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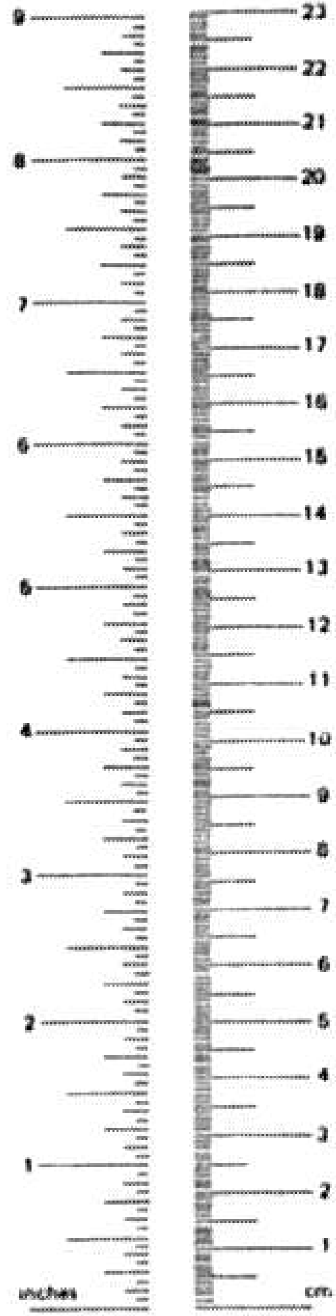
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

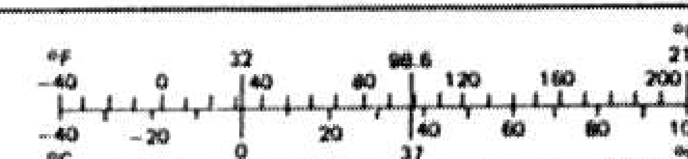
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2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

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



Approximate Conversions from Metric Measures

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



PREFACE

This volume is the third of three volumes dealing with the Vehicle/Track Interaction Assessment Techniques (IAT) which were developed by the Transportation Systems Center (TSC) and its contractors: Arthur D. Little, Inc. (ADL), Battelle Columbus Laboratories (BCL), ENSCO Inc., Kaman Sciences Corporation (KSC), Systems Control Technology Inc.(SCT), and The Analytic Sciences Corporation (TASC).

This information was developed from the Stability Assessment Facility for Equipment (SAFE) Program. That program had direct input from the railroad affiliated personnel of the International Government-Industry Track Train Dynamics Research Program and the Federal Railroad Administration, Track Safety Research Division.

The Vehicle/Track Interaction problems addressed by the IAT, called "Performance Issues," are listed below:

- Hunting;
- Twist and Roll;
- Pitch and Bounce;
- Yaw and Sway;
- Steady State Curving;
- Spiral Negotiation;
- Dynamic Curving;
- Steady Buff and Draft;
- Longitudinal Train Action; and
- Longitudinal Impact.

These problems have been responsible for compromising rail vehicle stability in the past and are expected to be important issues for consideration in future designs.

The IAT has evolved over the past few years through experience gained in conducting a number of tests dealing with vehicle/ track interaction. Essentially, the IAT is a systematic approach using a standardized set of procedures and tools (i.e., elements) for identifying, diagnosing and solving stability problems in a rail vehicle already in revenue service and for assessing the stability of a new or modified vehicle (freight car, passenger car, or locomotive) prior to its introduction into revenue service. The primary goal of the IAT is to provide a means of assessing the adequacy of rail vehicle stability at a minimum cost. This is accomplished by:

- Systematically developing an approach for identifying stability problems;
- Identifying the test procedures and tools necessary to assess the stability characteristics of the rail vehicles;
- Reducing, through the use of computer models, the amount of testing required;
- Summarizing the state-of-the-art in tools;
- Standardizing the nomenclature in stability assessment; and
- Providing the ability to compare data from different tests.

Although the IAT can determine the potential for derailment as a result of excessive motion between the wheel and rail or because of undesirable levels of wheel/rail interaction forces, it does not explicity deal with derailments resulting from the failure of a vehicle or track component due to wear, fatigue, or excessive stress caused by these forces. Also, the IAT has been developed to assess the dynamic performance of most types of freight cars, locomotives, and passenger cars; however, particular type of vehicle may not be sensitive to all Performance Issues. Therefore, the IAT incorporates a procedure for identifying the principal Performance Issues of concern for any vehicle design.

The IAT is organized in the form of Assessment Procedures. For each of three objectives of the IAT, a distinct Procedure is identified and presented in the form of a flow chart. Thus, a procedure is defined for:

- The Modified Vehicle Assessment;
- The Vehicle Problem Diagnosis; and
- The Prototype Vehicle Assessment.

Each procedure requires a number of steps to be conducted in order to meet the Specific Assessment Objective. Often, but not always, test must be conducted to meet the Assessment Objective. These tests are distinctly different and complementary to the revenue service testing to which a new or modified vehicle is generally subjected. The IAT tests are designed to subject a vehicle or consist to a severe service environment which is simulated using test tracks or laboratory equipment. In this way, the range of dynamic characteristics of a vehicle could be brought out in a relatively short time. Achieving the same goal by means of a revenue service testing procedure may require extensive testing in many miles of track.

This document, which provides information on test and analysis procedures incorporated in the IAT, is divided into two parts. The first part introduces the IAT and provides the basic information on various Assessment Procedures and the steps to be taken in performing them. The second part consists of fifteen sections, each detailing one aspect of the Assessment Techniques. In this way, a potential user need only read Part 1 to understand the key aspects of the IAT; the details provided in the second part can be studied later while the user is gaining further knowledge of the IAT or before actually utilizing the IAT for Vehicle Performance Assessment.

This document was developed under the guidance of the TSC, with the following principal contributing individuals:

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The organizations involved in developing the document are shown on the next page.

SECTIONS	PRINCIPAL CONTRIBUTING ORGANIZATIONS*
PART I (ALL SECTIONS)	ADL
PART II	
A. Resources Available for Investigating Performance Issues	ADL
B. Accident History Investigation	ADL
C. Vehicle/Track Simulation Models	ADL/TSC
D. Rail Vehicle Model Validation	SCT
E. Test Plan Summaries	TSC
F. Test Facilities	ADL
G. Track Geometry Perturbations	TSC
H. Rail/Track Stiffness Measurements, Variations, and Simulations	TSC/BCL
I. Performance Indices	TASC
J. Analytical Techniques	ADL/ENSCO
K. Wayside and Onboard Instrumentation	TSC/ENSCO
L. Data Management	TSC
M. Field Test Planning	KSC
N. Vehicle Characterization	ADL/ENSCO
O. Reference Vehicle Usage	TASC

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This volume, the third of a three volume set, includes the following sections of Part II:

- J. Analytical Techniques
- K. Wayside and Onboard Instrumentation
- L. Data Management
- M. Field Test Planning
- N. Vehicle Characterization
- O. Reference Vehicle Usage

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SECTION J
ANALYTICAL TECHNIQUES

J.1 Introduction

The data gathered in a test program (or from computer simulations) conducted under the IAT are generally not very useful unless they are converted to a more interpretable format through data analysis. This section deals with a number of techniques which can be employed to accomplish this task. Each technique is illustrated with an example and references are provided to sources which contain more information on these techniques.

Depending on the complexity of the techniques employed, a data analysis can be considered to belong to one of the three levels -- Levels 1, 2, and 3, which include the following techniques:

Level 1

- Simple statistics; and
- Resonant frequency analysis.

Level 2

Level 1 plus;

- Threshold exceedance analysis;
- Frequency spectral analysis; and
- Damping ratio calculation.

Level 3

Level 2 plus;

- Probability distribution analysis; and
- Regression analysis.

The selection of the data analysis level is based on the Response Variable being analyzed, as well as on the Test Category, i.e., whether the test was a Proof Test, Diagnostic Test, or Service Environment Test. This is illustrated in Table J-1, which is identified as Table 3-4 in

TABLE J-1: DATA ANALYSIS REQUIREMENTS FOR EACH PERFORMANCE ISSUE

TEST CATEGORY: Proof

RESPONSE VARIABLES		PERFORMANCE ISSUES: HUNTING	TWIST AND ROLL	PITCH AND BOUNCE	YAW AND SWAY	STEADY STATE CURVING	SPIRAL NEGOTIATION	DYNAMIC CURVING	STEADY BUFF & DRAFT	LONGITUDINAL TRAIN ACTION	LONGITUDINAL IMPACT
Rail & Tie Deflection	Lateral										
	Vertical										
Wheel Forces	Lateral					D2					
	Vertical					D2					
Truck Forces (Side & Complete)	Lateral					D2		D2	D2	D2	
	Vertical					D2		D2	D2	D2	
Body Accelerations	Roll		D1					D1			
	Pitch			D1				D1			D1
	Bounce			D1				D1			D1
	Yaw				D1			D1			
	Sway	D2			D1			D1			
	Longitudinal									D1	D1
Bolster Displacement (Relative to Body)	Roll		D1								
	Bounce		D1	D1							D1
Truck Acceleration	Pitch										D1
	Bounce										D1
	Yaw										
	Sway	D2									
	Longitudinal										
Truck Displacement (Relative to Body)	Roll										
	Pitch										
	Bounce			D1							
	Yaw										
	Sway										
	Longitudinal										
Axle Acceleration	Lateral										
Axle Displacement (Relative to Truck)	Lateral										
	Yaw										
Wheel Displacement (Relative to Rail)	Lateral										
	Angle of Attack										
	Vertical						D1				
Coupler Forces	Vertical			D2							
	Lateral										
	Axial										
Coupler Displacements	Vertical										
	Lateral				D1						
	Axial										
Structural Stresses											
Deformation of Body											

D1 = Level 1 Data Analysis
D2 = Level 2 Data Analysis
D3 = Level 3 Data Analysis

TABLE J-1: DATA ANALYSIS REQUIREMENTS FOR EACH PERFORMANCE ISSUE (cont'd.)

TEST CATEGORY: Diagnostic

RESPONSE VARIABLES		PERFORMANCE ISSUES: HUNTING	TWIST AND ROLL	PITCH AND BOUNCE	YAW AND SWAY	STEADY STATE CURVING	SPIRAL NEGOTIATION	DYNAMIC CURVING	STEADY BUFF & DRAFT	LONGITUDINAL TRAIN ACTION	LONGITUDINAL IMPACT
Rail & Tie Deflection	Lateral										
	Vertical										
Wheel Forces	Lateral	D2				D2		D2			
	Vertical	D2	D2			D2	D2	D2			
Truck Forces (Side & Complete)	Lateral	D2			D2	D2	D2	D2	D2	D2	
	Vertical	D2			D2	D2	D2	D2	D2	D2	
Body Accelerations	Roll		D1				D1	D1			
	Pitch			D1				D1			D1
	Bounce			D1				D1			D1
	Yaw	D2			D1		D1	D1			
	Sway	D2			D1		D1	D1			
	Longitudinal										D1
Bolster Displacement (Relative to Body)	Roll		D1				D1	D1			
	Bounce		D1	D1							D1
Truck Acceleration	Pitch										D1
	Bounce										D1
	Yaw	D2									
	Sway	D2									
	Longitudinal										D1
Truck Displacement (Relative to Body)	Roll		D1				D1	D1			
	Pitch			D1							
	Bounce			D1							
	Yaw	D2			D1	D1	D1	D1			
	Sway				D1		D1	D1			
	Longitudinal										D1
Axle Acceleration	Lateral	D2									
Axle Displacement (Relative to Truck)	Lateral	D2									
	Yaw	D2									
Wheel Displacement (Relative to Rail)	Lateral Angle or Attack					D1					
	Vertical		D1				D1				
Coupler Forces	Vertical									D2	D2
	Lateral								D2	D2	D2
	Axial								D2	D2	D2
Coupler Displacements	Vertical			D1						D1	D1
	Lateral				D1				D1	D1	D1
	Axial								D1	D1	D1
Structural Stresses											
Deformation of Body											

D1 = Level 1 Data Analysis
D2 = Level 2 Data Analysis
D3 = Level 3 Data Analysis

TABLE J-1: DATA ANALYSIS REQUIREMENTS FOR EACH PERFORMANCE ISSUE (cont'd.)

TEST CATEGORY: Service Environment

RESPONSE VARIABLES		PERFORMANCE ISSUES: HUNTING	TWIST AND ROLL	PITCH AND BOUNCE	YAW AND SWAY	STEADY STATE CURVING	SPIRAL NEGOTIATION	DYNAMIC CURVING	STEADY BUFF & DRAFT	LONGITUDINAL TRAIN ACTION	LONGITUDINAL IMPACT
Rail & Tie Deflection	Lateral				D3	D3		D3	D3		
	Vertical		D3	D3				D3			
Wheel Forces	Lateral	D3			D3	D3		D3	D3		
	Vertical	D3	D2		D3	D3	D3	D3	D3		
Truck Forces (Side & Complete)	Lateral	D3			D3	D3	D3	D3	D3	D3	
	Vertical	D3			D3	D3	D3	D3	D3	D3	
Body Accelerations	Roll		D3					D3			
	Pitch			D3				D3			D3
	Bounce			D3				D3			D3
	Yaw	D3			D3			D3			D3
	Sway	D3			D3			D3			D3
	Longitudinal									D3	D3
Bolster Displacement (Relative to Body)	Roll		D3					D3			
	Bounce		D3	D3							D3
Truck Acceleration	Pitch										D3
	Bounce										D3
	Yaw	D3						D3			
	Sway	D3						D3			
	Longitudinal										D3
Truck Displacement (Relative to Body)	Roll		D3					D3			
	Pitch			D3							
	Bounce			D3							
	Yaw	D3			D3	D3		D3			
	Sway	D3			D3			D3			
	Longitudinal										D3
Axle Acceleration	Lateral	D3			D3						
Axle Displacement (Relative to Truck)	Lateral	D3				D3		D3			
	Yaw	D3			D3	D3		D3			
Wheel Displacement (Relative to Rail)	Lateral	D3			D3	D3		D3			
	Angle of Attack	D3			D3	D3		D3			
	Vertical		D3				D3	D3			
Coupler Forces	Vertical									D3	D3
	Lateral								D3	D3	D3
	Axial								D3	D3	D3
Coupler Displacements	Vertical			D3						D3	D3
	Lateral				D3				D3	D3	D3
	Axial								D3	D3	D3
Structural Stresses											D3
Deformation of Body											D3

D1 = Level 1 Data Analysis
D2 = Level 2 Data Analysis
D3 = Level 3 Data Analysis

Part 1 of the document. As shown in the table, a Proof or Diagnostic Test requires Levels 1 and 2 data analysis, whereas a Service Environment Test needs Level 3 data analysis. Once analyzed, many of these variables are used in developing Performance Indices, as described in Subsection 3.2 of Part 1; the others are required for additional interpretation of the test results.

The specific analytical techniques to be applied for Response Variables which are to be used for calculating Performance Indices are provided in Table 3-8 in Subsection 3.2. However, the techniques to be used for the other variables are not identified. For these variables, Table J-2 can guide the user to the most appropriate data analysis techniques.

The following subsections describe the various analytical techniques along with illustrative examples.

J.2 Technical Discussion

The data available for analysis are generally in a digital format, with discrete values recorded every so many milliseconds. The first task after obtaining the data is to go through a quality control process in which the data channels having absurd values (zero, much larger than expected, and so on) are identified and discarded. At this stage, the lost channels are synthesized from raw data, if at all possible. Also, new channels are created from the existing data channels. The prime examples are L/V ratios and rigid body accelerations.

Once all channels, measured and synthesized, are available, the data analysis can be performed according to the techniques identified in the following pages. The selection of techniques to use is dictated primarily by the requirements posed by Performance Indices. Additional analysis is generally performed by an analyst seeking further understanding of the vehicle/consist behavior.

TABLE J-2: ANALYTICAL TECHNIQUE SELECTION GUIDELINES

DATA ANALYSIS OBJECTIVE	TECHNIQUE WHICH CAN TYPICALLY BE USED	DESCRIBED IN SUBSECTION
Obtaining Performance Indices	• Simple Statistics • Threshold Exceedance Analysis • Damping Ratio Calculation	J.2.1.1 J.2.2.1 J.2.2.3
Extrapolating Performance to that on Other Tracks	• Regression Analysis	J.2.3.2
Estimating Probability of Derailment	• Probability Distribution Analysis • Threshold Exceedance Analysis • Simple Statistics	J.2.3.1 J.2.2.1 J.2.1.1
Diagnosis of a Dynamic Problem	• Simple Statistics • Resonant Frequency Analysis • Threshold Exceedance Analysis • Damping Ratio Calculation • Frequency Spectral Analysis	J.2.1.1 J.2.1.2 J.2.2.1 J.2.2.3 J.2.2.2
Identifying Natural Frequencies	• Resonant Frequency Analysis • Frequency Spectral Analysis	J.2.1.2 J.2.2.2

J.2.1 Level I Data Analysis

J.2.1.1 Simple Statistics

The simple statistical descriptors of a particular Response Variable are calculated in the following manner:

Mean: $\frac{\sum_{i=1}^{n} x_i}{n}$, where X_i is a digitized time series of the Response Variable X containing n values. This time series may represent vehicle response over a test segment or over the whole test zone depending on the test objectives.

Maximum: peak positive value;

Minimum: peak negative value;

Root Mean Squares: $\sqrt{\frac{\sum_{i=1}^{n} x_i^2}{n}}$;

Standard deviation from the mean (σ): $\sqrt{(RMS)^2 - (MEAN)^2}$;

J.2.1.2 Resonant Frequency Analysis

Simply stated, the resonant frequency analysis attempts to correlate the frequencies of the input a vehicle receives from the track perturbations with the natural frequencies of the vehicle in the modes being excited by the perturbations. The relationships between the perturbation types and the vehicle modes excited by them are shown below:

Perturbation Type	Vehicle Mode
Crosslevel	Roll
Profile	Pitch and Bounce
Alignment, Gauge	Yaw and Sway

A substantial increase in the motion of the vehicle in a particular mode can be expected if an input frequency coincides with one of the natural frequencies in that mode. As a simple case, assume that a vehicle with velocity, V, is going over a track incorporating sinusoidal perturbations (of any type) with wavelength, λ. The frequency of the input received by the vehicle, f, will then be:

$$f = \frac{V}{\lambda} \tag{J.1}$$

This input will have a peak amplitude which is determined by the perturbation amplitude,* the truck center distance and the wheel base as shown in Table J-3. These equations indicate that, depending on the truck center distance,** certain perturbation wavelengths provide more input to one mode of vehicle motion than another. This is schematically shown in Figure J-1, in which an "even mode" (E) represents bounce, sway, and roll, whereas an "odd mode" (O) represents pitch and yaw. Thus, a vehicle with 39 feet truck center distance will experience largely yaw motion on a track incorporating 78 feet wavelength alignment perturbations, whereas the same vehicle will experience largely sway motion on a track incorporating 39 feet wavelength alignment perturbations. The details of these are provided in Ref. 1.

An example of the effect of truck center distance and wheel base on the input amplitude is shown in Figures J-2 and J-3. In these figures, the gains (i.e., the sine and cosine terms in the equations shown in Table J-3) for a locomotive (SDP-40F) in yaw and sway modes are plotted as functions of wavelength. As the figure shows, an

* This assumes that the track is relatively stiff. A vehicle operating over a more compliant track will see a somewhat different amplitude.

** The effect of wheel base is usually negligible, unless the perturbation wavelength is very short, say less than 20 feet.

TABLE J-3: THE EFFECTS OF TRUCK CENTER DISTANCE AND WHEEL BASE ON PERTURBATION INPUT

MODE	PEAK-TO-PEAK AMPLITUDE OF THE INPUT	
Roll	$2\tan^{-1}\left(\frac{C}{2G}\left\|\cos\frac{\pi L}{\lambda}\cos\frac{\pi b}{\lambda}\right\|\right)$	radians
Pitch	$2\tan^{-1}\left(\frac{P}{L}\left\|\sin\frac{\pi L}{\lambda}\cos\frac{\pi b}{\lambda}\right\|\right)$	radians
Bounce	$P\left\|\cos\frac{\pi L}{\lambda}\cos\frac{\pi b}{\lambda}\right\|$	inches
Yaw	$2\tan^{-1}\left(\frac{A}{L}\left\|\sin\frac{\pi L}{\lambda}\cos\frac{\pi b}{\lambda}\right\|\right)$	radians
Sway	$A\left\|\cos\frac{\pi L}{\lambda}\cos\frac{\pi b}{\lambda}\right\|$	inches

C = Crosslevel amplitude (peak-to-peak)

P = Profile amplitude (peak-to-peak)

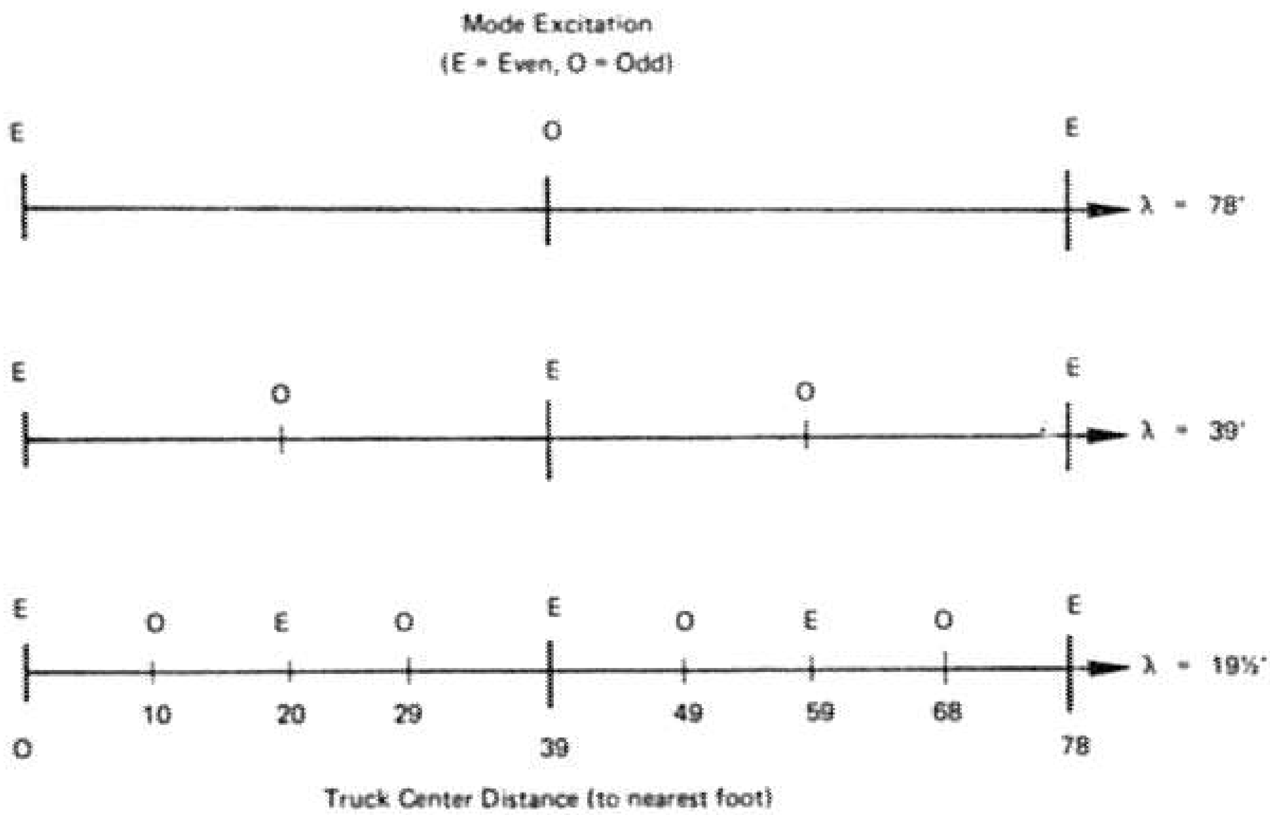
A = Alignment amplitude (peak-to-peak)

G = Nominal Gauge

L = Truck center distance

b = Wheel base

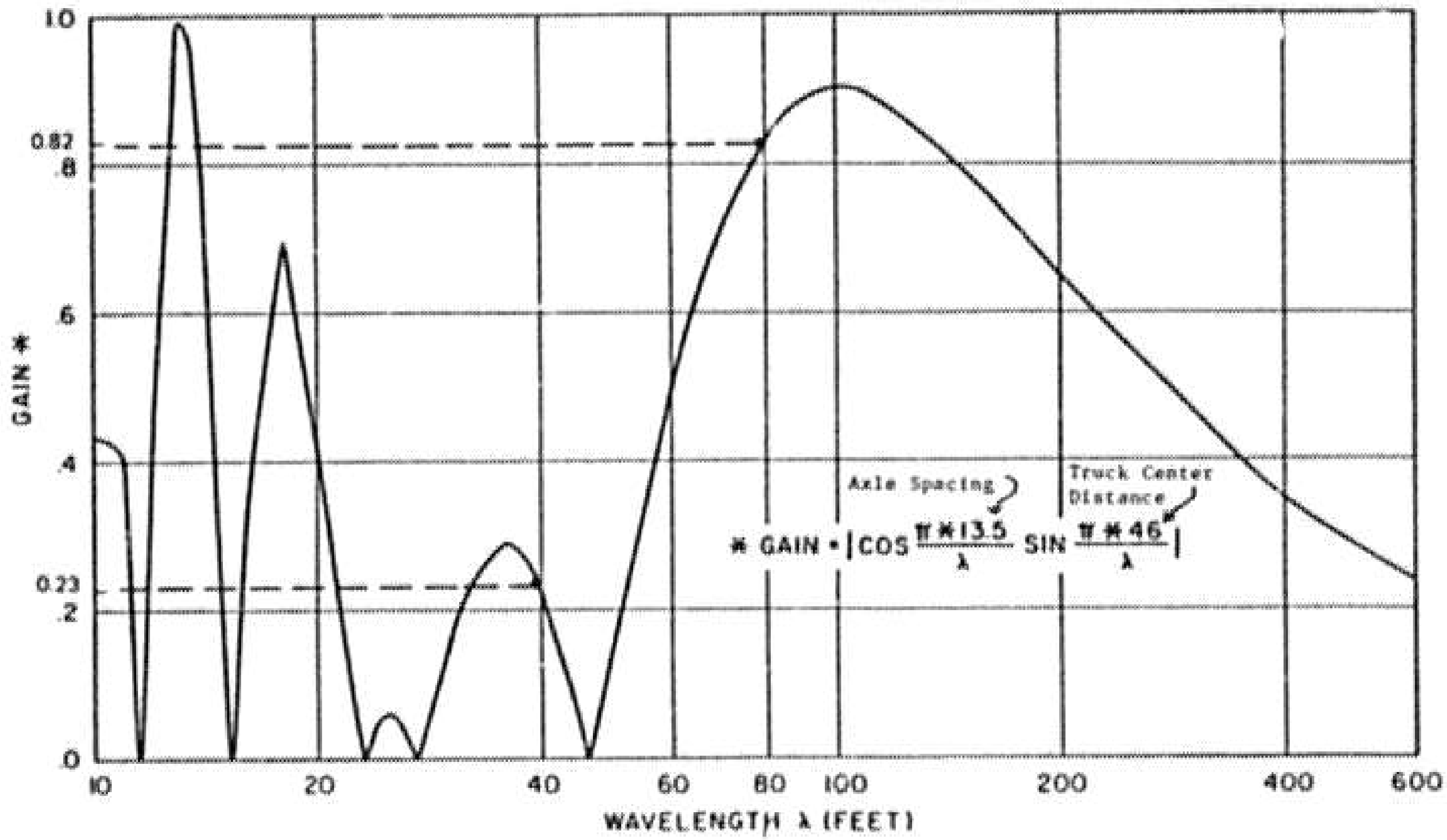
| | = Absolute value



Note: Truck centers lying between nodal points (E, O) will excite both modes, with the input energy being distributed between the two modes based upon how close the truck center lies to either node.

FIGURE J-1: RELATIONSHIP BETWEEN TRUCK CENTER DISTANCE AND TYPE OF EXCITATION

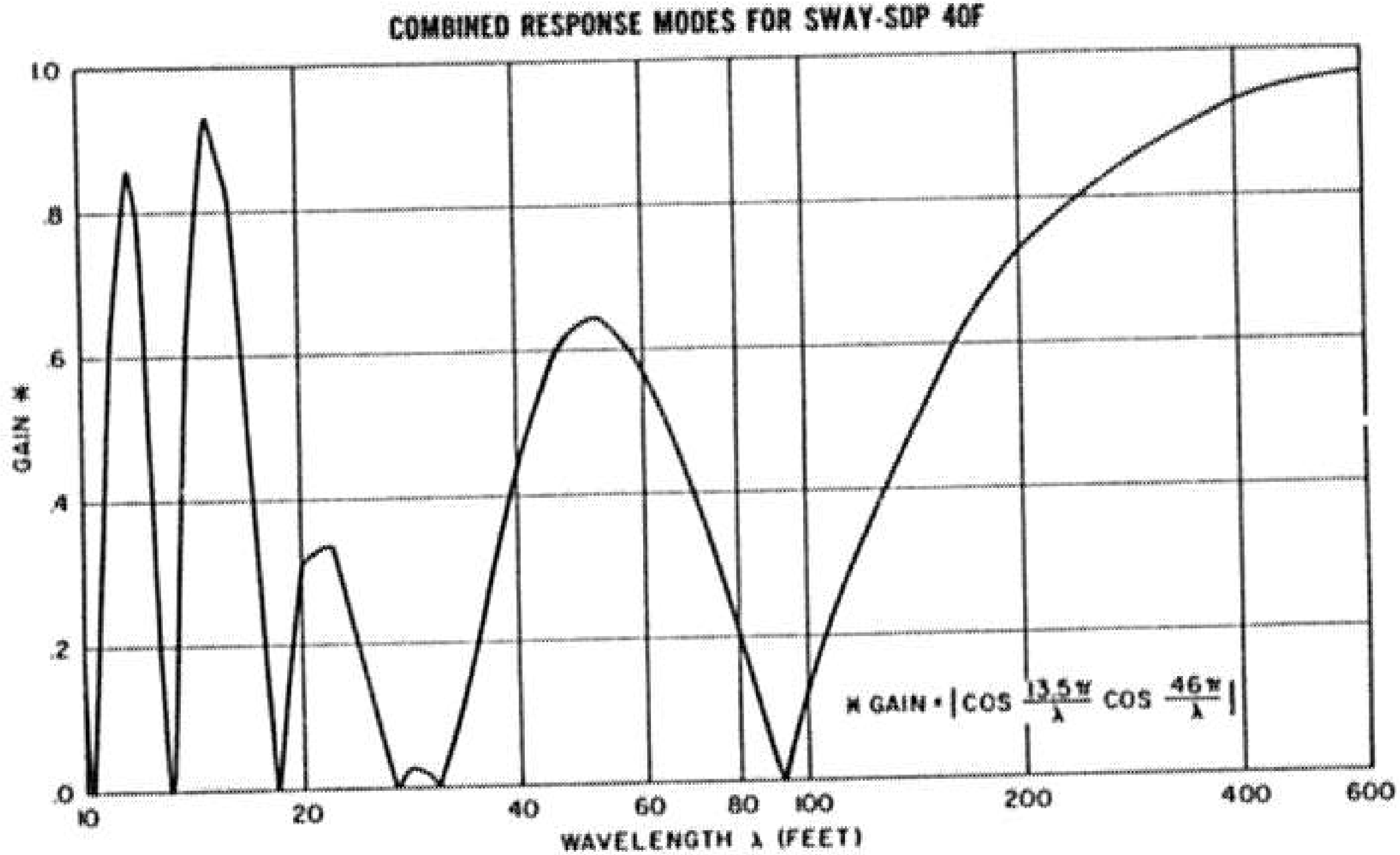
COMBINED RESPONSE MODES FOR YAW-SDP 40F



Source: Ref. [1]

Vehicle: SDP-40F Locomotive

FIGURE J-2: THE EFFECT OF PERTURBATION WAVELENGTH ON THE YAW INPUT TO A VEHICLE



Source: Ref. [2]

Vehicle: SDP-40F Locomotive

FIGURE J-3: THE EFFECT OF PERTURBATION WAVELENGTH ON THE SWAY INPUT TO A VEHICLE alignment perturbation with wavelength 92 feet causes the vehicle to experience a large yaw motion, but hardly any sway motion.

So far, we have assumed that the perturbations are sinusoidal in shape. Often, they are not. In these cases, equivalent sinusoidal components have to be developed using Fourier Transformation [Ref. 3], as shown in Figure J-4. This process will convert the given perturbation shape into a number of equivalent sinusoidal components with different amplitudes and with wavelengths which are given by λ/n ($n = 1, 2, 3, \ldots$), where λ is the basic wavelength. For the purpose of resonant frequency analysis, only the components with large amplitudes need to be selected and treated as individual sinusoidal perturbations.

The use of Fourier Transformation is illustrated through an example shown in Figure J-5. In this, two popular types of perturbation, piecewise linear and rectified sinewave, which have actually been used in a test program [Ref. 4], are analyzed.

The resulting values of relative amplitudes (C_n) show that perhaps the first two components of either perturbation shapes (78 ft. and 39 ft. wavelength components for the piecewise linear and 39 ft. and 19.5 ft. wavelength components for the other) should be studied, the others neglected.

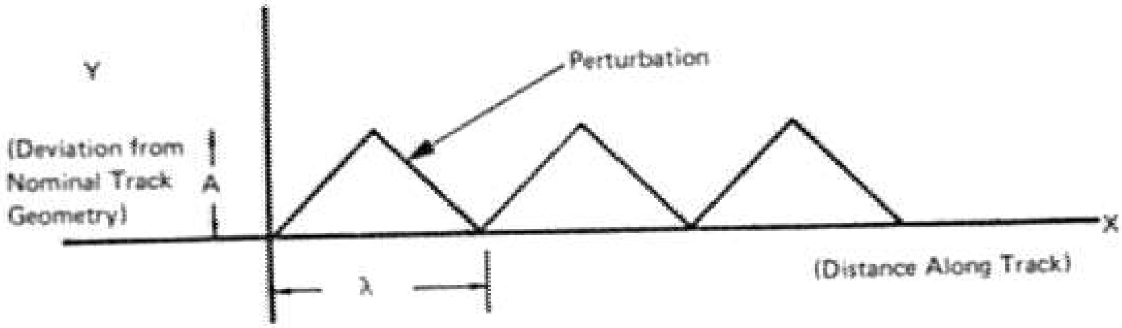
To summarize, the resonant frequency analysis is to be performed in the following way:

1. Transform the given perturbation shape into equivalent sinusoidal components using the Fourier Transformation shown in Figure J-2.

2. For each wavelength with significant amplitude, determine the input amplitude, using equations given in Table J-2, and input frequency using Equation J.1.

3. Compile a table of input frequencies corresponding to components with significant <u>input</u> amplitudes.

4. Repeat Steps 2 and 3 for different test speeds.



$$Y = f(x) = \frac{1}{2}C_o + A \sum_{n=1}^{\infty} C_n \cos \frac{2\pi n x}{\lambda}$$

$$C_n = \sqrt{a_n^2 + b_n^2}$$

Where $$a_n = \frac{2}{A\lambda} \int_{-\frac{\lambda}{2}}^{\lambda/2} f(t) \cos \frac{2n\pi t}{\lambda} \, dt$$

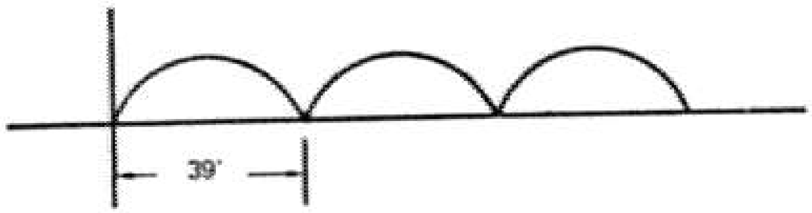
$$b_n = \frac{2}{A\lambda} \int_{-\lambda/2}^{\lambda/2} f(t) \sin \frac{2n\pi t}{\lambda} \, dt$$

FIGURE J-4 FOURIER TRANSFORM OF A PERTURBATION SHAPE

Fourier Transform:

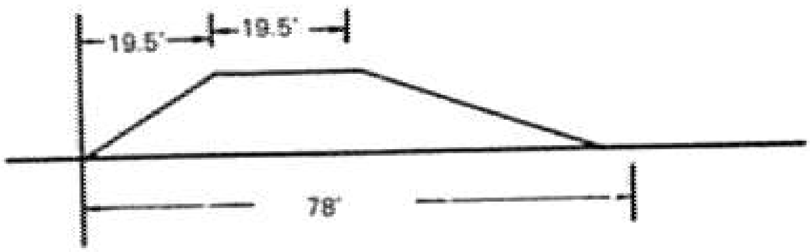
$$f(x) = \frac{C_0}{2} + A\,\Sigma C_n \cos\left(\frac{2n\pi x}{\lambda_1} - \tan^{-1}\left(\frac{b_n}{a_n}\right)\right)$$

Rectified Sine Perturbation



n	1	2	3	4	5	6	7	8	9	10
λ	39	19.5	13	9.75	7.8	6.5	5.571	4.875	4.333	3.9
c_n	0.4244	0.0849	0.0364	0.0202	0.0129	0.0089	0.0065	0.0050	0.0039	0.0032

Peicewise Linear Perturbation



n	1	2	3	4	5	6	7	8	9	10
λ	78	39	26	19.5	15.6	13	11.11	9.75	8.667	7.8
c_n	0.4531	0.1013	0.0504	0	0.0181	0.0113	0.0092	0	0.0056	0.0041

Source: Ref. [4]

FIGURE J-5 FOURIER TRANSFORM OF TYPICAL PERTURBATION SHAPE

The significant input frequencies for the completed speed range can then be compared with the vehicle natural frequencies in relevant modes, which are calculated as shown in Section N (Vehicle Characterization). If, in a particular speed range, a significant input frequency is equal to a natural frequency, the resulting resonance can explain the vehicle behavior in that speed range. Figure J-6 shows the relationship between the wavelengths of typical perturbations existing in revenue service and typical natural frequencies of different vehicle types.

J.2.2 Level 2 Data Analysis

J.2.2.1 Threshold Exceedance Analysis

This analysis provides information regarding the exceedance of a particular Response Variable above a predetermined threshold value. This exceedance can be characterized by many descriptors [Ref. 5], such as:

L_{95}: 95 percentile level (that level exceeded 5% of the time)

L_{T20MAX}: The maximum level which is exceeded for 20 msec

L_{T40MAX}: The maximum level which is exceeded for 40 msec

L_{T80MAX}: The maximum level which is exceeded for 80 msec

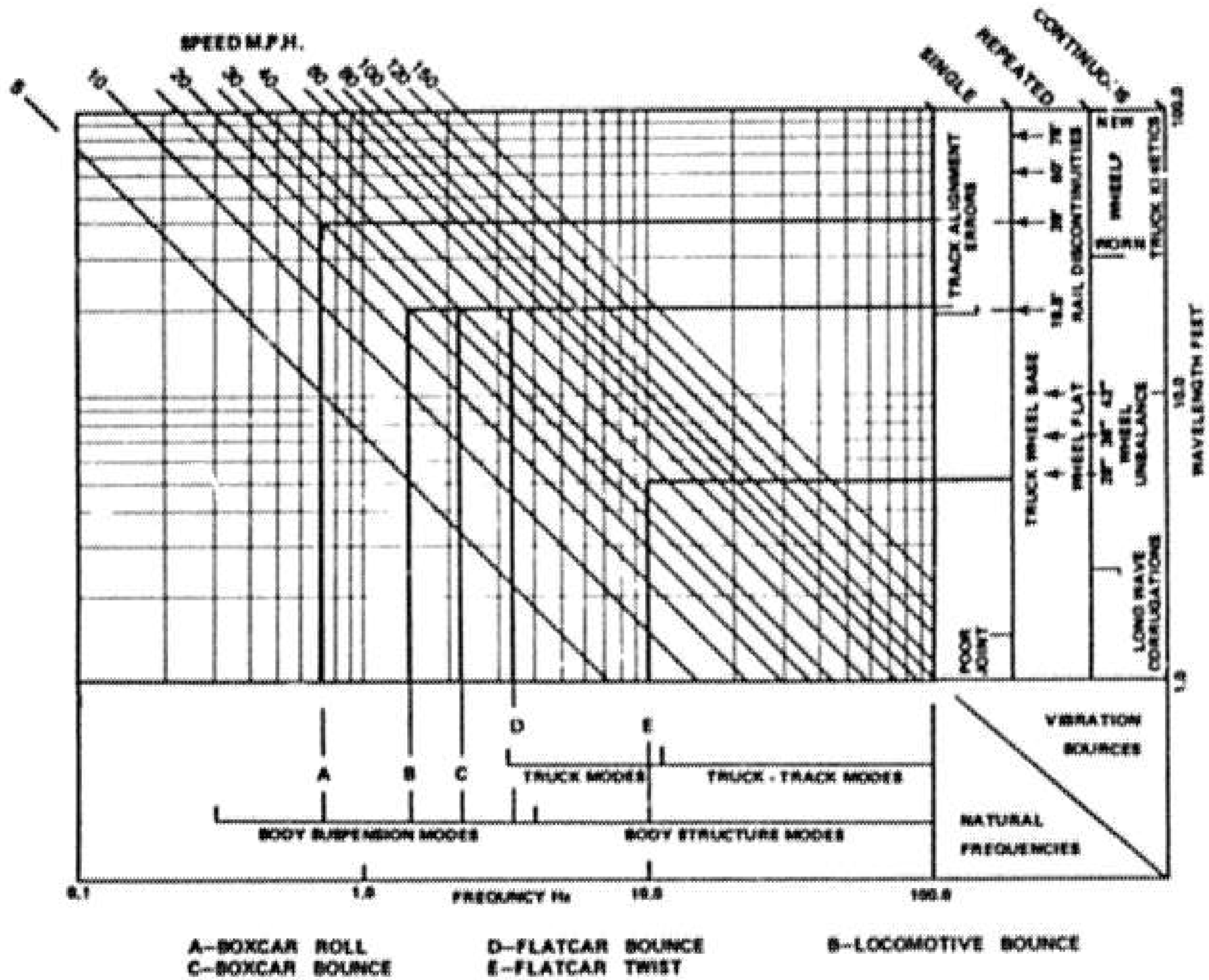
$L_{T20MEAN}$: The level at which the mean of all the exceedance times is 20 msec

$L_{T40MEAN}$: The level at which the mean of all the exceedance times is 40 msec

$L_{T80MEAN}$: The level at which the mean of all the exceedance times is 80 msec

L_{TMAX95}(seconds): The maximum exceedance at L_{95} threshold level

$L_{TMEAN95}$(seconds): The mean exceedance duration at L_{95} threshold level.



Source: TASC Data.

FIGURE J-6: THE RELATIONSHIP BETWEEN THE WAVELENGTHS OF TYPICAL REVENUE SERVICE PERTURBATIONS AND TYPICAL VEHICLE NATURAL FREQUENCIES

This analysis is particularly useful in interpreting the wheel force data. This is because the effect of a wheel force which exists for very short time [Ref. 6] on vehicle or rail behavior is generally insignificant because of inertia of the vehicle and of rail. Thus, L_{95} or L_{T20MAX} may be better descriptors of the wheel force than a peak value. Also, all of the above descriptors can be obtained per perturbation cycle, test segment, or test zone, as dictated by the test objectives.

The above descriptors can be calculated by developing arrays which store the intermediate data related to exceedances (see Ref. 7). An exceedance of a threshold occurs when the data values increase from below to above a threshold and then, after some time above that threshold, decreases to below that threshold. Such an occurrence is one exceedance of that threshold and has a time duration associated with it. During data processing, the number of exceedances and the times of exceedance of each threshold value can be recorded to provide the following four arrays:

- Array 1, total time of exceedance;
- Array 2, number of exceedances;
- Array 3, maximum duration time of any exceedance; and
- Array 4, mean duration time of all the exceedances.

From these arrays, the exceedance descriptors can be calculated in the following way:

L_{95}: The total time of exceedance for various threshold values are stored in Array 1, from which the level which is exceeded only 5% of the time can be obtained through extrapolation.

L_{T20MAX}, L_{T40MAX}, L_{T80MAX}: The maximum duration times at various exceedance levels can be stored in Array 3. Using these data, the peak levels which are exceeded for 20, 40, and 80 msec can be found using extrapolation.

$L_{T20MEAN}$, $L_{T40MEAN}$, $L_{T80MEAN}$: Array 4 can provide the mean duration time of all exceedances at a particular threshold level. From these mean times, and the corresponding threshold levels, the levels which correspond to the mean exceedances of 20, 40, and 80 msec can be determined using extrapolation.

L_{TMAX95}: The maximum exceedance duration time corresponding to the L_{95} level (calculated as shown above) can be determined from Array 3 using extrapolation.

$L_{TMEAN95}$: The mean exceedance duration time corresponding to the L_{95} level can be determined from Array 4 using extrapolation.

An example of the Threshold Exceedance Analysis is shown in Figures J-7 and J-8 both of which show the response of a vehicle to a set of perturbations. The first of these two figures deals with intermediate data storage in the four arrays for the threshold levels of 20,000 and 40,000 lbs. The other figure uses these data to calculate the various descriptors associated with the analysis. The relative values of some of the key descriptors are compared with the maximum and mean values in Figure J-9, which shows the results of tests done at various speeds between 38 and 74 mph [Ref. 5].

J.2.2.2 Frequency Spectral Analysis

The Frequency Spectral Analysis is similar to the Resonant Frequency Analysis discussed in J.2.1.2, except this technique is generally used for characterizing a revenue service track as opposed to a test track with discrete perturbations. In this analysis, "Power Spectral Densities (PSDs)" of the various track parameters (gauge, alignment, crosslevel, and so on) are calculated using a "Fast Fourier Transform (FFT)" algorithm [Ref. 8]. Since this subject is relatively complex, and its treatment is readily available to an interested user [Ref. 9, 10 and 11, for example], no attempt is made to explain an FFT algorithm. The current advances in electronics makes it possible to obtain the PSD of a variable very quickly while the test is being done [Ref. 10 and 11].

