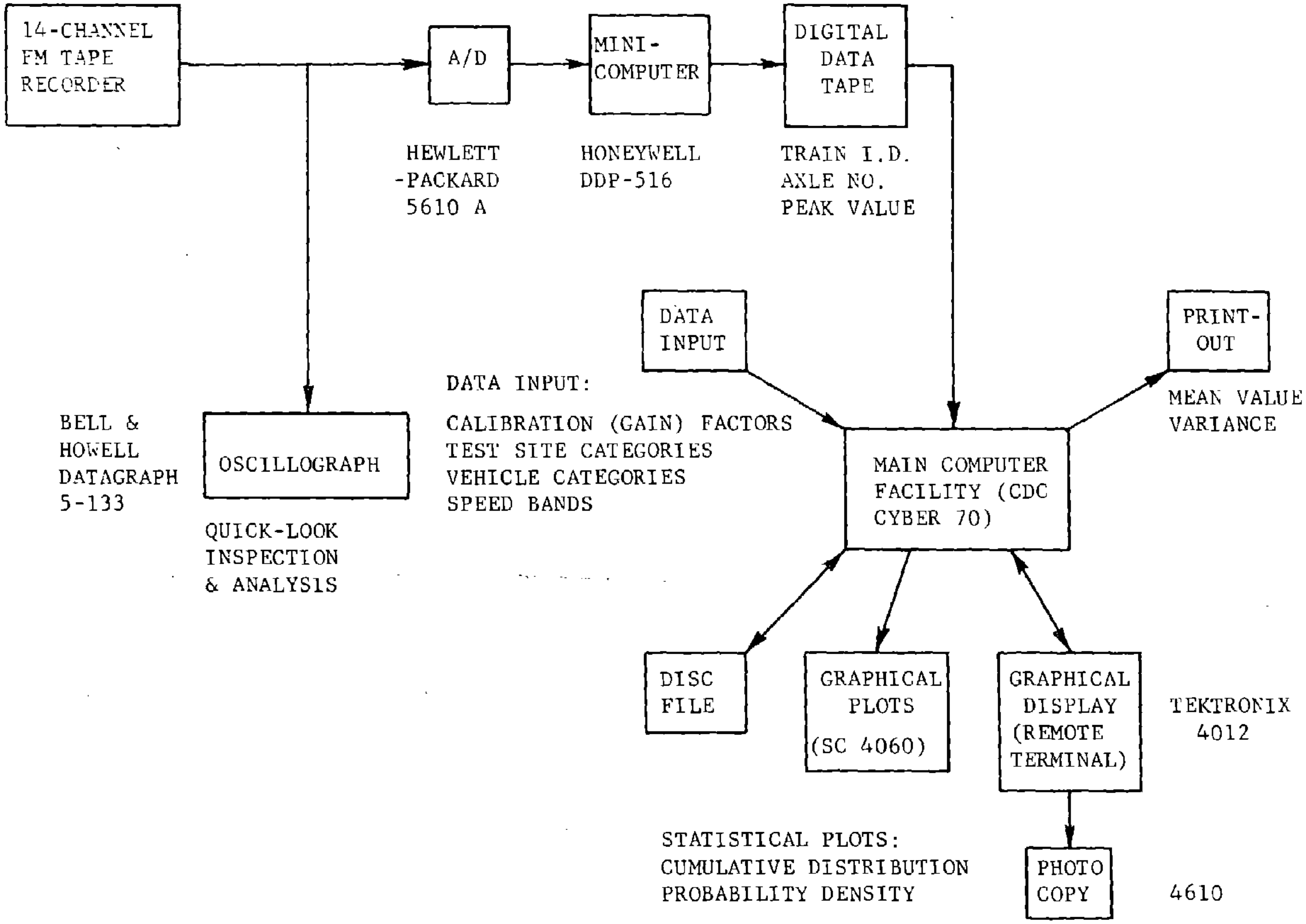


FIGURE 12-1. DATA ANLAYSIS PROCEDURES

of a train, will then be further processed by converting voltages to physical units (lb, in., etc.) and adding an identifying number for vehicle category and average speed. Three vehicle categories are recommended: (1) locomotives, (2) cars under 50 gross tons (GT) in weight, (3) cars over 50 GT in weight.

These categories provide a breakdown of major interest to the railroad community. Data for the three car categories will be sorted by computer by establishing average car weight from the vertical W/R load circuits.

The third step of data processing will involve the sorting of data and storage according to identification number on a disk file. The final step, then, will be the detailed statistical evaluation of the data, including the calculation of mean value and standard deviation for the response variables. The overall range of each measurement will be divided into the required number of intervals, and the number of peaks falling in each interval or amplitude "bin" for a given vehicle subcategory and speed band will be calculated. These categories will then be stored on disk according to the subcategory identification number. Subcategories and certain combinations of categories can then be called by identification number from the CDC Cyber 70 computer to generate the statistical probability density and cumulative distribution plots.

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APPENDIX

REPORT OF INVENTIONS

This report includes the experimental design and planning for a track measurement program utilizing state-of-the-art instrumentation. A careful review of the work performed indicates that no new inventions, discoveries, or improvements of inventions were made.