LATERAL WHEEL FORCE

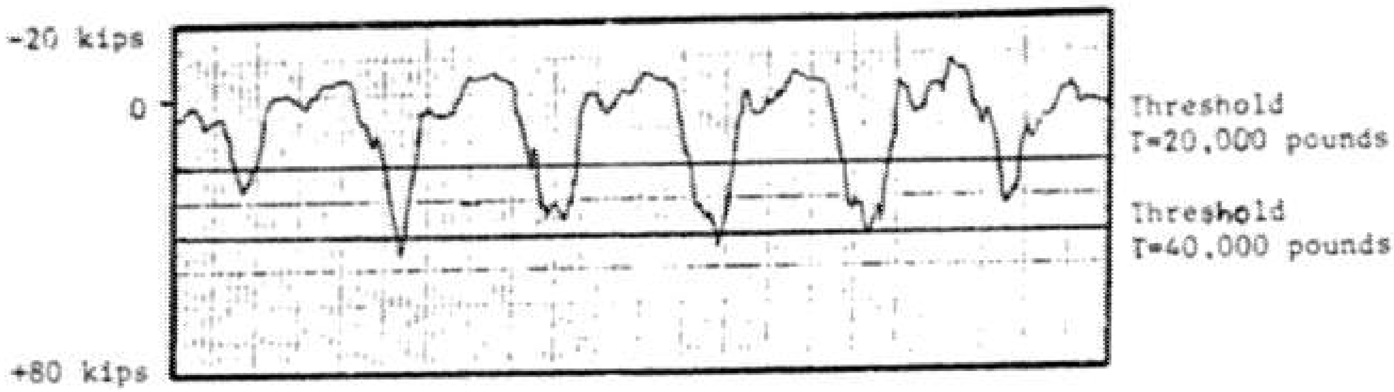


CHART SPEED = 1mm = 0.040 seconds

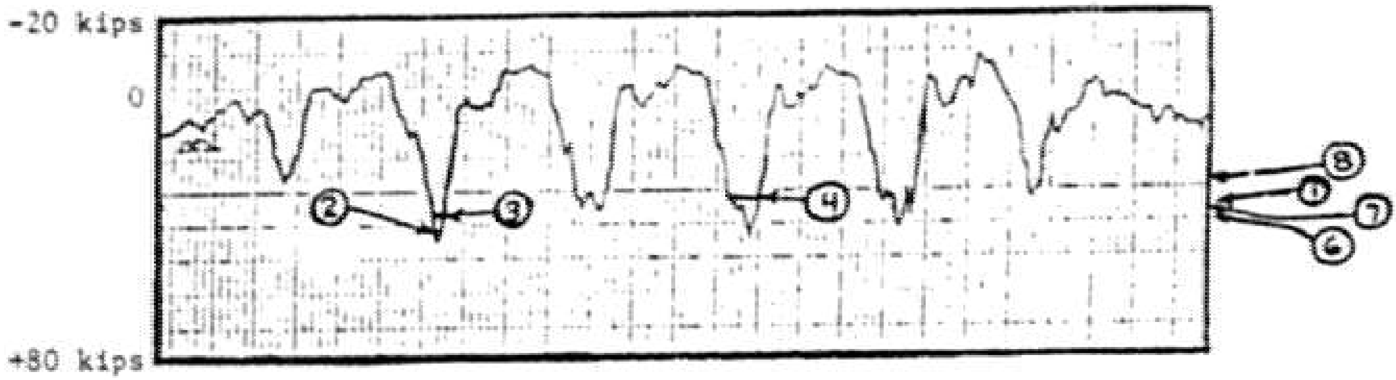
CONTENTS OF THE ARRAYS	AT T = 20,000	AT T = 40,000
ARRAY 1, Total Exceedance Time	1.04 sec	0.12 sec
ARRAY 2, Number of Exceedances	6 Exceedances	3 Exceedances
ARRAY 3, Maximum Exceedance Duration	0.20 sec	0.04 sec
ARRAY 4, Mean Exceedance Duration	0.17 sec	0.04 sec

Response Variable : Lateral Wheel Force, Lead Axle
Vehicle : SDP-40F

Source: Ref. [7]

FIGURE J-7: AN EXAMPLE OF DATA ARRAYS FOR TWO THRESHOLD LEVELS

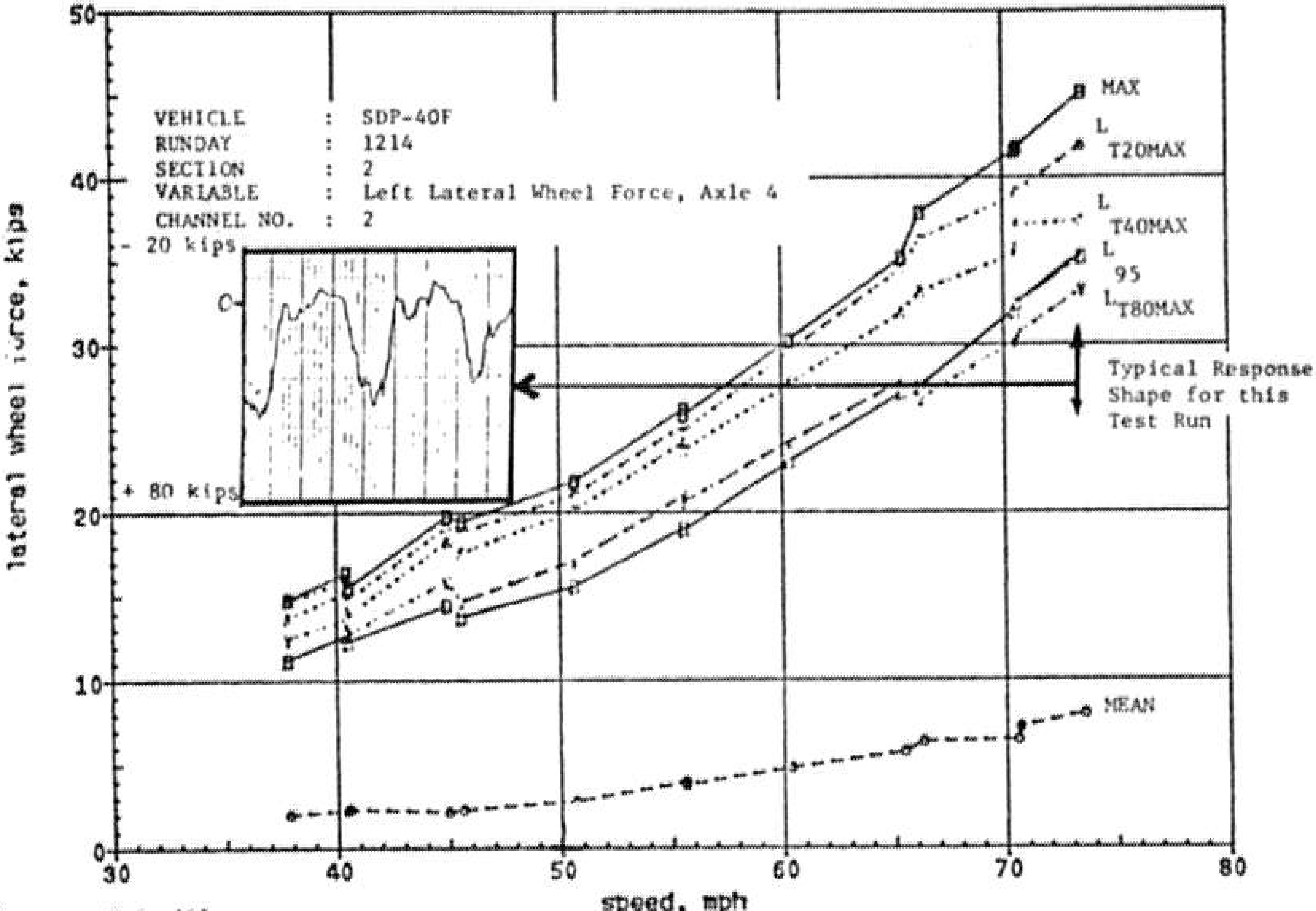
SDP-40F LATERAL WHEEL FORCE, LEAD AXLE



FROM:	DESCRIPTION	VALUE IN EXAMPLE
ARRAY 1	① L_{95}	35 kips
ARRAY 3	② $L_{T20\ MAX}$	42 kips
	③ $L_{T40\ MAX}$	37 kips
	④ $L_{T80\ MAX}$	33 kips
	⑤ $L_{T\ MAX\ 95}$ (at L_{95}, which = 35 kips)	.060 sec
ARRAY 4	⑥ $L_{T20\ MEAN}$	39 kips
	⑦ $L_{T40\ MEAN}$	36 kips
	⑧ $L_{T80\ MEAN}$	29 kips
	⑨ $L_{T\ MEAN\ 95}$ (at L_{95}, which = 35 kips)	.038 sec

Source: Ref. [7]

FIGURE J-8: TYPICAL EXCEEDANCE ANALYSIS RESULTS



Source: Ref. [5]

FIGURE J-9: A COMPARISON OF THE THRESHOLD EXCEEDANCE DESCRIPTIONS WITH MEAN AND MAXIMUM VALUES

A typical example of what this analysis would generate is shown in Figure J-10. The figure shows that the PSD of the crosslevel of a typical bolted track has a downward slope (i.e., long wavelength crosslevel variations have large amplitudes, short wavelength variations have small amplitudes). Also, peaks are observed at frequency values (expressed in cy/ft) between 2×10^{-2} and 0.1 (i.e., wavelength of 50 ft. to 10 ft.). These peaks would include the crosslevel variations with 39 ft. wavelength caused by dipped joints.

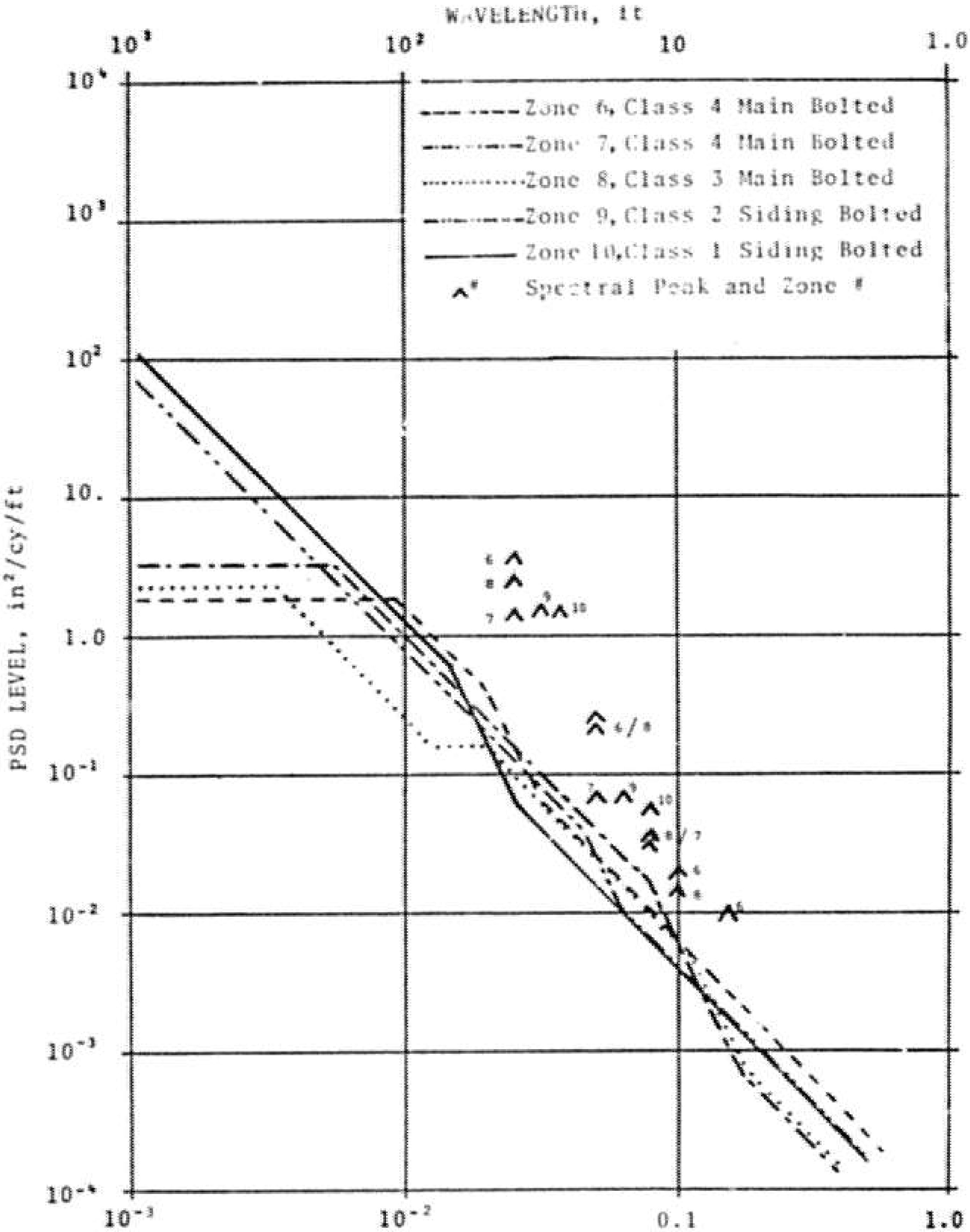
Such information is very useful in characterizing the input a vehicle receives from a revenue service track. This analysis can also be used in characterizing vehicle response. Just as high peaks at certain wavelengths in the PSD of a track parameter indicate particularly large input at those wavelengths, peaks in the PSD of a vehicle response variable at particular frequencies represent resonance of the vehicle at those frequencies. An example of this is shown in Figure J.11. Knowing thus both the input to the vehicle and its response would prove helpful in evaluating its performance on a revenue service track.

J.2.2.3 <u>Damping Ratio Calculation</u>

As mentioned earlier, in Table 3-8 of Part 1, the calculation of the Performance Indices for hunting requires obtaining the damping ratio of carbody and truck sway accelerations from their time history plots. The most common method of doing this is called the "Logarithmic Decrement Method." In Figure J-12, a variable is shown to reduce to a stable value after being excited by a transient perturbation. If successive amplitudes of this variation are x_1 and x_2, then:

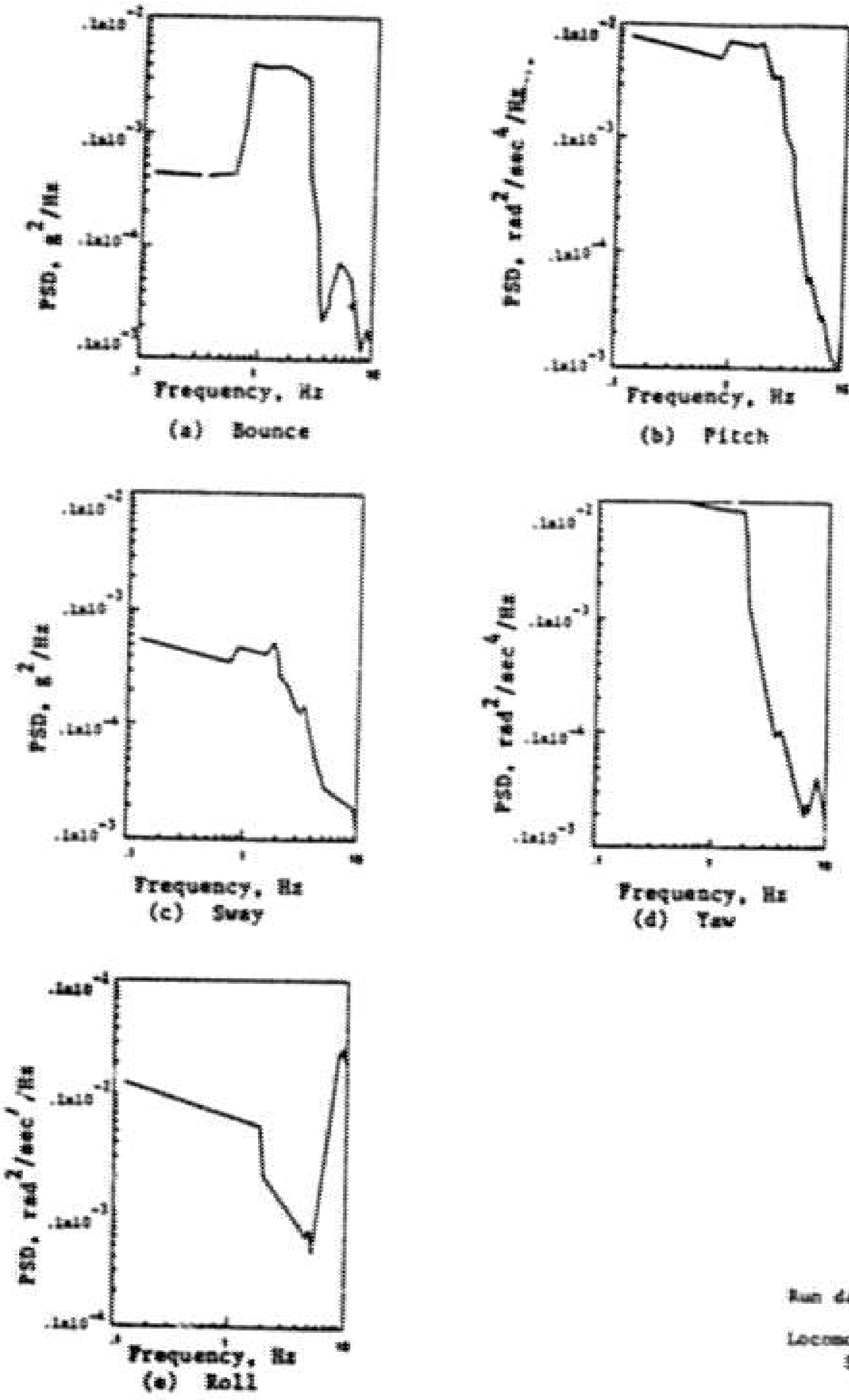
$$\text{Damping Ratio, } \xi = \sqrt{\left(\frac{\delta^2}{\delta^2 + 4\pi^2}\right)} \qquad (J.2)$$

$$\text{where } \quad \delta = \ln\left(\frac{x_1}{x_2}\right) \qquad (J.3)$$



Source: Ref. [9]

FIGURE J-10: TYPICAL POWER SPECTRAL DENSITY (PSD) OF A TRACK CHARACTERISTIC



Section 6

Piecewise Linear
Profile Perturbations

Section 8

Piecewise Linear
Alignment Perburbations

Section 7

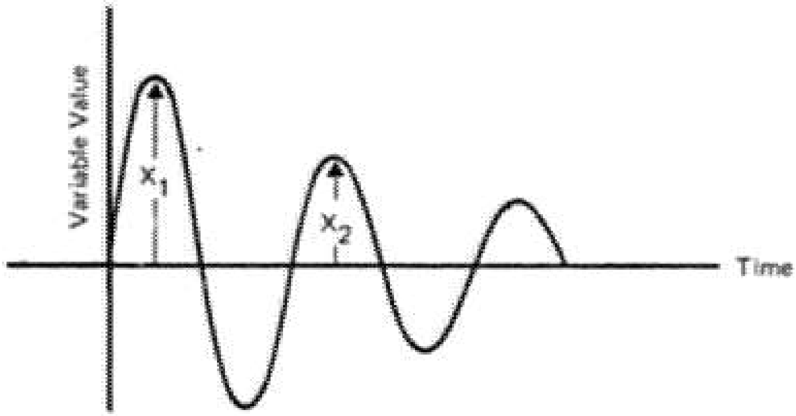
Piecewise Linear
Crosslevel Perturbations

Run day: 1202

Locomotive: SDP-40F
Speed: 43 MPH

Source: Ref. [5]

FIGURE J-11: TYPICAL PSD PLOTS OF VEHICLE RESPONSE VARIABLES



Amplitude Ratio $\frac{x_1}{x_2}$	Corresponding Damping Ratio ξ
1.21	0.03
1.88	0.1
3.61	0.2
7.21	0.3

FIGURE J-12 USING THE LOGARITHMIC DECREMENT METHOD FOR CALCULATING DAMPING RATIO

This is a linear representation of damping which in reality may be nonlinear in nature.

J.2.3 Level 3 Data Analysis

J.2.3.1 Probability Distribution Analysis

One of the applications of probability distribution analysis is to determine the repeatability of a parameter in a test program. The following procedure can be applied in this situation:

If it is assumed that the parameter being measured through testing (say, the peak value of lateral force) has a normal distribution, we can say with confidence level of (1-α) x 100% that the true mean value of the parameter μ_x will be bounded by:

$$\bar{x} - \frac{St_{n;\alpha/2}}{\sqrt{N}} \leq \mu_x \leq \bar{x} + \frac{St_{n;\alpha/2}}{\sqrt{N}} \qquad (J.4)$$

where

N = sample size (number of tests)

μ_x = true mean

$\bar{x}$ = calculated mean

$t_{n;\alpha/2}$ = percentage point of student t distribution (see Table J-4)

$n = N - 1$

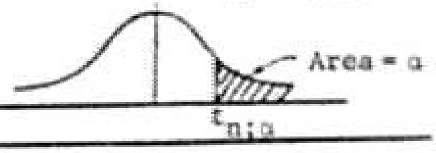
S^2 = calculated unbiased estimate of variance

$$S^2 = \frac{1}{N-1} \sum_{i=1}^{N} (x_i^2 - (\bar{x})^2), \qquad (J.5)$$

$$\bar{x} = \frac{\sum_{i=1} x_i}{N} \, . \qquad (J.6)$$

TABLE J-4: PERCENTAGE POINTS OF STUDENT t DISTRIBUTION

Value of $t_{n;\alpha}$ such that $Prob[t_n > t_{n;\alpha}] = \alpha$



n	α = 0.10	0.050	0.025	0.010	0.005
1	3.078	6.314	12.706	31.821	63.657
2	1.886	2.920	4.303	6.965	9.925
3	1.638	2.353	3.182	4.541	5.841
4	1.533	2.132	2.776	3.747	4.604
5	1.476	2.015	2.571	3.365	4.032
6	1.440	1.943	2.447	3.143	3.707
7	1.415	1.895	2.365	2.998	3.499
8	1.397	1.860	2.306	2.896	3.355
9	1.383	1.833	2.262	2.821	3.250
10	1.372	1.812	2.228	2.764	3.169
11	1.363	1.796	2.201	2.718	3.106
12	1.356	1.782	2.179	2.681	3.055
13	1.350	1.771	2.160	2.650	3.012
14	1.345	1.761	2.145	2.624	2.977
15	1.341	1.753	2.131	2.602	2.947
16	1.337	1.746	2.120	2.583	2.921
17	1.333	1.740	2.110	2.567	2.898
18	1.330	1.734	2.101	2.552	2.878
19	1.328	1.729	2.093	2.539	2.861
20	1.325	1.725	2.086	2.528	2.845
21	1.323	1.721	2.080	2.518	2.831
22	1.321	1.717	2.074	2.508	2.819
23	1.319	1.714	2.069	2.500	2.807
24	1.318	1.711	2.064	2.492	2.797
25	1.316	1.708	2.060	2.485	2.787
26	1.315	1.706	2.056	2.479	2.779
27	1.314	1.703	2.052	2.473	2.771
28	1.313	1.701	2.048	2.467	2.763
29	1.311	1.699	2.045	2.462	2.756
30	1.310	1.697	2.042	2.457	2.750
40	1.303	1.684	2.021	2.423	2.704
60	1.296	1.671	2.000	2.390	2.660
120	1.289	1.658	1.980	2.358	2.617

α = 0.995, 0.990, 0.975, 0.950 and 0.900 follow from $t_{n;1-\alpha} = -t_{n;\alpha}$

Source: Ref. [8]

For example, the values of S^2 and $\bar{x}$ for vertical wheel force peak value at 40 mph are found to be 0.423 and 42.597, respectively, from the four samples available. For 95% confidence level, $\alpha = 0.05$ and $t_{3;0.025} = 3.182$, from Table J-4. Then:

$$K = \frac{St_{3;0.025}}{\sqrt{4}} = \frac{\sqrt{0.423} \times 3.182}{\sqrt{4}}$$

$$= 1.02.$$

Thus, we are 95% confident that the true value lies between 42.597 ±1.02 kips. An example of such repeatability estimation using the probability distribution analysis is shown in Table J-5.

As mentioned above, this procedure is valid only if the variable being measured has a normal distribution. This can be checked using the Chi-square goodness-of-fit test described in Appendix J-A.

The other area in which the probability distribution analysis is useful deals with estimating the probability of derailment based on a limited revenue service testing. There are two requirements to be able to do this:

- A derailment criterion should be available; and
- Test data on the variables used by the criterion should be available.

Much work has been done and is being done to develop reliable derailment criteria (see Ref. 6 and 12). A simplified criterion puts limits on the wheel lateral force (L), wheel vertical force (V), and the ratio of the two (L/V ratio). This can be represented as shown in Figure J-13. In this diagram, a value of L and V combination which lies in the hatched area would be considered unsafe.

Now, to estimate the probability of derailment, one must determine the probability of L and/or V lying in the unsafe zone. Let:

$$Z = f(L,V) \qquad (J.7)$$

TABLE J-5: AN EXAMPLE OF THE USE OF PROBABILITY DISTRIBUTION FOR CALCULATION OF REPEATABILITY OF TEST VARIABLES

Values of K, where K is described as: We are 95% confident that actual mean value of descriptor is within ± K of measured mean value.

Tests Selected 35 mph {120801, 120803, 120814} 40 mph {120804, 120813, 121402, 121403}

Source: Ref. [5]

CHANNEL NUMBER	NAME	SPEED	RMS ± K 1†	RMS ± K 2†	MAXIMUM ± K 1†	MAXIMUM ± K 2†
1	Vertical Wheel Force (in kips)	35 40	29.32 ± 0.61	29.20 ± 0.4 29.41 ± 0.82	41.37 ± 1.94	43.379 ± 1.21 42.60 ± 1.02
2	Lateral Wheel Force (in kips)	35 40	4.35 ± 3.38**	5.75 ± 0.88** 5.89 ± 0.98	10.5 ± 4.46**	14.39 ± 10.2** 15.58 ± 1.1
26	Locomotive Vertical Acceleration (in g)	35 40*	0.026 ± 0.0025	0.022 ± 0.0014 0.028 ± 0.0008	0.079 ± 0.0136	0.08 ± 0.019 0.072 ± 0.011
30	Locomotive Lateral Acceleration (in g)	35 40*	0.043 ± 0.0025	0.052 ± 0.0028 0.060 ± 0.0024	0.029 ± 0.311	0.066 ± 0.006[illegible] 0.097 ± 0.011
60	Baggage Car Vertical Acceleration (in g)	35 40*	0.017 ± 0	0.013 ± 0.0014 0.018 ± 0.0008	0.048 ± 0.022	0.027 ± 0.013 0.053 ± 0.019
63	Baggage Car Lateral Acceleration (in g)	35 40*	0.043 ± 0.0076	0.056 ± 0.0124 0.075 ± 0.0039	0.051 ± 0.014	0.056 ± 0.0049 0.093 ± 0.0098

*May show effect of configuration change from 1208 to 1214.

†Represents Section No. (1 = Piecewise Linear Crosslevel, 2 = Piecewise Linear Alignment)

**May be due to rail surface condition change or instrumentation error.

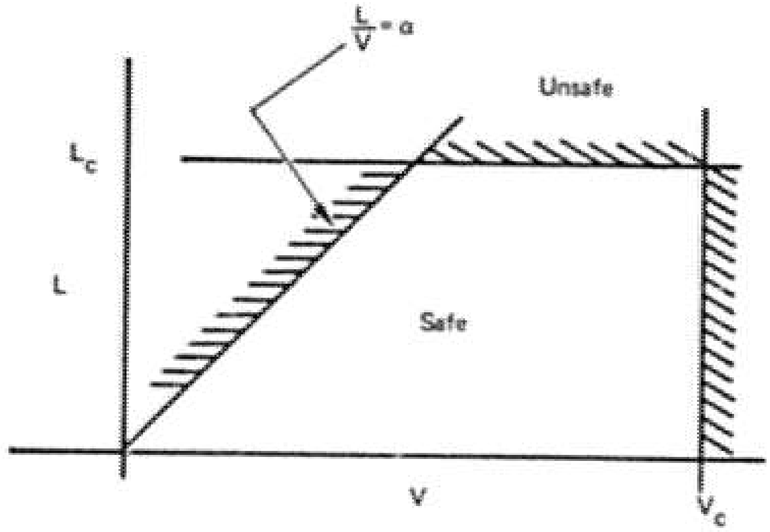


FIGURE J-13 A SIMPLIFIED DERAILMENT CRITERIA where L and V are the absolute lateral and vertical wheel forces and Z is the probability of occurrence of the L and V pair. One candidate of f(L,V) is the Bivariate Normal equation given by:

$$f(L,V) = \frac{1}{2\pi\sigma_L\sigma_V\sqrt{1-\ell^2}} \exp\left\{\frac{-1}{2(1-\ell)^2}\left[\left(\frac{L-\mu_L}{\sigma_L}\right)^2 - 2\ell\left(\frac{L-\mu_L}{\sigma_L}\right)\left(\frac{V-\mu_V}{\sigma_V}\right) + \left(\frac{V-\mu_V}{\sigma_V}\right)^2\right]\right\} \quad (J.8)$$

where μ_L = mean value of L;

μ_V = mean value of V;

σ_L = standard deviation of L;

σ_V = standard deviation of V; and

ℓ = correlation coefficient between L and V.

For a set of experimentally obtained L and V values, the first four of these parameters can easily be calculated using techniques shown in Subsection J.2.1.1. The last parameter can be calculated in the following way:

$$\ell = \frac{\sum_{V=0}^{\infty} \sum_{L=0}^{\infty} P_{ij} (L_i - \mu_L)(V_j - \mu_V)}{\sigma_L \sigma_V} \quad (J.9)$$

where P_{ij} = number of observations in $L_i \pm \delta L$ and $V_j \pm \delta V$ divided by the total number of observations. If both δL and δV are assumed to be 0.5 kips; $L_i - L_{i-1}$ = 1 kip and $V_j - V_{j-1}$ = 1 kip.

Once the expression for the probability distribution is obtained, the probability of L and/or V being in the unsafe safe zone can be found as:

$$P_{unsafe} = 1 - \left[\int_{L=0}^{L_c} \int_{V=0}^{L/\alpha} P(L,V) \cdot dL\, dV + \int_{L=0}^{L_c} \int_{V=\frac{L_c}{\alpha}}^{V_c} P(L,V) \cdot dL\, dV\right] \quad (J.10)$$

Ref [13] shows that the test data fits the Bivariate Normal distribution better if L is replaced by $\sqrt{L}$. If $L' = \sqrt{L}$, then the following values are obtained for all the curves on a particular revenue service track.

μ'_L = 1.79 kips

μ'_V = 28.18 kips

σ'_L = 0.55 kips

σ'_V = 4.12 kips

ℓ = 0.342

J.2.3.2 Regression Analysis

Regression analysis is a technique used to determine the relationship between a dependent and one or more independent variables. In the case where only one independent variable is involved, regression analysis is simply a "least squares fit" of one variable to the other. A typical case would be to derive the relationship between height and weight for adult males. Multiple variable or multivariate, regression analysis is, simply stated, the "least squares fit" of one dependent variable to more than one independent variable. An example of multivariate regression analysis would be tc determine the rate at which track geometry degrades in terms of physical parameters which might affect track degradation such as traffic density (in Million Gross Tons), rail weight and tie condition.

In addition to quantifying the relationship between a dependent variable and multiple independent variables, regression analysis quantifies the strength of the relationship (correlation coefficients and coefficients of determination - R^2), the significance of the relationships (t-value and F-value) and the confidence intervals for each regression coefficient.

Although regression analyses can accurately determine the statistical relationship between variables, it is encumbent upon the analyst to determine the physical significance of that relationship. A description of regression analysis terms and fundamentals is contained in Appendix J-B.

Other limitations which should be considered in applying regression analysis include:

1. Sample size determines accuracy and confidence limits for the results. (As a general rule, sample sizes of less than 20 are unacceptable - 50 to 100 is preferred minimum.)

2. Measurement errors which directly affect the accuracy and confidence limits of the results are difficult to account for.

3. Application of the results cannot (reliably) be extrapolated beyond the range of the data base from which the regression was derived.

4. Digital data acquisition and processing is required.

The specific application of regression analysis presented in this section involves the evaluation of the relationship between wheel/rail forces and track geometry. The data which supported this analysis were collected during the Chessie Test of Locomotives Ref. [14]. A general summary of the procedure for conducting vehicle/track regression analysis is shown below (Table J-6). A flowchart for the overall approach used in the case study analysis is shown in Figure J-14.

The specific objective in this example was to determine what track geometry characteristics contributed to excessive lateral wheel/rail forces and L/V ratios. Measurements of track geometry data and SDP-40F locomotive wheel/rail force data were made separately over the same track. Data were selected from 37 curves in the test zone. Statistical descriptors were developed for each parameter over each curve. The descriptors included minimum, 5th percentile, mean, 95th percentile, maximum, standard deviation and variance. The statistical data base, by curve, for vehicle response and track geometry were merged and a quality control check was performed to eliminate any

TABLE J-6: SUMMARY PROCEDURE FOR VEHICLE TRACK REGRESSION ANALYSIS

1. Define the independent (or control) variables of interest, based on the test objectives.

2. Define the dependent (or response) variables for the selected performance issues.

3. Select data segments for processing, check data quality.

4. Compute statistical descriptors (e.g., mean, standard deviation) for each variable of interest over the selected data segments.

5. Merge track geometry and vehicle response (independent and dependent) variable data bases.

6. Perform quality assurance check for statistical data base.

7. Define variables and descriptors for regression, define regression type and limits for test of significance.

8. Perform regressions.

9. Analyze results and modify regression, if required, and rerun.

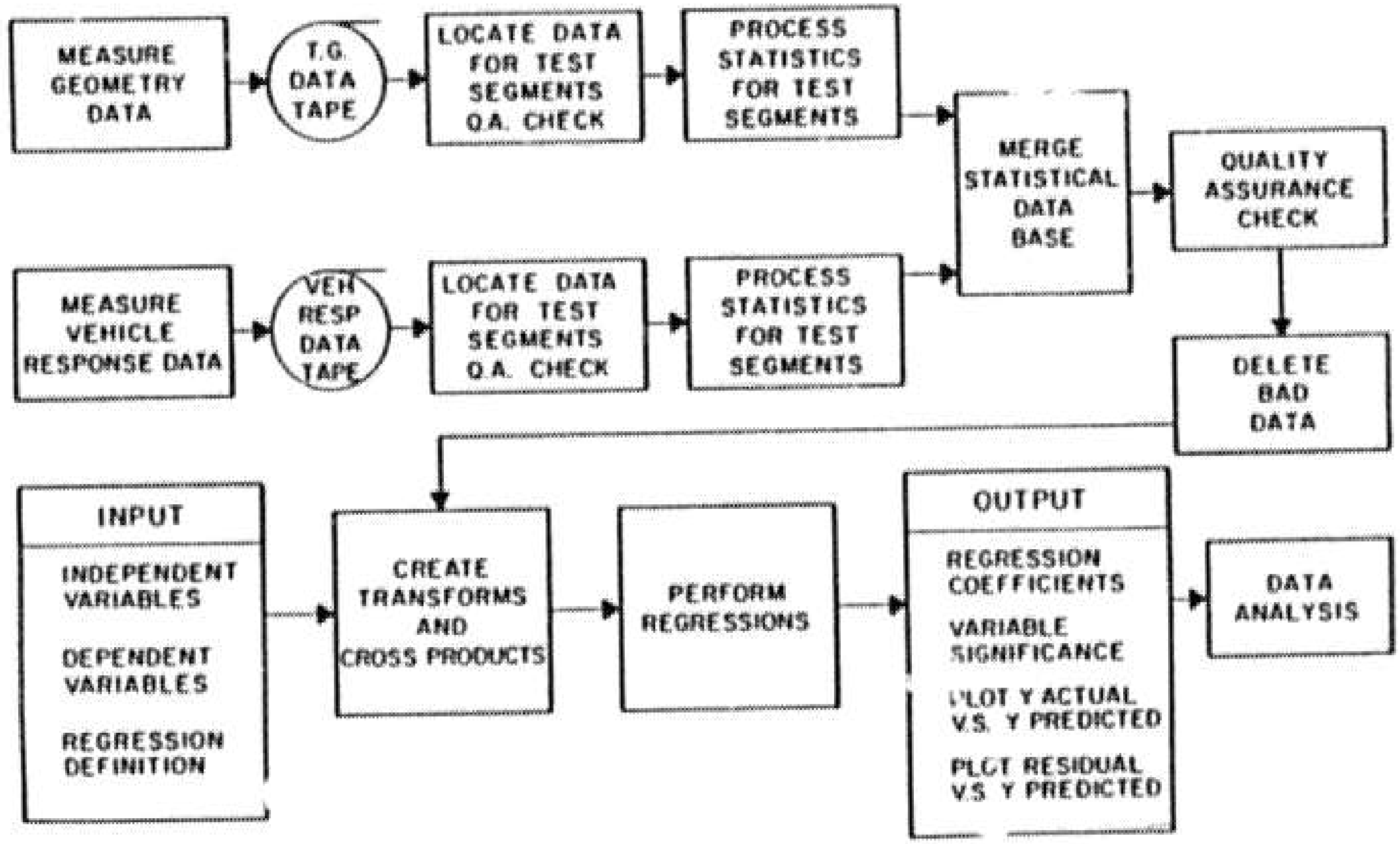


FIGURE J-14:

GENERAL FLOW CHART FOR EMPIRICAL EVALUATION OF VEHICLE – TRACK RESPONSE

outliers, due to instrumentation failures (typically full scale and zero values), from the analysis. The specific parameters and descriptors for analysis were selected and cross products of some descriptors were calculated to identify any combined effect (i.e., σ curvature and mean ΔE-underbalance).

Stepwise regressions were performed using the data base prepared and a regression analysis software program developed to support maintenance of way planning research Ref. [15].

The results for the SDP-40F show that the 95th percentile level of lateral force, L_{95}, is related to track geometry as follows:

$$L_{95} = 6290 + 1940(\Delta E) + 6700(\sigma_c) - 1170(D)$$

where

L_{95} = the 95th percentile level of lateral force (lbs)

ΔE = underbalance of operation (in)

σ_c = standard deviation of curvature (degrees per 100 feet)

D = 0 for right curves, 1 for left curves

A more detailed discussion of this case study can be found in Appendix J-C.

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APPENDIX J-A

TESTING A DISTRIBUTION FOR NORMALCY

In performing probability distribution analysis, we often assume that the values of a variable obtained during a test follow a normal distribution. Described briefly in this appendix is a method to evaluate this assumption.

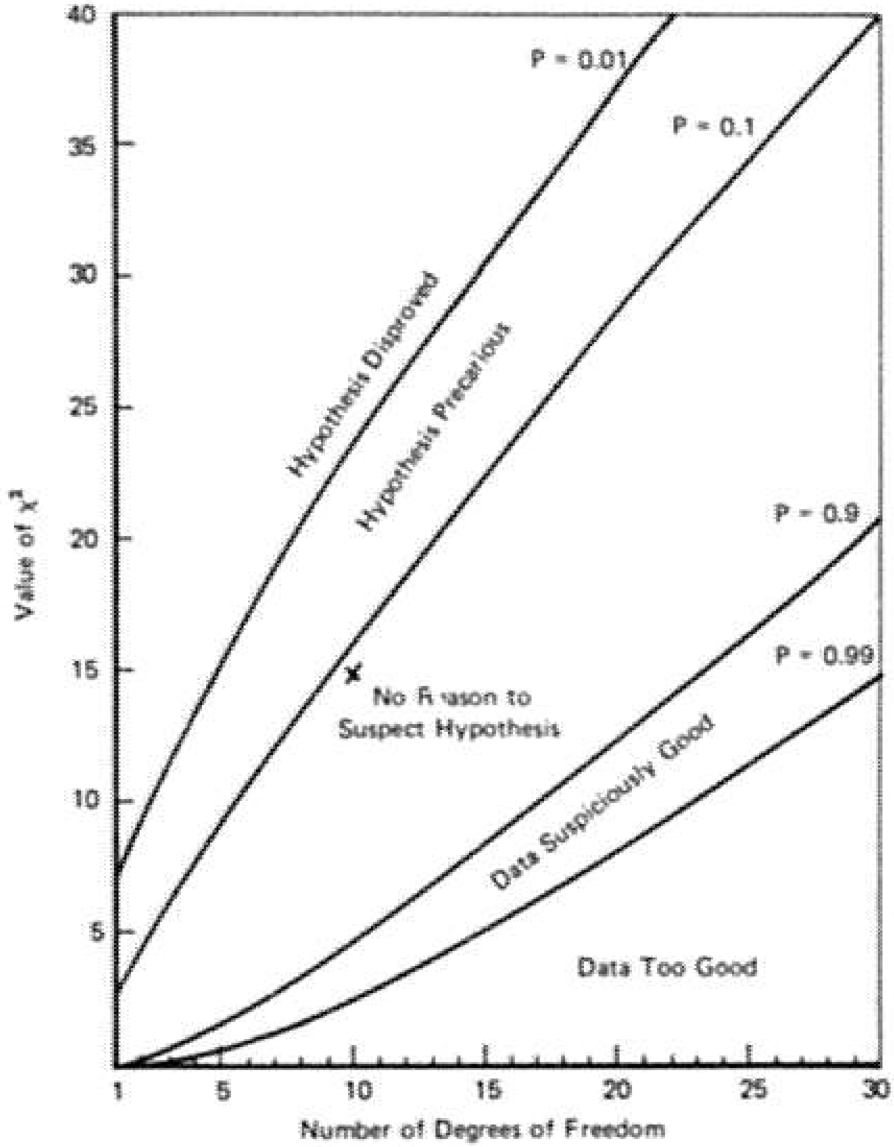
The test most commonly used to determine if a set of data fit some assumed distribution is called the χ^2 (Chi-squared) test [see Ref. A.1 and A.2, for example]. This test involves grouping the data into a number of intervals and then comparing the number of data in the ith interval (n_{oi}) to the number expected (n_{ei}) if the hypothesis of normalcy were true. The value of χ^2 is then calculated as:

$$\chi^2 = \sum_{\substack{\text{all} \\ \text{intervals}}} \frac{(n_{oi} - n_{ei})^2}{n_{ei}} \qquad \text{(J-A.1)}$$

Knowing the value of χ^2 and the number of intervals, one can determine from Figure J.A-1 whether the hypothesis of normalcy is good or not. In the figure, the number of degrees of freedom is the number of intervals minus three. Also, the values of P in the figure refer to the probability level. For example, if the value of χ^2 lies on the line marked $P = 0.1$, there is only one chance in ten that if the data does fit the hypothesis (i.e., if the probability distribution is normal), a value of χ^2 as large as this would have been observed. For a probability level of <1% ($P \leqq 0.01$), the hypothesis is assumed to be disproved. Also, for the probability level of >99%, the data are assumed to be too good, i.e., the data may have been "adjusted" [Ref. A.1].

A couple of aspects of this technique need to be discussed further:

1. How to define intervals, and
2. How to obtain the expected number of data points in each interval.



Source: Ref. [A.1]

FIGURE J-A-1 EVALUATING THE VALIDITY OF A HYPOTHESIS USING THE VALUE OF χ^2

There are basically two ways to define intervals. The first way is to select them in such a way that the expected number of data points in each interval is equal. For a normal distribution, this would lead to the intervals being larger at two ends and smaller near the mean value. The second way is to select intervals of equal width, in which case the number of data points in the middle (near the mean) will be higher than that at either end. Since the second way is slightly easier to implement then the first, we will highlight it in the illustrative example shown later.

In order to select the internal width by the second way, we first need to calculate the mean ($\bar{x}$) and standard deviation (σ) of the data in a manner shown in Subsection J.2.1.1. Once these values are obtained, Ref. A.2 recommends that the interval width should be 0.4 times standard deviation. Also, it is desirable to have at least five data points in each interval. Thus, the intervals at the two ends may need to be grouped together to achieve this requirement.

Once the intervals are defined, the expected number of data points in each interval can be calculated as follows:

$$z_i = \frac{x_i - \bar{x}}{\sigma} \qquad \text{(J-A.2)}$$

where x_i is the lower value of the ith interval,

$\bar{x}$ is the mean value of the data set, and

σ is the standard deviation of the data set

$$y_i = p(z_i) \qquad \text{(J-A.3)}$$

where p( ) is the ordinate of the standardized normal density function obtained from Table J-A.1.

Finally,

$$n_{ei} = y_i \times \frac{N}{\sum_{\text{all } i} y_i} \qquad \text{(J.A-4)}$$

TABLE J-A.1: ORDINATES OF THE STANDARDIZED NORMAL DENSITY FUNCTION

$$p(z) = \frac{1}{\sqrt{2\pi}} e^{-z^2/2}$$

z	0.00	0.01	0.02	0.03	0.04	0.05	0.06	0.07	0.08	0.09
0.0	0.3989	0.3989	0.3989	0.3988	0.3986	0.3986	0.3982	0.3980	0.3977	0.3973
0.1	0.3970	0.3966	0.3961	0.3956	0.3951	0.3945	0.3939	0.3932	0.3925	0.3918
0.2	0.3910	0.3902	0.3894	0.3884	0.3876	0.3867	0.3857	0.3847	0.3836	0.3825
0.3	0.3814	0.3802	0.3790	0.3778	0.3765	0.3752	0.3739	0.3725	0.3712	0.3697
0.4	0.3683	0.3668	0.3653	0.3637	0.3621	0.3605	0.3589	0.3572	0.3555	0.3538
0.5	0.3521	0.3503	0.3485	0.3467	0.3448	0.3429	0.3410	0.3391	0.3372	0.3352
0.6	0.3332	0.3312	0.3292	0.3271	0.3251	0.3230	0.3209	0.3187	0.3166	0.3144
0.7	0.3123	0.3101	0.3079	0.3056	0.3034	0.3011	0.2989	0.2966	0.2943	0.2920
0.8	0.2897	0.2874	0.2850	0.2827	0.2803	0.2780	0.2756	0.2732	0.2709	0.2685
0.9	0.2661	0.2637	0.2613	0.2589	0.2565	0.2541	0.2516	0.2492	0.2468	0.2444
1.0	0.2420	0.2396	0.2371	0.2347	0.2323	0.2299	0.2275	0.2251	0.2227	0.2203
1.1	0.2179	0.2155	0.2131	0.2107	0.2083	0.2059	0.2036	0.2012	0.1989	0.1965
1.2	0.1942	0.1919	0.1895	0.1872	0.1849	0.1826	0.1804	0.1781	0.1758	0.1736
1.3	0.1714	0.1691	0.1669	0.1647	0.1626	0.1605	0.1582	0.1561	0.1539	0.1518
1.4	0.1497	0.1476	0.1456	0.1435	0.1415	0.1394	0.1374	0.1354	0.1334	0.1315
1.5	0.1295	0.1276	0.1257	0.1238	0.1219	0.1200	0.1282	0.1163	0.1145	0.1127
1.6	0.1109	0.1092	0.1074	0.1057	0.1040	0.1023	0.1006	0.0989	0.0973	0.0957
1.7	0.0940	0.0925	0.0909	0.0893	0.0878	0.0863	0.0848	0.0833	0.0818	0.0804
1.8	0.0790	0.0775	0.0761	0.0748	0.0734	0.0721	0.0707	0.0694	0.0681	0.0669
1.9	0.0656	0.0644	0.0632	0.0620	0.0608	0.0596	0.0584	0.0573	0.0562	0.0051
2.0	0.0540	0.0529	0.0519	0.0508	0.0498	0.0488	0.0478	0.0468	0.0459	0.0449
2.1	0.0440	0.0431	0.0422	0.0413	0.0404	0.0396	0.0387	0.0379	0.0371	0.0363
2.2	0.0355	0.0347	0.0339	0.0332	0.0325	0.0317	0.0310	0.0303	0.0297	0.0290
2.3	0.0283	0.0277	0.0270	0.0264	0.0258	0.0252	0.0246	0.0241	0.0235	0.0229
2.4	0.0224	0.0219	0.0213	0.0208	0.0203	0.0198	0.0194	0.0189	0.0184	0.0180
2.5	0.0175	0.0171	0.0167	0.0163	0.0158	0.0154	0.0151	0.0147	0.0143	0.0139
2.6	0.0136	0.0132	0.0129	0.0126	0.0122	0.0119	0.0116	0.0113	0.0110	0.0107
2.7	0.0104	0.0101	0.0099	0.0096	0.0093	0.0091	0.0088	0.0086	0.0084	0.0081
2.8	0.0079	0.0077	0.0075	0.0073	0.0071	0.0069	0.0067	0.0065	0.0063	0.0061
2.9	0.0060	0.0058	0.0056	0.0055	0.0053	0.0051	0.0050	0.0048	0.0047	0.0046
3.0	0.0044	0.0043	0.0042	0.0040	0.0039	0.0038	0.0037	0.0036	0.0035	0.0034
3.1	0.0033	0.0032	0.0031	0.0030	0.0029	0.0028	0.0027	0.0026	0.0025	0.0025
3.2	0.0024	0.0023	0.0022	0.0022	0.0021	0.0020	0.0020	0.0019	0.0018	0.0018
3.3	0.0017	0.0017	0.0016	0.0016	0.0015	0.0015	0.0014	0.0014	0.0013	0.0013
3.4	0.0012	0.0012	0.0012	0.0011	0.0011	0.0010	0.0010	0.0010	0.0009	0.0009
3.5	0.0009	0.0008	0.0008	0.0008	0.0008	0.0007	0.0007	0.0007	0.0007	0.0006
3.6	0.0006	0.0006	0.0006	0.0005	0.0005	0.0005	0.0005	0.0005	0.0005	0.0004
3.7	0.0004	0.0004	0.0004	0.0004	0.0004	0.0004	0.0003	0.0003	0.0003	0.0003
3.8	0.0003	0.0003	0.0003	0.0003	0.0003	0.0002	0.0002	0.0002	0.0002	0.0002
3.9	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0001	0.0001

Source: Ref. [A.2]

Note: Above values are valid for both positive and negative values of Z.

where N is the total number of data points and n_{ei} is the expected number of data points in the ith interval.

An example of this procedure is shown in Table J.A-2. In this example, a set of 162 data points, with values lying between 0 and 18, is tested for normalcy. First, the mean and standard deviation for the data set are obtained. Since σ is 3.12, an interval which is 1 unit wide is considered appropriate. Next, the values of z_i, y_i, and n_{oi} are calculated using equations J-A.2, J-A.3, and J-A.4. The corresponding observed values are obtained by classifying the data set into the nineteen intervals. Now, as suggested earlier, the intervals at the two ends need to be grouped together, because some of them hold less than 5 data points. Thus, intervals 0-4 and 16-18 are grouped together and a new set of n_{oi} and n_{ei} values are established. The next three columns show how the value of x^2 can be obtained from n_{oi} and n_{ei}. This value is plotted in Figure J-A.1 as shown. According to the boundaries shown in the Figure, there is no reason to suspect that the data presented does not follow a normal distribution.

TABLE J-A.2: SETTING UP A χ^2 CALCULATION

x_i	$x_i - \bar{x}$	$z_i = \frac{x_i - \bar{x}}{\sigma}$	Ordinate $y_i = p(z_i)$	n expected, i.e., n_{ei}	n Observed, i.e., n_{oi}	x_i	n_{oi}	n_{ei}	$(n_{oi} - n_{ei})$	$(n_{oi} - n_{ei})^2$	$(n_{oi} - n_{ei})^2/n_{ei}$
0	-9.65	-3.09	0.003	0.2	1						
1	-8.65	-2.77	0.009	0.5	1						
2	-7.65	-2.45	0.020	1.0	0	0-4	6	7.8	1.8	3.24	0.41
3	-6.65	-2.13	0.041	2.1	2						
4	-5.65	-1.81	0.077	4.0	2						
5	-4.65	-1.49	0.131	6.8	4	5	4	6.8	2.8	7.88	1.16
6	-3.65	-1.17	0.201	10.4	9	6	9	10.4	1.4	1.96	0.20
7	-2.65	-0.85	0.278	14.4	22	7	21	14.4	6.6	43.6	3.03
8	-1.65	-0.53	0.347	18.0	18	8	18	18.0	0	0	0
9	-0.65	-0.21	0.390	20.2	25	9	25	20.2	4.8	23.0	1.14
10	+0.35	+0.11	0.397	20.6	23	10	23	20.6	2.4	5.8	0.28
11	+1.35	+0.43	0.364	18.9	15	11	15	18.9	3.9	15.2	0.81
12	+2.35	+0.75	0.301	15.6	7	12	7	15.6	8.6	74.0	4.74
13	+3.35	+1.07	0.225	11.7	12	13	12	11.7	0.3	0.9	0.08
14	+4.35	+1.39	0.152	7.9	8	14	8	7.9	0.1	0.1	0.01
15	+5.35	+1.71	0.092	4.8	8	15	8	4.8	3.2	10.2	2.13
16	+6.35	+2.04	0.050	2.6	2						
17	+7.35	+2.36	0.025	1.3	2	16-18	5	4.5	0.5	0.25	0.56
18	+8.35	+2.68	0.011	0.6	1						Sum = 14.55 = χ^2

Total number of Data Points, N = 162; Mean, $\bar{x}$ = 9.65; Standard Deviation, σ = 3.12.

Source: Ref. [A.1]

APPENDIX J-B

VEHICLE/TRACK REGRESSION ANALYSIS CASE STUDY

J-B-1 INTRODUCTION

This appendix to the analysis techniques section of the IAT Handbook describes the data measurement, instrumentation, recording, data processing and data analysis techniques available for the empirical derivation of statistical relationships between track geometry inputs and vehicle response. These techniques are presented and discussed within the framework of a case study involving the determination of the statistical relationship between track geometry inputs and locomotive wheel/rail force response. The data used were collected during the test of SDP-40F and E-8 locomotives on Chessie track in 1977. (see Ref. B-1 for a complete description of these tests).

This case study presents a practical application of regression analysis techniques to stability assessment. A rail vehicle, the SDP-40F locomotive, was believed to have a higher than normal accident rate. A simulated revenue service test was conducted during which recordings of both track geometry and vehicle response data were made. An E-8 locomotive, believed to have a good accident record, was also evaluated as a baseline for comparison with the SDP-40F. Statistical summaries of the data were developed and regression analysis was used to determine which, if any, aspects of the vehicles' operating environment (i.e., track geometry conditions) could be linked to known derailment indicators (i.e., excessive lateral wheel rail force).

During the test, track geometry data were collected using the FRA track geometry measuring cars (T-1/T-3). These cars ran in consist with an E-8 locomotive which was instrumented to measure lateral and vertical wheel/rail forces. The track geometry data and wheel/rail force data were simultaneously recorded onboard an FRA data acquisition car (T-7).

The results of the case study presented here show, as expected, that high levels of lateral wheel rail force are strongly related to underbalance operation in curves. As with earlier studies performed on curves of 2° to 3°, the SDP-40F appears to be affected more strongly by underbalance than does the E-8 locomotive, the baseline unit. Also the SDP-40F is more affected by long wavelength alignment disturbances (as indicated by variations in curvature) while the E-8 is sensitive to shorter wavelength alignment disturbance (as indicated by variations in gauge).

This appendix seeks to acquaint the reader with regression analysis techniques and demonstrate their applicability in determining the causes and/or conditions related to the poor dynamic performance of a rail vehicle.

J-B-2 TECHNICAL APPROACH TO CASE STUDY

In planning the test, track geometry inputs, train operating conditions, and vehicle maintenance conditions were identified as the primary independent test variables. Only the effects of track geometry are addressed in this appendix. Two simulated revenue consists, one with an instrumented SPD-40F locomotive and a second with an instrumented E-8 locomotive were used during the test. The E-8 locomotive was used as a baseline for comparison with the SDP-40F because of its perceived relatively good safety record.

In order to get a variety of track geometry inputs, a test zone was selected which included 500 miles of typical class 3 track. To evaluate the effects of train operating and maintenance conditions a single test site, four miles in length, was selected for repeated testing. Lateral and vertical wheel rail forces, as indicators of derailment tendency, were selected as the primary dependent (or response) variables of interest. In order to measure wheel/rail force, strain gauged wheelsets were installed on both the E-8 and SDP-40F instrumented locomotives. The FRA track survey cars, T-1/T-3 were run in the E-8 consist to measure track geometry conditions throughout the test zone.

To enable correlation between the SDP-40F consist data and the track geometry data, accurate determination of track location was required. Therefore, the test operations plan specified that manual entries of milepost locations would be made for each data tape during the test. An Automatic Location Detection System (ALD) was installed on each consist to detect the location of switches and road crossings as a further aid to location identification.

The following sections describe the measurement requirements, test procedures, data processing and data analysis techniques used for the test. For additional information on test planning and test design the reader is directed to Section E, Test Plan Summaries, and Section K, Field Test Planning.

J-B-2.1 INSTRUMENTATION AND RECORDING REQUIREMENTS

The track geometry data measured by the FRA track geometry measurement consist T-1/T-3 and the E-8 wheel/rail force data were recorded on the same digital tape. The sample rate for the track geometry measurement systems was one sample every 2.42 feet. The data from this system was subsequently recorded in the vehicle response data stream at a sample rate of 250 Hz. Thus, the shortest wavelengths of track which could be measured were around 5 to 8 feet, which is adequate for evaluating most vehicle track interaction issues. The highest vehicle response frequency which could be resolved was around 100 Hz, which is more than enough range for any rail vehicle rigid body response mode. The track geometry data recorded included gauge, crosslevel, curvature, and left and right profile.

To facilitate data processing, speed, distance, milepost number and the location of switches and road crossings were also recorded with the track geometry data. An Automatic Location Detector (ALD), basically a capacitive proximity detector, was used to identify the location of the switches and road crossings. Location identification for the E-8 consist was quite simple because the geometry data could be used to clearly identify the location of each curve in the test zone. The instrumented E-8 locomotive preceeded the geometry cars by 282 feet in the consist. For the SDP-40F consist, accurate location of the data for each curve depended upon the manual entries of milepost numbers made every time a milepost was passed by the locomotive. Calculated distance, in feet, beyond each milepost was to be used to help locate curves, however, errors and dropouts in the onboard speed measurement precluded this. Therefore, strip charts of lateral wheel force, from milepost to milepost were used to identify curve locations. A summary description of the track geometry measurements can be found in Table JB-1.

Lateral and vertical wheel/rail forces were measured using strain gauged, instrumented wheelsets installed in both the E-8 and SDP-40F locomotives. Carbody accelerations were measured on both locomotives and suspension displacements were measured on the SDP-40F. Only the wheel/rail force measurements are addressed here. (See Ref. B-1 for a complete description of the instrumentation and test). A summary description of the vehicle response measurements is contained in Table JB-2.

J-B-2.2 TEST PROCEDURES

In conducting a diagnostic type test with two consists (one baseline) over many miles of track special care must be taken to control the independent variables and to ensure data from the consists is selected from the same track locations.

The effect of acceleration as an independent parameter was minimized during the test by maintaining a nearly constant speed throughout each test curve.

To enhance the ability to compare performance of the two locomotives, the consists were intended to pass through each test zone

TABLE JB-1

TRACK GEOMETRY MEASUREMENTS DESCRIPTION

Data Recorded	- Left and Right Profile (62 foot MCO)
	- Gauge
	- Crosslevel
	- Curvature
	- Automatic Location Detection
	- Speed and Distance
Sampling Rate	- 2.42 (ft/sample) or 0.413 (sample/ft)
Instrumentation	
Profile	- Inertial Profilometer
Gauge	- Non-contacting Servo Magnetic Gauge System
Crosslevel	- Compensated Inertial Cross-level System
Curvature	- Inertial based Curvature System
Location	- Capacitive Automatic Location Detector
Milepost	- Manual Entry (Forward Observer)
Speed & Distance	- Axle-driven Optical Encoder

TABLE JB-2

VEHICLE RESPONSE MEASUREMENTS DESCRIPTION

Data Recorded	- Lateral W/R Force - Vertical W/R Force - L/V Ratio - Automatic Location Detector (ALD) - Speed and Distance - Milepost
Filtering	- 100 Hz Corner on 4-Pole Bessel Filter (12 Db/octave)
Sampling Rate	- 256 Hz
Instrumentation	
Wheel Forces	- Strain Gauge Instrumented Wheelset
Location	- Capacitive Automatic Location Detector (ALD)
Milepost	- Manual Entry (Forward Observer)
Speed & Distance	- Axle-driven Optical Encoder

at the same speed. This was not always possible since slow orders, local traffic conditions and instrumentation calibration/maintenance stops varied, even though the consists were run on the same day to minimize the effect of changing conditions.

Every effort was made to eliminate data biases (zero offset) and scale factor errors which can directly affect the results of the subsequent regression analysis.

J-B-2.3 DATA PROCESSING AND ANALYSIS

A general flowchart for the data processing required to perform the vehicle track interaction regressions is shown in Figure JB-1.

This flowchart is shown for separate track geometry and vehicle response data tapes as recorded for the SDP-40F consist. For the E-8 consist, the geometry and vehicle response data were recorded on the same data tape. The geometry and vehicle dynamics measurements for the E-8 consist were, however, displaced in time due to the distance between the locomotive and the geometry car (282 feet).

J-B-2.3.1 LOCATING DATA FOR PROCESSING

Test segments were identified for processing which included the bodies (distance between spirals) of 99 curves for the E-8 consist and 38 curves for the SDP-40F consist. To ensure that the independent track geometry variables are controlled, each curve in the test zone was treated as a separate statistical sample. Only the data from the bodies of the curves was introduced into the analysis. If data from the spirals or adjacent tangent track were included in the statistics for a given curve then the means and standard deviations of the geometry parameters, particularly curvature and crosslevel, would be "contaminated" with the non-curve data. The same holds true for the response data. Therefore, it too had to be selected from the body of the curve

GENERAL FLOW CHART FOR EMPIRICAL EVALUATION OF VEHICLE – TRACK RESPONSE

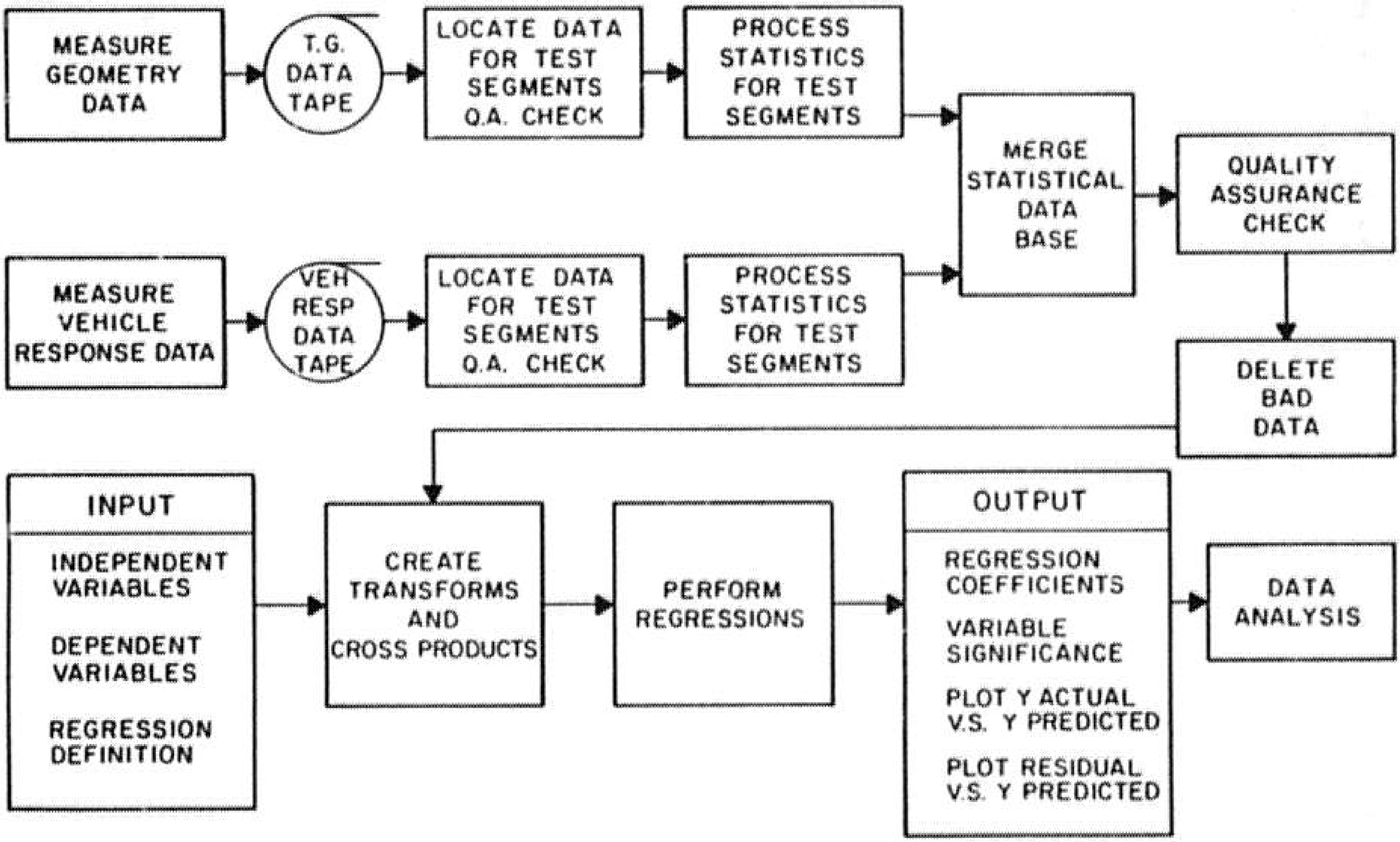


Figure JB-1

only. If spiral performance analysis is desired the data should be filtered to include only the wavelengths of interest prior to statistical processing.

Summaries of the track geometry data tapes were created which defined the location, in milepost plus feet, of the approximate start and end of each curve. From the test logs, the tape numbers, and approximate record numbers, for the dynamic data for each curve were identified. Time history plots of crosslevel, curvature, wheel forces and ALD data were produced in the vicinity of each curve for both test consists. For the E-8 consist data tape, which included the geometry measurement, the location and duration of the curve body data was precisely located ±50 feet using the crosslevel plot. Given the location of the track geometry data on tape, the E-8 vehicle response data was easily located by advancing (in the data stream) a time equal to the distance between the wheel force and geometry measurements (282 feet) divided by the average speed through the zone (in feet per second). (See Figure JB-2).

For the SDP-40F consist, without geometry measurements, the approximate location of curves were identified by the manual milepost entires (accurate to ±100 feet). Lateral force and ALD data were plotted for the SDP-40F consist on a mile by mile basis for each mile which contained at least one test curve of interest. The approximate location of the curve was estimated knowing the time elapsed between mileposts. The duration of the curve is known in feet from the geometry data. Knowing the speed of the consist in the vicinicy of the curve the approximate duration, in seconds, of the data within the curve was calculated.

Knowing the approximate location and duration of the SDP-40F data for the test curve of interest, the time history plots of the lateral force channels were searched in the vicinity of the curve for lateral force activity of the duration (in seconds) expected.

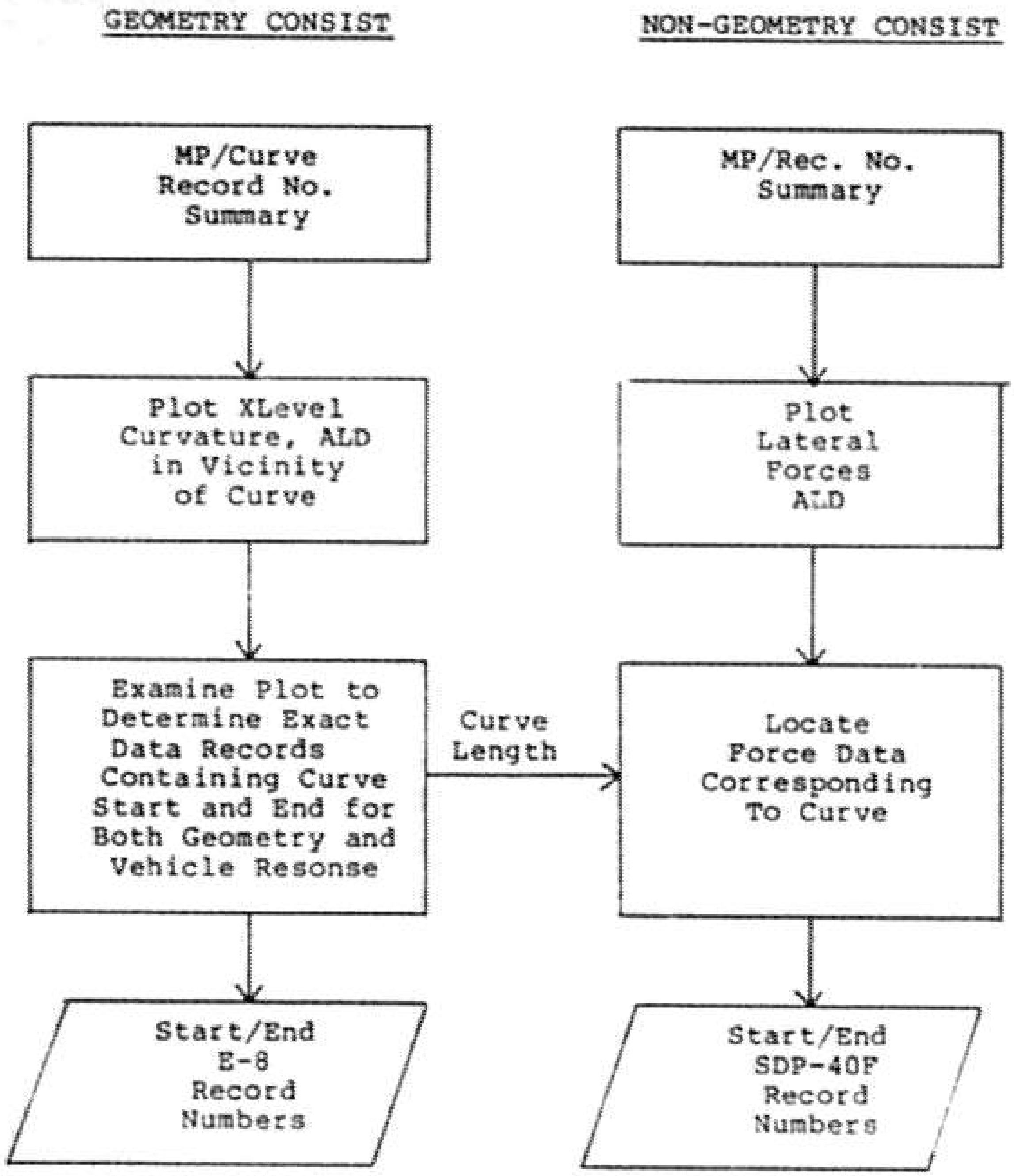


Figure JB-2 Location of Data Segments for Quality Control (Q.C.) and Processing

The caveat to this approach is that the identification of the curve is dependent upon an indirect measurement, lateral force. However, this is a fairly reliable means of detecting curves where high levels of lateral force are experienced. Also ALD events, such as road crossings or switches, can be used as a secondary check of location. * more direct way of determining location would be to integrate the measured speed to get the distance from the last milepost. This in fact was used where practical. However, data dropouts due to an instrumentation failure in the speed measurement prevented its use for many segments in this test.

To further identify curve locations for a non-geometry consist the measurement of truck to carbody yaw angle (as an indicator of curvature) or manual entries for the start and end of curves can also be helpful but they were not used in this test.

J-B-2.3.2 STATISTICAL DESCRIPTORS

Once the test curves were located the plots were examined to make sure that the data contained no noise or unusual signatures such as spikes or drop outs. Data bases were then compiled which contained the track geometry and vehicle response statistical descriptors for each test segment (see Table JB-3).

The statistical descriptors calculated for each test segment were the mean, standard deviation, maximum, minimum, 5th percentile and 95th percentile values. The 95th percentile is the value below which the data remains below 95% of the time for a given test segment. The 5th percentile is the value below which the data remains 5 percent of the time for a given test segment. The 95th percentile and 5th percentiles are perhaps better indicators of extreme values than are the minimum and maximum values because they are not as susceptible to short duration data drop outs and spikes. (See Figure JB-3.)

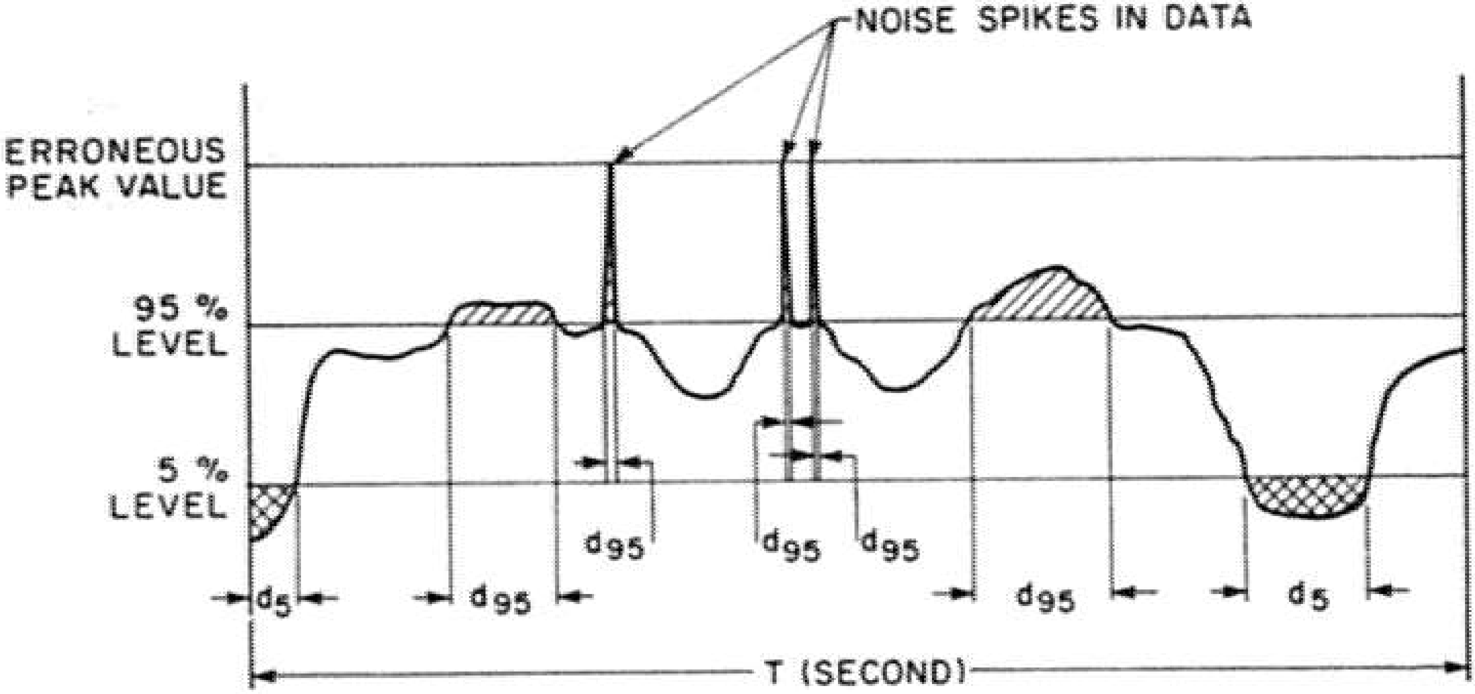
TABLE JB-3
STATISTICAL DESCRIPTORS

INDEPENDENT VARIABLES

Variable Number	Parameter	Descriptor	Symbol
X_1	Speed	Mean	$\overline{V}$
X_2	Curvature	Mean	$\overline{C}$
X_3	Curvature	Standard Deviation	$\sigma(C)$
X_4	Curvature	Variance	$\sigma^2(C)$
X_5	Gauge	Mean	$\overline{G}$
X_6	Gauge	Standard Deviation	$\sigma(G)$
X_7	Gauge	Variance	$\sigma^2(G)$
X_8	Crosslevel	Standard Deviation	$\sigma(XL)$
X_9	Unbalance	Mean	$\overline{\Delta E}$
X_{10}	-	-	$V*\sigma(C)$
X_{11}	-	-	$\Delta E*\sigma(C)$

DEPENDENT VARIABLES

Variable	Parameter	Descriptor	Symbol
Y	High rail lateral	95th Percentile	L_{95}



EXAMPLE TIME HISTORY
SHOWING 5% AND 95% LEVELS

95% Level = level which the data is below 95% of the time. Level is selected such that $\frac{T - \Sigma d_{95}}{T} = .95$.

5% Level = level which the data is below 5% of the time. Level is selected such that $\frac{\Sigma d_5}{T} = .05$.

Note: Because of their short duration, noise spikes have little effect on the calculation of 5% and 95% values.

Figure JB-3. Description of 5% Level and 95% Level Statistics

The statistical data base for the SDP-40F and track geometry data were merged by curve number. As a final quality control check prior to regression analysis the data base was examined to make sure that no full scale or erroneous zero value data had been included.

Separate data bases for left and right curves were created for each locomotive. This was done so that regressions could be performed for the high and low rail (outside and inside) wheel forces separately.

J-B-3 REGRESSION ANALYSIS

Regression analysis provides a simple method for the determination of functional relationships between variables. The resultant linear relationships between a dependent variable and multiple independent variables is generally expressed in the form:

$$y' = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \ldots \beta_m x_m$$

where

y' = the estimated value of the dependent variable
β_i = the regression coefficient for the i^{th} independent variable
β_0 = the constant term

The regression analysis performed in the case study was based on software developed by ENSCO in support of the maintenance of way planning system program for the Federal Railroad Administration, Office of Research and Development. Complete documentation of this software can be found in Volume III, Software Documentation (Ref. B-2). Before reviewing the regressions performed in this study it will be helpful to review the terms used in describing regression analysis in this report.

Dependent Variable (y): A variable which is estimated using one or more independent variables. Wheel/rail force descriptors are treated as dependent (or response) variables in this study.

Independent Variable (x): A variable which is used to estimate the dependent variable. Track geometry parameters of gauge, crosslevel, curvature and operational parameters of speed and underbalance are the independent variables in this study.

Dummy Variable: A dummy variable is used to describe a variable which has two or more distinct levels. A dummy variable "D" was used in this study to identify direction of curvature; for right curve D=0, for left curves D=1.

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

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

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

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

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

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

Correlation Coefficient: It is a measure of the linear dependency of two variables. The correlation coefficient varies from -1 to 1. An absolute value close to unity indicates a strong linear dependency. On the other hand, a value close to zero indicates no linear relationship.

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

Adjusted Coefficient of Determination (R^2): This is the R^2 value adjusted for the number of independent variables. R^2 values increase with each added variable. However, the adjusted coefficient of determination increases only if the added variable is significant. All R^2 values used in this report are adjusted coefficients of determination.

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

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

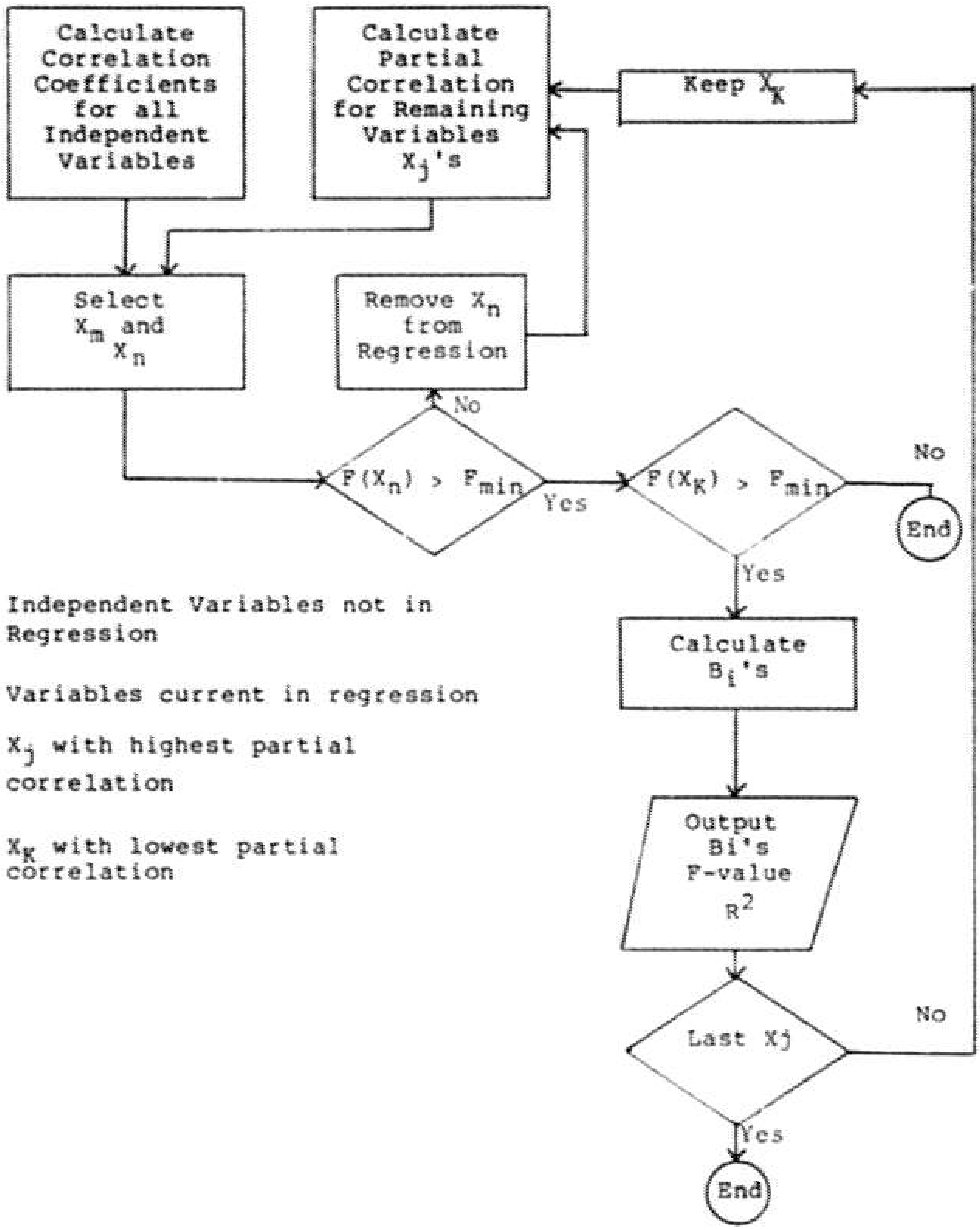
In performing any regression analysis the primary task of the analyst is to select the optimum regression for his requirements. He must decide which independent or control variables should be included in the regression. Generally, the more independent variables which are included in the regression, the better the prediction. Of course, as more variables are added the costs of obtaining the input data for the regressions and the costs of data processing will both increase for applications of the final regression. A point of diminishing return is reached as each new variable provides only marginal improvement in the regression. The significance of adding each new independent variable should be determined and a decision should be made as to whether or not it should be included in the regression. If the total number of independent variables is small or if the independent variables to be included in the regression can be inferred from physical conditions (i.e., mean lateral wheel/rail should be related to underbalance of operation) then the independent variables to be put into the regression model are easily defined. If the number of independent parameters is relatively large and/or the physical significance of the parameters is not obvious then a stepwise regression can aid in the selection of variables.

Once the analyst has prepared the data base which contains samples of the dependent and all independent variables of interest a stepwise regression is the most efficient way of selecting the independent variables to be included in the regression. A stepwise regression adds one variable at a time to the regression. As each new variable is added the F statistic is calculated for all variables in the regression to determine their significance.

In performing the stepwise regressions the regression equation is developed by adding one independent variable (x_i) at a time. The (x_i) with the highest partial correlation coefficient with the dependent variable (y), is selected for inclusion in the regression. An analysis of variance is then performed to determine the quality of the resultant regression.

The F-value is calculated for the regression equation as a test of significance (see Appendix J-C). The F-value for each variable included in the regressions is compared with the minimum value set for inclusion and retention in the analysis. If the F statistic for a particular variable is too low, that variable is removed from the regression, but could be reconsidered on later steps. The minimum F-values for inclusion and retention are inputs to the software.

A stepwise linear regression was used in the case study to determine the relationship between the statistical descriptors of lateral wheel/rail force and track geometry data in Table JB-3 (see Appendix J-C for complete definition of regression analysis terms and techniques). Each response descriptor was evaluated independently for left and right curves. The general flow of the data processing for stepwise regression analysis is shown in Figure JB-4. Analyses were also performed by modifying the data base to include cross products of speed and curvature and underbalance of operation (cant deficiency) and curvature.



X_j's = Independent Variables not in Regression

X_K's = Variables current in regression

X_m = X_j with highest partial correlation

X_n = X_K with lowest partial correlation

Figure JB-4. Stepwise Regression Analysis Data Processing Flow

The minimum F-value, which defines the statistical significance required for inclusion and retention of each independent variable in the regression was set at 2.0. The output from this processing includes tabulations of the regression coefficients (bi's), the coefficient of determination (R^2), and the F-values for the variable added at each "step" of the regression. Plots of y-actual vs y-predicted; and residual versus y-predicted were also produced. These plots were examined to see if the residuals exhibited any nonlinear trends. If nonlinear trends were observed then transforms of the Y_i's and X_i's such as ($\log x_i$) and X_i^n could be considered. No nonlinear trends were observed in the test data. However, residual plots were helpful in identifying outliers. Regression equations were subsequently developed by eliminating these outliers.

J-B-4 RESULTS OF ANALYSIS

Regressions were performed to determine the relationship between the high rail SDP-40F lateral wheel/rail forces and track geometry input. Data were taken from 37 curves in the test zone. The 95th percentile of high rail lateral force, L_{95}, was the wheel/rail force descriptor for each curve. The results for the SDP-40F, summarized in Table JB-4, show that the SDP-40F is sensitive to underbalance of operation (ΔE), standard deviation of curvature (σ_c) and direction of curvature (D).

The final regression was:

$$L_{95} = 6293 + 1940\,(\Delta E) + 6701\,(\sigma_c) - 1169\,(D)$$

with:

R^2	= .715
L_{95}	in pounds
ΔE	in inches
σ_c	in degrees
D	= 0 for right, 1 for left curves

TABLE JB-4

STEPWISE REGRESSION RESULTS, SDP-40F, HIGH RAIL WHEEL/RAIL FORCES

$\bar{Y}$	R^2	F	Standard Error L_{95}
8,799	0.75	5.7	1,221

$$L_{95} = 6293 + 1940\Delta E + 6701(\sigma_c) - 1169(D)$$

Independent Variables

Variable	Mean	Standard Deviation
ΔE	0.778	0.764
σc	0.261	0.130
D	0.639	0.487

SDP-40F HIGH RAIL L_{95}
CONTRIBUTION OF TERMS

Term	Regression Coefficient		Contribution of Mean	Contribution of Standard Deviation
	Value	Std.Error		
Constant	6,293	-	6,293	-
ΔE	1,940	302	1,500	1,482
σc	6,701	1,785	1,745	870
D	-1,169	468	- 750	569
	TOTAL		8,788	

L_{95} Mean = 8,799

L_{95} Standard Deviation = 2,454

The final results indicated that ΔE contributed slightly more than σ_c in determining L_{95} and that, statistically, the left curves produced force levels roughly 1200 pounds lower than the right curves. This could be caused by differences in the way the locomotive negotiates left and right curves or differences in the characteristics of the curve population.

An earlier study (Ref. B-1) using only data from curves of 2 to 3 degrees produced the following regression:

$$L_{95} = 4{,}100 + 400\,\bar{C} + 17{,}300\,(\sigma_c) + 40{,}100\,(\sigma_G^2) + 1{,}800\,\Delta E$$

where:

σ_G^2 = the variance of gauge (inches^2)
$\bar{C}$ = mean curvature (degrees)

In this case $\bar{C}$ contributed from 800 to 1200 pounds, σ_c from 2200 to 5500 pounds, σ_G^2 from 400 to 2900 pounds and ΔE from 0 to 5400 pounds.

In the current analysis, including curves from 0° to 7° the regression coefficent of ΔE to L_{95} is roughly the same while the coefficient for σ_c decreased significantly. The effects of gauge variation and mean curvature did not contribute significantly to the latest regression.

Analysis of the E-8 locomotive was performed for a larger data base which included 99 curves. Due to a known imbalance in the locomotive's suspension system, separate analyses were performed for right and left curves. The results of this analysis are summarized in Tables JB-5 and JB-6. The results for the right hand curves produced a relatively low R^2 value of .63. For this

TABLE JB-5

STEPWISE REGRESSION RESULTS, E-8 HIGH HIGH RAIL FORCES -(LEFT) CURVES

	$\bar{Y}$	R^2	F	$S_e(Y)$
$L_{95} = 6368 - 1119\ (\bar{C}) + 1032\ (\Delta E) + 6396\ (\sigma XL)$	11,141	.78	9.25	1422

Variable	Mean	Standard Deviation
$\bar{C}$	-2.56	1.650
ΔE	0.437	1.460
σXL	0.227	0.108

E-8 HIGH RAIL L_{95}

CONTRIBUTION OF TERMS

Term	Regression Coefficient		Contribution of Mean	Contribution of Standard Deviation
	Value	Std.Error		
Constant	6,368		6,368	-
$\bar{C}$	-1,119	142	2,864	-1,846
ΔE	1,032	168	451	658
σXL	6,396	2103	1,452	691
	TOTAL		11,135	

L_{95} Mean = 11,141

L_{95} Standard Deviation = 3,017

TABLE JB-6

STEPWISE REGRESSION RESULTS, E-8
HIGH RAIL FORCES, + (RIGHT) CURVES

	$\bar{Y}$	R^2	F	$S_e(Y)$
$L_{95} = 4773 + 1249\ (\bar{C}) + 81910\ (\sigma^2 G)$	10,731	0.63	15.7	2023

Variable	Mean	Standard Deviation
$\bar{C}$	2.890	1.750
$\Delta E^* \sigma c$	0.228	0.593
$\sigma^2 G$	0.029	0.015

E-8 HIGH RAIL L_{95}
CONTRIBUTION OF TERMS

Term	Regression Coefficent		Contribution of Mean	Contribution of Standard Deviation
	Value	Std.Error		
Constant	4,773	-	4,773	-
$\bar{C}$	1,249	176	3,610	2,186
$\sigma^2 G$	81,910	20,690	2,375	1,229
	TOTAL		10,758	

L_{95} Mean = 10,731

L_{95} Standard Deviation = 3,321

regression mean curvature and σ^2 gauge were identified as the major contributors to L_{95}. From analysis performed in support of the test of locomotives on Chessie track σ^2, gauge was found to be a good indicator of short wavelength alignment irregularities.

For the left curves L_{95} was found to be related to ΔE but the ΔE regression coefficient for the E-8 was about half that for the SDP-40F in the current analysis.

Mean curvature was a major contributor to L_{95} for the E-8 in left curves and σ_{XL} - the standard deviation of crosslevel was a minor contributor.

APPENDIX J-C
REGRESSION ANALYSIS*

This appendix discusses regression analysis in textbook format for easy reference to Section J-B. The reader is referred to any advanced text book on applied regression analysis for details.

J-C-1 MULTIPLE LINEAR REGRESSION

J-C-1.1 FUNCTIONAL RELATIONSHIP

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

$$y = \alpha + \beta_1 x_1 + \beta_2 x_2 + \ldots \beta_m x_m \qquad (1)$$

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

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

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

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

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

***This appendix is reprinted, with minor changes, from the report entitled "A Prototype Maintenance of Way Planning System," FRA/ORD-80-47.1, Volume I. (Reference B-2)**

J-C-1.2 DERIVATION OF THE METHOD

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

$$y_i = b_0 + \sum_{j=1}^{m} b_j x_{ij} + e_i \qquad (3)$$

The error of estimate e_i is given by

$$e_i = y_i - b_0 - \sum_{j=1}^{m} b_j x_{ij} \qquad (4)$$

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

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

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

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

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

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

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

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

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

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

$$(X'X)b = X'Y \qquad (7)$$

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

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

and Y is the column vector of length n given by

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

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

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

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

J-C-1.3 ASSUMPTIONS

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

J-C-1.4 TRANSFORMATION OF VARIABLES

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

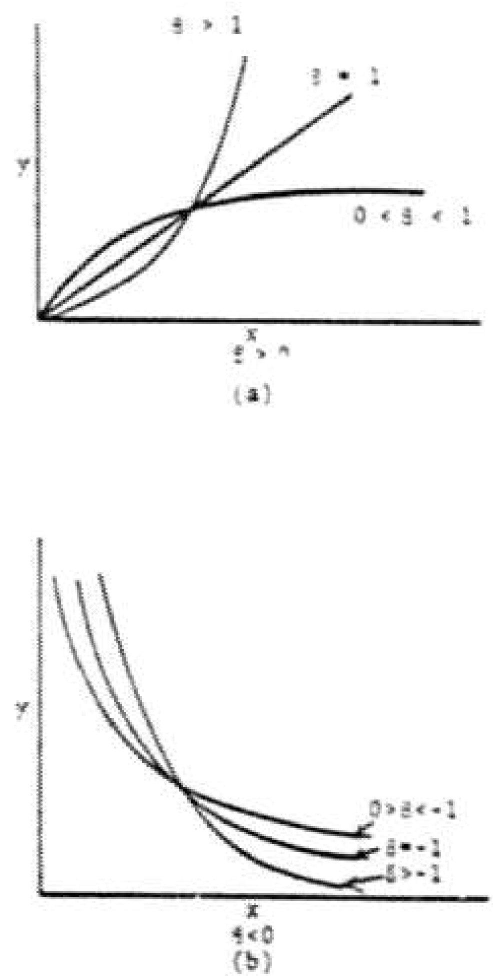


Figure JC-1. Graph of $y = \beta_0 x^{\beta}$

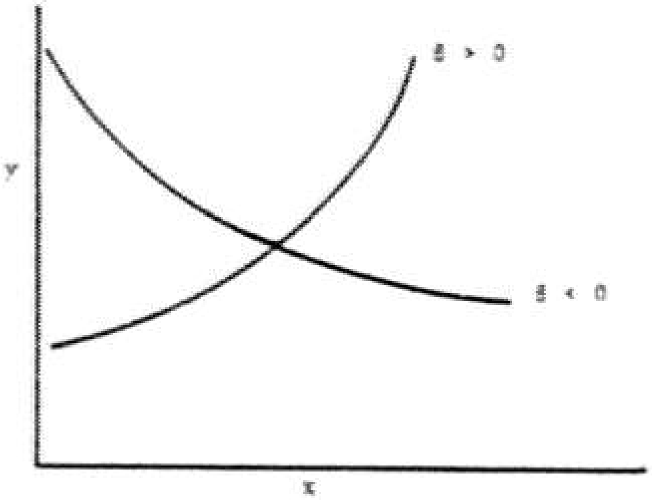


Figure JC-2. Graph of $y = \beta_0 + \beta \log x$

J-C-1.5 DUMMY VARIABLES

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

Track Class	z_1	z_2	z_3
0	0	0	0
1	1	0	0
2	0	1	0
3	0	0	1

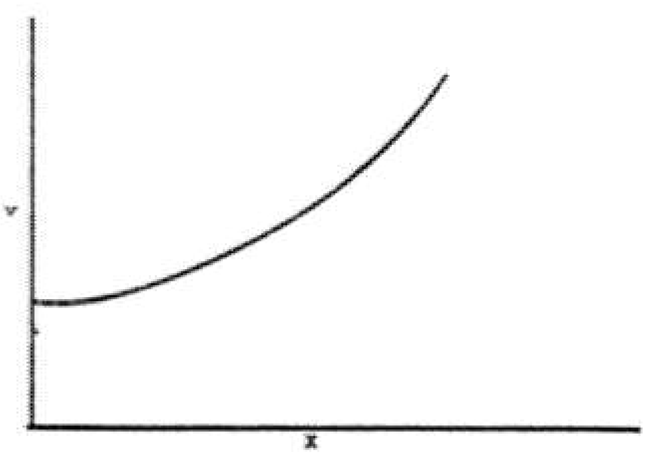


Figure JC-3. Graph of $y = \beta_0 + \beta x^2$

TABLE JC-1

LINEARIZABLE FUNCTIONS

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

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

J-C-1.6 ANALYSIS OF VARIANCE

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

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

It can be shown* that

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

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

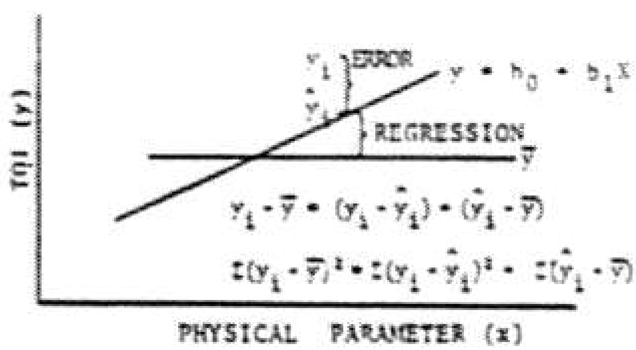


Figure JC-4. Partitioning the Total Variation of y

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

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

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

$$SST = SSE + SSR \qquad (11)$$

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

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

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

H_1: At least one $\beta \neq 0$

we compute the F value as follows:

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

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

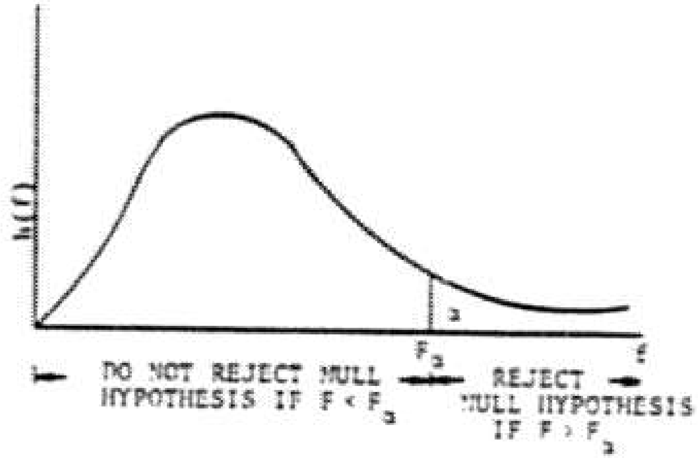


Figure JC-5. Test of the Significance of Regression Equation

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

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

J-C-1.7 STANDARD ERROR OF ESTIMATE

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

TABLE JC-2

ANALYSIS OF VARIANCE TABLE

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

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

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

J-C-1.8 CORRELATION COEFFICIENT

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

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

where

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

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

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

From Equation (13),

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

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

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

or

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

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

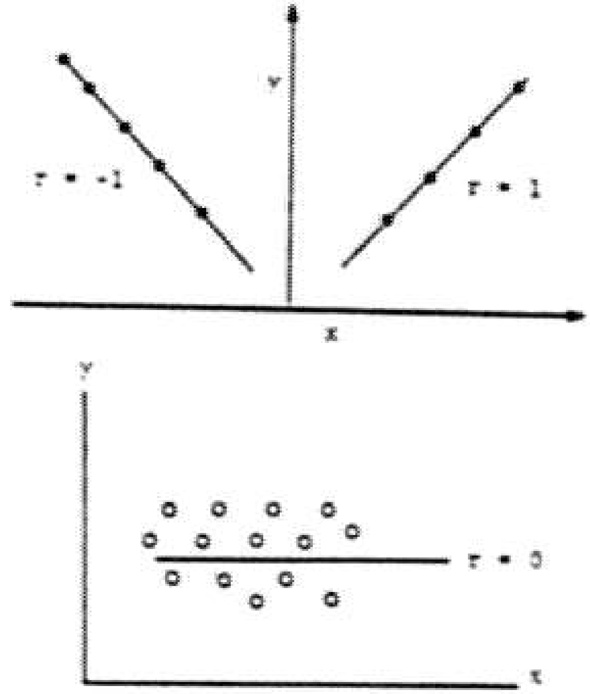


Figure JC-6. Interpretation of Extreme Values of Correlation Coefficients

evident from equation 15 that $(100 \times r^2)$ percent of the variation in the values of y may be accounted for by the lienar relationship with the variable x.

J-C-1.9 COEFFICIENT OF DETERMINATION

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

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

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

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

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

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

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

J-C-1.10 TESTING THE INDIVIDUAL REGRESSION COEFFICIENTS

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

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

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

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

$$H_0: \beta_i = 0$$
$$H_1: \beta_i \neq 0$$

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

J-C-1.11 CONFIDENCE INTERVALS FOR REGRESSION COEFFICIENTS

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

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

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

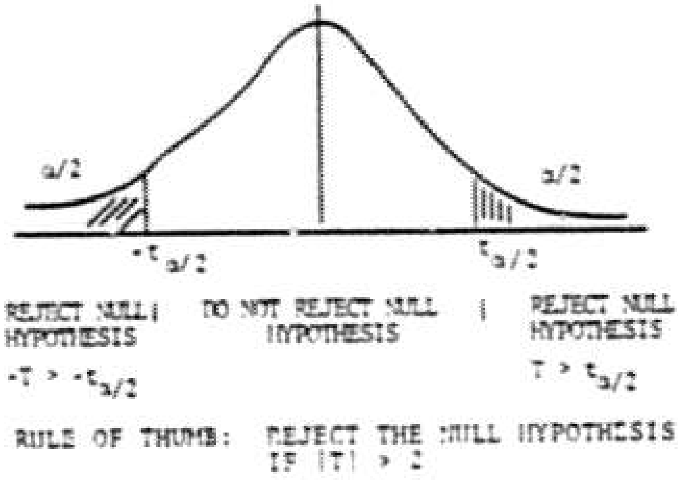


Figure JC-7. Test of Individual Regression Coefficients for Null Hypothesis

J-C-2.0 STEPWISE REGRESSION

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

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

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

J-C-3.0 AUTOREGRESSION

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

$$y_t = a + b_o y_{t-1} + b_i x_i, \ldots b_m x_m \qquad (21)$$

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

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

SECTION K

WAYSIDE AND ONBOARD INSTRUMENTATION

K.1 Introduction

This section contains the technical information coverning all aspects of instrumentation needed to support theoretical predictions and test results addressed in other sections of this document. In Volume I, procedures are outlined to provide a guide to assess specific vehicle problems and determine a general approach to finding the solution. Volume I leads into Section E, Volume II where the specific problem is analyzed in more detail and a test plan is generated as a further guide. This test plan contains the pertinent information needed to design the instrumentation scheme for the test.

The format used in this section is based around providing the instrumentation requirements for solving performance problems related to vehicle dynamics and the interaction of the vehicle with the track. These performance problems are addressed in terms of specific vehicle performance issues. The performance issues are characterized and quantified through the related performance and test parameters (subsection K.2). These parameters are then investigated with regard to the measurement requirements (subsection K.3) to provide the information needed to design this instrumentation for the test. Information for selecting and installing on-board instrumentation is contained in subsection K.4. The contents of the subsection is summarized at the end with labels showing instrumentation required and a sketch of the instrumentation lay out for each performance issue. Subsection K.5 (Wayside Instrumentation) contains the information needed to select and install wayside instrumentation.

Techniques for synchronizing and recording are given in subsection K.6. Information is provided to synchronized data acquisition locations within an on-board and wayside station or between on-board and wayside stations.

Special equipment and techniques that have been identified as important or unique are covered in subsection K.7.

K.2 PERFORMANCE ISSUES AND TEST PARAMETERS

K.2.1 PERFORMANCE ISSUES

The design and construction of rail vehicles have evolved over the years to a limited number of categories especially in the United States. If one examined the history of safety performance problems in these vehicles, it would be found that each generic type of rail vehicle tends to have certain dynamic modes which appear repeatedly. As a result, if one can identify all of the major problematic dynamic modes, most of the performance problems related to vehicle dynamics can be addressed. Under an earlier study Ref. [1], major problematic modes have been identified and referred to as stability performance issues; these are:

- Hunting
- Twist and Roll
- Pitch and Bounce
- Yaw and Sway
- Steady-state Curving
- Spiral Negotiation
- Dynamic Curving
- Steady Buff and Draft
- Longitudinal Train Action
- Longitudinal Impact

For existing and new rail vehicles which do not deviate drastically from the current generic types of designs, the above performance issues can be expected to address all of the potential stability performance problems related to vehicle dynamics. Because of the vastly greater requirements in cost and effort to investirate dynamic behavior of long trains, it was decided that the initial consideration for V/T IAT would be limited to single-vehicle dynamics in a short train, therefore excluding the last two performance issues listed above.

The V/T IAT is to provide uniform means of evaluating safe performance of vehicles and track by establishing a standardized approach to the test procedures. Special track conditions and operating scenarios can be used to systematically examine each of the performance issues and to identify and isolate any unsatisfactory characteristics in the vehicle. In order to characterize and to quantify each of the performance issues, a set of variables must be used. These variables must be clear indicators of the mode and the magnitude of the vehicle dynamic response and they should also provide a measure of the degree of severity of the response as a safety risk. Before discussing the requirements on instrumentation to collect the data, some delineation of the parameters of interest would be helpful.

K.2.2 PARAMETERS OF INTEREST

Many parameters are involved in causing a particular response in a vehicle. For the purpose of adopting a consistent set of notations for Vehicle/Track Interaction testing applications, a general grouping of the parameters is made as follows:

CONTROL VARIABLES: those variables that are controlled by the experiment conductor, e.g.,

- Speed
- Track characteristics (curvature, elevation, spiral design, etc.)
- Intentionally introduced track perturbations (wave shape, wavelength, magnitude, etc.)
- Operating modes (power, braking, dynamic braking, drift, etc.)
- Rail surface condition (dry, sanded, wet, lubricated, etc.)
- Adjustable parameters in the vehicle (wheel profile, damping rate, spring rate, clearances in truck components, load configuration, etc.)

RESPONSE VARIABLES: those variables that describe the outcome of the experiment, e.g.,

- Inertial response (accelerations, velocities, displacements with respect to an inertial reference)
- Relative displacement between vehicle components (spring deflection, carbody roll with respect to truck, etc.)
- Internal forces and stresses (damping force, truck frame stress, etc.)
- External forces (wheel-rail contact forces, coupler forces, force vector crossing, etc.)

VEHICLE CHARACTERISTICS: those parameters that are inherent to the vehicle design and are not changed during the experiment, e.g.,

- Vehicle mass and inertia
- Structural dimensions and clearances
- Properties of fixed suspension components

Instruments are required to measure the vehicle characteristics and the response variables in an assessment experiment. Most of the design characteristics and some of the control variables can be measured once during the experiment and no continuous monitoring is required. Some of the control variables and all of the response variables require continuous monitoring during dynamic tests. Monitoring of control variables is needed to insure that intended test conditions (speed, power, braking level, etc.) are achieved; response variable data are needed during the test for safety monitoring and for pre- and post-test analysis.

K.3 MEASUREMENT REQUIREMENTS

This section contains discussions of general requirements for measurements to be performed in safety assessment for railroad equipment. Many of the measurements have been made by conventional tools which require no special instrumentation; others may require instrumentation that is tailored for the application. Those measurement requirements that can be met by conventional techniques are mentioned in this section and not elaborated further in this report. Measurements requiring special instrumentation are covered in more detail in the subsequent sections of this report.

K.3.1 CONTROL VARIABLES

K.3.1.1 TRACK CHARACTERIZATION

Track geometry constitutes the main input to externally excited dynamic stability response in a vehicle. Parameters of interest include gauge, superelevation, alignment and profile of each rail, and track curvature. These parameters in a static mode can be measured manually by conventional hand tools such as a gauge and crosslevel bar and a string line. More precise measurements can be obtained by survey techniques using optical equipment. Loaded geometry, which is what a moving vehicle senses, may not be obtained accurately by manual methods. An automated track geometry measuring car can provide an accurate geometry survey at loads and speeds similar to standard railroad traffic.

Track stiffness/compliance in the vertical and the lateral directions are important to the track-train interaction. Dynamic measurement techniques are under development. The only reliable methods that can be used today are static techniques which define the load-versus-deflection relationship for a single point on the track through a loading/unloading process. Continuous measurement of track stiffness under a dynamic moving load may become available in the future if research programs are successful.

Surface conditions of rails and cross-sectional profile of rail head are also measured manually by hand tools today. A device for measuring static and steady-state coefficient of friction on the gauge-side of the rail was used on the perturbed track test of locomotives Ref. [3] and on a transit car rolling resistance test Ref. [4]. This approach, however, has some drawbacks (see Section K.3.1.4). Rail cross-section profilers that produce graphical plots mechanically are available in the market. A device that can store digitized data of the rail cross-section shape on magnetic tape has been developed Ref. [5]. However, rail cross-section profiling continuously over the length of track is not yet available.

K.3.1.2 VEHICLE CHARACTERIZATION

Control variables of vehicles being tested include load variations, changes in suspension elements, clearances and wheel profile, etc. For each of the configurations considered in the assessment, the measurement requirements are the same as those to be discussed later in design characteristics. The measurements would be repeated, using the same instrumentation and technique, for each of the configurations under consideration.

K.3.1.3 OPERATION VARIABLES

Operation variables are generally needed in real time, in addition to post-test analysis, to insure that the specified test conditions are achieved.

Vehicle speed can be measured from axle rotation by a voltage generator or by the combination of an encoder and a time-base generator. Distance and acceleration can be obtained easily also with the second technique. One common undesirable feature in axle-driven speed/distance measuring systems is that they include errors due to wheel slippage, tread conicity, curving, braking and traction. A separate measuring wheel with a cylindrical tread and a low-resistant mount can allow slip-free measurement of speed and distance. A speed signal is often available in a locomotive or a self-propelled car, most of them are derived from gear-tooth counting. The accuracy of the built-in systems is generally not adequate for test control purposes.

Brake pipe pressure and brake cylinder pressure can be measured by standard transducers connected to the brake system. Actual brake shoe pressure or the braking force are more difficult to measure. Strain-gauged brake beam and load cells placed in the brake rigging have been used to measure the applied brake force. Although some riggings have components which can be instrumented to measure the brake force to the wheel, it is rather difficult to do in typical riggings. In general, the multiple load path problem, the shock and vibration and the high temperature near the brake shoe make it difficult to obtain reliable measurements.

Throttle position, motor current for traction or braking and other parameters associated with locomotives and self-propelled cars have generally been measured by the equipment manufacturer during development. One can usually rely on the manufacturer to provide the equipment or the technique for these measurements. Catenary voltage, fuel flow rate and fuel consumption rate are related primarily to operating efficiency and are generally not measured for stability assessment. Live-wire measurement of electrical or dynamic properties of the pantograph is an extremely difficult problem. The manufacturer should be consulted when designing a measurement system. Measurement of pantograph dynamics under dead-wire conditions is a much simpler task; conventional displacement/velocity transducers can then be used. Typical fuel systems in diesel locomotives maintain a very high flow rate from the fuel tank to and back from the engine. The difference between the outward and the return flow rates is the actual consumption rate. It is important to have highly accurate and matched flow meters if the consumption rate is to be derived by differencing the two measured rates. Volumetric type of low rate meters are sensitive to temperature variations. Compensations for temperature changes are necessary if a fine resolution is required. Schemes have been developed to introduce special modifications to the fuel system to measure the net fuel consumption rate directly (ConRail). It would be advisable to work closely with the equipment manufacturer in order to avoid undesirable consequences due to the modification.

K.3.1.4 ENVIRONMENTAL CONDITIONS

Several variables environmental conditions should also be monitored, including but not be limited to ambient temperature, humidity, wind velocity and direction, and prepicipation (type, rate, and cumulative amount). When freezing conditions exist, prior history of freeze-thaw cycles should be obtained for the current season to assess ballast conditions. Perhaps another important environmental parameter for some performance issues is the coefficient of friction between the wheel and rail interface. Hand-held measurement devices have shown limited success due to the relatively light loads applied. Perhaps the best way to evaluate the friction coefficients is to lock-up one axle of a test vehicle and measure the change in force required to move it. This technique duplicates the load and contact geometry encountered under actual test conditions.

K.3.2 RESPONSE VARIABLES

K.3.2.1 WHEEL-RAIL CONTACT AREA

Forces transmitted through the rail-wheel contact area are the most important response variables in stability considerations. High vertical or lateral loads can cause structural degradation or failure which may lead to derailment. High L/V over some duration of time is known to cause rail rollover or wheel climb. Low vertical force on a wheelplate is an indication of potential wheel lift.

Continuous monitoring of wheel forces has been done successfully by instrumented wheel spokes or wheelplates Ref. [6, 7, 8]. Instrumented adapter plates and axles have also been used Ref. [9]. Estimation of dynamic lateral forces can be made if the inertial properties and acceleration measurements are available Ref. [10].

The advantage of using a vehicle-borne force measuring technique is the continuous monitoring of the force-time history over all track locations tested. If comparisons of force levels for different vehicles (or the same vehicle with different suspension configurations) are intended, an instrumented track location may be more appropriate. Strain gauges applied to the rail have been used successfully to measure instantaneous force levels as wheels pass by the instrumented location Ref. [11].

Lateral wheel position relative to the rail and the angle-of-attack when the wheel is flanging are important parameters in assessing wheel climb potential and rail wear rate. A vehicle-borne system would monitor the response of one wheel on a continuous basis while a track-side system would obtain a single instantaneous measurement as each wheel passes through the instrumented location. Both contact type Ref. [12] and non-contact type Ref. [13] transducers have been used to measure the wheel position and the angle-of-attack onboard a vehicle. To date, these attempts have achieved only limited success. A wayside angle-of-attack system has been used on some field test Ref. [14].

Wheel-rail contact geometry determines the effective center line of the track which is generally different from the geometric center line as both the rails and the wheels are worn. The actual location of the contact patch on each rail and the slope of the contact surface are the key parameters which control the dynamic center line of a rolling axle, An instrument to measure the static relative geometry of the wheels and the rails is available Ref. [15] from which the contact geometry can be derived using a computer program. This method is a slow station-by-station measurement technique for monitoring the contact geometry.

When a vertical load shift causes a wheel to unload completely, the wheel may lift off the rail as the load shift continues. The vertical distance during a wheel lift is an important stability parameter since the derailment potential is much greater if the wheel flange clears the top of the rail. A contact-type system has been used successfully in a twist-and-roll test in which a small wheel is mounted on an arm pivoted from the truck frame, the wheel is kept in contact with the rail by a spring load. A vertical lift of the running wheel from the rail will register as angular movement of the pivot arm. A non-contact transducer can be used in a similar way to measure wheel lift. Since it is not possible to place the contact wheel of the non-contact transducer directly over the wheel-rail contact point, an error is introduced due to profile variations in the rails. This error can be minimized by using a pair of transducers, one leading and one trailing the wheel being measured, and by placing the measuring points as close as possible to the wheel-rail contact point. The error can be eliminated if a baseline is established for the track by running the system slowly enough to insure that no wheel lift is occurring. The baseline measurement represents a three-point mid-chord offset measurement of the rail surface.

A video camera mounted on the truck can be a relatively simple alternative to monitor lateral wheel position, wheel climb and wheel lift. Although quantitative values are difficult to obtain the occurrence of flange contact and wheel lift can be observed. Some of the problems encountered with video monitoring include the survivability of camera and lighting, and the relatively short duration of wheel climb events (can be 50 msec or less) which is difficult if not impossible to observe with normal 30 frame/sec video. High speed video (120 frames/sec) may not survive the environment.

K.3.2.2 <u>TRACK RESPONSE</u>

Track response parameters include forces and stresses in the rails, fasteners, ties, ballast and subgrade; relative and absolute movements in these components; and vibration levels.

Force levels are of interest in the rails and the fasteners; pressure measurements are more appropriate in ties, ballast and subgrade. Rails and fasteners have been instrumented to serve as load cells for force measurement.

Strain-gauged rails have shown better overall success in recent years than instrumented tie plates. Conventional pressure transducers can be used in ballast and subgrade measurements.

Simple displacement transducers have been used to measure gauge widening at the base of the rails. Rotation of the rails under load could add significantly to gauge which would not be detectable at the rail base. A more accurate method is to use linear displacement transducers to measure railhead-to-tie movements on the field side of the rail. Rail base movement can be measured the same way from which the rotation of the rail can be calculated.

Absolute lateral movements of the rail or the tie are generally measured from a reference point fixed to an anchor far enough away from the track so that it would not be disturbed by a passing train. Vertical movements of the rails or the tie can be measured with respect to a rod driven several feet deep into the track bed. The bottom of the rod is firmly anchored to the sub-grade while the upper portion is isolated from the surrounding soil and ballast by a tubular sleeve so that their movements under load will not affect the stationarity of the rod. All of the displacement measurements discussed above are designed to monitor the movement of a single point on the track on a continuous basis as vehicles pass through the point.

Stress levels in ties can be measured if the material is suitable for strain gauge application (concrete or steel). Surface strain/stress levels are useful for studying load distributions in ties; they are not sufficiently informative for calculating wheel-rail loads. It is possible to convert an entire tie into a load cell for vertical and lateral load measurement, however, inserting an instrumented tie in place of a regular tie would cause considerable disturbance to the ballast which will change the properties of the track structure.

K.3.2.3 TRUCK AND SUSPENSION RESPONSES

Dynamic movements between truck components can be measured by conventional displacement transducers if their sizes and ability to withstand shock are acceptable (100 g shock at the axle level, unsprung, 25 g shock at the truck frame level, beyond primary suspension, and 5 g shock at the carbody level, beyond secondary suspension are typical). High velocities and repeated oscillations about equilibrium positions are to be expected in truck component movements. Typical recoil-string type rotary displacement transducers may require special modifications to avoid frequent breakage or high wear rate on contact areas. Non-contact type proximity sensors are useful when the maximum range is small, usually less than an inch. An added advantage of a noncontact sensor is the insensitivity to movements of the surface being measured in directions normal to the measurement direction. A cantilevered reed, strain-gauged on both sides for bending strain, has been used as a transducer to measure displacement at the end of the reed. Such a transducer is rugged and reasonably linear if the bending strain is kept relatively small.

Multi-dimensional movement is a general problem in making measurements in a rail vehicle. The distance change between two points in a vehicle is often caused by several components of movements in different suspension elements. It is not always possible to obtain direct measurements for each of the components, thus, special mechanical arrangements are often used to isolate a component of the movement or to reduce the sensitivity to other components. It is also possible to resolve the components mathematically from indirect measurements using trigonometric relationships.

Accelerations on truck components are measurable with accelerometers. Shock and vibration levels on truck components are extremely high, selection of transducer is critical in meeting the requirements. Low frequency, low acceleration levels should be measured by servo-type transducers; they must be mechanically isolated if used in an environment of high shock such as the unsprung parts of the truck. Strain-gauge type transducers are more rugged than servo-types but are less accurate. Crystal-types can withstand very high shock levels and can measure high frequency oscillations but the accuracy is relatively poor and the sensitivity drops down to zero for very low frequencies.

Force levels in truck components can be measured either by placing transducers in series with the load path or by converting the component into a transducer. Strain gauges are generally used on truck components for stress/strain measurement or for measuring forces applied to the component. The component must then be calibrated in a controlled environment to determine the sensitivity and any measurement errors when the component is used as a force transducer. Truck side frames, bolsters, axles and wheels have been used for such purposes. When load cells are placed in the load path, it is important to insure that the addition does not change the geometric or the stiffness characteristics of the system. Instrumented bearing adapter plates and instrumented thrust bearing caps are two of the examples of in-series load measurement techniques.

K.3.2.4 CARBODY RESPONSES

Rigid body movement of a carbody is characterized by six degrees of freedom. These degrees of freedom can be defined most conveniently by the six components of inertial acceleration. These can be measured by three linear accelerometers and three rotational accelerometers or by three pairs of linear accelerometers. Linear accelerations in a vehicle are directly proportional to forces experienced by passengers or lading carried by the vehicle. It should be noted that inertial and gravitational accelerations are sensed equally by most acceleration transducers. Oscillatory accelerations are sensed by all types of accelerometers. If transducers used have frequency responses down to d.c., the graviational acceleration and centrifugal acceleration will also be measured. Mounting and locations are important with respect to vehicle bending modes.

Roll angle of a vehicle with respect to the gravity vector is an important stability parameter because of the potential for rollover or wheel climb. Direct measurement of the tilt angle (with respect to gravity) can be made with a pendulum or a gyro-stabilized pendulum. Rate-of-turn gyros can be used to measure inertial angular velocities. Gyros are generally delicate instruments and can only be used in a well isolated environment such as inside a vehicle.

In testing carbody roll response, an important safety concern is the total vertical unloading on one side of the vehicle which may lead to vehicle rollover. A useful parameter for monitoring this rollover potential is "vector crossing"; this is the distance from the track center line where the combined inertial and gravitational force vector passes through the plane of the track. The parameter will assume the value zero when the vehicle is travelling steadily on level tangent track; it moves toward the low rail if the vehicle travels below balance speed and it moves towards the high rail if the vehicle is travelling above balance speed. When the vector crossing point reaches either the high rail or the low rail, the vehicle is on the verge of rolling over. Continuous monitoring of vector crossing can be done if vertical force measurements are made continuously by instrumented wheelsets or other means.

The position of the resultant force calculated from the measured vertical forces on all of the wheels in a vehicle is equal and opposite to the combined inertial and gravitational force acting on the vehicle. It should be noted that the potential for vehicle overturning should be based on force vectors from both trucks and must include forces coming from every mass element in the vehicle as well as any external force applied to the vehicle (such as lateral wind load). While it is possible to calculate the vector crossing from measured accelerations and suspension system movements, it will not include the effects due to external loads.

Structural deformations in a vehicle are superimposed onto the rigid body motions. Accelerations at various points in a vehicle are different due to the structural deformation. Since structural deformations are generally of small amplitudes, linear modal analysis techniques are applicable. In extracting structural mode shapes from test data, it is customary to use multiple transducers placed in selected positions in a vehicle and the dynamic measurements made by these transducers are processed coherently to obtain a modal decomposition of the total vibration response. For instance, the structural modes of flatcars were obtained using this method Ref. [16]. In the flatcar test, twelve vertical accelerometers were mounted at selected positions on the flatcar; the data from these transducers were analyzed to show that dynamic vibrations in the flat car can be described adequately by the first and second modes in bending and in torsion.

K.3.3 DESIGN CHARACTERISTICS

K.3.3.1 GEOMETRIC PARAMETERS

Dimensions, geometric configurations and clearances of a vehicle can be obtained from manufacturer's drawings and verified by physical measurements. Standard gauges are available to measure wheel properties such as tape, rim thickness, tread profile and flange thickness. A device is available to measure and record the tread profiles of both wheels on the same axle simultaneously for the purpose of defining true wheel/rail contact geometry Ref. [17].

K.3.3.2 MASS AND INERTIA

Vehicle mass and inertia parameters are important in determining how a vehicle responds to dynamic inputs. Total weight and the weight distribution in the horizontal plane can be obtained by conventional scales used for weighing rail cars. If the vertical loading on each individual wheel is to be determined, conventional scales may not be adequate since they usually weigh one axle or one truck at a time. Hydraulic jacks equipped with a load cell or a pressure gauge can be used to lift an individual wheel off the rail slightly to determine the load carried by the wheel. Interpolation would be necessary to convert the measured load at the jacking point to that at the wheel-rail contact point after measurements have been made on both ends of an axle. The above procedure can be applied to both empty and loaded configurations.

Weight distribution of the center of gravity of an empty or a loaded vehicle in the vertical direction is more difficult to determine. It is possible to use data provided by the manufacturer and calculations to estimate the center-of-gravity (c.g.) height. A way to verify the result experimentally is to measure the shift in vertical weight distribution as a vehicle is tilted on super-elevated track. Jacking of wheels to measure wheel loads is more difficult on canted track; it would be much easier if instrumented wheels or strain-gauged rails were available for the experiment. As most vehicle suspension systems allow the carbody to roll and shift laterally when parked on canted track, the apparent shift in vertical load distribution would include the effect due to the cant angle in the track as well as those caused by the additional roll and shift in the suspension. Measurements of the suspension system roll and shift must be made and included in the calculation in order to isolate the effect of track cant and center of gravity (c.g.) height. The contributions to total mass from the truck components and from the carbody are mixed when weight measurements are made at the wheel-rail contact points. The most reliable experimental method to isolate the two is to perform truck measurements independently when the truck is separated from the car body.

Pitch and yaw inertias of truck and carbody can be estimated by mathematical calculations if the mass distributions are known accurately. Experimental methods exist but require rather elaborate mechanical arrangements. In general, a simple harmonic oscillator is created using the component being measured to provide the mass inertia and a related spring rate. This could be a gravitational or a spring-mass pendulum with the mass moving in the pitch or the yaw mode. The fundamental frequency of the oscillator can be measured which in turn can be used to calculate the rotational moment of inertia.

K.3.3.3 DEFORMABLE ELEMENTS

Spring and damper characteristics are usually available from suppliers, however, the actual characteristics in the installed configurations have been found to differ from manufacturer's data. Suspension elements can be tested as individual components in laboratories. Assembled vehicles/trucks have also been tested in laboratories for the purpose of defining the as-installed characteristics Ref. [18].

Laboratory tests of vehicle suspension elements generally cannot achieve the type of dynamic loads or the environment as those experienced in actual service. It is possible to use force and deformation measurements made in the vehicle under operating conditions to characterize the suspension elements. Deformations (displacement, velocity, etc.) of suspension elements are relatively easy to measure; force measurements are generally more difficult because they have to be made in series with the true load path. In many cases, the force applied to an element can be estimated from inertia and acceleration measurements made on the masses attached to the suspension element. This technique has been applied successfully to characterize the dynamic properties of the secondary suspension elements in a locomotive truck Ref. [19]. In this case, response variables during tests are needed. The method is applicable only within the range of deformation and force available from the test data.

Elastic properties of structure members in a vehicle can sometimes play an important role in vehicle response. Warp in flatcars and twist in boxcars are some of the examples. Measurement of these properties involves laboratory procedures which monitors the deformations while a controlled load is applied. Conventional instruments are available for making these measurements; it is the apparatus for load application that requires tailoring for each case.

K.4 ONBOARD INSTRUMENTATION

K.4.1 VEHICLE-BORNE WHEEL/RAIL FORCE MEASUREMENT

The measurement of the wheel/rail force vector is vitally important to the understanding of the interaction between a rail vehicle and the track. Additionally, knowledge of the wheel/rail forces enable the characterization of vehicle components and inertial properties. Currently, the state-of-the-art offers several techniques which are capable of reasonably accurate measurements of wheel/rail forces generated under field conditions.

For the determination of rail vehicle wheel forces both direct force measurement and inertial force measurement techniques should be considered. Direct force measurement techniques include instrumented wheelsets and journal load cells. Inertial force measurement is performed by measuring the accelerations of the major vehicle components (i.e., wheelsets, trucks and carbody) and multiplying by the effective mass of each. Depending upon the goals of a particular test program any of the approaches may be best applied. For example, if steady response is of interest only direct force measurement can be applied. Creep force and dynamic wheel force measurements require instrumented wheelsets. Dynamic truck and axle forces can be measured with instrumented wheelsets or a combination of journal load cells and accelerometers. Table K-4.1, "Applications of Force Measurement Techniques", summarizes the techniques which may be applied to each measurement task. In many cases instrumented wheelsets can be supplemented or replaced by another technique for a more thorough or cost effective measurement. This will is discused further in Section K.4.1.3.

K.4.1.1 REQUIREMENTS FOR WHEEL/RAIL FORCE MEASUREMENT

The measurements of wheel/rail forces are primarily performed in addressing a stability performance issue. These may be categorized as wheel climb, rail rollover, gauge widening, panel shift, and rock off. Depending on which of these issues is to be addressed, requirements will vary.

For weak track, onboard measurement of gauge to identify locations of poor lateral restraint should be made to augment W/R force data analysis.

The requirement for the number of instrumented wheelsets, for example, is a direct function of stability issue. Wheel climb involves the determination of the peak ratio of lateral to vertical (L/V) forces, the location of the wheel rail contact point and the wheel angle of attack. Thus, a single instrumented wheelset would be sufficient if placed in the worst case (maximum L/V) position. Rail rollover requires complete knowledge of truck L/V and, therefore, requires a complete truck set of instrumented wheelsets, two or three wheelsets per truck.

A complete truck set is also required when investigating rock off which necessitates the evaluation of the wheel unloading index* (WUI).

Under some circumstances it may be desirable to measure the reaction between an entire rail vehicle equipped with two trucks with two or more axles each. This situation could arise, for example, in determining the overturning tendency of a car through a curve.

K.4.1.2 DESIGN SPECIFICATION FOR WHEEL/RAIL FORCE MEASUREMENT

As is the case for any transducer, a wheel/force measurement system must conform to certain design parameters. Also in establishing values for these parameters certain compromises must be made based on the requirements. First, these parameters will be defined. Second, based on recent experience in use of state-of-the-art systems, recommendations are made on the nominal values of each parameter.

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*WUI = 1 - $V_L/V_H/3$ where V_L is the vertical force on the least loaded wheel and V_H is the sum of the vertical forces of the remaining three wheels.

Sensitivity

One of the first parameters to be addressed in any system is sensitivity. The system output in response to an applied load must be high enough to provide an adequate signal to noise ratio and preferably be linear. Since most systems being considered presently involve strain measurement in one form or another and the strain levels are typically small (on the order of 10 ppm*), sensitivity often assumes the role of deciding factor.

Crosstalk

Crosstalk, as used in the present context, implies an apparent measured force in a given direction, resulting from the application of an orthogonal force; e.g., an apparent lateral force due to a vertical force. Although it is obvious this is an undesirable effect, it is not necessary to eliminate crosstalk from the raw signals since it is relatively easy to correct if it is linear and constant with respect to angularity. This is discussed further in Section K.4.1.3.4.

Load Point Sensitivity

The sensitivity of a measurement of force to its path of transmission is referred to as load point sensitivity. Depending on the system employed this may be either the wheel/rail contact point or the axle/side frame contact point. In either case it is desirable to minimize the sensitivity of the force measured to change in load point.

Ripple

Ripple, which is associated primarily with the instrumented wheelset, is an apparent harmonic content in the output as the wheelset set revolves under a constant load. Ripple usually comes about due to one of two reasons. Strain fields as seen by a strain gauge bridge are generally modulated by the wheel rotation resulting in a periodic output containing fundamentals as well

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*part per million

as harmonics. Processing schemes are used to reconstruct the measured force from the modulated signals. Such schemes are generally not able to remove 100% of the modulation. A second cause is due to the lack of symmetry in the wheelplate or in the placement of gauges. A much more irregular shaped ripple would result. Ripple is easily identifiable since it is associated with the wheel revolution and can be filtered out for steady state analyses. Higher harmonics, especially those that cause the ripple to have irregular shapes, cannot be corrected by simple filtering or simple algorithms. Knowing the precise angular position of the wheelset is usually necessary in order to make those corrections.

TABLE K-4.1 APPLICATION OF FORCE MEASUREMENT TECHNIQUES

FORCE MEASUREMENTS

TECHNIQUE	WHEEL CREEP STEADY STATE DYNAMIC	AXLE STEADY STATE	TRUCK STEADY STATE	AXLE DYNAMIC	TRUCK DYNAMIC
INSTRUMENTED WHEELSETS	1	1	1	1	1
JOURNAL LOAD CELLS		2	2		
INERTIA MEASUREMENT				3	3
JOURNAL LOAD CELLS PLUS AXLE INERTIA				2	2

1-MOST COSTLY AND MOST ACCURATE 3-LEAST COSTLY AND LEAST ACCURATE

Centrifugal Effects

The inertia of the wheelset itself will induce strains under a spinning motion which may be output through the instrumentation as though they were forces. Centrifugal forces are proportional to the square of velocity and can therefore become significant at the higher speeds. By the choice of strain gauge bridge pattern, it is possible to circumvent this effect with no loss of sensitivity.

Thermal Effects

Wheels under rail vehicles typically cycle through a temperature range often as wide as two hundred degrees Fahrenheit. As a result, thermal stresses are created which are the same order of magnitude as those caused by the forces. Thermal effects usually produce a radially symmetrical strain field similar to centrifugal effects; the same technique can be used to eliminate the effect from the output.

Based on the foregoing discussion, Table K-4.2 summarizes nominal values for the design parameters of a wheel/rail force measurement system. Note that each category is broken down into vertical and lateral force measurement. The first category, sensitivity, is based on the strain-gauged wheelplate concept and is, therefore, not entirely representative of all the wheel/rail force measurement techniques. It does, however, represent a worst case or lower bound on acceptable sensitivity and should be used as such.

Under the category of crosstalk are given two levels of error. As mentioned earlier, the actual value of the crosstalk error is not important as long as it is less than about 10 percent because self correcting algorithms will reduce this error source to almost negligible levels.

This specification of load point sensitivity is given in percent error per inch of load point movement on the wheel tread. This value is connected again with the strain gauged wheelplate technique and is a rather high upper bound of acceptability. Typically, the actual load point sensitivity may be half that shown in Table K-4.2.

TABLE K-4.2 NORMINAL DESIGN SPECIFICATION FOR WHEEL/RAIL FORCE MEASUREMENT SYSTEM

	Vertical Force Measurement	Lateral Force Measurement
Sensitivity		
Minimum	5με/kip	15με/kip
Crosstalk		
Raw	≤10%*	≤10%*
Corrected	≤1%	≤1%
Load Point Sensitivity	6%/in.	2.5%/in.
Ripple		
Simple Load	6%	5%
Combined Load	7%	6%
Centrifugal		
Raw	3-5%	Negligible
Corrected	Negligible	Negligible
Thermal		
Raw	0.5%/deg. F	0.5%/deg. F
Corrected	Negligible	Negligible

*Percentages represent percent error of true value; e.g. 10% implies 1000 ± 100 lb_f.

με = micro-inches per inch (strain)

Ripple comprises the largest single source of error uncorrectable by simple algoritims in a wheel/force measurement system as indicated in Table K-4.2. The distinction between simple and combined load ripple is that under simple loading, force is applied only in the direction for which the bridge in question is designed. Combined load ripple includes the effect of harmonic distortion caused by a load normal to the desired direction. This is similar to crosstalk but unlike crosstalk is not correctable by a simple technique.

Note that Table K-4.2 shows centrifugal effects in the vertical force measurement column only. This again is a trait of the strain-gauged wheelplate technique and is simply included here for completeness.

The last category of parameters specified in Table K-4.2 is thermal effects. Thermal drift, as it is known, is the largest single contributor to system error before corrective action. Recall that a typical thermal cycle for any wheel is greater than 100 degrees. Furthermore, ambient temperatures independent of all other factors will generally vary 20 degrees during a test day. Thus thermal effects if not corrected for will cause errors between 10 and 50 percent. Fortunately both centrifigual and thermal errors are readily amenable to simple yet effective corrections which must be done for each wheel independently.

K.4.1.3 WHEEL/RAIL FORCE MEASUREMENT SYSTEMS AND TECHNIQUES

The following discussion of vehicle-borne systems and techniques used to measure wheel/rail forces will make use of a three part classification system. The categories to be used are (1) journal load cells, (2) inertial techniques, and (3) instrumented wheelsets. This latter category may be further subdivided into three subdivisions: instrumented axles, instrumented standard wheelplates, and instrumented special wheelplates.

K.4.1.3.1 JOURNAL LOAD CELL

Many railroad trucks, especially locomotive trucks, are designed to transmit lateral forces between the truck frame and the axles through thrust bearings installed at the ends of the axles. With this type of design, the load path for a lateral force goes from a wheel flange through the axle to the thrust bearing on the opposite end of the axle and continues through the bearing housing and to the truck frame. Since the thrust bearing is a focal point in the lateral load path, specially designed load cells have been used to fit in the space normally occupied by the thrust bearings for measuring the lateral force transmitted through that point. The Electro-Motive Division of General Motors (EMD) has used this technique on many types of trucks employing nonrotating bearing end-caps.

One advantage of this measuring technique is that the measurement is made in the line of the load path. Secondly, it introduces a minimal modification to the mechanical characteristics of the truck. Furthermore, the end-cap/thrust bearing load cell can be pre-assembled and installed in any vehicle quickly and the output is a direct continuous measurement of the lateral force which requires no special processing.

This measurement approach is limited to the type of trucks which use the thrust bearing design or can be modified to accept such a bearing. Furthermore, there are certain disadvantages. Since the thrust bearing and the wheel-rail contact points are separated by the wheel and axle set, the inertial forces due to lateral movements (which are not easily measured) of the wheel and axle mass, including the traction motor and gear box, in some cases, are not measured by the thrust bearing load cell even though they contribute to the lateral forces at the wheel-rail contact points. Because of the built-in freeplay between the wheelset and the truck frame, at most one of the two thrust bearings will be carrying a lateral load at any time. The force, as measured by the load cell in action, is representative of the total lateral force applied to the axle from the truck frame and should be equal and opposite to the sum of the lateral forces applied through the wheel-rail contact points on both wheels (except for the inertial forces due to lateral accelerations of the axle mass as discussed above). It is, therefore, not possible to resolve the lateral force at each wheel-rail contact point. In Figure K-4.1, the lateral forces acting on a single axle are shown for an instant when the axle is experiencing a lateral acceleration $\ddot{x}$. Assuming that the wheel axle set and the components that are fastened to the axle are moving together at the same acceleration, then the inertial force can be represented by $M\ddot{x}$, with M being the total mass in the wheel-axle assembly. The dynamic force equilibrium in the lateral direction implies that:

$$H_L = F_{RF} + F_{RC} + F_{LC} + M\ddot{x} + Mg\sin\theta$$

in which H_L is the force measured by the thrust bearing load cell on the left end of the axle, F_{RF} is the flange contact force on the right wheel, F_{RC} and F_{LC} are the creep forces on the right and left wheel tread, $M\ddot{x}$ is the inertial force due to lateral dynamics and $Mg\sin\theta$ is the gravitational force component due to track crosslevel θ. It should be noted that the inertial acceleration $\ddot{x}$ may contain a component caused by steady-state curving and a component by pure lateral translation. The steady-state translational component will be oscillatory in nature and of a relatively high frequency.

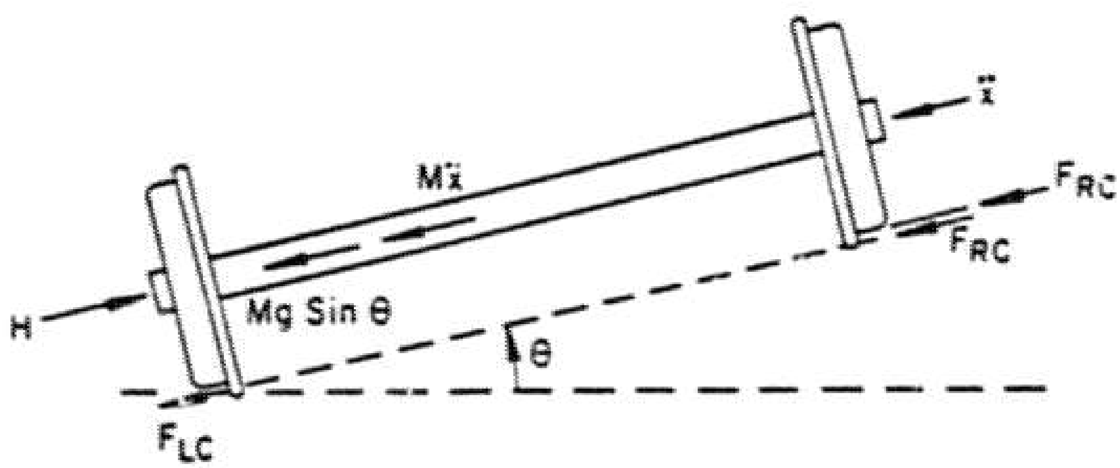

FIGURE K-4.1 DYNAMIC FORCE BALANCE ON AXLE

The equation given above and Figure K-4.1 can also be used to illustrate the difference between the load cell technique and the instrumented wheel techniques. Instrumented wheels, with the strain gauges located in the wheelplates or spokes, will measure the forces (F_{RF} + F_{RC}) and F_{LC} directly. The only portion of the force not measured by instrumented wheels are the contributions to the inertial forces from the mass in the wheel rims.

K.4.1.3.2 INERTIAL MEASUREMENT TECHNIQUE

Major contributors to the lateral wheel-rail force are the dynamic motions of a vehicle perpendicular to the direction of travel. These motions produce forces which are directly relatable to the inertial properties of the vehicle components and their accelerations in the lateral direction. Several researchers have installed accelerometers on vehicle components in an attempt to estimate the wheel-rail forces from acceleration measurements. These attempts were often unsuccessful due to several difficulties: the choice of a suitable transducer; adequate mounting to protect the transducer from the high levels of shock and vibrations in the truck; evaluation of the "effective mass" due to the presence of simultaneous linear and rotational motions, and the lack of a reliable independent force measuring technique to verify the results.

In order to successfully collect the acceleration data on each mass element in the vehicle and truck which contributes to lateral inertial force, an appropriate transducer must be used on each of the mass components to accommodate the different vibration environments and the different characteristics of the acceleration signal being measured. Crystal or strain-gauge type accelerometers are sufficiently rugged to survive the high shock levels in the truck environment, unfortunately they either do not have the necessary low frequency response or the resolution needed in the frequency range of interest. During the Perturbed Track Test (PTT) of locomotives conducted in 1978 at the Transportation Test Center in Pueblo, Colorado, foam isolation mounting was used to mount capacitive accelerometers on truck components. Data collected by this technique were successfully used in calculating total lateral truck force. The estimated total truck forces were verified by using data from instrumented wheelsets performing the measurements simultaneously Ref. [10].

Advantages of this technique are that it requires no modifications to the vehicle and truck components; the transducers are standard off-the-shelf components and are relatively easy to install in any vehicle; and, a breakdown of the inertial force components is available in the calculation process which provides insight to the make-up of the total force and the phase relationships among the force components. For instance, in the example presented above, the carbody dynamics clearly is the dominating contributor to the high levels of lateral truck forces observed.

Disadvantages of the technique are: mass and inertial properties of vehicle and truck are not always well known; freeplays due to clearances in a truck and axle assembly may not allow the characterization of the mass movements by only a few degrees of freedom; and, some truck components may not permit easy mounting of transducers. In addition to these disadvantages, there are basic limitations on using this technique for estimating wheel forces. First of all, the inertial technique can, at most, provide total axle force measurement; it will not resolve the forces on the left and right wheels. In a three axle truck, the number of variables makes it insufficient to resolve individual axle forces. In a two axle truck, it is possible to resolve individual forces on each axle. However, longitudinal creep forces as well as centerplate friction will introduce uncertainties in the final estimates.

K.4.1.3.3. INSTRUMENTED WHEELSET TECHNIQUES

In the evaluation of rail vehicle dynamic performance the instrumented wheelset is unsurpassed in the measurement of wheel/rail forces. The instrumented wheelset can provide accurate continuous measurements of lateral and vertical wheel/rail forces.* They can measure frequencies up to 100 Hz or more, limited only by the fundamental resonant frequencies of the wheelset.

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*Note: When using instrumented wheelsets, the braking systems must be removed or de-activated to prevent any contact or heating of the wheel which will cause damage to the strain gauges and calibrations.

Because the measurement is made in close proximity to the rail contact point (i.e., the wheelplate), the error introduced by inertial forces beyond the measurement point is negligible.

A number of techniques have been developed over the past decade or more. The more recent techniques all provide for a continuous measurement of both lateral and vertical forces. These wheelsets have been made using standard AAR wheels (e.g., Federal Railroad Administration/ENSCO, Inc., Electro-Motive Division of General Motors (EMD)), "S" shaped wheelplates (e.g. ASEA/Swedish State Railway) and spoked wheels (e.g., British Rail, Japanese National Railways). Non-standard wheels while increasing cost can be effective in reducing errors due to crosstalk and load point sensitivity.

In addition to the strain gauged wheelplates there is also the strain gauged axle or axle bending technique as it is commonly referred to. In most common applications a special narrow pedestal adaptor which serves as a load cell is used to measure the vertical loads. In conjunction with this the bending moment on the axle is used to extract lateral forces. There are three fundamental shortcomings of this system. First, the inertial mass of the wheels are neglected which contribute significantly to the wheel/rail forces. Second, the geometry of the narrow pedestal adaptor is extremely complex making it a load cell with very poor load point sensitivity characteristics. Finally, a wheel position encoder or strobe is required which adds further complexity and hence uncertainty in the system.

For the reasons outlined above the remainder of the discussion of wheel/force measurement will deal exclusively with the strain gauged wheelplate technique as applied to standard AAR wheelplates. Furthermore, for the purposes of illustration use will be made of the current FRA instrumented wheelset technique.

Design Concepts

The characteristics of a particular instrumented wheelset are determined by its loaded strain field and the placement of strain gauge bridges within that field. The design of a bridge pattern for producing lateral force signals and that for vertical force signals are distinctly different. A vertical force creates a relatively local strain field within the wheelplate in an area between the hub and the wheel/rail contact point. A lateral force creates a more distributed strain field affecting a much larger portion of the wheelplate.

To understand the mechanism for the development of the lateral and vertical strain fields for a typical AAR wheel cross-section, it is best to consider the reactions produced at the wheel hub rather than the rail contact point. A lateral load at the wheel/rail contact point produces a shear load along the direction of the axle and a significant bending moment at the hub (See Figure K-4.2). A vertical load applied at the rim produces primarily a vertical shear load at the hub and a relatively small hub moment (See Figure K-4.3). The vertical load creates local compressive stresses in the wheelplate between the contact point and the hub combined with a distributed stress field due to the small hub moment.

An effective vertical bridge must be sensitive to the local vertical effects and at the same time cancel the distributed strain fields due to any laterally induced hub moment and axial force. Conversely, a lateral bridge must sense either the axial hub force or hub moment due to lateral loads and be insensitive to the "local" strains due to vertical loads.

Effective lateral and vertical force measuring bridges have been applied to standard wheel crossections. This design is sensitive to the lateral hub moment in measuring lateral force. The "special" wheel section and spoked wheel techniques are generally designed to sense the axial force due to lateral loading. The advantage in sensing the hub moment is that the system can take advantage of the sinusoidal characteristic of the bridge output to eliminate thermal and centrifugal effects (which are dc biases) by high-pass filtering. By sensing the lateral axial force the "special" wheel techniques can minimize sensitivity to vertical crosstalk. But because of their dc bridge output they require centrifugal and thermal calibration to assure elimination of these effects.

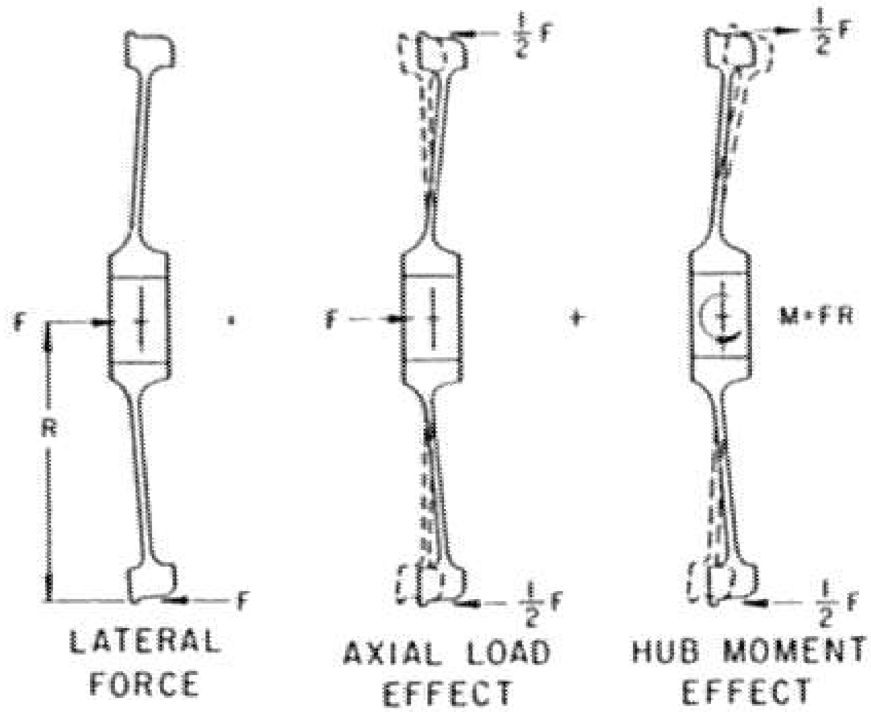


FIGURE K-4.2 LATERAL FORCE STRAIN DISTRIBUTION

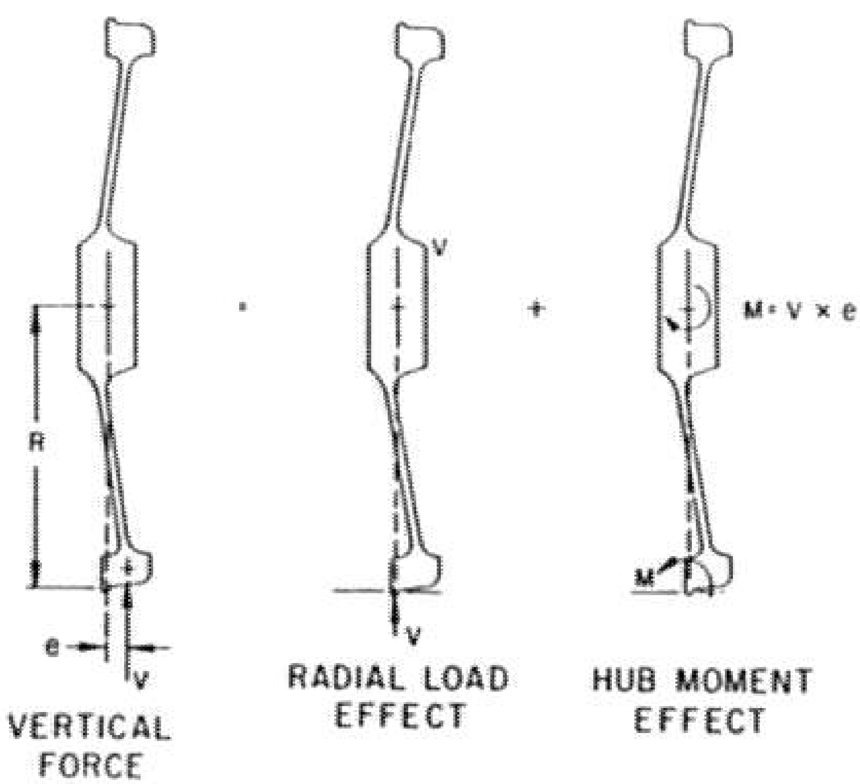


FIGURE K-4.3 VERTICAL FORCE STRAIN DISTRIBUTION

K.4.1.3.4 CURRENT FRA INSTRUMENTED WHEELSET APPROACH

The FRA instrumented wheelsets typify many facets of the state-of-the-art and may be used to illustrate specific design considerations in using wheels as force transducers. The basic objective of the design of force measuring wheels is to obtain adequate primary sensitivity for high signal/noise ratio and high resolution while controlling crosstalk, load point sensitivity, ripple, and the effects of heat, centrifugal force and longitudinal forces. The design philosophy is to choose strain gauge bridge configurations which inherently minimized as many extraneous influences as possible and which are responsive to the general strain patterns expected in any rail wheel subjected to vertical and lateral forces. Such bridge configurations can be adapted to the standard production wheels of the desired test vehicles, eliminating problems of supply, mechanical compatibility, and possible alterations of vehicle behavior due to special wheels. The radial locations of the strain gauges are optimized for each wheel size and shape while their angular locations are fixed by the chosen bridge configurations. Locomotive, passenger coach and freight car wheels having a large variation in tread diameter and wheelplate shape have been instrumented successfully using the same general procedures.

The vertical force measuring bridges follow a concept used by ASEA/Swedish State Railways Ref. [20]. Each bridge consists of eight strain gauges arranged in a Wheatstone bridge having two gauges per leg. Each leg of the bridge has one strain gauge on the field side and one strain gauge on the gauge side of the wheel. The four legs are evenly spaced 90° apart on the wheel as shown in Figure K-4.4. The general strain distribution in a typical rail wheelplate due to a purely vertical load is characterized by maximum strains which are compressive and highly localized in the wheelplate above the point of rail contact. As the pair of gauges in each leg of the bridge consecutively passes over the rail contact point, two negative and two positive peak bridge outputs occur per revolution. By correctly choosing the radial position of the gauges, the bridge output as a function of rotational position of the wheel can be made to resemble a triangular waveform having two cycles per revolution. The purpose of having gauges on both sides of the wheelplate in each leg is to cancel the effect of changes in the bending moments in the wheelplate due to lateral force and the change of axial tread/rail contact point.

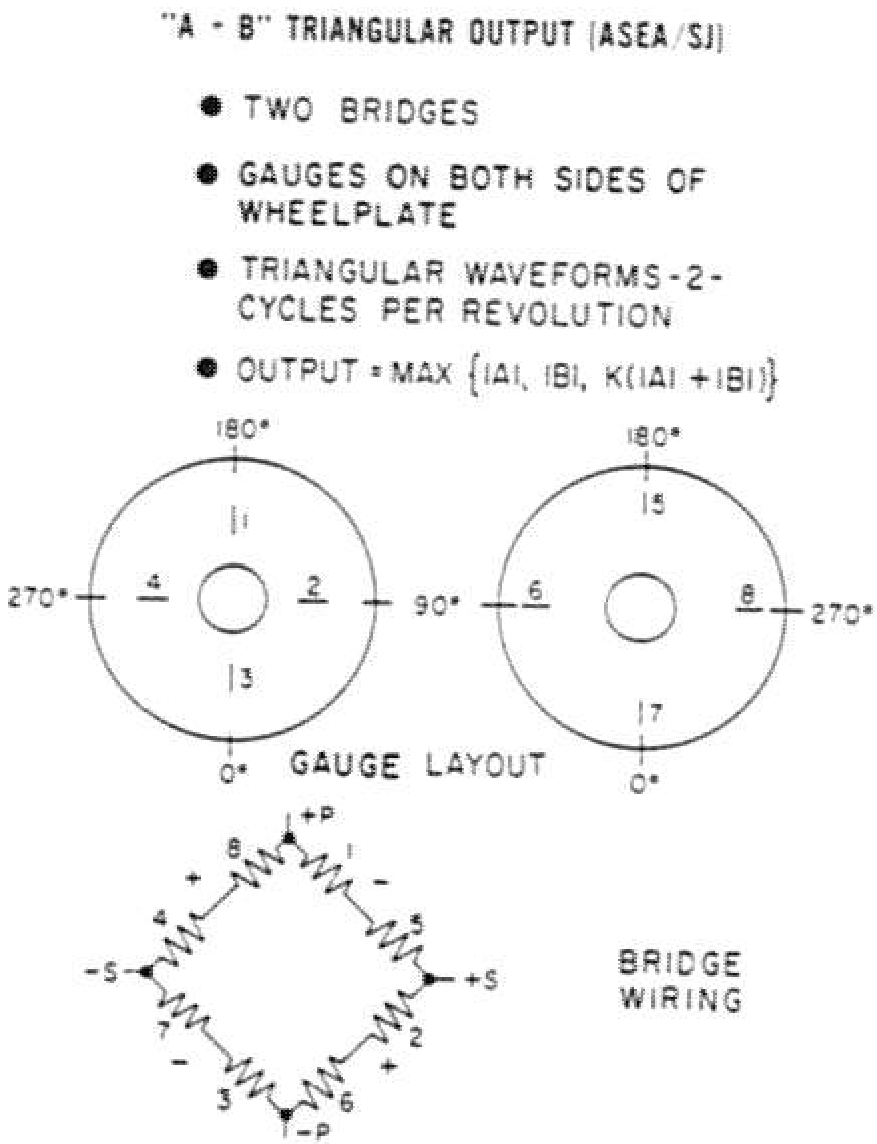


FIGURE K-4.4 VERTICAL FORCE MEASUREMENT BRIDGE

When two triangular waveforms, equal in amplitude and out of phase by one fourth the wavelength, are rectified and added, the sum is a constant equal to the peak amplitude of the individual waveforms. In order to generate a strain signal proportional to vertical force and independent of wheel rotational position, the outputs of two identical vertical bridges out of phase by 45° are rectified and summed as shown in Figure K-4.5. Since the bridge outputs do not have the sharp peaks of true triangular waveforms, the sum of one bridge peak and one bridge null is lower than that of the sum of two ideal triangular waves. In order to reduce the ripple or variation in force channel output with wheel rotation, the bridge sum is scaled down between the dips coinciding with the rounded bridge peaks. By taking as the force channel output the greatest of either individual bridge output or the scaled down sum of both bridges, the scaling down is applied selectively to the part of the force channel output between the dips as shown in Figure K-4.5.

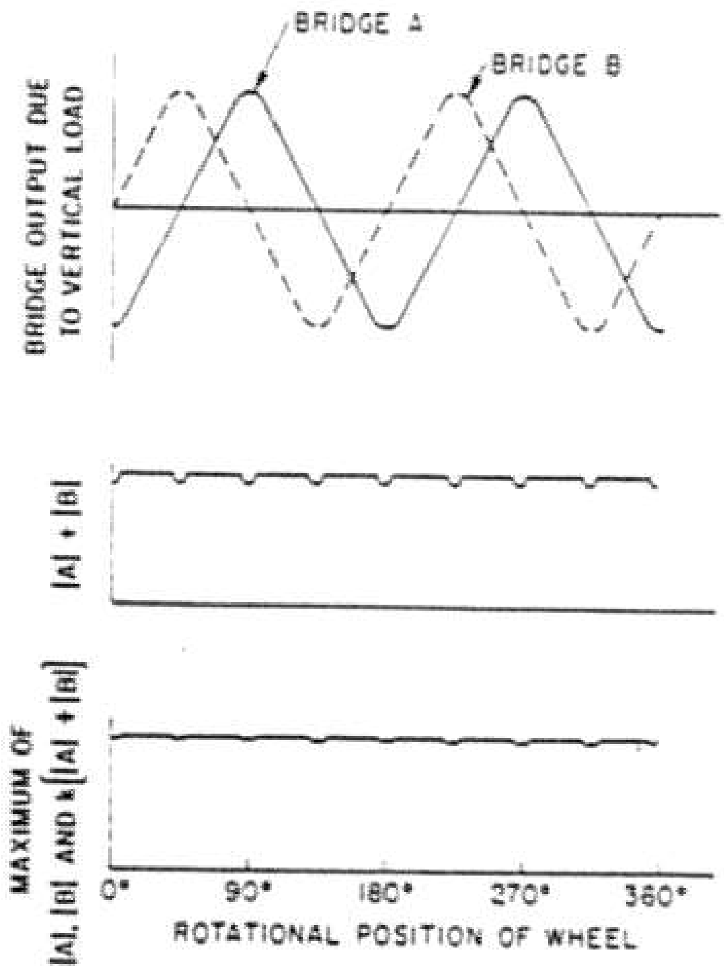


FIGURE K-4.5 TRIANGULAR OUTPUT AND "A + B" PROCESSING

The general strain distribution of a typical rail wheelplate due to a purely lateral flange force is characterized by two components as shown in Figure K-4.2. One component is a function of radius only because the wheelplate acts as a symmetric diaphram in opposing the lateral force at the axle. The second component results from the moment about the hub caused by the flange force and it tends to vary at a given radius with the cosine of the angular distance from the wheel/rail contact point. The strain distributions on the gauge and field sides of the wheelplate are similar in magnitude but opposite in sign.

Lateral force measuring bridges which follow a concept advanced by EMD Ref. [8] take advantage of the general strain distribution in a standard wheelplate. As shown in Figure K-4.6, each bridge is composed of eight gauges evenly spaced around the field side of the wheelplate at the same radius. The first four adjacent gauges are placed in legs of the bridge that cause a positive bridge output for tensile strain and the next four gauges are placed in legs causing a negative bridge output for tensile strain. The resulting bridge cancels out the strain due to the axial load because all eight gauges are at the same radius with four causing negative bridge outputs. However the bridge is sensitive to the sinusoidal strain component associated with the hub moment due to the flange force because the tensile strains and the compressive strains above and below the axle are fully additive in bridge output twice each revolution (once as a positive peak and once as a negative peak). Radial gauge locations may be chosen such that the bridge output varies sinusoidally with one cycle per wheel revolution. Two identical bridges 90° out of phase are used to obtain a force channel output independent of wheel rotational position as a consequence of the trigonometric identity:

$$\sqrt{(L\sin\theta)^2 + (L\sin[\theta + 90^\circ])^2} = L \text{ for any } \theta .$$

However, the bridge outputs are usually not modulated by a pure sinusoid and therefore the computed $|L|$ will contain a ripple of higher harmonics.

The first step in the production of instrumented wheels is the machining of all wheels in a production group to an identical contour. The contour is dictated by the AAR minimum allowable wheelplate thickness and by the production variation of the available sample of wheels. The machining contour is usually close to the original design shape but at the minimum thickness. The thinning of the wheelplate is the easiest step in maximizing sensitivity because it does not involve compromise with the other measurement properties of the wheel.

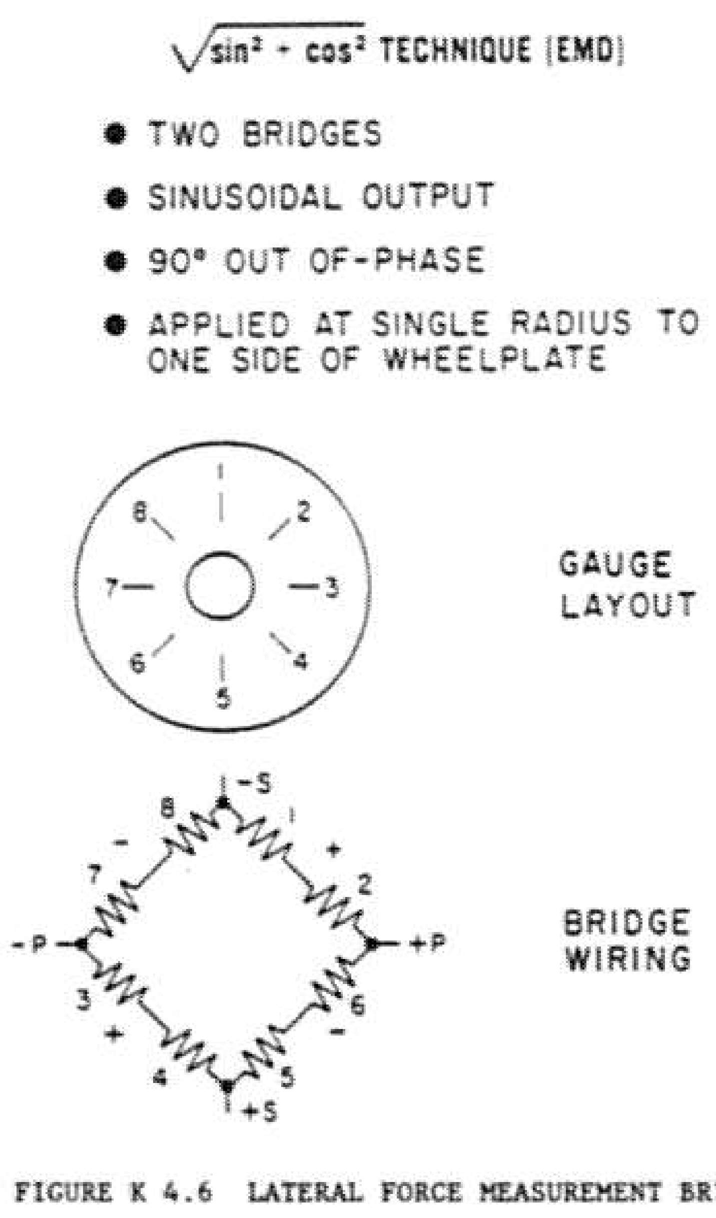


FIGURE K 4.6 LATERAL FORCE MEASUREMENT BRIDGE

In order to precisely select the radial locations of the strain gauges for the best compromise between primary sensitivity, crosstalk, ripple, and sensitivity to axial load point variation, a detailed empirical survey of the strains induced in the given wheelplate by the expected service loads is made. The use of wheels machined to an identical profile makes the empirical approach to wheelset instrumentation practical because the results of the strain survey apply to all wheels in the group. The calibration loads and the reference lateral position of the wheel on the rail should reflect the type of experiment in which the wheels will be used.

For example, wheels destined to measure high speed curving forces should be loaded to about 1-1/2 times the nominal vertical wheel load (to simulate load transfer) with the rail adjacent to the flange to determine the primary vertical sensitivity. Primary lateral sensitivity should be determined from a high lateral load (corresponding to expected L/V ratios) applied with a device which bears against the gauge sides of two wheels on an axle at the tread radius and spreads. Loads applied in this manner create strains of equal magnitude and opposite sign to those produced by the hub moment effect of a flange load but they eliminate the extraneous effect of the vertical load hub moment (treated as crosstalk) from the determination of primary lateral sensitivity. A combined vertical and lateral loading at the expected service L/V ratio level, accomplished by forcing the wheelset laterally against a rail while maintaining a vertical load, is necessary to select strain gauge locations for minimal crosstalk. Vertical loadings at several points across the tread should be taken to evaluate the sensitivity to axial load point.

The strain survey is generally conducted with strain gauges applied at intervals of one inch or less on both field and gauges sides of the wheelplate along two radial lines separated by 180° of wheel arc. The calibration loads are applied every 15° of wheel revolution until the strain along 24 equally spaced radial lines on both gauge and field side has been mapped for each load.

Once the strain field has been completely mapped, the data is stored in the memory of a computer. Conceptually the strain field may be thought of as three-dimensional surface, two spatial dimensions and strain, which resembles a topographical map. By specifying the bridge configuration and gauge location on the wheelplate the computer is then used to simulate bridge outputs which are pseudo-processed to produce the output of one wheel revolution under a given load condition. From this an evaluation of the design parameters is made. By varying bridge locations in a systematic manner a best compromise of the design parameters is found. Once suitable bridge locations are identified, one of each is applied to a machined wheelplate. A calibration is conducted and the output is then compared with the computer simulation. If satisfactory agreement is found the remaining bridges are applied and the wheelsets are prepared for field testing.

K.4.1.3.5 SUMMARY AND COMPARISON OF WHEEL/RAIL FORCE MEASUREMENT TECHNIQUES

The selection of a force measurement system is dependent upon the requirements, the schedule and the budget of a particular test program. In each of the previous sections the capabilities and limitations of the individual force measurement systems have been presented.

The instrumented wheelset provides the best availble measurement of wheel/rail forces. It is the most accurate but is generally the most costly. If an evaluation of wheel/rail wear or wheel climb phenomena is required, only an instrumented wheelset can provide the data. As pointed out earlier, only an instrumented wheelset can measure lateral wheel force. However if track panel shift, for example, is under investigation, only lateral axle force is required. Therefore an instrumented wheelset or journal load cells plus an axle accelerometer can be used. The instrumented wheelset provides improved accuracy but at a higher cost.

Similarly, if rail rollover, which is usually related to truck force, is of concern, then any of the available approaches can be applied. The inertial technique employing a suite of accelerometers may be the best approach for a quick look or a preliminary investigation. Its accuracy may be acceptable to gain insight into a particular vehicle dynamics problem.

Table K-4.3, "Onboard Measurement of Wheel/Rail Loads - Comparison of Techniques," presents a summary of the relative accuracy, cost, lead time and limitations of each of the techniques discussed. The researcher may choose between accelerometers, journal load cells, standard instrumentated wheelsets or special instrumented wheelsets to measure rail vehicle forces.

TABLE K-4.3 ONBOARD MEASUREMENT OF WHEEL/RAIL LOADS COMPARISON OF TECHNIQUES

APPROACH	MEASUREMENTS REQUIRED	OVERALL ERROR	COST	LEAD TIME	REMARKS
JOURNAL LOAD CELL	VERTICAL FORCE - BOTH BEARINGS LATERAL FORCE - OPPOSITE BEARING	10 - 30%	LOW TO MODERATE ($5K - $20K)	SHORT - MODERATE (1 - 3 MOS)	- GOOD FOR QUICK LOOK LOW COST - NET AXLE LATERAL FORCE - AXLE INERTIAL FORCES ARE LIMITED - FREQUENCY RESPONSE IS LIMITED (< 10 - 20 Hz) BY AXLE INERTIA (NOT GOOD FOR IMPACTS)
INERTIAL (ACCELERATION)	LATERAL ACCELERATION - CAR BODY - TRUCK FRAME - AXLES	10 - 20%	LOW TO MODERATE ($5K - $20K)	SHORT - MODERATE (1 - 3 MOS)	- GOOD FOR NET TRUCK LATERAL FORCE - FREQUENCY RESPONSE IS LIMITED (< 10 Hz)
INSTRUMENTED WHEELSET (STANDARD)	VERTICAL FORCE - 2 BRIDGES PER WHEEL LATERAL FORCE - 2 BRIDGES PER WHEEL LONGITUDINAL FORCE - AXLE TORQUE ONE TO TWO BRIDGES PER WHEEL	~5%	MODERATE ($30K - $60K)	MODERATE (3 MOS)	- USES STANDARD AAR WHEEL PROFILE - MODERATE COST AND LEAD TIME - NO THERMAL OR CENTRIFUGAL EFFECTS - SMALL LOAD POINT SENSITIVITY
INSTRUMENTED WHEELSET (SPOKED)	VERTICAL FORCE LATERAL FORCE LONGITUDINAL FORCE	LESS THAN 5%	HIGH ?	LONG ?	- THERMAL CALIBRATION - IMPROVED ACCURACY

K.4.1.4 DATA TRANSMISSION

One of the fundamental design problems of most wheel/rail force measurement systems is the transmission of signals from a rotating frame of reference to a stationary platform. This is further complicated by the severe environment in which the transmission must take place. The rotating system, the wheelset, is unsprung and experiences the extreme dynamic inputs from the track with vibration levels as high as 50 g's and shocks of the order of several hundred g's. Furthermore, this environment is contaminated with many forms of debris including grease, dust, water, gravel and other objects with relatively large kinetic energy content.

In spite of this it is possible to accomplish the transmission using off-the-shelf hardware. Over the past several years of rail research different techniques and combinations of techniques have been used with varying degrees of success. These include optical encoders, FM transmitters, and amplification within the rotating system. To date the most effective means of transmitting across the rotating interface has been accomplished through the use of high quality slip rings.

Slip rings offer a number of advantages. They are rugged, reliable and are capable of transmitting low level signals of the order of 10 millivolts with a background noise of less than 200 microvolts. This is a signal to noise ratio of 50 which is more than adequate. Slip rings are very simple mechanical devices and require little or no maintenance or troubleshooting once they are installed and checked out. The worst problem encountered in the use of these devices is broken solder joints which are easily traced and corrected. Perhaps the greatest disadvantage of a slip ring is its finite life. Depending on the application a slip ring will provide excellent transmission quality for 2000 miles of operation (including non-test movements) and usually acceptable quality for 5000 miles. Fortunately, they may be easily replaced at a moderate cost (~$800 each) or refurbished for less (~$300 each).

Based on these facts, the slip ring is the current best choice of transmission device for wheel/rail force measurement systems. There may, however, arise circumstances that may dictate the use of an alternative technique. This must be evaluated on a case by case basis.

K.4.1.5 INSTRUMENTED WHEELSET SIGNAL PROCESSOR

As has been pointed out in previous sections, signals coming directly from the instrumented wheelset, either wheelplate or axle, are not immediately proportional to a wheel/rail force. It is necessary to combine in some prescribed manner two of the direct or raw signals to obtain a signal which is directly proportional to force.

Given today's state-of-the-art in electronics technology, it is a straightforward matter to perform the wheelset signal processing in real-time; i.e., as the raw signals are received. In fact, current wheelset processors actually perform several functions including scaling and some conditioning of the signals. Basically the wheelset processor provides the following features:

- o high-pass filtering of incoming raw signals to eliminate centrifugal and thermal effects
- o scale signal
- o perform processing algorithms including squaring, adding, taking square root, subtracting, and perform logical function of selecting largest value
- o calculate L/V for individual axles and for complete truck.

Figure K-4.7 shows the basic data flow through a wheel processor. Strain is sensed by the Wheatstone bridges on the wheelplate (or axle) generating signals S. The S signals are transmitted through the slip ring and are first scaled, G, and high passed filtered. The scaled lateral signals, L, are then squared and summed. The square root of the sum represents the raw or uncorrected lateral force. The scaled vertical signals are passed through a circuit yielding the corresponding absolute values which are summed and scaled to compensate for ripple as explained in Section K.4.1.2). The maximum of either of the individual bridge outputs or the scaled sum is then output as the raw or uncorrected vertical force. The raw forces are subsequently corrected for crosstalk and output along with the ratio of lateral to vertical force, L/V.

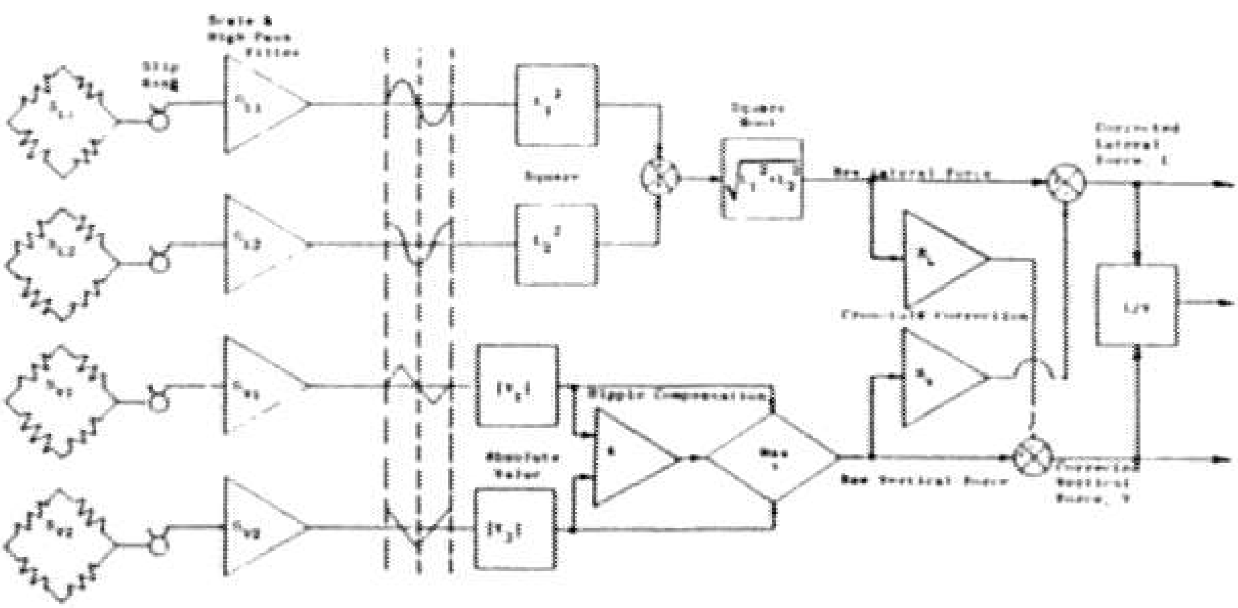


FIGURE K-4.7 WHEELSET PROCESSOR

The wheelset processor may be either analog or digital. Under normal circumstances the signal conditioning, scaling and high pass filtering is always analog. That part of the signal processing downstream of the wave forms shown in Figure K-4.7, however, may be implemented using either analog circuits or in software on a digital computer. In the latter case anti-alias filters are required immediately following the signal conditioning. The choice of type of wheelset processor will depend on a number of items such as the number of instrumented wheelsets to be processed, the availability of a digital computer capable of meeting the real-time processing requirements, personnel resources and time constraints. Both methods of processing are comparable in terms of accuracy and frequency response (>100 Hz or better). The advantage of an analog processor is that it is stand alone and may become simply a component of the instrumented wheelset. This makes the display and/or recording of the wheel/rail force measurement much more flexible since the expense of a digital computer is not necessary. A digital processor offers the advantage of handling more than one wheelset and performing other tasks, such as statistically summarizing data in real-time, depending on the capacity and speed of the computer. The digital processor also provides insurance in terms of repeatability checks and uniformity of processing. If correction of ripple or other sources of error in higher harmonics are needed or if non-linear corrections are necessary, a digital processor can perform these function's much more easily. In either case the ability to view in real-time the wheel/rail forces being measured is invaluable in conducting field experiments and monitoring parameters such as L/V for safe operations.

K.4.2 DISPLACEMENT MEASUREMENT TECHNIQUES AND TRANSDUCERS

Understanding of rail vehicle behavior often requires a precise knowledge of its kinematic behavior, in particular the relative displacements. In general, this may be broken down into three categories. The first is intra-vehicular; that is, the relative displacements between the discrete components of a vehicle. The second is the displacement between the vehicle and the rail. In this case the displacements of interest are in only two of the three orthogonal directions. These are the vertical and lateral directions. Longitudinal displacement or location along the track is dealt with in Section K.6. A third category of displacement measurements is intervehicular. This includes such things as coupler angle and distance between cars.

K4.2.1 DISPLACEMENT TRANSDUCER SPECIFICATION

Based on the requirements set forth in the preceeding paragraph, Table K.4.4 summarizes the basic parameter specification for the selection of displacement transducers. Note that such parameters as linearity and cross axis sensitivity are not included here. Parameters such as these are more dependent on the specific application. Those specifications given in Table K-4.4, however, are a necessary set of conditions which must be met by a transducer to provide a basis for one of the three types of measurement.

The first three columns of Table K-4.4 are based on measurement requirements. The fourth column specifies the vibration environment which the transducer must be able to survive. The acceleration levels given are somewhat conservation and may be mitigated by detailed knowledge of the actual environment to be encountered. This is also the technique of mechanical isolation or shock mounting which can enable a precision transducer to operate in an environment normally beyond its intended range. For example, 5 g servo-accelerometers have been operated for nearly one thousand miles on the narrow pedestal adaptor of a freight truck with complete success.

Returning attention to the first three columns of Table K-4.4, it is seen that the range and resolution requirements are not overly demanding. Typically the dynamic range (ratio of resolution to range) is 60 dB or 1%. Similarly the frequency response requirements are relatively low. This is a result of the large inertia of most rail vehicles and their components. The relatively high specification of frequency response of intravehicular measurements is related to elastic deformations which are of limited interest. Thus, for the majority of displacement measurement applications a frequency response of 10 Hz is adequate. At the other end of the spectrum almost all rail vehicle measurement requires the ability to measure static displacements.

Fortunately, there are currently available a number of transducers which meet the specifications. These are discussed in the next section.

TABLE K-4.4 DISPLACEMENT TRANSDUCER SPECIFICATIONS

Requirement	Range (±)	Resolution	Frequency Response (DC to)	Dynamic Environment
Intra-vehicular	.1-10in.	.01-.1	10-30Hz	5-10g
Inter-vehicular	10-30in.	.1-.25	2-5Hz	5-10g
Vehicle Rail	1-2in.	01-.1	5-10Hz	10-50g

TABLE K-4.5 A COMPARISON OF DISPLACEMENT TRANSDUCER CHARACTERISTICS

TRANSDUCER TYPE	RANGE	RESOLUTION	ACCURACY	COMMENTS
Potentiometric	2-20 in.	0.01 in.	3%	Easy to Field-Deploy
Linear Variat'l Differential Transformer	.25-15 in.	Infinite	1%	
Electromagnetic Eddy Current	2-5 in.	0.01-0.1 in.	3-5%	
Strain Gauge	.1-1 in.	0.001-0.01	1%	Generally Small Used for Component Deflection
Accelerometer	N/A	Dependent on Processing	Dependent on Processing	Inertial Applications only No Static Capability
Gyroscope	10°	0.01°	1-3%	Direct Angular Measurement

K.4.4.2 DISPLACEMENT TRANSDUCERS

The discussion of displacement transducers will be conducted on a generic basis. Table K-4.5 summarizes the characteristics of the principal types of displacement measuring devices.

K.4.2.2.1 POTENTIOMETRIC

Potentiometric displacement transducers are a simple rugged and inexpensive device and as a consequence are the most widely used type of displacement transducer in rail vehicle research. The measurement component of this transducer is a rotary potentiometer of high linearity and good resolution. A drum-like pulley attached to the potentiometer shaft serves to convert the rotary input of the potentiometer to a linear displacement.

Given a potentiometer of ten rotations full scale, the linear range becomes ten times the circumference of the pully. Infinite resolution is possible, 0.5% linearity is common and ranges from one inch to 30 inches are readily available, with a 1% accuracy. Signal conditioning requirements are minimal for this type of device and a useful frequency response can be realized up to 20 Hz.

K.4.2.2.2. LINEAR VARIABLE DIFFERENTIAL TRANSFORMER

The Linear Variable Differential Transformer (LVDT) is more complicated and more expensive than the potentiometric type of transducer. The LVDT, however, is particularly well suited to the measurement of displacements of small magnitudes (Table K-4.5). Signal conditioning requirements are more demanding than for the potentiometric device; however, the LVDT measures displacements which are an order of magnitude smaller than the potentiometric transducer.

Development of the LVDT has produced a variety of designs that are rugged, highly accurate, linear and compact. The principal of operation is based upon changes of mutual inductance between a single transformer primary and two symetrically opposed secondaries. Changes of mutual inductance are initiated by the linear motion of an axial metal slug that penetrates the transformer axis. Displacement of the metal slug along the transformer axis produces predictable outputs for the LVDT.

K.4.2.2.3 ELECTROMAGNETIC/EDDY CURRENT DEVICES

Displacement between an electrically conducting surface and an eddy current transducer may be measured accurately. There is a strong dependency on the target geometry however. The ideal geometry is an infinite plane target at no more than one sensor diameter from the measurement transducer. This ideal situation seldom exists in the rail test environment.

There are presently available eddy current displacement devices that perform well in the single plane measurement situation. Measurements from 0.1 to 4 inches are easily made with 1% linearity. The target device may be in rotational motion during measurement as the eddy current transducer is never in physical contact with the target.

Many variations of the eddy current transducer have been fabricated for the purpose of performing rail test measurements. Linearity is normally a problem that is contended with by assigning a polynomial description of the transducer calibration to each individual device.

Isolation of the transducer in terms of the influence of factors that compromise the prime measurement is a difficult problem to solve. Any metal surface that moves in proximity to the eddy current transducer, whether this movement represents the intended measurement or not, does modulate the sensor output.

The lateral position of a rail wheel relative to the railhead including flange contact and wheel angle of attack, are measured with considerable difficulty. The basis of these measurements demands the ability to measure the magnitude of the dimensions from the gauge side of the railhead to the outside of the wheel flange, both in front of and behind the rail wheel. Furthermore, this measurement should be made as close to the wheel footprint as possible.

Electromagnetic eddy current displacement transducers have been used successfully as the wheel-rail lateral displacement device. Calibration of this type of device requires meticulous attention and the description of device linearity represents a further degree of difficulty during data processing.

The physical position of this type of transducer is necessarily a few inches above the railhead and transducer destruction occurs frequently.

K.4.2.2.4 STRAIN GAUGE TRANSDUCERS

Strain gauge technology is extremely well developed and transducers based on the technology are available for a wide variety of applications. Displacement transducers using strain gauges are based on the physical deformation of a surface and these measurements may represent the bending, tension or compression modes.

The small physical size of the strain gauge allows measurement access in situations that often preclude the use of other devices. Measurements of displacement may be performed by vendor-produced components. The alternative to this method involves the option of custom-designed transducers using individual strain gauges. Here, the limitations are represented only in terms of the designer's ingenuity.

The frequency response of strain gauge systems extend into the kHz region. Strain gauge signals are very small, generally in the microvolt range. The total strain gauge system performs well as a result of highly developed signal conditioning apparatus that produces stable, noise free, high level signals from low microstrain inputs.

K.4.2.2.5 ACCELEROMETERS FOR DISPLACMENT MEASUREMENTS

Theoretically displacement may be derived from measurement of acceleration by a procedure involving a double integration. In practice, however, this is a rather difficult task because any small error in the measured acceleration will rapidly grow as an accumulated error. For example, alignment deviations due to motion in the directions normal to that in which the measurement of displacement is desired result in small accelerations which when integrated introduce low frequency drift.

Special applications, however, may arise which require an absolute or inertial reference frame and for which only the dynamic component of displacement is desired. Such a situation may come about for example when investigating a performance issue such as hunting. Generally speaking, however, the attendant complications of the use of accelerometers as displacement measuring devices discourages their use when reasonable alternative methods are available.

K.4.2.2.6 GYROSCOPE

The gyroscope stands alone as the transducer for the measurement of absolute angular displacement. Gyroscopes are somewhat expensive but highly developed and readily available. Furthermore, when quantifying the carbody roll angle of a rail vehicle during the negotiation of a rock and roll (consecutive low joints on tangent track) the gyroscope is absolutely essential.

There are two types of gyroscopes. An absolute gyroscope is capable of measuring angular displacement with respect to two axes up to 15^{o} about each. Rate gyroscopes may also be used; however, because this type of transducer measures the rate of change of angular orientation, absolute angles must be obtained through processing. Processing of rate gyroscope output is similar to the processing of acceleration data for displacement in that integration is involved. In this instance only single integration is required but the same fundamental problem of drift over the long term is present.

K.4.3 ACCELEROMETERS

The primary transducer used to quantify rail vehicle dynamic behavior is the accelerometer. Measurement of acceleration provides an accurate picture of the dynamic response of a rail vehicle through the use of an inertial reference frame which for most purposes is a fixed frame of reference. Also a convenient unit of measure is available which normalizes measurements of acceleration on the earth's surface. The unit referred to is the gravity, denoted g, which is nominally 32.2 ft/sec^2 (9.81m/sec^2). Thus, when a lateral acceleration at a given location is said to be 0.25 g, it is intuitive that a lateral force equal to one fourth of a component's weight was generated.

Accelerometers are required at all mass levels of a rail vehicle from the sprung mass, the carbody and side frames, to the unsprung mass, the wheelset and journal bearings. Although accelerations on the sprung mass are generally less than those on the unsprung mass, several g's of acceleration may be experienced on both the carbody and truck at the higher frequencies (>100 Hz).

Saturation of the accelerometers at high frequencies can be avoided by the use of shock mounts or mechanical isolators.

A mechanical isolator serves to pass with unity gain those inputs below approximately 100 Hz while attenuating those above 150 Hz. Use of this arrangement has shown that typically truck accelerations are less than 10 g and in most cases 5 g and carbody acceleration less than 2 g and in most cases 1 g. An added advantage of such an isolator is extended life of the transducer due to a reduction in vibratory energy absorbed by the transducer itself.

K.4.3.1 ACCELEROMETER SPECIFICATION

The specification of an accelerometer for use as a means of measuring the dynamic response of a rail vehicle will depend to a rather large extent on whether the acceleration is to be measured on a sprung (typically the carbody and truck bolster) or an unsprung (typically the truck sideforms and wheelset) mass. The acceleration environment of the carbody is fundamentally different from that of the truck. Carbody accelerations are generally less than 1 g and characterized as low frequency. Truck accelerations are considerably higher on the order of 50 g in some instances with significant spectral content out to 100 Hz.

Table K-4.6 summarizes a set of nominal specifications for the measurement of acceleration on both sprung and unsprung masses.

TABLE K-4.6. NOMINAL ACCELEROMETER SPECIFICATIONS

Mass Level	Range	Resolution	Frequency Response	Linearity
Sprung (Carbody and truck bolster)	± 2 g	.01 - .005 g	To 30 Hz	.1 - .5%
Unsprung (Truck sideframes and wheelsets)	±50 g	.1 g	To 100 Hz	.1 - 1%

The specifications given in Table K-4.6 are somewhat conservative and could be difficult to meet from a practical standpoint. For example, a transducer capable of measuring 50 g with 0.1 g resolution requires a dynamic range of 54 dB. Although such transducers exist they are not capable of measuring very low (static) accelerations. If, however, the signal of interest is lower than the environment frequency to be encountered the use of the mechanical isolator discussed earlier may reconcile the hardware and requirements. An example of this arises when hunting is the performance issue under investigation. That is, hunting is known to be a low frequency (~3 Hz) phenomenon with associated levels of acceleration of less than 10 g. By using the mechanical isolator with the proper characteristics a 10 g accelerometer may be employed with a dynamic range of 40 dB.

K.4.3.2 ACCELEROMETERS

Various types of accelerometers are currently available on a commercial basis. Each type of accelerometer is based on a principle of operation which gives the accelerometer certain characteristics. Thus, depending on the intended application, a given generic type of accelerometer may offer some advantage over the other types available.

In this section the four primary types of accelerometers which have been found to perform acceptably in the rail environment are discussed. Although the list of currently available accelerometers is far more extensive the majority are special purpose, such as seismic exploration, and as such are not suited to rail research application. Table K-4.7 provides a brief summary of the characteristics of the accelerometers to be discussed. This table contains ranges or typical values for each type of transducer and not specific values. Furthermore, it should be kept in mind that power supplies and signal conditioning will decrease the accuracy and resolutions given.

TABLE K-4.7 A COMPARISON OF TYPICAL ACCELEROMETER CHARACTERISTICS

	Ranges	Resolution	Temperature	Frequency	Linearity	Transverse Axis	Noise	Comments
Servo	±5 to ±100 g	.002 g	32° to 250°F	0 to 200 Hz	±0.02 %	.003 g/g	1 mVrms	must be shock protected
Piezo-elec-tric	±1 to ±10^5 g	as low as 0.01 g	-100° to 250°F	1 to 50 kHz	±1% 0(H)	5%	0.2 mVp/p	no d.c. response
Capaci-tive	±1 to ±10^4 g	Infinite	±.02% fs/°F 0 to 150°F	0 to 10 kHz	±1% ±0.1%(H)	0.01 g/g	2 mVrms	must be balanced
Strain Gauge	±.01 to ±10^3 g	Infinite	±.01% fs/°F -65 to 250°F	0 to 1 kHz	±1% ±1%(H)	.02 g/g	Unknown	must be balanced

(H) Hysteresis fs Full scale P/P Peak to Peak

K.4.3.2.1 SERVO-ACCELEROMETERS

Servo or closed-loop type accelerometers offer accuracy, stability and reliability several orders of magnitude greater than open loop types. Basically, this type of accelerometer operates on a force balance principle.

Acceleration acting on a small mass or a rotor with a small eccentricity within the accelerometer creates force and a resultant motion. The mass is suspended in a magnetic field such that motion within the field creates an electrical signal.

When this signal is properly amplified and supplied to a force or a torque generator acting on the mass, an equilibrium is produced which restores or maintains the mass' position in the field. The current used to position the mass is proportional to the acceleration being experienced. By permitting this current to pass through a stable resistor, a voltage porportional to acceleration is developed.

The advantage of this type of accelerometer is that the two main sources of inaccuracy in the open-loop accelerometer, the non-linear mechanical spring and displacement to voltage convertor, are eliminated. The primary disadvantage of this sytem is its relative vulnerability to impulsive shocks which create an over-range situation that the torque generator cannot handle.

There are two types of servo-acceleromters, the pendulous with a pivot mount and non-pendulous with a flexure mount. The flexure types tend to perform better in a shock environment such as the rail environment since the flexures do not degrade with only moderate over-ranging. In contrast the pendulous types use a pivot, generally a jewelled pivot, which tends to degrade with even minor over-ranging.

Other advantages of the servo accelerometer are its long term stability, a high level output typically greater than 1 volt per g and its low frequency response down to d.c. The frequency response is limited typically to 200 Hz which is acceptable for almost all rail research applications.

K.4.3.2.2 PIEZOELECTRIC ACCELEROMETERS

Accelerometers which make use of either crystals or ceramic materials which exhibit piezoelectric effects are very useful in certain aspects of rail research. Very simply, this type of accelerometers uses a material which when compressed generates an electric charge much like static electricity. Thus, by placing a seismic mass over a piezoelectric crystal, an acceleration of this mass will compress the crystal creating a charge proportional to the acceleration. A charge amplifier then converts the charge into an electric signal proportional to the acceleration.

Until recently it was the conversion of the charge to the electrical signal which was the major draw back of this type of transducer. This was because the charge amplifier was physically remote to the crystal requiring the charge to be transmitted over cables which have relatively large capacitive effects due to such simple things as bending. Presently however, piezoelectric transducers employ field effect transitors (FET) located in the transducer immediately adjacent to the crystal which converts the signal to an electrical potential.

The piezoelectric has two primary advantages. First it is virtually indestructible. It contains no moving parts and can withstand severe over-ranging with only minimal time for discharge of the excess charge build up. Secondly piezoelectric accelerometers have the highest response capability of any type of accelerometer, in some cases as high as 100 kHz. This, however, has limited value in rail research applications.

The piezoelectric accelerometer has two major draw backs. First, it does not have the ability to measure steady state or constant acceleration. It is by nature a.c. coupled or a high pass filter. Piezoelectrics have been developed which can measure accelerations as low as 0.1 Hz (10 second duration) which is often sufficiently low for rail research applications. Perhaps the largest problem with the piezoelectric transducer is its transverse axis sensitivity. As shown in Table K-4.7, piezoelectric transverse sensitivity is two orders of magnitude above any other type of transducer. Care must be exercised in the use of this type of accelerometer in environments where accelerations in mutually orthogonal directions are of equal magnitude.

K.4.3.2.3 CAPACITIVE ACCELEROMETERS

The capacitive accelerometer offers a reasonable compromise between the servo and piezoelectric accelerometer in terms of range, accuracy and ruggedness. The capacitive accelerometer consists of a one piece thin stiff metal disc and flexures assembled between two fixed insulated metal electrodes. The disc in this type of transducer serves as the seismic mass whose motion is proportional to the magnitude of the acceleration vector perpendicular to the electrodes. Because the capacitance between the central disc and either electrode is a direct function of the distance between them, an electrical signal is produced which is proportional to acceleration.

The advantage of the capacitive accelerometer is its improved survivability over the servo-accelerometer type along with wider range of freuqency response. At the same time the capacitive accelerometer has the static measurement capability that the piezoelectric accelerometers do not have and also has much better transverse axis sensitivity characteristics.

Associated with capacitive accelerometers are certain disadvantages. First, the transducer is placed in a circuit which must be balanced under specified conditions. Furthermore, unbalancing can lead to drift in the measured signal as the power supply or other components of the circuit unbalance the transducer. Second, because of its open-loop characteristics, its linearity and hysteresis characteristics can be a limiting factor.

K.4.3.2.4 STRAIN GAUGE ACCELEROMETERS

Another type of transducer which is both rugged and reasonably accurate is the strain gauge accelerometer. The principle of operation is similar to other accelerometers in that a seismic mass is involved. The force or actually deflection created by the acceleration vector is sensed using a strain gauge.

Strain gauge accelerometers have the advantage of no moving parts and accuracy of the order of 1 percent. Additionally, the strain gauge accelerometer offers near infinite resolution and excellent frequency response, both at high frequency and down to DC.

Disadvantages with this type of accelerometer are encountered in powering and balancing the circuit similar to the difficulties with the capacitive accelerometers. A second difficulty lies in the relatively low level signal generated per unit acceleration. This puts increased emphasis on stable amplifiers.

K.4.4 TRACK GEOMETRY MEASUREMENT

K.4.4.1 APPLICATION TO PERFORMANCE ISSUES

In order to properly evaluate the previously defined performance issues such as curving response, steady state curving, spiral negotiation and dynamic curving, inputs from the track should be analyzed. These inputs, due to design characteristics as well as perturbations in track geometry, must be accurately measured. The measurement of track geometry can be performed using several different methods. These methods can be grouped as follows: manual measurements including the use of land surveying techniques; automated measurement using track geometry measurement vehicles; highly specialized equipment such as the Track Geometry Device (TGSD); and improvising by using the special test vehicle. Each of these methods has certain advantages and disadvantages which will be examined in this section.

K.4.4.2 <u>AUTOMATED MEASUREMENT VEHICLES</u>

Automated measurement vehicles come in a variety of sizes and capabilities and provide the results rapidly when track geometry measurements are required. They range from the hi-rail vehicles similar to that developed under TSC sponsorship, through the mid-sized vehicles such as the Plasser EM-80/110 and the Matissa 422 to the full-sized heavy vehicle like T1/T3, T2/T4, T-6 and T-10 produced by ENSCO for the FRA and similar full-sized vehicles developed by several railroads. These vehicles are similar in that each has automated data collection and processing capability. However, measurement capability, speed, system configuration and reporting capability will vary according to the vehicle.

Latest design of the FRA full-sized heavy vehicles such as T-6 and T-10 use inertial and noncontact proximity sensors to provide fully loaded measurements of gauge, crosslevel, warp, curvature, profile and alignment of each rail. In addition, support signals such as speed, distance and location are also generated.

The gauge and crosslevel signals are point measurements and can be measured down to zero mph. The gauge system uses noncontact proximity sensors with a servo feedback system, and the crosslevel system uses a Compensated Acceleration System (CAS) as a measurement technique. Warp is computed from crosslevel as the difference in crosslevel over some specified distance, typically 31 or 62 feet and is provided down to zero mph. Curvature is measured using an inertial technique which gives the rate of turn per 100 feet, and can be measured down to 3 mph. Profile on T-6 is computed using two methods. The first is an inertial measurement which is used above 15 mph; the second method is a four point chord measurement which can be used from zero mph up to 50 mph. Both methods display the data as the mid-chord offset (MCO) from a 62' chord. Profile on T-10 uses only the inertial method, can operate down to 4 mph, and is displayed as the MCO of a 62 foot chord. The alignment system on both T-6 and T-10 uses an inertial method and is displayed as the MCO of a 62' chord. The low speed cutoff for alignment on T-6 is 25 mph, and on T-10 it is 15 mph. T-6 has a maximum operating speed of 100 mph while the maximum operating speed of T-10 is 85 mph. Both cars are limited by real-time data processing speed.

The data collection and processing systems on T-6 and T-10 are centered around high performance minicomputers in which the algorithms used to calculate the track geometry parameters are implemented. The standard output from these cars is analog strip chart recordings of all the processed track geometry parameters, an on-line digital exception report listing all the data exceptions sensor data, support signals, and location information.

The sensors are mounted in close proximity to the measurement axles which have a loading of approximately 20 tons each. This loading ensures a track geometry measurement made under dynamic load.

The mid-sized measurement vehicles provide gauge, crosslevel, twist or warp, profile and alignment of each rail. Contact wheel type sensors are used to provide gauge, profile, twist and alignment. Crosslevel is measured using either a gyroscopic pendulum or a compensated accelerometer system depending on the manufacturer. Gauge and crosslevel are measured and presented as point measurements. Profile and alignment are measured as three point chords and presented as the MCO from a pre-selected chord. The typical measured profile chord is 10 meters and the typical alignment measured chord is 8.6 or 10 meters depending on the manufacturer. The selected chords used for profile and alignment may vary, but each has the capability of calulating a 62' chord for processing purposes. Warp is generally measured at a fixed base using two adjacent axles; however, an option is offered to compute warp at other base lengths from the crosslevel signal. Warp can be presented as any of several base lengths depending on the manufacturer and user selected option.

Each of these measurement vehicles has an analyzer which is typically a minicomputer. The signal processing is accomplished mainly in the analog domain but with a trend toward more digital capability with more recent designs. The typical output from these systems include a strip chart recording, a digital report (their formats vary depending on the manufacturer) and a digital data tape. Analog magnetic tape recording capabilities are generally offered as an option. The measurement speed of these vehicles is zero to either 60 or 80 mph, depending on the manufacturer. The three measurement axles used for sensor locations have different loadings. The running axles carry a load of approximately 10 tons while the measurement axles carry loads of one ton or less again, depending on the manufacturer. This variance in the axle loading may, depending on the track conditions, cause a small difference in the computed parameter. This condition is generally acceptable but not ideal.

The smaller, more lightweight automated measurement cars are called hi-rail vehicles. These highway vehicles are modified to incorporate a limited capability of operating on railroad track. These hi-rail vehicles operate at reduced speeds with the maximum being 25-30 mph and come in a variety of sizes and weight. Some vehicles in this group are offered by Plasser (EM-25) and Dapco (TEC-100). These hi-rail vehicles use a mechanical wheel type contact sensor for gauge, a compensated accelerometer system (CAS) for crosslevel and a three point contact system (EM-25) or a four point contact system (TEC-100) for profile and alignement. Warp is computed from crosslevel in both systems. In addition, the TEC-100 offers curvature which is a parameter derived from alignment. The gauge and crosslevel measurements are presented as point measurements. The twist or warp signal is presented at a fixed base preselected by the user. The profile and alignment signals are presented as the midchord off-set from one of a preselected set of chords which include the 62 foot chord.

These systems are centered around a minicomputer which provides the data collection and processing functions as well as the reporting function. The typical output from these systems is a strip chart recording of all the processed data, a digital exception report and a digital tape containing the raw sensor data. Also included on the tape are the support signals such as speed and distance and relevant location and identification information.

K.4.4.3 TRACK GEOMETRY SURVEY DEVICE

The FRA Track Geometry Survey Device (TGSD) is a low speed, manually operated, very accurate device presently housed at the Transportation Test Center (TTC) in Pueblo, CO.

The TGSD measures gauge and crosslevel directly and the (x, y) coordinates of profile and alignment. The gauge system uses mechanical contact sensors to provide the gauge measurement. The crosslevel system uses a pendulum to produce the basic crosslevel signal and is the only signal monitored during normal operation.

The profile and alignment (x, y) coordinates are generated from signals derived from a photo-detector which locks on to a laser beam sent from a separate track unit at a distance up to 225 feet. These (x, y) coordinate values are recorded along with the gauge, crosslevel, and other survey information on a digital tape which is the only system output. There is no on-line processing capability with this unit. The data tape is then sent to a computer facility for off-line processing. The computer and software system is currently maintained by ENSCO. The TGSD can only be operated at night and needs and experienced crew during normal operation.

K.4.4.4 DATA ACQUISITION VEHICLE

A fourth means of obtaining track geometry measurements is to process selected signals by instrumentation on the data acquisition test vehicle. This approch has the obvious advantage of supplying the precise track geometry which induced the vehicle response. That is, it is well known that track geometry can and will change to varying extents with time and use. This approach would measure track geometry in parallel with the vehicle's response circumventing this problem.

In order to measure track geometry using signals coming from the test vehicle, a mid-level minicomputer system or maximum capability microcomputer is required including the software and all algorithms. Special sensors and analog processing is also a necessity. Today's track geometry measurements are complex and require interactive correction terms in addition to a great deal of special processing. For these reasons a track geometry system would have to be in addition to the existing capability of a special test vehicle if they were to require special test processing and track geometry processing simultaneously. If they could be run sequentially then the hardware/software requirements for the track geometry computer configuration could be integrated into those for special tests. The addition of the sensors and analog processing equipment will still be required along with the track geometry software for the computer.

The software would have to be specially adapted for use by the special test vehicle. All special considerations such as power, environmental, and work areas must be given in addition to those things indigenous to a track geometry vehicle such as cable runs, special undercar lights and special calibration mountings for sensors. Once the system is installed on the special test vehicle it must remain on that vehicle and can't be moved to another vehicle without major changes.

K.4.4.5 MANUAL MEASUREMENTS

Manual measurements can be made with a variety of instruments. In general there are two methods of making manual measurements. The first method is to use standard off-the-shelf hardware. Standard off-the-shelf hardware has several different measurement capabilities. These capabilities range from simple measurement of gauge and crosslevel using a bar type device requiring manual placement for each measurement reading through gauge and crosslevel using a measurement mounted bar type device which is rolled down the track to a track analyzer providing gauge, crosslevel, profile and alignment data. The track analyzer uses sectional tubes inserted end-to-end to create and extend the measurement chord for profile and alignment. Most of these devices use meters, rods, or levels to indicate to the operator the value of the measurement. The operator reads these values and records them in a log. Manual chord measurements for profile and alignment can be made using string and a distance measuring device such as a ruler. This method is very time consuming, heavily labor intensive, and is highly dependent on the competency test crew for accuracy.

The second method for acquiring manual measurements is to use a surveying crew and instruments (transit level, etc.). This method can provide good accuracy at a reasonable cost but is still time consuming and will only provide unloaded track data.

In using either of the above methods it must be remembered that all data collection is taken in log form by the test crew. If the data is to be automated at a later date, the data must be manually entered into a processor or storage device.

K.4.4.6 SUMMARY

In reviewing the track geometry measurement methods available to support a test program one must conside the location of the test track, length of the test track, including the test zone or zones, available equipment, available personnel, capability of personnel, standard to which track must be measured and time.

In general the use of full sized vehicles is preferable since they can provide fully loaded, accurate, dynamic, repeatable data very quickly. Tests have been run that demonstrate the repeatability and accuracy of these cars. Midsized test cars and hi-rail vehicles can also provide data quickly but do not have the capability of making a fully loaded measurement. All the above mentioned test cars (full sized, midsized, and hi-rail) can provide the track geometry measurement data in real time. In addition, these cars also provide a threshold-level report with locations of each perturbation for a quick check of the test zone.

If the test zone is extremely short and the TGSD may be used. It can provide very accurate data, but there are drawbacks to using the TGSD. It is difficult and time consuming to move from location to location; it requires an experienced crew and it does not provide real-time data.

Manual measurements can be used if unloaded static measurements are acceptable, labor is available, time is plentiful and a low level of accuracy is acceptable. Both time and accuracy in making manual measurements are very dependent on the personnel involved. As a result, the repeatability of manual measurements is generally much poorer than automated systems. If one uses one of the more complex devices then the repeatability and accuracy improves but is still dependent on the personnel involved.

To incorporate the capability of adding track geometry measurement capability to an existing test vehicle is expensive and, unless implemented using a comprehensive plan, will not provide the desired capabilities or results. Track geometry measurements utilize digitally implemented complex algorithms, including interactive correction terms between parameters, and special processing techniques. Sensor placement and analog preprocessing are also significant to the data accuracy and repeatability. As a result, unless the test program is of sufficient duration to justify an expenditure to add this capability the use of an existing automated track geometry test vehicle is a better solution.

4.5 PERFORMANCE ISSUE ONBOARD INSTRUMENTATION SELECTION GUIDE

The following section provides complete guidelines to the selection of instrumentation to address the major performance issues addressed by the V/TIAT process. This information is provided in three parts. The first is an instrumentation requirements summary; the second is an instrumentation layout; and the third outlines the processing methodology. These three summary sheets are cross referenced.

If the evaluation of specific components is desired, a subset of the instrumentation defined for the related performance issues may be selected at the discretion of the user. For example, if the comparison of two lateral secondary suspension elements is desired than a measurement of element deflection and one of lateral carbody acceleration above the truck centerplate may be sufficient.

TABLE K-4.8 INSTRUMENTATION REQUIREMENTS FOR PERFORMANCE ISSUE - HUNTING

MINIMUM INSTRUMENTATION REQUIREMENT

*	TRANSDUCER	LOCATION	POSITION	ORIENTATION	RANGE	FREQ. RESPONSE	TYPE	COMMENTS
1	ACCELEROMETER	CARBODY	A-END	LATERAL	±2 g	0 - 30 Hz	SERVO HARD MOUNT	
2	ACCELEROMETER	CARBODY	B-END	LATERAL	±2 g	0 - 30 Hz	SERVO HARD MOUNT	
3	ACCELEROMETER	AXLE	LEADING AXLE TRAILING TRUCK	LATERAL	±10 g	0 - 30 Hz	SERVO SHOCK-MOUNT	
4	ACCELEROMETER	AXLE	TRAILING AXLE TRAILING TRUCK	LATERAL	±10 g	0 - 30 Hz	SERVO SHOCK-MOUNT	
5	DISPLACEMENT	CARBODY TO TRUCK	TRAILING TRUCK	LONGITUDINAL	±10 in	0 - 30 Hz	POTENTIOMETER	
6	ACCELEROMETER	AXLE	LEADING AXLE TRAILING TRUCK	LONGITUDINAL	±10 g	0 - 30 Hz	SERVO SHOCK-MOUNT	

OPTIONAL INSTRUMENTATION

*	TRANSDUCER	LOCATION	POSITION	ORIENTATION	RANGE	FREQ. RESPONSE	TYPE	COMMENTS
7	INSTRUMENTED WHEELSET	TRAILING TRUCK	LEADING AXLE RIGHT SIDE	LATERAL	± 10 kips	0 - 100 Hz	INSTRUMENTED WHEELPLATE	
8	INSTRUMENTED WHEELSET	TRAILING TRUCK	LEADING AXLE LEFT SIDE	LATERAL	± 40 kips	0 - 100 Hz	INSTRUMENTED WHEELPLATE	
9	INSTRUMENTED WHEELSET	TRAILING TRUCK	LEADING AXLE RIGHT SIDE	VERTICAL	5 - 50 kips	5 - 100 Hz	INSTRUMENTED WHEELPLATE	
10	INSTRUMENTED WHEELSET	TRAILING TRUCK	LEADING AXLE LEFT SIDE	VERTICAL	5 - 50 kips	5 - 100 Hz	INSTRUMENTED WHEELPLATE	

* SEE FIGURE K-4.8 AND TABLE K-4.15 FOR INSTALLATION LOCATIONS AND PROCESSING METHODOLOGY

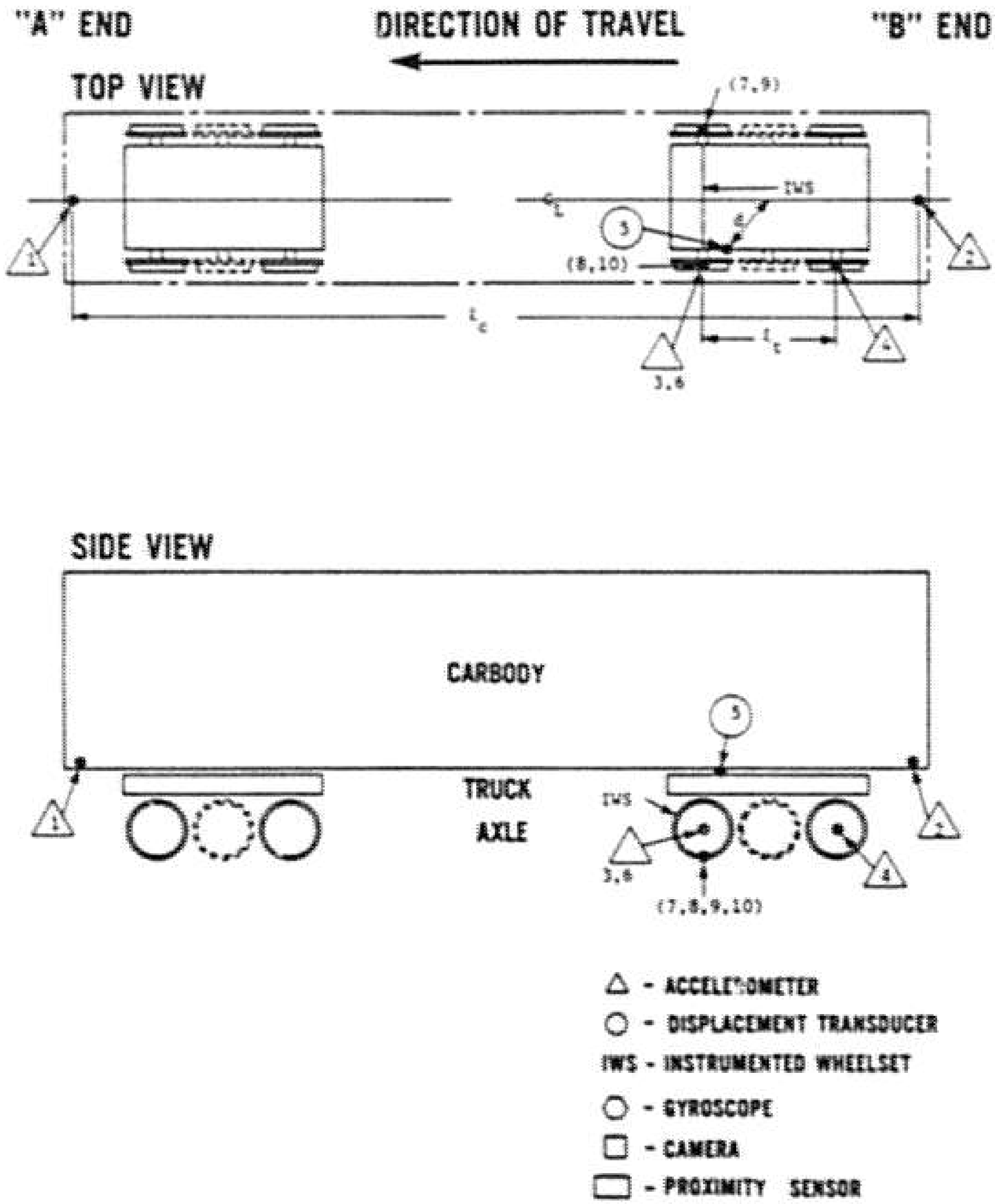


FIGURE K-4.8 INSTRUMENTATION LAYOUT FOR HUNTING *

* SEE TABLE K-4.8 FOR TRANSDUCER PROPERTIES

TABLE K-4.9 INSTRUMENTATION REQUIREMENTS FOR PERFORMANCE ISSUE - TWIST AND ROLL

MINIMUM INSTRUMENTATION REQUIREMENT

*	TRANSDUCER	LOCATION	POSITION	ORIENTATION	RANGE	FREQ. RESPONSE	TYPE	COMMENTS
1	GYROSCOPE	CARBODY	C.G.	VERTICAL	±10°	0 - 10 Hz	ABSOLUTE	AAR SPEC D-65 REQUIRED
2	ACCELEROMETER	CARBODY	C.G.	LONGITUDINAL	±2 g	0 - 30 Hz	SERVO HARD MOUNT	SAME AS ABOVE
3	ACCELEROMETER	CARBODY	A-END	LATERAL	±2 g	0 - 30 Hz	SERVO HARD MOUNT	SAME AS ABOVE
4	ACCELEROMETER	CARBODY	B-END	LATERAL	±2 g	0 - 30 Hz	SERVO HARD MOUNT	SAME AS ABOVE
5	ACCELEROMETER	CARBODY	A-END ON CENTER LINE	VERTICAL	±2 g	0 - 30 Hz	SERVO HARD MOUNT	SAME AS ABOVE
6	ACCELEROMETER	CARBODY	B-END RIGHT	VERTICAL	±2 g	0 - 30 Hz	SERVO HARD MOUNT	SAME AS ABOVE
7	ACCELEROMETER	CARBODY	B-END LEFT	VERTICAL	±2 g	0 - 30 Hz	SERVO HARD MOUNT	SAME AS ABOVE
17	ACCELEROMETER	CARBODY	A-END RIGHT	VERTICAL	±2 g	0 - 30 Hz	SERVO HARD MOUNT	SAME AS ABOVE
18	ACCELEROMETER	CARBODY	B-END LEFT	VERTICAL	±2 g	0 - 30 Hz	SERVO HARD MOUNT	SAME AS ABOVE

OPTIONAL INSTRUMENTATION

*	TRANSDUCER	LOCATION	POSITION	ORIENTATION	RANGE	FREQ. RESPONSE	TYPE	COMMENTS
8	DISPLACEMENT	CARBODY TO TRUCK	RIGHT SIDE	VERTICAL	±10 in	0 - 10 Hz	POTENTIOMETER	CARBODY TO TRUCK ROLL
9	DISPLACEMENT	CARBODY TO TRUCK	LEFT SIDE	VERTICAL	±10 in	0 - 10 Hz	POTENTIOMETER	CARBODY TO TRUCK ROLL
10	DISPLACEMENT	SPRING GROUP	RIGHT SIDE	VERTICAL	±10 in	0 - 10 Hz	POTENTIOMETER	SPRING GROUP DEFLECTION
11	DISPLACEMENT	SPRING GROUP	LEFT SIDE	VERTICAL	±10 in	0 - 10 Hz	POTENTIOMETER	SPRING GROUP DEFLECTION
12	CAMERA	LEAD AXLE	AXLE CENTERLINE	VERTICAL	-	-	VIDEO	DETERMINE WHEEL LIFT
13	INSTRUMENTED WHEELSET	TRAILING TRUCK	LEADING AXLE RIGHT SIDE	LATERAL	±40 kips	0 - 100 Hz	INSTRUMENTED WHEELPLATE	
14	INSTRUMENTED WHEELSET	TRAILING TRUCK	LEADING AXLE LEFT SIDE	LATERAL	±40 kips	0 - 100 Hz	INSTRUMENTED WHEELPLATE	
15	INSTRUMENTED WHEELSET	TRAILING TRUCK	AXLE RIGHT SIDE	VERTICAL	0 - 50 kips	0 - 100 Hz	INSTRUMENTED WHEELPLATE	
16	INSTRUMENTED WHEELSET	TRAILING TRUCK	AXLE LEFT SIDE	VERTICAL	0 - 50 kips	0 - 100 Hz	INSTRUMENTED WHEELPLATE	

* SEE FIGURE K-4.9 AND TABLE K-4.16 FOR INSTALLATION LOCATIONS AND PROCESSING METHODOLOGY

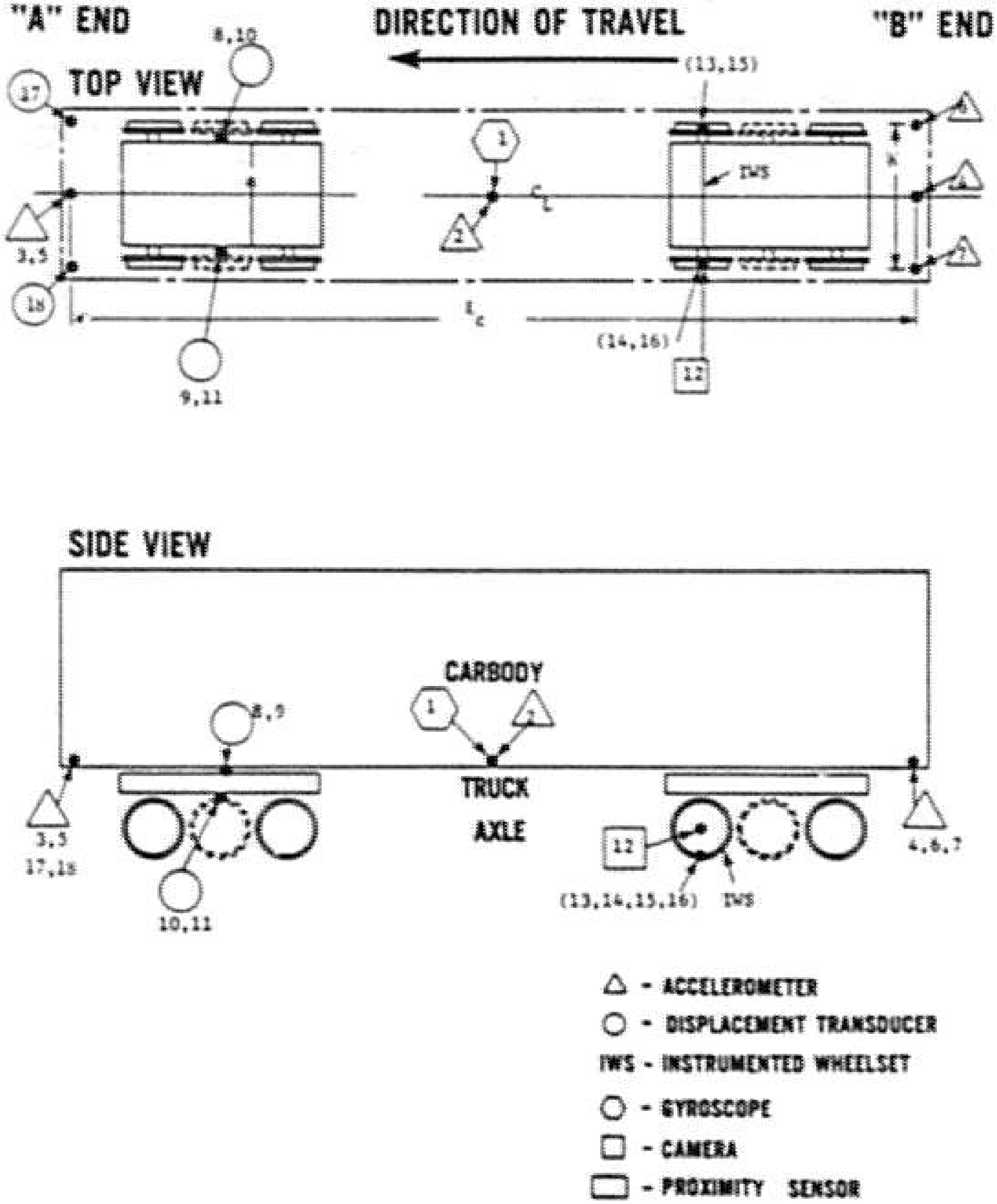


FIGURE K-4.9 INSTRUMENTATION LAYOUT FOR TWIST AND ROLL *

* SEE TABLE K-4.9 FOR TRANSDUCER PROPERTIES

TABLE K-4.10 INSTRUMENTATION REQUIREMENTS FOR PERFORMANCE ISSUE - PITCH AND BOUNCE

MINIMUM INSTRUMENTATION REQUIREMENT

*	TRANSDUCER	LOCATION	POSITION	ORIENTATION	RANGE	FREQ RESPONSE	TYPE	COMMENTS
1	ACCELEROMETER	CARBODY	A-END ON CENTERLINE	VERTICAL	± 2 g	0 - 30 Hz	SERVO HARD MOUNT	
2	ACCELEROMETER	CARBODY	B-END ON CENTERLINE	VERTICAL	± 2 g	0 - 30 Hz	SERVO HARD MOUNT	

OPTIONAL INSTRUMENTATION

*	TRANSDUCER	LOCATION	POSITION	ORIENTATION	RANGE	FREQ RESPONSE	TYPE	COMMENTS
3	DISPLACEMENT	SPRING GROUP	RIGHT SIDE	VERTICAL	± 10"	0 - 10 Hz	POTENTIOMETRIC	SPRING GROUP DEFLECTION
4	DISPLACEMENT	SPRING GROUP	LEFT SIDE	VERTICAL	± 10"	0 - 10 Hz	POTENTIOMETRIC	

* SEE FIGURE K-4.10 AND TABLE K-4.18 FOR INSTALLATION LOCATIONS AND PROCESSING METHODOLOGY

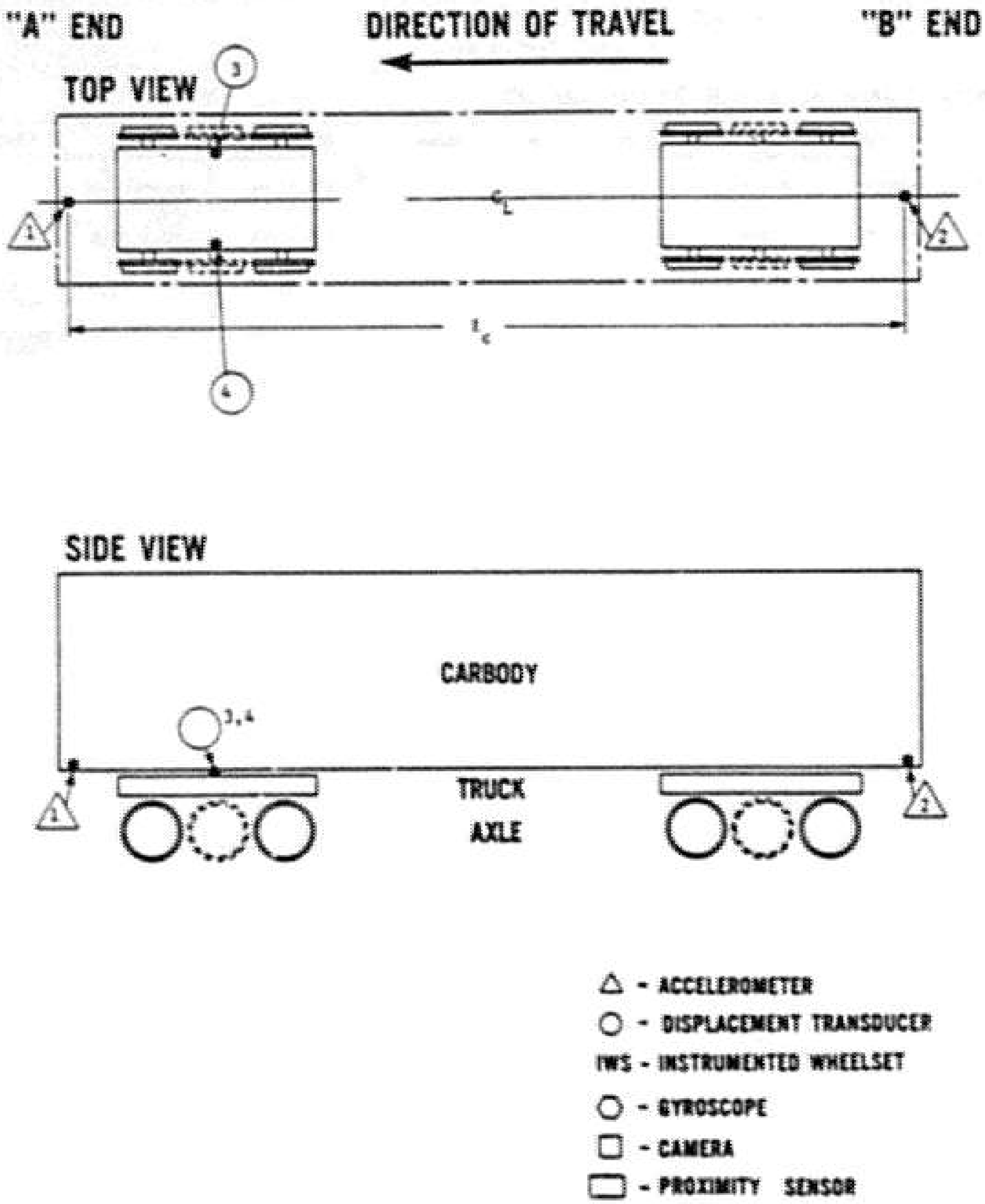


FIGURE K-4.10 INSTRUMENTATION LAYOUT FOR PITCH AND BOUNCE *

* SEE TABLE K-4.10 FOR TRANSDUCER PROPERTIES

TABLE K-4.11 INSTRUMENTATION REQUIREMENTS FOR PERFORMANCE ISSUE YAW AND SWAY

MINIMUM INSTRUMENTATION REQUIREMENT

*	TRANSDUCER	LOCATION	POSITION	ORIENTATION	RANGE	FREQ. RESPONSE	TYPE	COMMENTS
1	ACCELEROMETER	CARBODY	A-END	LATERAL	± 2 g	0 - 30 Hz	SERVO HARD MOUNT	
2	ACCELEROMETER	CARBODY	B-END	LATERAL	± 2 g	0 - 30 Hz	SERVO HARD MOUNT	
3	DISPLACEMENT	CARBODY TO TRUCK	RIGHT SIDE	VERTICAL	± 10"	0 - 10 Hz	POTENTIOMETRIC	CARBODY TO TRUCK ROLL
4	DISPLACEMENT	CARBODY TO TRUCK	LEFT SIDE	VERTICAL	± 10"	0 - 10 Hz	POTENTIOMETRIC	CARBODY TO TRUCK ROLL

OPTIONAL INSTRUMENTATION

*	TRANSDUCER	LOCATION	POSITION	ORIENTATION	RANGE	FREQ. RESPONSE	TYPE	COMMENTS
5	INSTRUMENTED WHEELSET	TRAILING TRUCK	LEADING AXLE RIGHT SIDE	LATERAL	± 40 kips	0 - 100 Hz	INSTRUMENTED WHEELPLATE	
6	INSTRUMENTED WHEELSET	TRAILING TRUCK	LEADING AXLE LEFT SIDE	LATERAL	± 40 kips	0 - 100 Hz	INSTRUMENTED WHEELPLATE	
7	INSTRUMENTED WHEELSET	TRAILING TRUCK	AXLE RIGHT SIDE	VERTICAL	0 - 50 kips	0 - 100 Hz	INSTRUMENTED WHEELPLATE	
8	INSTRUMENTED WHEELSET	TRAILING TRUCK	AXLE LEFT SIDE	VERTICAL	0 - 50 kips	0 - 100 Hz	INSTRUMENTED WHEELPLATE	

* SEE FIGURE K-4.11 AND TABLE K-4.17 FOR INSTALLATION LOCATIONS AND PROCESSING METHODOLOGY

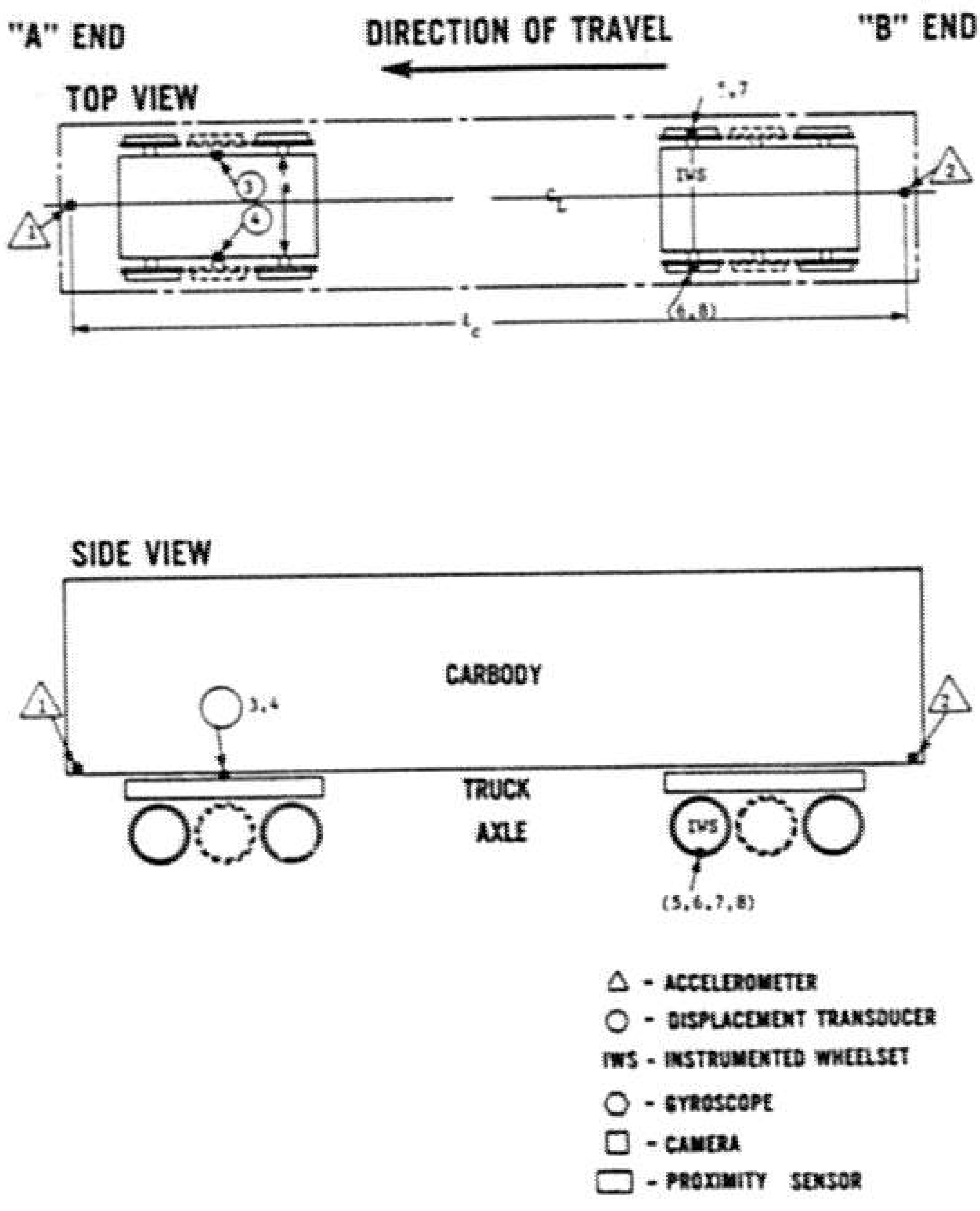


FIGURE K-4.11 INSTRUMENTATION LAYOUT FOR YAW AND SWAY *

* SEE TABLE K-4.11 FOR TRANSDUCER PROPERTIES

TABLE K-4.12 INSTRUMENTATION REQUIREMENTS FOR PERFORMANCE ISSUE STEADY-STATE CURVING

MINIMUM INSTRUMENTATION REQUIREMENT

*	TRANSDUCER	LOCATION	POSITION	ORIENTATION	RANGE	FREQ. RESPONSE	TYPE	COMMENTS
1	INSTRUMENTED WHEELSET	TRAILING TRUCK	LEADING AXLE RIGHT SIDE	LATERAL	± 40 kips	0 - 100 Hz	INSTRUMENTED WHEELPLATE	
2	INSTRUMENTED WHEELSET	TRAILING TRUCK	LEADING AXLE LEFT SIDE	LATERAL	± 40 kips	0 - 100 Hz	INSTRUMENTED WHEELPLATE	
3	INSTRUMENTED WHEELSET	TRAILING TRUCK	LEADING AXLE RIGHT SIDE	VERTICAL	0 - 50 kips	0 - 100 Hz	INSTRUMENTED WHEELPLATE	
4	INSTRUMENTED WHEELSET	TRAILING TRUCK	LEADING AXLE LEFT SIDE	VERTICAL	0 - 50 kips	0 - 100 Hz	INSTRUMENTED WHEELPLATE	
5	INSTRUMENTED WHEELSET	TRAILING TRUCK	TRAILING AXLE RIGHT SIDE	LATERAL	± 40 kips	0 - 100 Hz	INSTRUMENTED WHEELPLATE	
6	INSTRUMENTED WHEELSET	TRAILING TRUCK	TRAILING AXLE LEFT SIDE	LATERAL	± 40 kips	0 - 100 Hz	INSTRUMENTED WHEELPLATE	
7	INSTRUMENTED WHEELSET	TRAILING TRUCK	TRAILING AXLE RIGHT SIDE	VERTICAL	0 - 50 kips	0 - 100 Hz	INSTRUMENTED WHEELPLATE	
8	INSTRUMENTED WHEELSET	TRAILING TRUCK	TRAILING AXLE LEFT SIDE	VERTICAL	0 - 50 kips	0 - 100 Hz	INSTRUMENTED WHEELPLATE	
9	ACCELEROMETER	CARBODY	CENTERLINE A-END	LATERAL	± 2 g's	0 - 30 Hz	SERVO HARD MOUNT	PASSENGER COMFORT
10	ACCELEROMETER	CARBODY	CENTERLINE B-END	LATERAL	± 2 g's	0 - 30 Hz	SERVO HARD MOUNT	
11	*							

*Transducers 11-14 are duplicates of 1-4 and would be used only if 3 axle trucks were involved.

OPTIONAL INSTRUMENTATION

*	TRANSDUCER	LOCATION	POSITION	ORIENTATION	RANGE	FREQ. RESPONSE	TYPE	COMMENTS
15	ACCELEROMETER	AXLE	LEADING AXLE TRAILING TRUCK	LATERAL	± 10 g	0 - 30 Hz	SERVO SHOCK MOUNT	
16	ACCELEROMETER	AXLE	TRAILING AXLE TRAILING TRUCK	LATERAL	± 10 g	0 - 30 Hz	SERVO SHOCK MOUNT	
17	DISPLACEMENT	SECONDARY SUSPENSION	RIGHT SIDE	LATERAL	± 5"	0 - 10 Hz	POTENTIOMETRIC	
18	DISPLACEMENT	SECONDARY SUSPENSION	LEFT SIDE	LATERAL	± 5"	0 - 10 Hz	POTENTIOMETRIC	
19	DISPLACEMENT	PRIMARY SUSPENSION	RIGHT SIDE	LATERAL	± 5"	0 - 10 Hz	POTENTIOMETRIC	
20	DISPLACEMENT	PRIMARY SUSPENSION	LEFT SIDE	LATERAL	± 1"	0 - 10 Hz	POTENTIOMETRIC	
21	PROXIMITY	TRAILING TRUCK LEADING WHEEL SIDE FRONT	RIGHT SIDE	LATERAL	± 3"	0 - 20 Hz	MAGNETIC	TO PROVIDE WHEEL AOA
22	PROXIMITY	TRAILING TRUCK LEADING WHEEL REAR SIDE	RIGHT SIDE	LATERAL	± 3"	0 - 20 Hz	MAGNETIC	TO PROVIDE WHEEL AOA

* SEE FIGURE K-4.12 AND TABLE K-4.19 FOR INSTRUMENTATION LOCATION AND PROCESSING METHODOLOGY

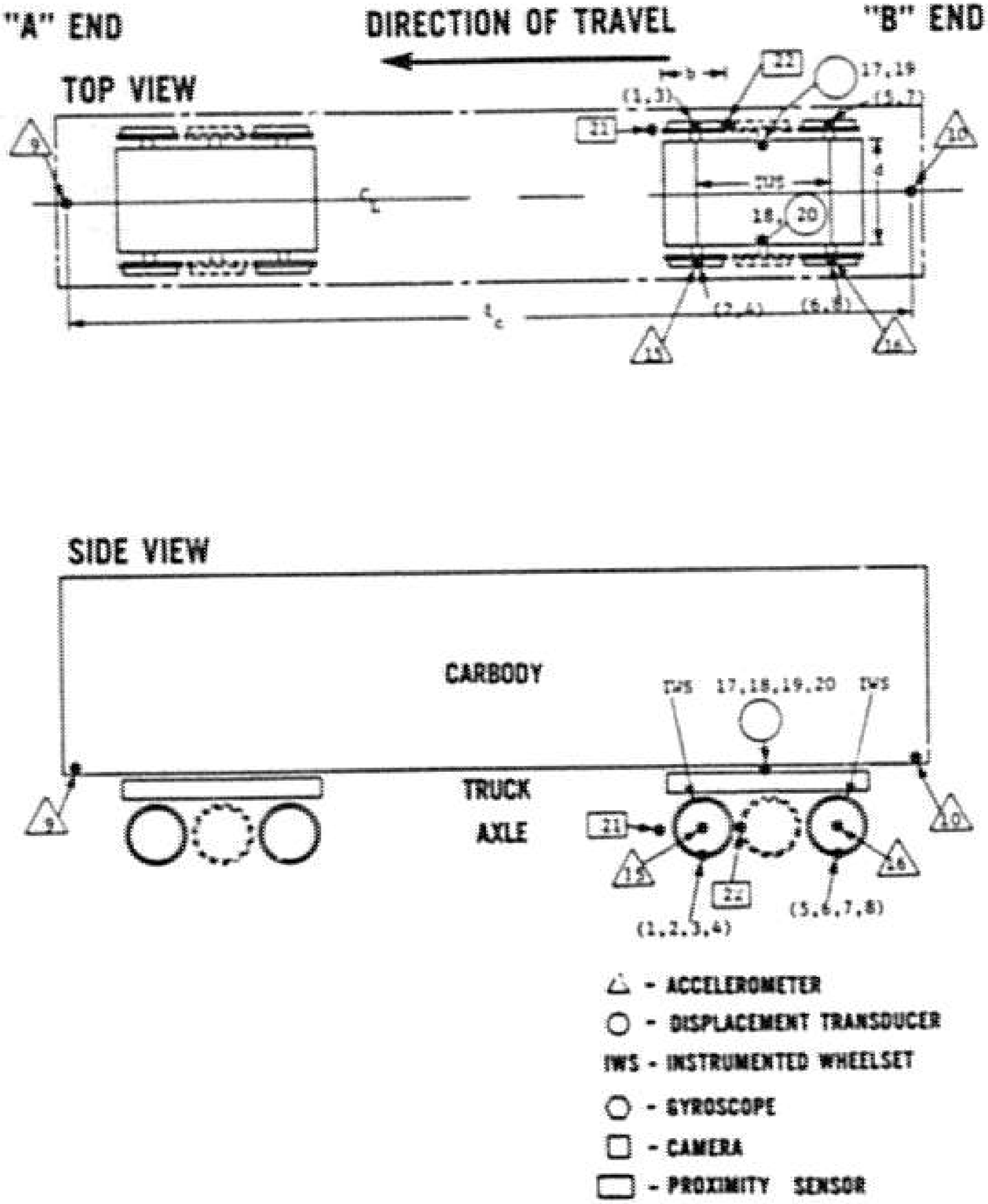


FIGURE K-4.12 INSTRUMENTATION LAYOUT FOR STEADY-STATE CURVING *

* SEE TABLE K-4.12 FOR TRANSDUCER PROPERTIES

TABLE K-4.13 INSTRUMENTATION REQUIREMENTS FOR PERFORMANCE ISSUE - SPIRAL NEGOTIATION

MINIMUM INSTRUMENTATION REQUIREMENT

*	TRANSDUCER	LOCATION	POSITION	ORIENTATION	RANGE	FREQ. RESPONSE	TYPE	COMMENTS
1	INSTRUMENTED WHEELSET	TRAILING TRUCK	LEADING AXLE RIGHT SIDE	LATERAL	± 40 kips	0 - 100 Hz	INSTRUMENTED WHEELPLATE	
2	INSTRUMENTED WHEELSET	TRAILING TRUCK	LEADING AXLE LEFT SIDE	LATERAL	± 40 kips	0 - 100 Hz	INSTRUMENTED WHEELPLATE	
3	INSTRUMENTED WHEELSET	TRAILING TRUCK	LEADING AXLE RIGHT SIDE	VERTICAL	0 - 50 kips	0 - 100 Hz	INSTRUMENTED WHEELPLATE	
4	INSTRUMENTED WHEELSET	TRAILING TRUCK	LEADING AXLE LEFT SIDE	VERTICAL	0 - 50 kips	0 - 100 Hz	INSTRUMENTED WHEELPLATE	
5	INSTRUMENTED WHEELSET	TRAILING TRUCK	TRAILING AXLE RIGHT SIDE	LATERAL	± 40 kips	0 - 100 Hz	INSTRUMENTED WHEELPLATE	
6	INSTRUMENTED WHEELSET	TRAILING TRUCK	TRAILING AXLE LEFT SIDE	LATERAL	± 40 kips	0 - 100 Hz	INSTRUMENTED WHEELPLATE	
7	INSTRUMENTED WHEELSET	TRAILING TRUCK	TRAILING AXLE RIGHT SIDE	VERTICAL	0 - 50 kips	0 - 100 Hz	INSTRUMENTED WHEELPLATE	
8	INSTRUMENTED WHEELSET	TRAILING TRUCK	TRAILING AXLE LEFT SIDE	VERTICAL	0 - 50 kips	0 100 Hz	INSTRUMENTED WHEELPLATE	
9	ACCELEROMETER	CARBODY	CENTERLINE A-END	LATERAL	± 2 g's	0 - 30 Hz	SERVO HARD MOUNT	PASSENGER COMFORT
10	ACCELEROMETER	CARBODY	CENTERLINE B-END	LATERAL	± 2 g's	0 - 30 Hz	SERVO HARD MOUNT	
11	*							
	*Transducers 11-14 are duplicates of 1-4 and would be used only if 3 axle trucks were involved.							
15	ACCELEROMETER	CARBODY	C.G.	LONGITUDINAL	± 2 g	0 - 30 Hz	SERVO HARD MOUNT	AAR SPEC D-65
16	ACCELEROMETER	CARBODY	A-END ON CENTERLINE	VERTICAL	± 2 g	0 - 30 Hz	SERVO HARD MOUNT	SAME AS ABOVE
17	ACCELEROMETER	CARBODY	B-END RIGHT	VERTICAL	± 2 g	0 - 30 Hz	SERVO HARD MOUNT	SAME AS ABOVE
18	ACCELEROMETER	CARBODY	A-END LEFT	VERTICAL	± 2 g	0 - 30 Hz	SERVO HARD MOUNT	SAME AS ABOVE

OPTIONAL INSTRUMENTATION

*	TRANSDUCER	LOCATION	POSITION	ORIENTATION	RANGE	FREQ. RESPONSE	TYPE	COMMENTS
19	ACCELEROMETER	AXLE	LEADING AXLE TRAILING TRUCK	LATERAL	± 10 g	0 - 30 Hz	SERVO SHOCK MOUNT	
20	ACCELEROMETER	AXLE	TRAILING AXLE TRAILING TRUCK	LATERAL	± 10 g	0 - 30 Hz	SERVO SHOCK MOUNT	
21	DISPLACEMENT	SECONDARY SUSPENSION	RIGHT SIDE	LATERAL	± 5"	0 - 10 Hz	POTENTIOMETRIC	
22	DISPLACEMENT	SECONDARY SUSPENSION	LEFT SIDE	LATERAL	± 5"	0 - 10 Hz	POTENTIOMETRIC	
23	DISPLACEMENT	PRIMARY SUSPENSION	RIGHT SIDE	LATERAL	± 1"	0 - 10 Hz	POTENTIOMETRIC	
24	DISPLACEMENT	PRIMARY SUSPENSION	LEFT SIDE	LATERAL	± 1"	0 - 10 Hz	POTENTIOMETRIC	
25	PROXIMITY	TRAILING TRUCK LEADING WHEEL FRONT SIDE	RIGHT SIDE	LATERAL	± 3"	0 - 20 Hz	MAGNETIC	TO PROVIDE WHEEL AOA
26	PROXIMITY	TRAILING TRUCK LEADING WHEEL REAR SIDE	RIGHT SIDE	LATERAL	± 3"	0 - 20 Hz	MAGNETIC	TO PROVIDE WHEEL AOA

* SEE FIGURE K-4.13 AND TABLE K-4.20 FOR INSTRUMENTATION LOCATIONS AND PROCESSING METHODOLOGY

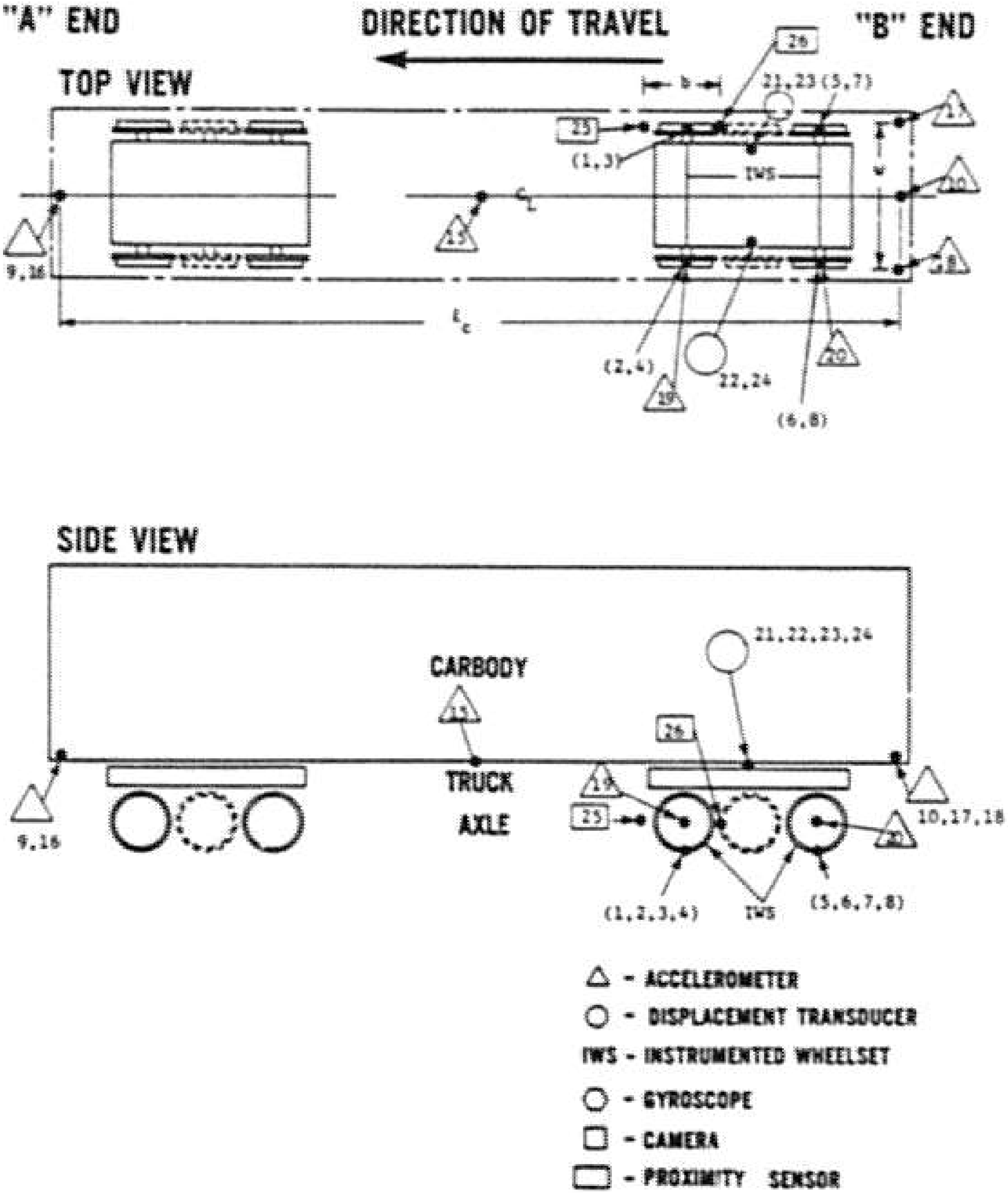


FIGURE K-4.13 INSTRUMENTATION LAYOUT FOR SPIRAL NEGOTIATION *

* SEE TABLE K-4.13 FOR TRANSDUCER PROPERTIES

TABLE K-4.14 INSTRUMENTATION REQUIREMENTS FOR PERFORMANCE ISSUE DYNAMIC CURVING

MINIMUM INSTRUMENTATION REQUIREMENT

*	TRANSDUCER	LOCATION	POSITION	ORIENTATION	RANGE	FREQ. RESPONSE	TYPE	COMMENTS
1	INSTRUMENTED WHEELSET	TRAILING TRUCK	LEADING AXLE RIGHT SIDE	LATERAL	± 40 kips	0 - 100 Hz	INSTRUMENTED WHEELPLATE	
2	INSTRUMENTED WHEELSET	TRAILING TRUCK	LEADING AXLE LEFT SIDE	LATERAL	± 40 kips	0 - 100 Hz	INSTRUMENTED WHEELPLATE	
3	INSTRUMENTED WHEELSET	TRAILING TRUCK	LEADING AXLE RIGHT SIDE	VERTICAL	0 - 50 kips	0 - 100 Hz	INSTRUMENTED WHEELPLATE	
4	INSTRUMENTED WHEELSET	TRAILING TRUCK	LEADING AXLE LEFT SIDE	VERTICAL	0 - 50 kips	0 - 100 Hz	INSTRUMENTED WHEELPLATE	
5	INSTRUMENTED WHEELSET	TRAILING TRUCK	TRAILING AXLE RIGHT SIDE	LATERAL	± 40 kips	0 - 100 Hz	INSTRUMENTED WHEELPLATE	
6	INSTRUMENTED WHEELSET	TRAILING TRUCK	TRAILING AXLE LEFT SIDE	LATERAL	± 40 kips	0 - 100 Hz	INSTRUMENTED WHEELPLATE	
7	INSTRUMENTED WHEELSET	TRAILING TRUCK	TRAILING AXLE RIGHT SIDE	VERTICAL	0 - 50 kips	0 - 100 Hz	INSTRUMENTED WHEELPLATE	
8	INSTRUMENTED WHEELSET	TRAILING TRUCK	TRAILING AXLE LEFT SIDE	VERTICAL	0 - 50 kips	0 - 100 Hz	INSTRUMENTED WHEELPLATE	
9	ACCELEROMETER	CARBODY	CENTERLINE A-END	LATERAL	± 2 g's	0 - 30 Hz	SERVO HARD MOUNT	PASSENGER COMFORT
10	ACCELEROMETER	CARBODY	CENTERLINE B-END	LATERAL	± 2 g's	0 - 30 Hz	SERVO HARD MOUNT	
11	*							
	*Transducers 11-14 are duplicates of 1-4 and should be used only if 3 axle trucks were involved.							
15	ACCELEROMETER	CARBODY	C.G.	LONGITUDINAL	± 2 g	0 - 30 Hz	SERVO HARD MOUNT	AAR SPEC [illegible]
16	ACCELEROMETER	CARBODY	A-END ON CENTERLINE	VERTICAL	± 2 g	0 - 30 Hz	SERVO HARD MOUNT	SAME AS ABOVE
17	ACCELEROMETER	CARBODY	B-END RIGHT	VERTICAL	± 2 g	0 - 30 Hz	SERVO HARD MOUNT	SAME AS ABOVE
18	ACCELEROMETER	CARBODY	B-END LEFT	VERTICAL	± 2 g	0 - 30 Hz	SERVO HARD MOUNT	SAME AS ABOVE

OPTIONAL INSTRUMENTATION

*	TRANSDUCER	LOCATION	POSITION	ORIENTATION	RANGE	FREQ. RESPONSE	TYPE	COMMENTS
19	ACCELEROMETER	AXLE	LEADING AXLE TRAILING TRUCK	LATERAL	± 10 g	0 - 30 Hz	SERVO SHOCK MOUNT	
20	ACCELEROMETER	AXLE	TRAILING AXLE TRAILING TRUCK	LATERAL	± 10 g	0 - 30 Hz	SERVO SHOCK MOUNT	
21	DISPLACEMENT	SECONDARY SUSPENSION	RIGHT SIDE	LATERAL	± 5"	0 - 10 Hz	POTENTIOMETRIC	
22	DISPLACEMENT	SECONDARY SUSPENSION	LEFT SIDE	LATERAL	± 5"	0 - 10 Hz	POTENTIOMETRIC	
23	DISPLACEMENT	PRIMARY SUSPENSION	RIGHT SIDE	LATERAL	± 1"	0 - 10 Hz	POTENTIOMETRIC	
24	DISPLACEMENT	PRIMARY SUSPENSION	LEFT SIDE	LATERAL	± 1"	0 - 10 Hz	POTENTIOMETRIC	
25	PROXIMITY	TRAILING TRUCK LEADING WHEEL FRONT SIDE	RIGHT SIDE	LATERAL	± 3"	0 - 20 Hz	MAGNETIC	TO PROVIDE WHEEL AOA
26	PROXIMITY	TRAILING TRUCK LEADING WHEEL REAR SIDE	RIGHT SIDE	LATERAL	± 3"	0 - 20 Hz	MAGNETIC	TO PROVIDE WHEEL AOA

* SEE FIGURE K-4.14 AND TABLE K-4.21 FOR INSTRUMENTATION LOCATIONS AND PROCESSING METHODOLOGY

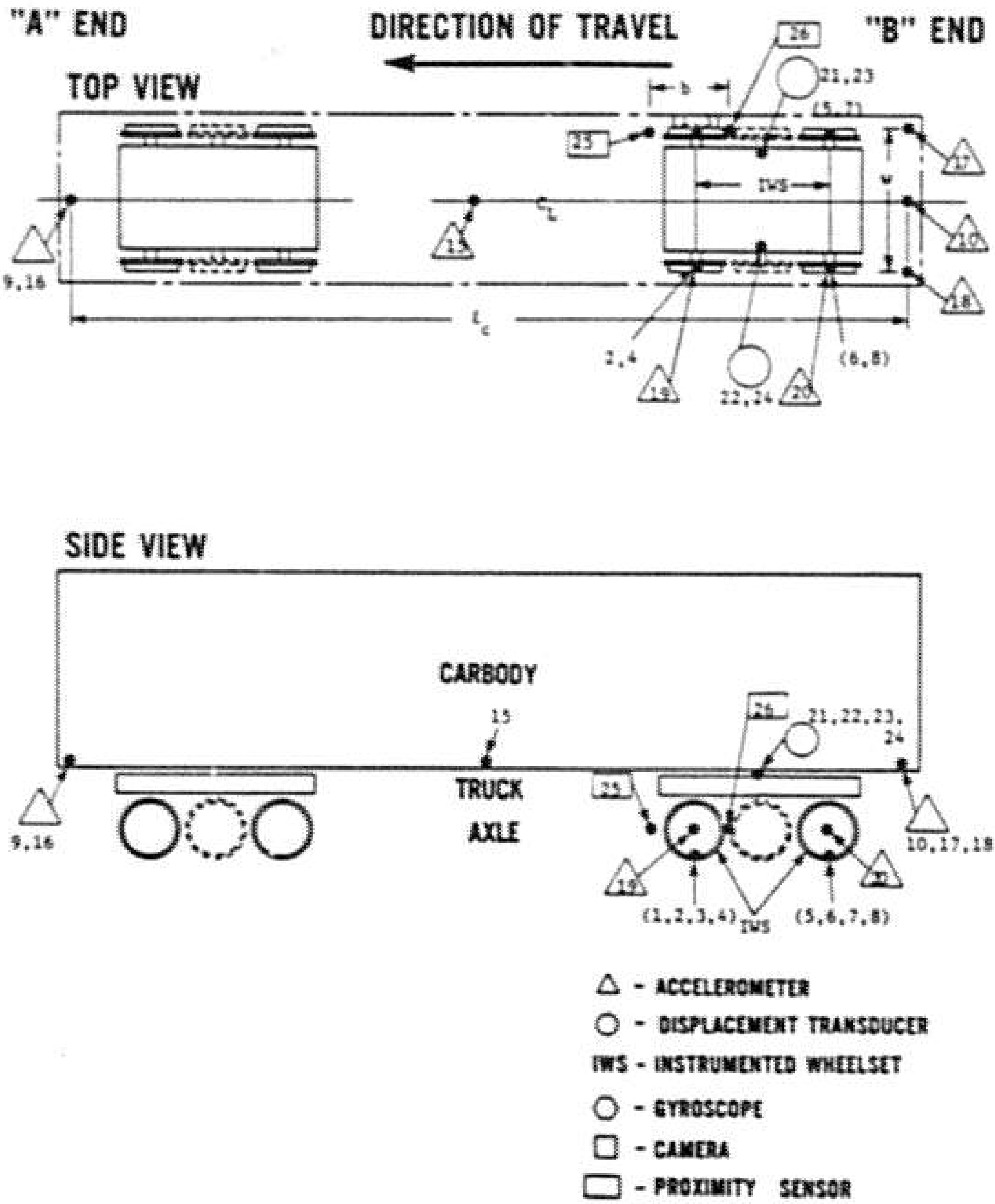


FIGURE K-4.14 INSTRUMENTATION LAYOUT FOR DYNAMIC CURVING *

* SEE TABLE K-4.14 FOR TRANDUCER PROPERTIES

TABLE K-4.15 PROCESSING METHODOLOGY - HUNTING

	UNITS
CARBODY SWAY = $(a_1 + a_2)/2$	g's
CARBODY YAW = $(a_1 - a_2)(386/\ell_c)$	radians/sec^2
TRUCK SWAY = $(a_3 + a_4)/2$	g's
TRUCK YAW = $(a_3 - a_4)(386/\ell_c)$	radians/sec^2
TRUCK SWIVEL = $\sin^{-1} X_5/d = 180\, X_5/\pi d$	degrees
Right Side Lateral Force, F_7	kips
Right Side Vertical Force, F_9	kips
Right Side L/V	-
Left Side Lateral Force, F_8	kips
Left Side Vertical Force, F_{10}	kips
Left Side L/V	

TABLE K-4.16 PROCESSING METHODOLOGY - TWIST AND ROLL

	UNITS
CARBODY TWIST = $(a_6 - a_7) + (a_{18} - a_{1[illegible]})(386/w)$	radians/sec^2
CARBODY SWAY = $(a_3 + a_4)/2$	g's
CARBODY BOUNCE = $\left[a_5 + \left(\frac{a_6 + a_7}{2}\right)\right]/2$	g's
CARBODY ROLL = $(a_6 - a_7)(386/w)$	radians/sec^2
CARBODY PITCH = $\left[a_5 - \frac{(a_6 + a_7)}{2}\right](386/\ell_c)$	radians/sec^2
CARBODY YAW = $(a_3 - a_4)(386/\ell_c)$	radians/sec^2
CARBODY TO TRUCE ROLL = $(X_8 - X_9)/a$	radians
Right Side Lateral Force, F_{13}	kip
Right Side Vertical Force, F_{15}	kips
Right Side L/V	-
Left Side Lateral Force, F_{14}	kips
Left Side Vertical Force, F_{16}	kips
Left Side L/V	

TABLE K-4.17 PROCESSING METHODOLOGY - YAW AND SWAY

	UNITS
CARBODY SWAY = $(a_1 + a_2)/2$	g's
CARBODY YAW = $(a_1 - a_2)(386/\ell_c)$	radians/sec^2
CARBODY TO TRUCK ROLL = $\frac{(Z_3 - Z_4)}{a}$	radians
Lateral Force Leading Axle Trailing Truck Right Side, F_5	kips
Vertical Force Leading Axle Trailing Truck Right Side, F_7	kips
L/V Leading Axle Trailing Truck Right Side	
Lateral Force Leading Axle Trailing Truck Left Side, F_6	kips
Vertical Force Leading Axle Trailing Truck Left Side, F_8	kips
L/V Leading Axle Trailing Truck	

TABLE K-4.18 PROCESSING METHODOLOGY - PITCH AND BOUNCE

	UNITS
CARBODY BOUNCE = $\left(\frac{A_1 + A_2}{2}\right)$	g's
CARBODY PITCH = $\left(\frac{A_1 - A_2}{2}\right)\left(\frac{386}{\ell_c}\right)$	radians/sec^2

TABLE K-4.19 PROCESSING METHODOLOGY - STEADY-STATE CURVING

	UNITS
CARBODY YAW = $(a_1 + a_2)/2$	g's
CARBODY SWAY = $(a_1 + a_2)(386/\ell_c)$	radians/sec^2
CARBODY TO TRUCK YAW = $\frac{(X_{18} - X_{19})}{\ell}$	radians/sec^2
Lateral Force Right Side Leading Axle Trailing Truck, F_1	kips
Vertical Force Right Side Leading Axle Trailing Truck, F_3	kips
L/V Right Side Leading Axle Trailing Truck,	-
Lateral Force Left Side Leading Axle Trailing Truck, F_2	kips
Vertical Force Left Side Leading Axle Trailing Truck, F_4	kips
L/V Left Side Leading Axle, Trailing Truck	-
Lateral Force Right Side Trailing Axle Trailing Truck, F_5	kips
Vertical Force Right Side Trailing Axle Trailing Truck, F[illegible]	kips
L/V Right Side Trailing Axle Trailing Truck Truck	-
Lateral Force Left Side Trailing Axle Trailing Truck, F_6	kips
Vertical Force Left Side Trailing Axle Trailing Truck, F_8	kips
L/V Left Side Trailing Axle Trailing Truck	-
Angle of Attack (AOA) = $\frac{F_{21} - F_{22}}{\ell}$	radians

TABLE K-4.20 PROCESSING METHODOLOGY - SPIRAL NEGOTIATION

		UNITS
CARBODY SWAY	$= (a_9 + a_{10})/2$	g's
CARBODY BOUNCE	$= \left[a_{16} + \frac{(a_{17} + a_{18})}{2}\right]/2$	g's
CARBODY ROLL	$= (a_{17} - a_{18})(386/w)$	$radians/sec^2$
CARBODY PITCH	$= [a_{16} - (a_{17} + a_{18})/2](386/\ell_c)$	$radians/sec^2$
CARBODY YAW	$= (a_{16} - a_{13})(386/\ell_c)$	$radians/sec^2$
Lateral Force Right Side Leading Axle Trailing Truck, F_1		kips
Vertical Force Right Side Leading Axle Trailing Truck, F_3		kips
L/V Right Side Leading Axle Trailing Truck,		-
Lateral Force Left Side Leading Axle Trailing Truck, F_2		kips
Vertical Force Left Side Leading Axle Trailing Truck, F_4		kips
L/V Left Side Leading Axle, Trailing Truck		-
Lateral Force Right Side Trailing Axle Trailing Truck, F_5		kips
Vertical Force Right Side Trailing Axle Trailing Truck, F_7		kips
L/V Right Side Trailing Axle Trailing Truck		-
Lateral Force Left Side Trailing Axle Trailing Truck, F_6		kips
Vertical Force Left Side Trailing Axle Trailing Truck, F_8		kips
L/V Left Side Trailing Axle Trailing Truck		-
Angle of Attack (AOA)	$= \frac{P_{25} - P_{26}}{b}$	radians

TABLE K-4.21 PROCESSING METHODOLOGY - DYNAMIC CURVING

	UNITS
CARBODY SWAY $= (a_9 + a_{10})/2$	g's
CARBODY BOUNCE $= \left[a_{16} + \frac{(a_{17} + a_{18})}{2}\right]/2$	g's
CARBODY ROLL $= (a_{17} - a_{18})(386/w)$	radians/sec^2
CARBODY PITCH $= [a_{16} - (a_{17} + a_{18})/2](386/\ell_c)$	radians/sec^2
CARBODY YAW $= (a_{16} - a_{10})(386/\ell_c)$	radians/sec^2
Lateral Force Right Side Leading Axle Trailing Truck, F_1	kips
Vertical Force Right Side Leading Axle Trailing Truck, F_3	kips
L/V Right Side Leading Axle Trailing Truck,	-
Lateral Force Left Side Leading Axle Trailing Truck, F_2	kips
Vertical Force Left Side Leading Axle Trailing Truck, F_4	kips
L/V Left Side Leading Axle, Trailing Truck	-
Lateral Force Right Side Trailing Axle Trailing Truck, F_5	kips
Vertical Force Right Side Trailing Axle Trailing Truck, F_7	kips
L/V Right Side Trailing Axle Trailing Truck	-
Lateral Force Left Side Trailing Axle Trailing Truck, F_6	kips
Vertical Force Left Side Trailing Axle Trailing Truck, F_8	kips
L/V Left Side Trailing Axle Trailing Truck	
Angle of Attack (AOA) $= \frac{P_{25} - P_{26}}{b}$	radians

K.5.0 WAYSIDE INSTRUMENTATION

K.5.1 INTRODUCTION

Wayside measurement of dynamic loads and displacements provides a fundamental basis for the evaluation understanding and design of both vehicle and track structure components and/or systems. Although wheel/rail load measurement data is considerably more prevalent than track structure deflection data, both are required to fully understand the complex vehicle/track structure interactions which take place.

In the past, vehicle/track interaction responses have been assessed either analytically or by testing on available track. Test results from a variety of different test conditions, locations, and procedures have made the comparison of vehicle performance characteristics extremely difficult. Furthermore, meaningful evaluations have been complicated by inconsistencies in measurement techniques and instrumentation.

It has been generally recognized Ref. [21] that future test programs would greatly benefit from significant improvements and standardization in the wayside instrumentation techniques used. Furthermore, it is also recognized that field testing typically incurs large expenditures of manpower, equipment and other resources associated with setting up test procedures, instrumentation, establishment of logistics, means to support data collection, searching for a representative site, tear down, etc.

K.5.2 MEASUREMENT REQUIREMENTS

In order to establish some type of baseline for selection of instrumentation, it was necessary to define a set of desired measurement parameters and requirements. The desired measurement parameters were basically derived from a brief literature search as summarized in Table K-5.1. As intended, the initial set of measurement requirements precipitated further "refinements", primarily with regard to accuracy requirements. The parameter ranges presented in Table K-5.2 are in some cases greater than those shown in Table K-5.1. These differences are attributable to recent (unpublished) test data in combination with anticipated V/T IAT tests and test conditions. Likewise the accuracy requirements shown in Table K-5.2 are considered necessary to satisfy the analysis requirements as presently defined.

TABLE K-5.1 LITERATURE SURVEY TO CHARACTERIZE EXPECTED RANGES AND REQUIRED ACCURACIES FOR SPECIFIED WAYSIDE MEASUREMENTS

MEASUREMENT	IDENTIFIED MEASUREMENT RANGES AND REFERENCE SOURCE (references in parenthesis)				
1. VERTICAL RAIL FORCE	24-40 kips static (11, pg. 8)	104 kips-impact loads from wheel flats (2, Pg. 4)	90 kips dynamic (13, pg. 24)	75 kips dynamic (7, pg. 44)	53 kips dynamic (5, pg. 560)
2. LATERAL RAIL FORCE	22 kips (2, pg. 4)	25 kips (7, pg. 44)	20-27.5 kips (5, pg. 566)	55 kips (13, pg. 27)	30 kips (17, pg. 26)
3. LATERAL RAIL BASE DISPLACEMENT	+ .25 in (transit ref) (14, pg. 23)				
4. TIE MOTION - Lateral	.25 - .3 (4, pg. 510-511)	.1 - .47 in (6, pg. C37)	.4 in (8, pg. 130)		
- Vertical	.25 - .5 in (6, pg. 57)	.8 in (6, pg. C31)			
- Longitudinal	+ 2.25 - skew (7, pg. 96)	.02 in typ. accuracy req'd for creep (7, Pg. 95)	.25 in (10, pg. 373)		
5. LATERAL RAIL HD. DISPLACEMENT	.13 in (5, pg. 567)	.3 in (13, pg. 53)	.5 in (15, pg. 27)		
6. VERTICAL RAIL HD. DISPLACEMENT	.37 in (9, pg. 254)	.06 to .125 in (9, pg. 256)	+.2 to -.8 in (15, pg. 27)		
7. LONGITUDINAL RAIL FORCE	13,000-35,000 lbs. (13, pg. 28-31)	60,000 lbs (16, pg. 3)			
8. TRACK MODULUS	500 - 13,000 psi (13, pg. 47)	16,000 psi (18, pg. 29)			
9. LONGITUDINAL RAIL DISPLACEMENT	+ .25 in. (transit ref) (14, pg. 46)				
10. DYNAMIC GAGE WIDENING	.02 to .25 in (1, pg. 6)	.475 in (5, pg. 569)	.75 in (quasi-static) (12, pg. 24)	1.0 in (Lab Tests) (17, pg. 36)	

TABLE K-5.2 SUMMARY OF TENTATIVE MEASUREMENT PARAMETERS AND MEASUREMENT REQUIREMENTS

Measurement Parameter	Maximum Range	Required Accuracy	Comments/Conditions
1. Vertical Rail Force	0 - 100 Kips (1)	± 1 kip	(1) Based upon single axle dynamic load for perturbed response of locomotive (+50 Kips Static) total truck loads could be substantially higher but spacial distribution of loads varies.
2. Lateral Rail Force	-20K to +75K (2)	± 1 Kip	(2) Negative loads nominally in range of -1 to -10 Kips. Peak of +75 Kips based upon locomotive response. Peak freight car typically in range of +24 Kips/axle. Again truck loads are significant; rail failure related work requires simultaneous joint event data superimposed with vertical load conditions.
	-0.1 to +0.15 (3)	± .005	(3) Based on nominal, new track stiffness under single axle response.
3. Rail Lateral Base Displacement	-.1 to +0.8 (4)	± .005	(4) Based upon stiffness of class 2 track with class 2 dynamic loads.
4. Tie Motion a) lateral translation	±.08 in (5)	±0.005	(5) Based on elastic deflection of track structure. Up to 1.0 in could be expected due to full truck loads
b) vertical translation	-0.10 to +0.4 (9)		
c) longitudinal translation	±.08 in	± .005	
d) rotation (vertical axis)	±0.45° (6)	± .01°	(6) Based on considerations of displacements as listed below.
e) rotation (lateral axis)	+0.08° (6)	± .005°	(7) Based on new track, newly spiked ties, nominal loads of 20 Kips/axle (Class 4 track)
f) rotation (longitudinal axis)	±0.7° (6)	± .01°	(8) Based on Class 2 track conditions, under single axle loads of 20-24 Kips. Under typical freight car truck loads, displacements of 2 to 2.5 inches might occur.
5. Lateral Rail Head Displacement	-0.15 to -0.2 to 1.5 (8)	± .005 ± .05	
6. Vertical Rail Head Displacement	-0.15 to +0.4 (9)	±.001(10)	(9) Based on track modulus of 2000 Lb/in/in, 40K axle loads on 70" truck, 70 ASCE rail (positive downward)
7. Longitudinal Rail Force	-50K to +100K (11)	± 10 Kips	(10) Based on compatibility with load accuracy.
8. Track Modulus	500 to 4,000 Lb/in/in (12)	(13)	(11) Based on CWR expansion under ΔT of 40°F
9. Longitudinal Rail Displacement	± 0.3 in	±0.01 in.	(12) Typical track ranges from 2000-3000 Lb/in/in; FAST track is extremely stiff at 4000 Lb/in/in; concrete tie track has been reported at 10,000 Lb/in/in.
10. Dynamic gauge widening	+0.05 to 0.5 (14)	±.005 in.	(13) Values are derived from load & displacement value.
	+0.05 to 2.0 (15)		(14) Based on nominal loads on new track (Class 6)
			(15) Based on Class 2 track and geometry near W/R limit.

K.5.3 DESCRIPTION OF WAYSIDE INSTRUMENTATION

This section provides an overview of the general instrumentation commonly used in the railroad industry to measure vehicle/track interactions at wayside stations. Load measuring techniques using conventional load cell and strain gauge instrumentation and discussed. Two types of displacement sensors are discussed: the conventional LVDT and the eddy-current concepts.

K.5.3.1 Load Measurements

Wayside wheel/rail loads are most commonly measured either directly on the rail using strain gauges or with the use of load-cell base plates at the rail/tie interface. A variety of strain gauge patterns have been used with varying degrees of success to measure both vertical and lateral loads.

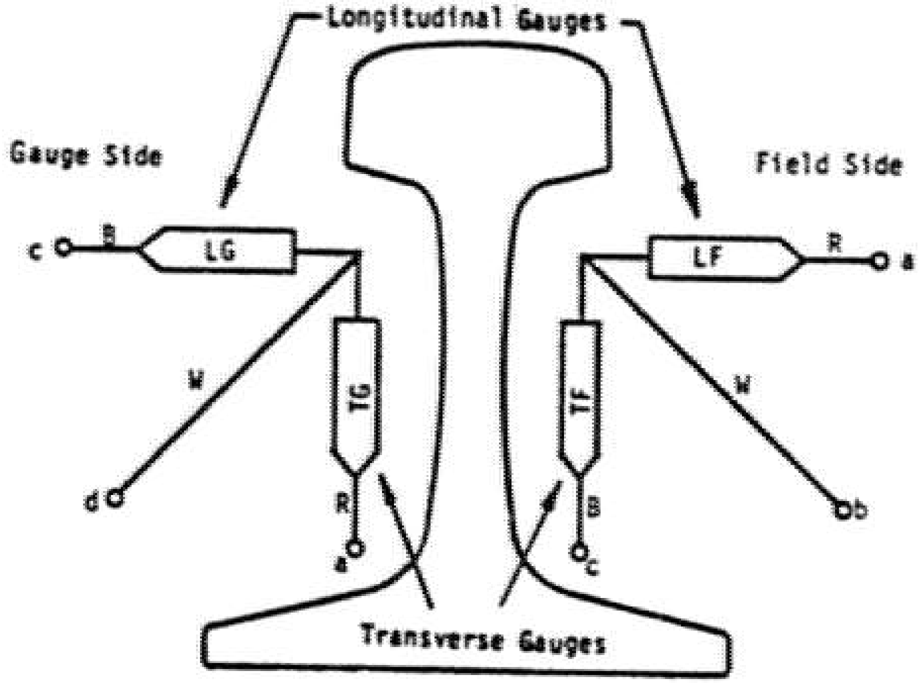
K.5.3.1.1 Strain Gauge Load Measurements

Strain gauges are commonly used to determine longitudinal, lateral and vertical loads in rails. Strain gauges directly measure the strain induced in the rail from which the load can be calculated or determined from a calibration curve.

K.5.3.1.1.1 Longitudinal Load Measurement

Longitudinal loads in rails are commonly determined by measuring the strain in the longitudinal and transverse direction on the web of the rail. Both two-arm and four-arm configurations are used. The four-arm configuration, shown in Figure K-5.1, consists of a two-arm configuration on each side of the web. The arrangement has the advantage over the single two-arm configuration in that the circuit compensates for rail bending in the horizontal plane. In both configurations, the strain gauges are attached to the rail at the neutral axis which helps to compensate for bending in the vertical plane.

The strain gauge configuration and electrical arrangement shown in Figure K-5.1 offer two useful benefits. First, the scheme compensates for effects of



NOTE: The physical gauge length is 1/8".

Gauge Lead Color Code

Black = B
White = W
Red = R

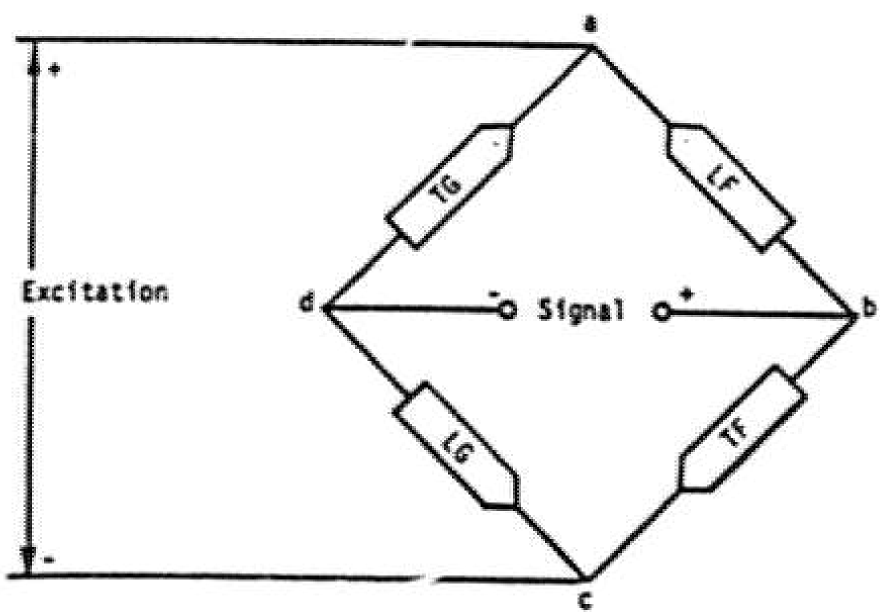
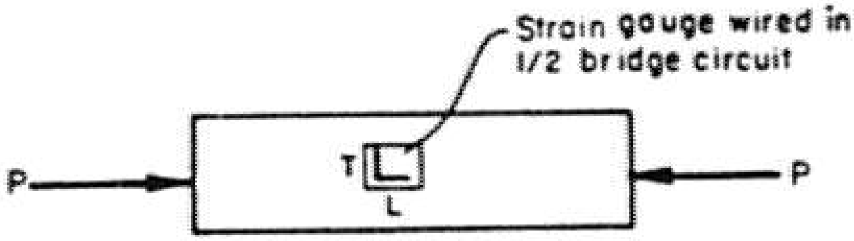


FIGURE K-5.1 WIRING FOR LONGITUDINAL LOAD FULL BRIDGE CONNECTION thermal expansion caused by temperature changes. If the expansion of the material is equal in all directions and not contrained, no force is generated therefore no strain is registered. Secondly, the bridge and strain gauge configuration is designed to provide a magnification factor of 2.6 (1.3 for the two-arm arrangement). The magnification factor for the half and full bridge weldable strain gauge circuits are determined as follows:



Assume no axial strain (ϵ) exists in the member. Thus, the element oriented in the direction of the strain (L in the sketch above) measures the strain (ϵ). The elemement oriented 90^{o} to the above element (T in the above sketch) will measure only the strain resulting due to the Poission's effect, or $\mu\epsilon$. Since the two elements are wired in a half bridge circuit, the two strain measurements are added. Thus the output of the circuit is:

$$\epsilon + \epsilon\mu \quad \text{or} \quad \epsilon(1+\mu)$$

From this, it can be seen that the quantity $1+\mu$ is the magnification factor. For this study, the Poisson ratio was taken to be 0.3. Thus the magnifications factor for the half bridge circuit of weldable strain gauge was $(1+0.3) = 1.3$.

For the full bridge circuit, each of the half bridge gauges has the above magnification factor. Thus for the full bridge circuit, the magnification factor is $2(1+\mu) = 2\,(1+0.3) = 2.6$.

Knowing the strain is a rail, the load (force) can be calculated from the following equation:

$$Force = EA\epsilon$$

Where, E is the elastic modulus of the material, A is the cross sectional area of the rail and ϵ is the measured strain.

K.5.3.1.1.2 Lateral and Vertical Load Measurement

In tests where lateral and vertical loads are needed, specific strain gauge schemes have been developed to perform the measurement. Figure K-5.2 shows the strain gauge configuration and electrical bridge used for each of the lateral and vertical load measuring techniques. For the lateral load measuring scheme, strain gauges are attached on the base of the rail at two locations on each side of the rail and connected electrically to measure the lateral bending moment of the rail. The specific details shown in Figure K-5.2 have been developed to eliminate "cross talk" from the vertical load components.

The configuration for the vertical load measurement also consists of a bending moment scheme where strain gauges are attached to the web of the rail at two locations on each side. This scheme, shown in Figure K-5.2, eliminates most of the "cross talk" from the lateral load components.

In both the lateral and vertical load schemes, the absolute load is determined by calibrating the instrumented rail section using a series of static loads which cover the range of loads expected in the test. The calibration procedure generates a linear plot of load verses strain.

K.5.3.1.2 Load Cell

Instrumented tie plates (Figure K-5.3) and K-5.4) have also been utilized to obtain rail/tie loads. If properly designed, installed and calibrated, instrumented tie plates can accurately measure the reaction forces at the rail/tie interface. A basic problem with instrumented tie plates is the potential for affecting the track structure characteristics (e.g., stiffness and load distribution).

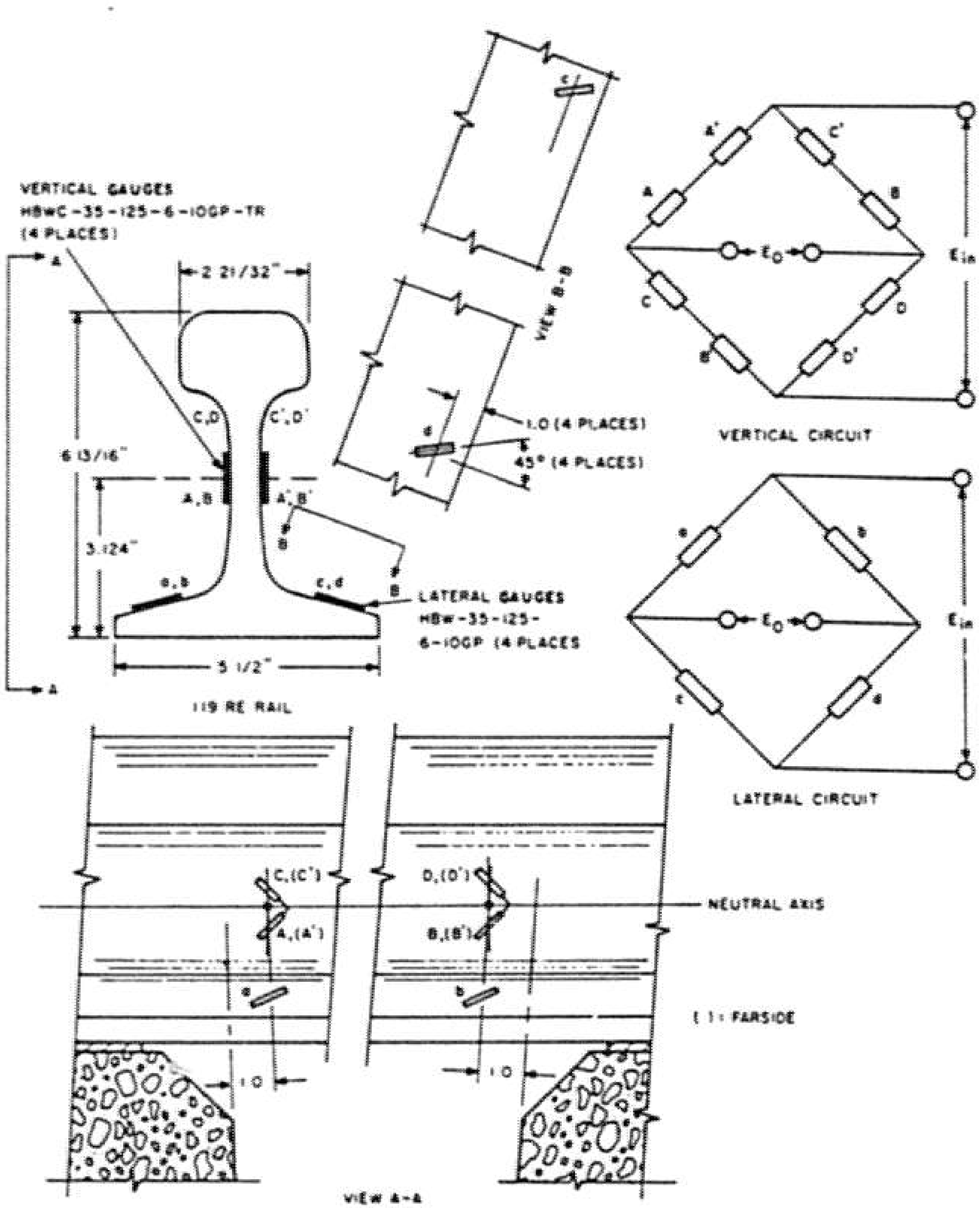


FIGURE K-5.2 TYPICAL IDENTIFICATION OF SPECIAL INSTRUMENTATION (L/V WHEEL-RAIL LOAD STRAIN GAUGE LOCATIONS AND CIRCUIT CONNECTIONS)

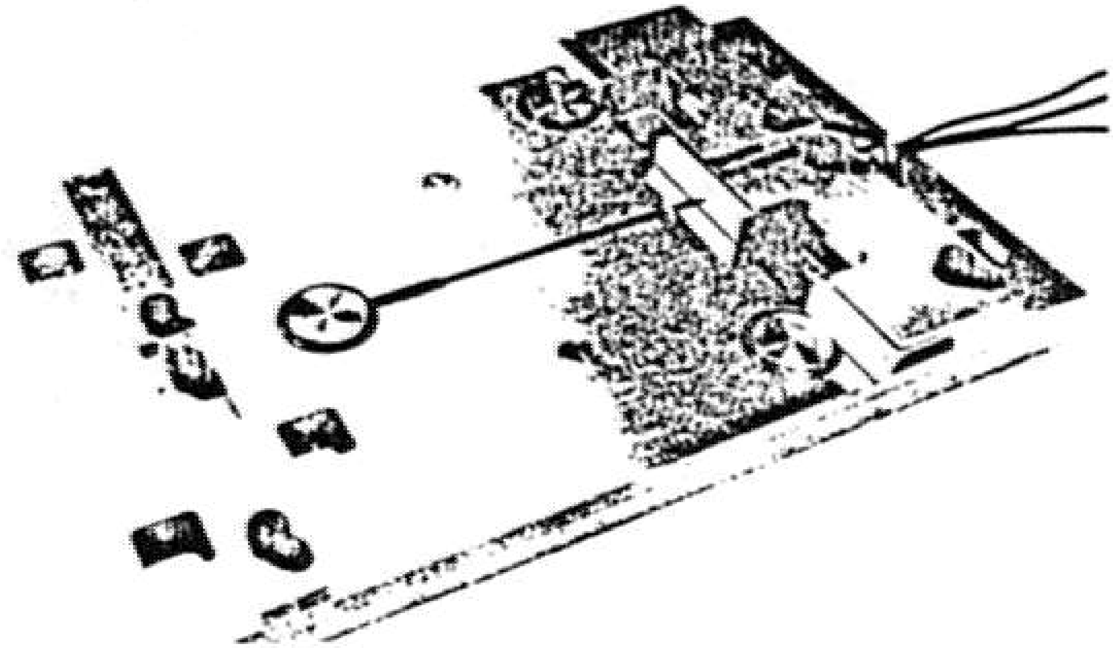


FIGURE K-5.3 LOAD CELL INSTRUMENTED TIE PLATE

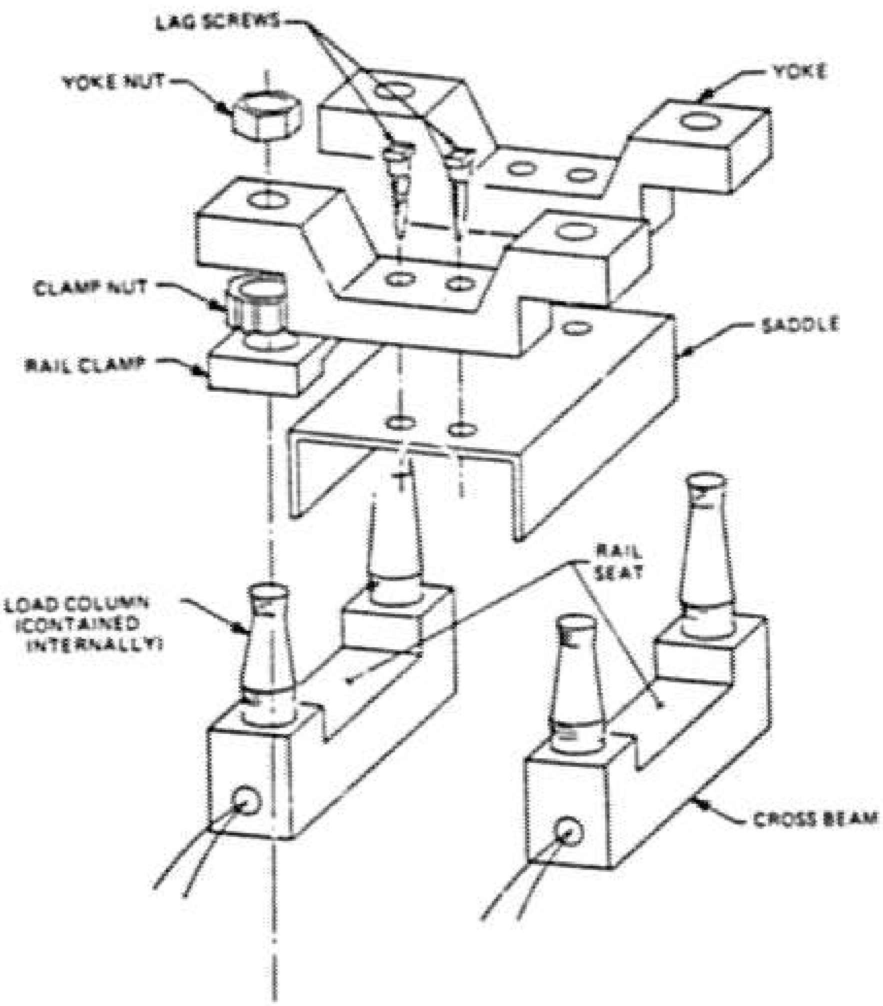


FIGURE K-5.4 VERTICAL AND LATERAL LOAD MEASURING TIE PLATE

K.5.3.2 Displacement Measurements

Wayside deflection measurements of the track structure have historically been obtained in one form or another for many years. Such measurements have been used for both rail and vehicle research and development. The utilization of these types of measurements, however, has been quite dependent upon the quality of measurement which could be made. For example, early measurements performed by the Talbot Committee in 1918 Ref. [22] utilized "Level Bars", "Depressions Plugs" and double exposure photography to obtain both static and quasi-static deflection measurements. The degree of accuracy which could be obtained with such "instrumentation" only allowed qualitative deflection measurements to be made -- therefore to infer dynamic track loading from such measurements, for example, would be nonproductive!

Currently linear variable differential transformers (LVDT's) are most commonly used to obtain both absolute and relative track structure measurements. Typically such transducers have provided seemingly good data for the types of test conditions to which they were subjected. The major problem with LVDT's results from the methods used to mount and attach these devices. The transducers themselves usually can provide the necessary performance capabilities with the possible exception of frequency response and adverse effects associated with certain environmental conditions. Typical LVDT instrumentation installations are described in Section K.5.3.2.1.

K.5.3.2.1 LVDT Instrumentation -- Methods for Measuring Static and Dynamic Track Deflections

Track deflection measurements include absolute deflections of the rail relative to a fixed reference, and relative deflections between track components. These deflections may occur in all six degrees of motion: vertical, lateral (transverse) and longitudinal translation; and angular motions of rail in roll (in the transverse plane), pitch (longitudinal rocking), or yaw. Vertical and lateral translation and rail roll angle are of primary interest for both static strength and dynamic displacement measurements. The longitudinal motion known as rail creep is of interest mainly for determining the ability of the rail anchor system to secure the rail longitudinally. Yaw motions of the track are considered of little consequence except, perhaps, under buckling conditions.

Several different absolute and/or relative measurements are needed to fully describe the upper track structure response to loads. The same basic measurements apply to both static and dynamic displacements. The requirements for the dynamic measurements are more stringent than the static measurement requirements because of the added frequency response needed and the need to provide for the survival of the transducer in the rugged operating environment of rail traffic. These displacements and their primary importance are:

(1) Rail vertical absolute displacement--used to define the track modulus and dynamic load/deflection characteristics.

(2) Rail head/tie lateral displacement--used to measure rail lateral restraint characteristics under both lateral and vertical loading.

(3) Tie/ground lateral displacement--data under traffic can document the occurrence of lateral shift of the tie in the ballast; used to establish track lateral strength limits.

(4) Rail rotation (roll)--used to document the mode of rail deflection and loading on tie/fastener system.

(5) Rail rotation (pitch)--used to determine loading environment on tie/fastener system.

(6) Rail/tie vertical displacement--used to determine dynamic load/deflection charactertistics and loading environment on tie/fastener system.

(7) Rail longitudinal displacement--used to determine tie/fastener rail restraint capabilities.

A major difficulty in measuring displacements is the establishment of references from which the measurements are to be made. Establishing "absolute" reference points adjacent to the track structure requires going deep enough, or far enough to the side of the track, to locate ground which does not move relative to the track. While pressures in the ballast/subgrade drop off quickly to something less than 3 lb/in^2 (21 kPa) at a depth of 40 inches (102 cm), both track structure modeling and field experiments have shown vertical deflections to decrease with depth more slowly. At a 40-inch depth, typically half the vertical deflection will still be measured.

Past experience has shown that absolute deflection measurements related to rail joint or rail fastener performance can be referenced to "ground" by attaching the transducer to a rod driven down into the subgrade. In the concrete tie track study Ref. [23], a 1-inch diameter steel rod was driven through a concentric hollow pipe casing through the ballast into the subgrade. The casing was about 4-ft long to isolate the rod from ballast movements; while the steel rod was 8 ft long and was driven into the ballast/subgrade until only about 8 inches projected above the ballast surface. In other field experiments, shorter rods have been used driven directly through ballast into the subgrade without benefit of the casing. Vertical deflections using a static calibration (viewed through an off-track transit) showed 0.18 inch deflection under a 30,000 lb (133 kN) point load. "Ground stakes" such as these have been used quite successfully for establishing reference points for lateral deflection measurements. When using this type of reference, the rod must be stiff enough to minimize deflections from any loads imposed by the measurement transducer. This is particularly important when dynamic measurements are being made which might excite a vibratory response in the reference rod. For the measurement of static lateral displacements, several programs have used 3-ft ground rods driven directly into the rail ballast. Since measurements were to be made at a number of different sites, the shorter rod allowed the rods to be installed and removed in a minimum of time. The errors introduced by the shorter rods were negligible since the displacements needed for the measurement of lateral track strength are large when compared with normal track deflections under traffic. A schematic diagram of a setup to measure lateral track displacements is shown in Figure K-5.5. The response of a section of track to lateral load exerted on the rail by hydraulic cylinders is shown in Figure K-5.6.

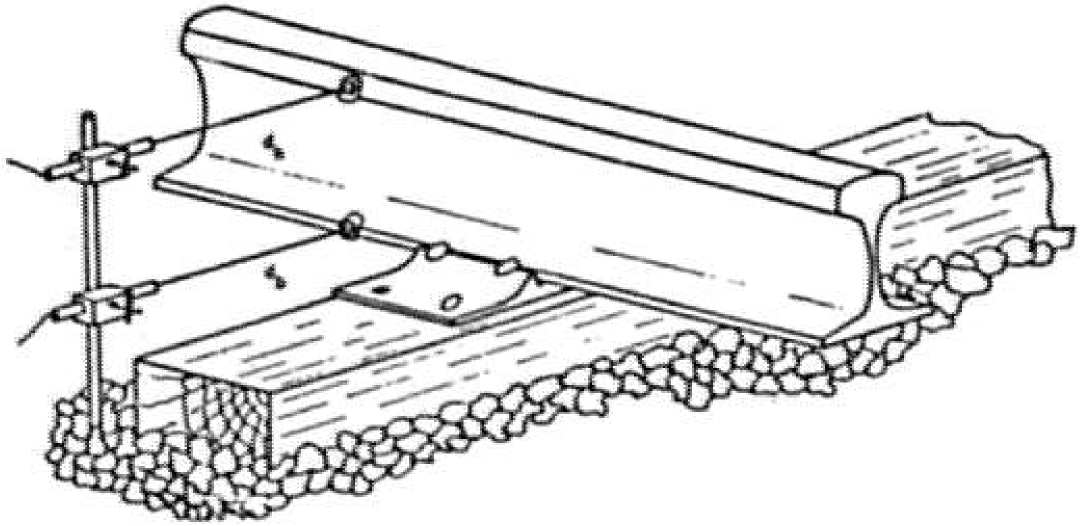


FIGURE K-5.5 DISPLACEMENT FIXTURE FOR ONE RAIL (SAME FOR OPPOSITE RAIL)

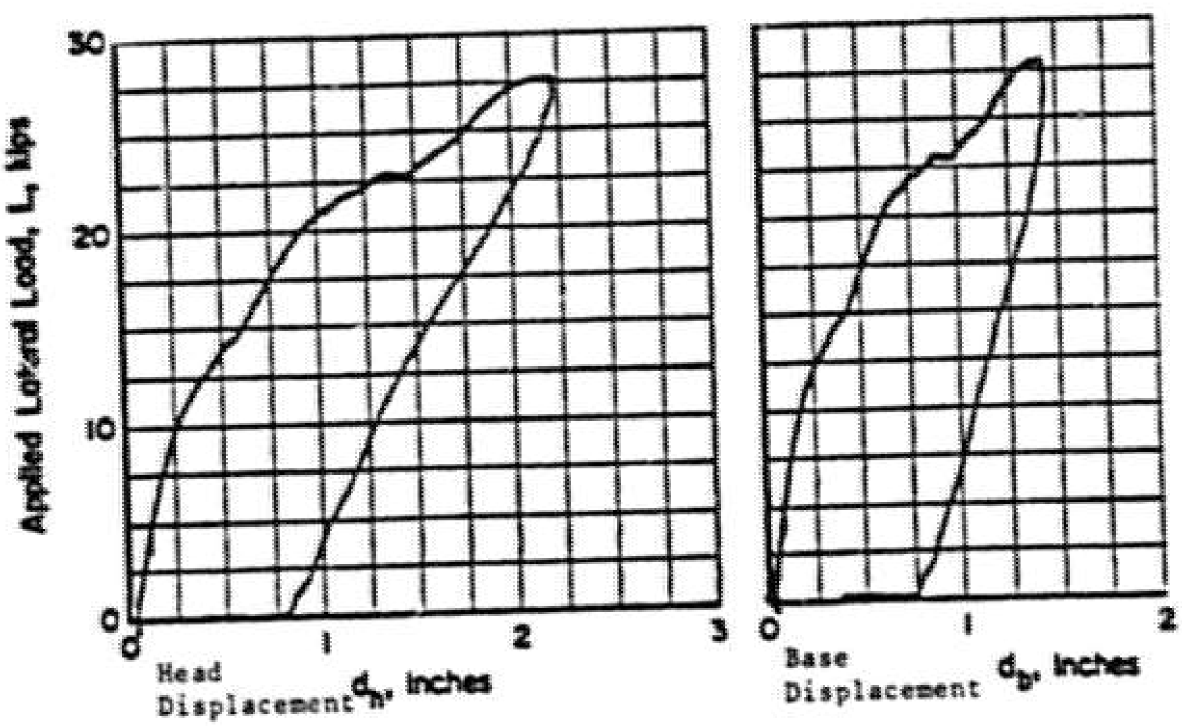


FIGURE K-5.6 LATERAL LOAD VS. RAIL HEAD AND BASE DISPLACEMENTS

Relative measurements must also be isolated from undesirable displacements. For example, if dynamic track gauge is to be measured and the tie is used as a reference for individual rail displacements, then tie bending could readily distort the intended output. The deflection fixture developed by Battelle for the Track Train Dynamics Program Ref. [24] is an example of a measurement system that provides displacement measurements of the rail without distortion from bending of a wood tie. A conceptual drawing of this fixture is shown in Figure K-5.7 and Figure K-5.8 shows the relative displacements which are measured. In addition, the fixture provides some degree of shock and vibration isolation for the transducers and signal conditioning electronics through elastomeric grommets and lag screws mounting the fixture to the tie. Acceleration levels on the tie can range typically up to 50 g under flat wheel impact loads. Typical deflection measurements from the fixture shown in Figure K-5.7 are illustrated in Figure K-5.9. Dynamic track gauge and rail rollover (of one rail only) under severe lateral impact loads due to empty freight car truck hunting are seen here, along with about 1 mm of permanent lateral shift of the tie.

In measurements on much stiffer concrete ties, a fixture which eliminates the effects of tie bending was found unnecessary. A conceptual drawing of a fixture used for recent measurements of concrete tie fastener/pad deflections Ref. [25] is shown in Figure K-5.10. Here the measured rail-to-tie displacements, along with fastener clip strains, were used to define the loading environment of rail fastener systems. Data were collected on both wood and concrete tie track segments containing a variety of fastener systems, and the results were reproduced in the laboratory to determine the required level of loading which simulated field conditions. The load levels so defined were then applied in fatigue tests of the fastener systems.

In an application of the fixture shown in Figure K-5.10, typical deflections for concrete and wood tie curved track are illustrated in Figures K-5.11 and K-5.12. Measurements were made with both deflection transducers and strain-gauged fastener clips. In these time histories of deflection under loaded FAST train cars, differences in "signature" between concrete tie track (Figure K-5.11) and wood tie track (Figure K-5.12) can be seen. On the concrete tie track, a combination curve and grade, the rail rolled outward and

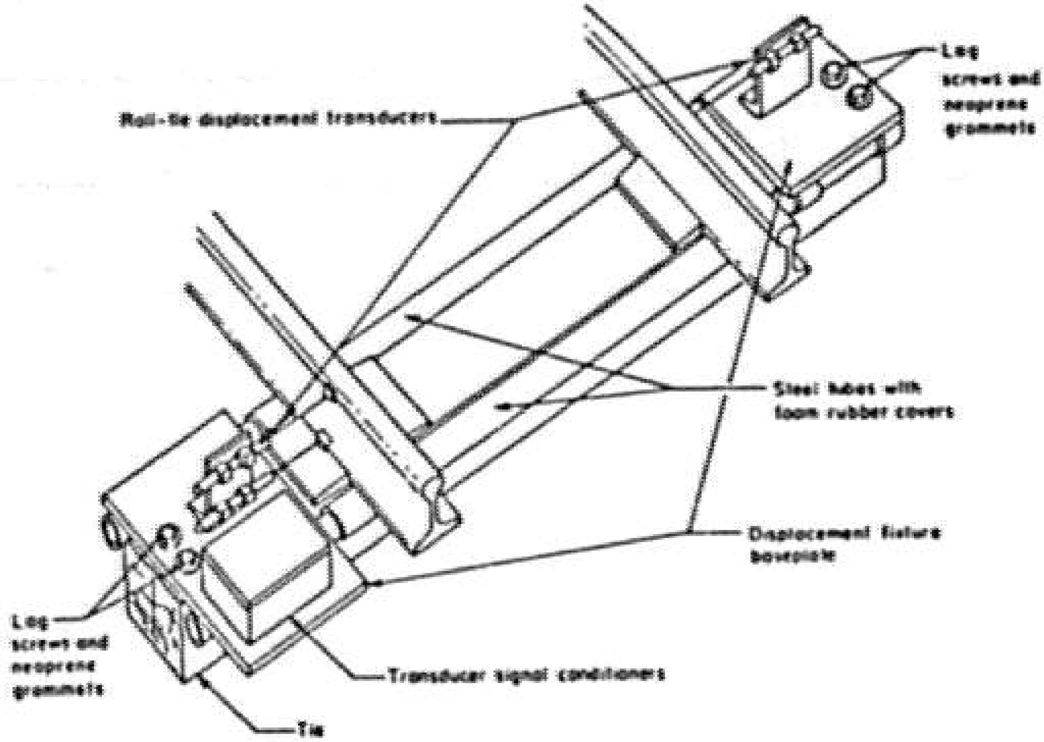


FIGURE K-5.7 STABLE BASE FIXTURE FOR UPPER TRACK STRUCTURE DYNAMIC RESPONSE MEASUREMENTS UNDER WHEEL/RAIL LOAD

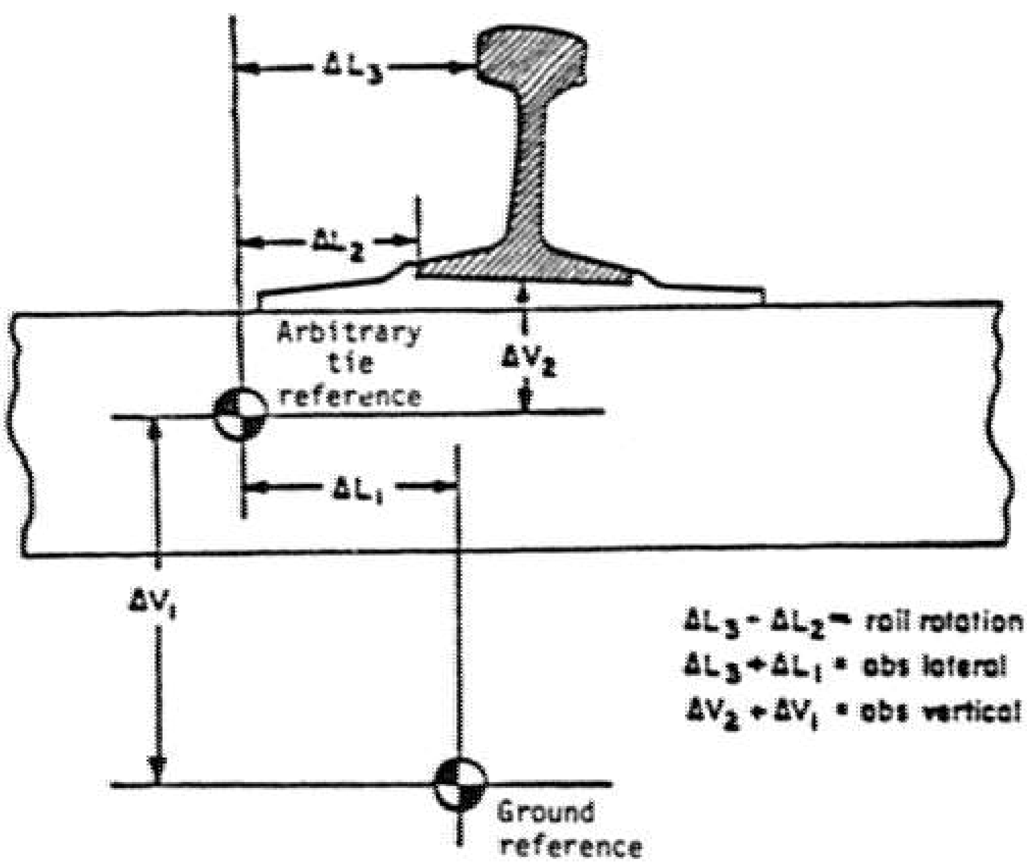


FIGURE K-5.8 MEASUREMENTS OF RELATIVE AND ABSOLUTE DISPLACEMENT NEEDED TO DEFINE UPPER TRACK STRUCTURE DYNAMIC RESPONSE TO WHEEL/RAIL LOADS

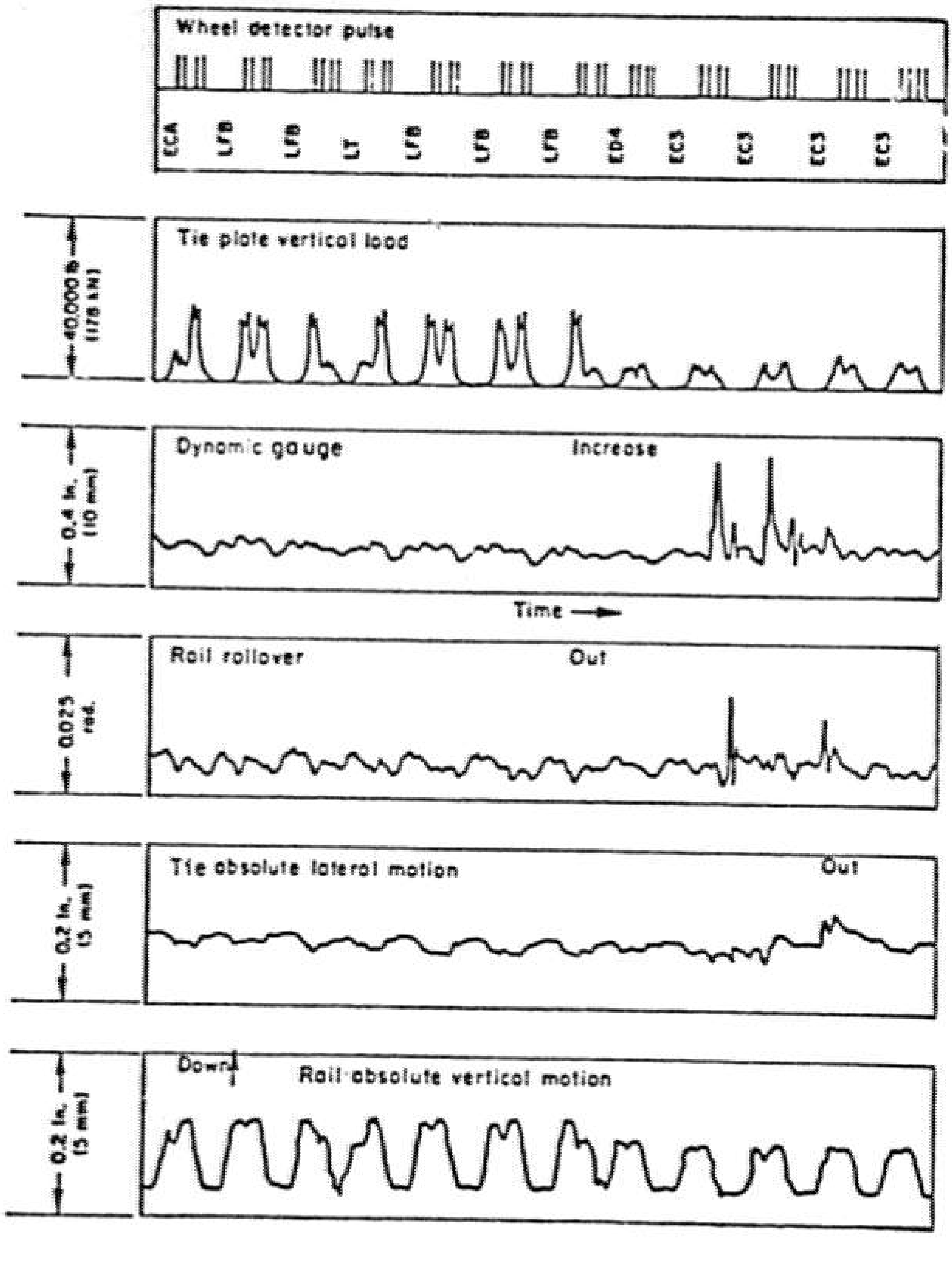


FIGURE K-5.9 TYPICAL TRACK DYNAMIC RESPONSE

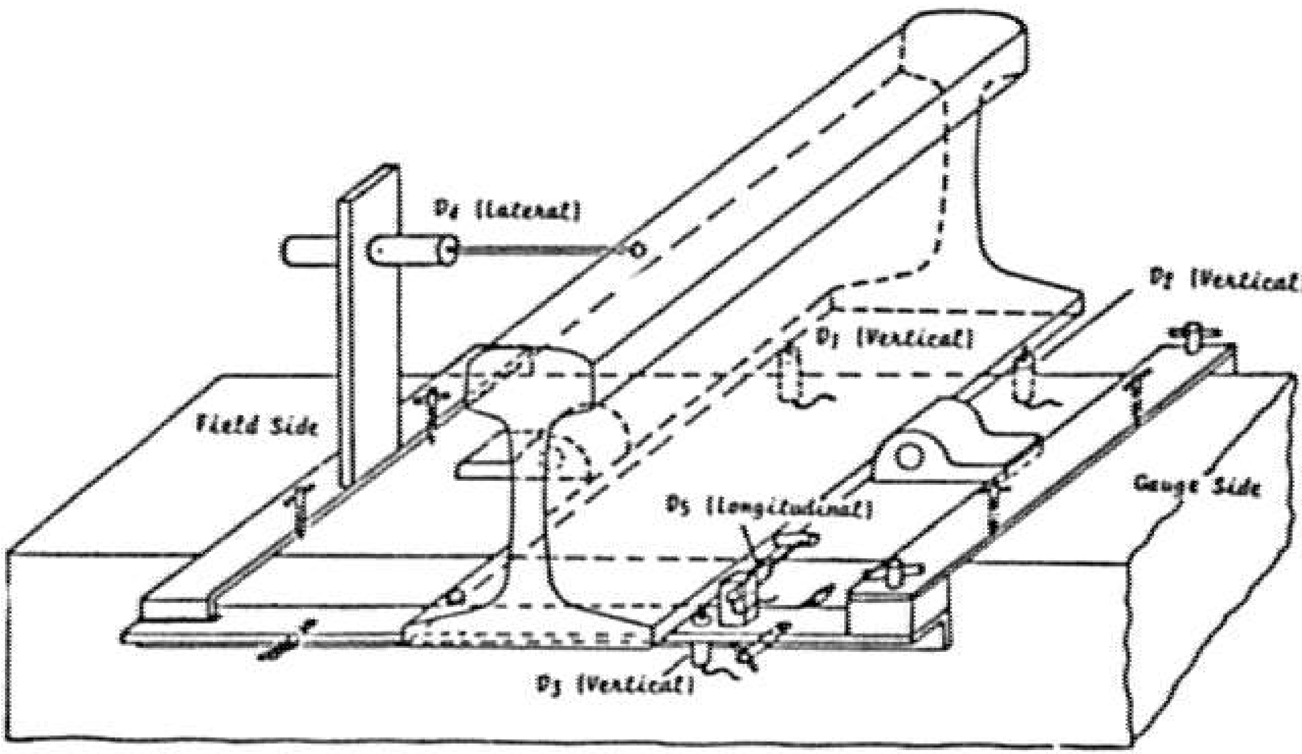


FIGURE K-5.10 FIXTURE FOR MOUNTING RAIL/TIE DISPLACEMENT TRANSDUCERS

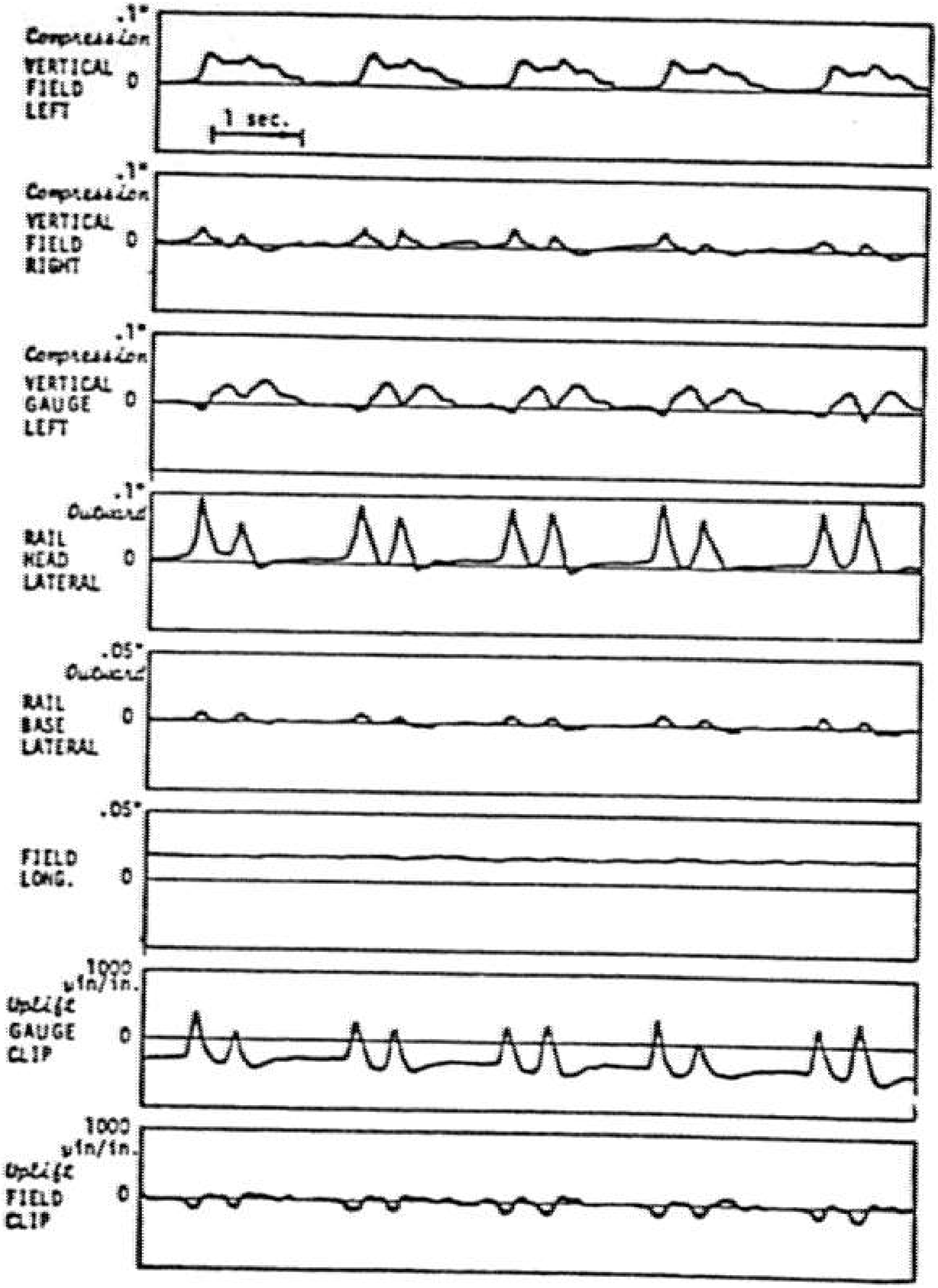


FIGURE K-5.11 TYPICAL RAIL/TIE DISPLACEMENTS AND FASTENER CLIP STRAINS ON CONCRETE TIE TRACK

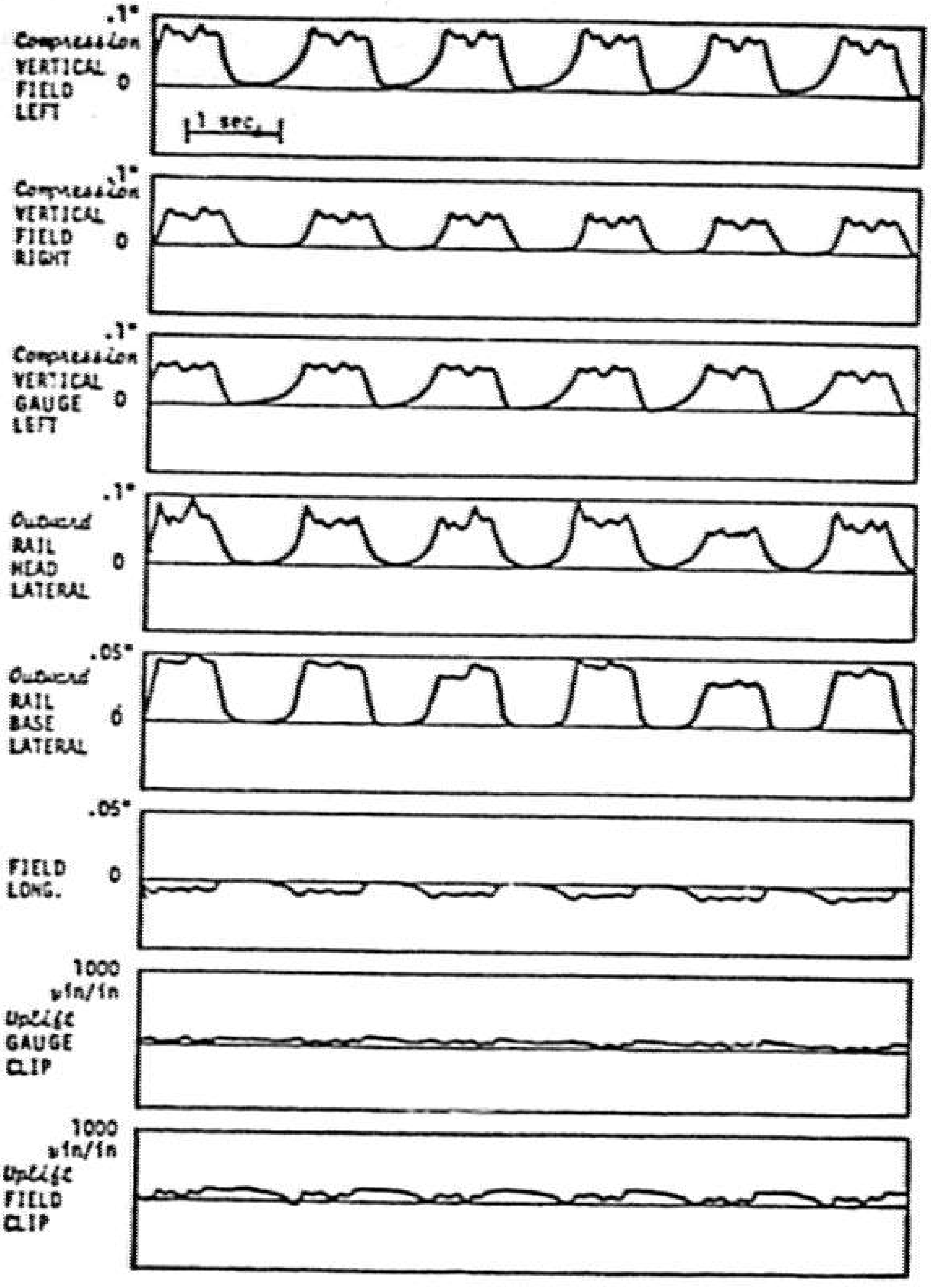


FIGURE K-5.12 TYPICAL RAIL/TIE DISPLACEMENTS AND FASTENER CLIP STRAINS ON WOOD TIE TRACK -- HIGH RAIL ON 5-DEGREE CURVE the gage clip received substantial uplift strain. The wood tie track was fastened with the same elastic clip attached to a steel tie plate. Very little clip strain developed, but the vertical rail/tie deflection was greater because the tie plate experienced bending as it conformed to the nonuniform surface of the wood tie.

In the fixture shown in Figure K-5.10 vertical rail deflections are measured relative to the tie. This measurement is useful in fastener evaluations, but is insufficient when trying to determine overall track vertical deflections or when track stiffness calculations are of interest. In order to obtain absolute vertical deflections a reference measurement point must be established outside the load influence zone of the ballast and sub-ballast. For normal stiffness track this requires a deeply driven ground rod which is isolated from the ballast movement. Once an isolated reference point is established then the methodology used for measuring the vertical deflections is the same as that used for measuring lateral deflections. A sketch of a fixture used in a recent field test is shown schematically in Figure K-5.13. Although it is restricted to small motions due to errors incurred when measuring large deflections good results were obtained from the fixture.

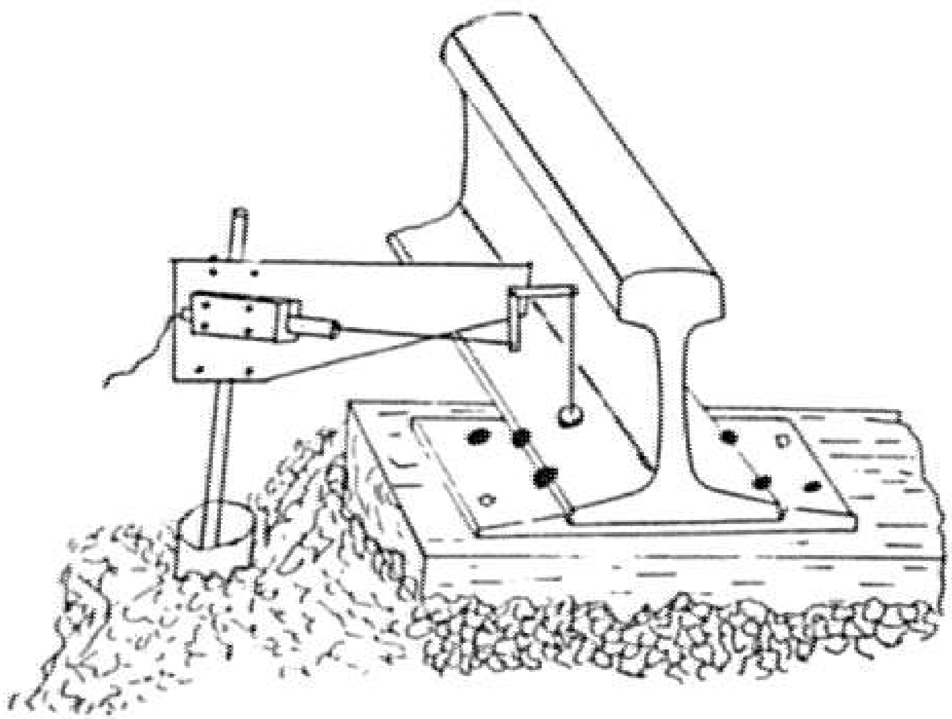


FIGURE K-5.13 VERTICAL DISPLACEMENT FIXTURE

K.5.3.3 DISPLACEMENT TRANSDUCERS

A variety of displacement transducers are suitable for making track deflection measurements. The optimum transducer type and range may vary, depending on the specific application. Criteria that must be considered in the choice of transducers are:

(1) Transducer range--track structural deflections may range from less than 0.25 inch (6.4 mm) to greater than 1 inch, full range (vertical deflections under load of 1-3/4 inches, 44.5 mm, have been observed at weak rail joints). Typical expected deflection ranges are shown in Table K-5.3.
(2) Transducer accuracy--resolution, linearity and hysteresis commensurate with measurement goals must be achieved.
(3) Frequency response--a transducer bandwidth of 100 Hz is usually sufficient for deflection measurements. Deflections decrease rapidly with increased frequency (remember, even a 500 g oscillation when at 700 Hz is only 10 mils).
(4) Instrumentation compatibility--power requirements, output voltage level and impedance, good signal/noise ratio, etc.
(5) Ruggedness--vibration tolerance and shock survival g levels suitable to transducer mounting point.
(6) Electrical noise immunity--not affected by stray electrical signals in rail due to signalling or power return.
(7) Electrical isolation from rail--cannot ground rail signals.
(8) Insensitivity to other motion degrees of freedom--primarily a function of the transducer mounting fixture design and transducer attachment scheme.
(9) Ease of calibration in situ--transducer must allow system end-to-end physical calibration under field conditions.
(10) Protection from environment--the transducer should preferably by hermetically sealed against moisture, salt spray, dust, sand, etc.
(11) Transducer cost.

TABLE K-5.3 TYPICAL EXPECTED DEFLECTION RANGES

	Concrete or wood tie track, positive fasteners, good condition	Wood tie track, cut spikes, good condition	Wood tie track, poor condition
Vertical, absolute	0.25 in (6.4 mm)	0.50 in (12.7 mm)	1.0 in (25.4 mm)*
Vertical, rail/tie	0.15 in (3.8 mm)	0.25 in (6.4 mm)	0.5 in (12.7 mm)
Lateral, rail head	0.25 in (6.4 mm)	0.75 in (19.1 mm)	1.5 in (38.1 mm)
Lateral, rail base	0.10 in (2.5 mm)	0.40 in (10.2 mm)	0.5 in (12.7 mm)
Longitudinal	0.10 in (2.5 mm)	**	**

* Greater deflections at joints in poor condition.

** Rail may "run" under traffic...must be checked at site.

Although the displacement transducer in itself does not affect the track characteristics, it is usually difficult (as discussed in the previous section) 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 at a point well away from the track. Ground vibrations have introduced noise into these measurements, or target lighting has caused problems. An Austrailian firm has recently introduced a laser tracking system with the detector head mounted to the rail and a tripod-mounted low-power laser set typically 16 ft (5 m) away from the track. A range of $\pm$10 mm (0.4 inch) and a frequency response of 0 to 1 kHz is noted in the technical specifications. Other optical units have appeared on the market, but the cost and complexity of the units are considered prohibitive.

Noncontacting displacement transducers (the eddy current type) have sufficient accuracy and frequency bandwidth for the majority of dynamic displacements of interest. The range of such noncontacting transducers is marginal for some static deflection measurements, the maximum range of currently available units being 2 inches or less. The eddy current displacement units also have the disadvantage that they must be calibrated at each installation to correct for different target geometry and material properties as these parameters affect the transducer gain, offset, and linearity. Another disadvantage of the eddy current transducers is that as the effective maximum range of the transducer increases, the size of the transducer also increases. This may cause problems with clearances and/or obtaining a target of sufficient size.

Contacting transducers utilize either direct attachment or a spring-loaded plunger to attach to the measurement point. The two main types of contacting transducers are potentiometers and the Linear Variable Differential Transformer (LVDT). Both types are available with ranges and accuracies suitable for track deflection measurements. Contamination of the sliding electrical contact may present problems with potentiometer units. This contact is also subject to shock and vibration problems in the severe environment presented during dynamic measurements. Linear Potentiometer type displacement transducers are superior to the cable actuated potentiometer transducers. Both units should perform satisfactorily for static measurements, but when using cable type potentiometers ("string pots") care must be taken to eliminate cable vibration which would give measurement errors. Obtaining sufficient frequency response for dynamic measurements can present a problem for cable-type potentiometers. 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. The main advantage of potentiometer units is low cost.

Direct fixation of the core of differential transformers is less of a problem because their weight; and consequentially, attachment forces are low. In the past nonmagnetic threaded "ready rod" has been used to attach the transformer core to the rail components. A phenolic block cemented to the rail has proven quite successful as a means of attaching to the rail head and/or base. The cemented block is able to withstand the high rail acceleration levels (shock pulses over 1000 g have been recorded under flat wheels) and provide electrical isolation from the rail. The rod also provides sufficient isolation from orthogonal motions of the rail, particularly the rail "running" motion in the longitudinal direction, yet is reasonably immune to its own transverse vibrations. This arrangement is susceptible to ice, ballast, or dragging equipment, and for more permanent installations a protective shroud is recommended.

Past experience has shown that the Linear Variable Differential Transformer (LVDT) offers excellent performance characteristics for measuring dynamic displacements. The LVDT consists of a primary transformer winding excited by a sinusoidal voltage of 3 to 15 volts rms amplitude, and a frequency from 60 to 20,000 Hz. Two series-opposing secondary windings have sinusoidal voltages induced in them by the primary. As the iron core of the transducer is moved relative to the secondary windings, a larger mutual inductance (coupling) is induced in one relative to the other, and a net voltage increase is produced from the device. The output voltage undergoes a 180 degree phase shift when going through the null (zero) position Ref. [26]. A fully-integrated version of the LVDT, called the DCDT, has built-in high-frequency excitation and signal conditioning, providing the demodulated direct-current signal at the output. This transducer provides a DC signal directly proportional to the relative displacement of the core to the transducer body. Output voltage levels range up to ± 20 volts full scale for an excitation up to 30 volts DC (older models required both the plus and minus voltage polarities). Typical DCDT specifications range as follows shown in Table K-5.4.

TABLE K-5.4 TYPICAL DCDT SPECIFICATION RANGES

Working Range*	Frequency Response (-3 dB)	Linearity	Ripple
0.050"	300 to 500 Hz	0.025% to	0.5%
0.10 to 0.25"	115 to 500 Hz	0.5% of	to 1%
0.50 to 2.00"	100 to 110 Hz	full	of full
3.0 to 10"	50 to 75 Hz	scale	scale

*30% to 50% overrange is typical.

These transducers are extremely rugged, with typical mechanical specifications allowing a vibration tolerance of 10 g at 2 kHz, and a survival shock level of 250 g for 11 milliseconds pulse duration. Therefore, the transducer can operate satisfactorily in the shock and vibration environment typical of the railroad tie, but cannot be mounted directly to the rail.

K.5.3.4 Noncontact Displacement Sensors

The purpose of this section is to present some preliminary design concepts which illustrate the overall system application of noncontact displacement sensors. It should be emphasized that the drawings presented are concept drawings only and should not be considered as preliminary design drawings.

K.5.3.4.1 Basic Design Constraints and Guidelines

A properly designed wayside measurement system should not interfere with routine maintenance operations or noticeably affect track structure characteristics. Therefore, it is necessary to identify those constraints which would affect the design of such a system. The primary concern is with the basic reference platform structure and support pedestals.

Figure K-5.14 shows a crib area cross-section which would dictate the maximum reference platform beam size for a cross-beam design configuration. Per discussions with TSC personnel, it appears reasonable to allow W to equal the crib width if necessary as long as H is less than or equal to the tie height and avoids contact with the rail under loads.

The design constraints which would be imposed by maintenance requirements are somewhat dependent upon a specific design configuration for a wayside measurement system and the maintenance policies associated with special way side equipment. For example, if a cross-beam were placed beneath the rails in the crib area, it would obviously need to be removed during automatic tamping operations. However, depending upon maintenance policies, it may be permissible to manually maintain or defer maintenance on selected crib areas. If a cantilevered instrumentation mounting beam were utilized, a relatively small portion of the outlying crib area would need to be disturbed.

One of the primary tasks which must be addressed in the development of a wayside measurement system is the optimum design and location of the reference platform support pedestals. This task was not within the scope of this discussion. However, to establish guidelines for such a task, Figure K-5.15 was prepared based upon discussions with personnel at the Transportation Test Center (TTC) in Pueblo, CO.

The last guideline considered in regard to the instrumentation support structure is the degree of height adjustment which may be needed. If some type of semi-permanent installation is contemplated, it should provide height adjustment capability. Per discussions with TSC personnel, a total height adjustment of 2 inches should accommodate normal subgrade settlement.

K.5.3.4.2 Instrumentation Mounting Beam Concepts

Selection of the best instrumentation mounting beam configuration and support structure is dependent upon the intended application as well as upon the optimum location, etc., of the support pedestals. If portability is of primary concern, then a configuration which minimizes installation disturbance

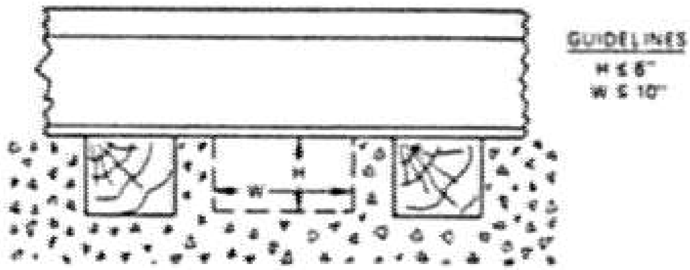


FIGURE K-5.14 ALLOWABLE CROSSBEAM ACCESS AREA

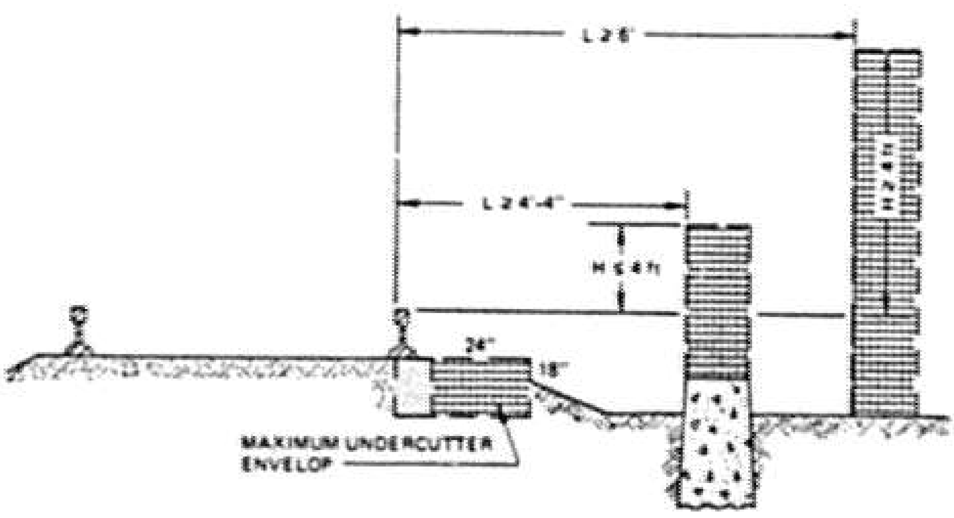


FIGURE K-5.15 WAYSIDE EQUIPMENT CLEARANCE REQUIREMENTS of the track structure is very important. On the other hand if a measurement system is being considered for a semi-permanent installation, then the initial installation requirements are not as critical.

Selection of the best instrumentation support beam configuration cannot be made until a detailed design and analysis study has been performed. A trade-off study is needed which includes a vibration analysis of the various design configurations based upon realistic vibration environments and representative soil/ballast conditions. Two basic instrumentation mounting beam configurations are discussed
below.

K.5.3.4.2.1 Single Cross Beam Configuration

This approach would utilize a cross beam beneath the rails supported by two pedestals located in the vicinity of the ballast shoulder. If a metal beam were used, one end of the beam would be restrained in all three orthogonal axes and against rotation about the beam longitudinal centerline. The opposite end would be allowed to float in the direction of the beams' longitudinal axis to prevent excessive thermal expansion forces from being transmitted to the pedestal. Height adjustment of the beam could be accommodated by the use of shims which would be placed at the pedestal to beam interface. Some type of trough would most likely be required to isolate the cross beam, to aid installation, and to minimize the loss of ballast support for the adjacent ties.

If a suitably designed composite beam were utilized as depicted in Figure K-5.16, then thermal expansion effects would be insignificant such that a "floating end" could be eliminated. As shown in Figure K-5.16, four degree of freedom alignment units (i.e., swivel mount with a vertical lead screw adjustment) would be utilized to facilitate set-up and adjustment of the measurement system.

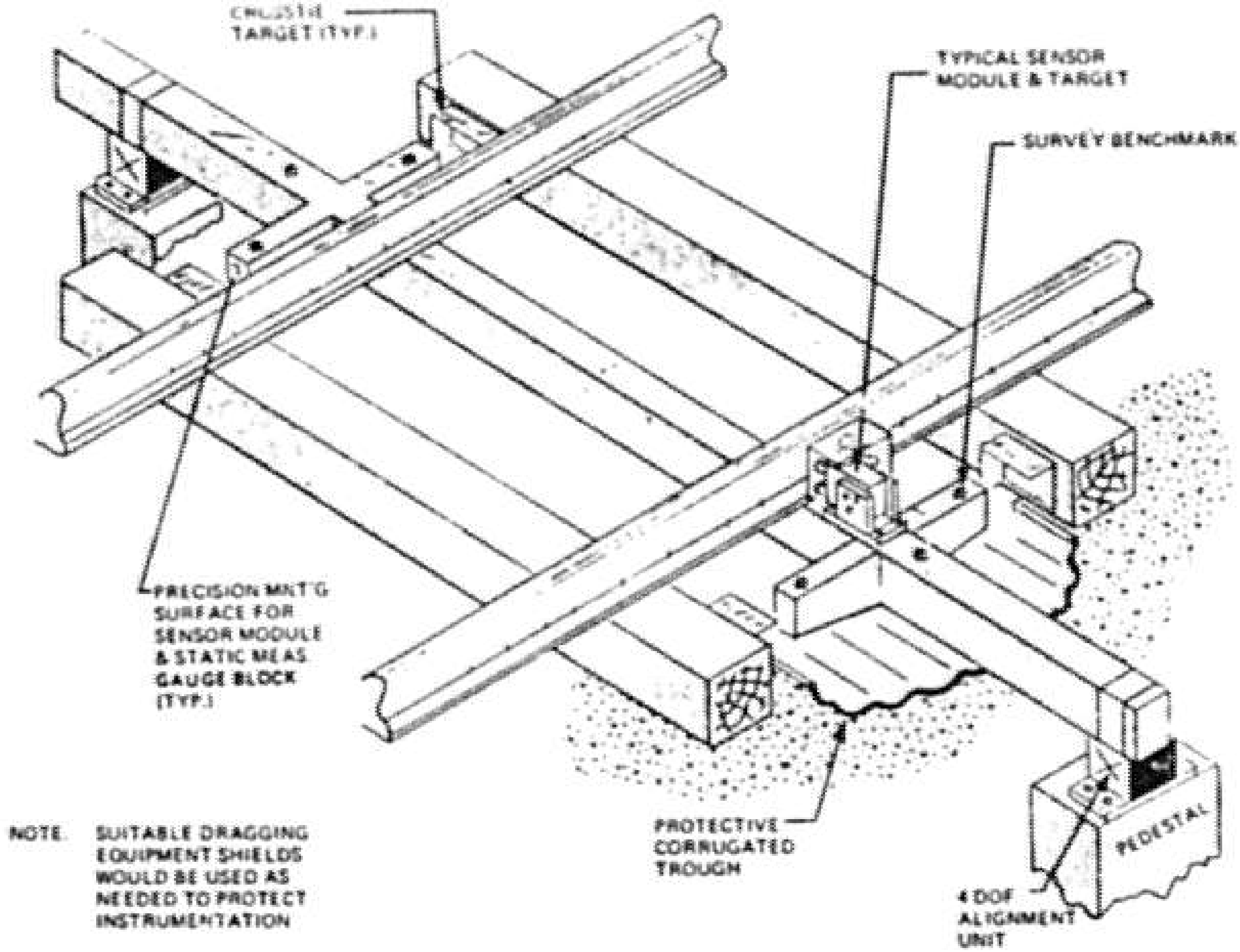


FIGURE K-5.16 SINGLE CROSS BEAM INSTRUMENTATION MOUNTING CONFIGURATION

K.5.3.4.2.2 Cantilevered Beam Configuration

A potential problem with the cross beam configuration mentioned above is the need to remove a good portion of the ballast in the crib area and the somewhat limited access area which results.

A second mounting beam configuration is shown in Figure K-5.17. This approach would utilize two cantilevered mounting beams on the field side of each rail. The main advantage of this approach is the minimal disturbance of the crib area due to installation of the mounting beams. A disadvantage would be the added complexity and cost associated with two separate mounting beams. In addition, the calibration requirements for this configuration might be somewhat more involved. The cantilever approach could, however, lend itself to a completely portable system for short term, dynamic tests in that the support pedestals could be designed to be portable (e.g., the pedestals would consist of stackable "dead-weights" installed at grade with minimal site preparation).

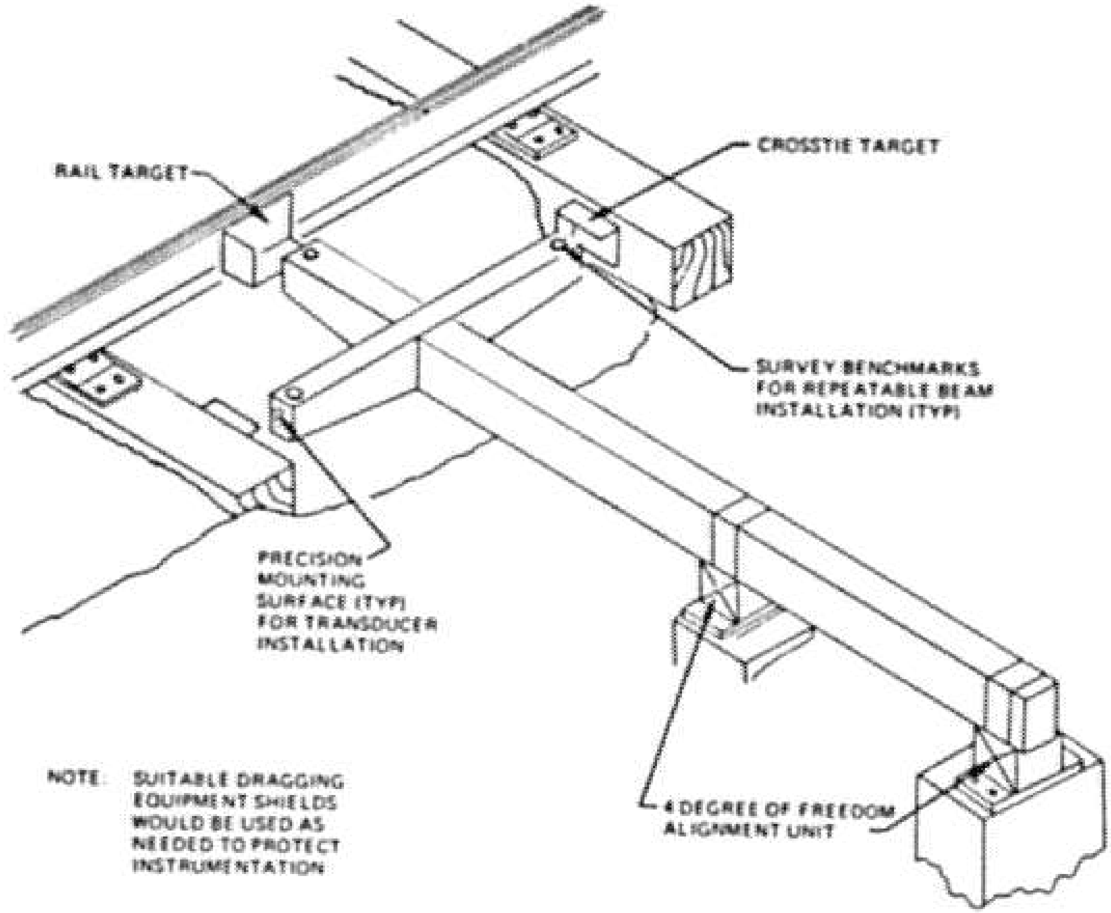


FIGURE K-5.17 CANTILEVERED INSTRUMENTATION MOUNTING BEAM CONFIGURATION

K.5.3.4.2.3 Use of Composite Materials

As shown in Table K-5.3, the accuracy requirements for the type of measurement system under study are quite stringent (e.g., 5% displacement accuracy). Such requirements present some challenging design problems in terms of the reference platform support structure. Of special concern are the adverse effects of thermal expansion and ground vibration.

A very promising design approach is to utilize a specially formulated composite material to fabricate the instrumentation support beams. This relatively new composite has a near-zero coefficient of thermal expansion and a high modulus of elasticity. The material thus combines exceptional dimensional stability over a wide temperature range with unusually high st-ength and stiffness.

The composite consists of graphite fibers and glass fibers in a plastic resin matrix. The graphite fibers have a negative coefficient of thermal expansion, and the glass fibers and resin matrix have a positive coefficient; that is, the graphite contracts and the glass and resin expand as the temperature increases. When the materials are combined in the proper proportion, they produce a nearly thermally-inert composite material. The final product is only three-fifths as dense as aluminum, yet has an elastic modulus of 18 to 24 million psi.

Personnel experienced in composite materials and fabrication have reviewed the application requirements associated with a wayside measurement system and agree this would be an excellent application for composite materials. Results of a preliminary engineering study for a 14 ft. composite cross beam as shown in Figure K-5.16 and an 8 ft. cantilever beam (Figure K-5.17) show that the weight of the beams themselves would be approximately 35 lbs. and 20 lbs. respectively. Due to the high strength to weight ratio of these materials, it is estimated that the beam natural frequency, including sensor modules, would be in the neighborhood of 200 Hz or better.

K.5.3.4.3 Sensor Modules

As discussed in Section 6, three displacement transducers are required (per rail) to determine rail translation and rotation in a vertical plane perpendicular to the longitudinal rail axis, and a fourth transducer is needed to obtain longitudinal rail deflection (per rail).

A basic requirement associated with the sensor triad used to derive rail section vertical/lateral translation and rotation is the need to locate a pair of sensors relative to the same target surface which is at a right angle to a second target surface seen by the third sensor.

To optimize noncontact sensor performance, clamp-on aluminum rail targets would be utilized as discussed in Section K.4.4.4. Therefore, the actual location of the sensors is dependent upon the final design configuration of both the target and the instrumentation reference platform. The overall objective is to design a single sensor module which could house up to 4 different transducers. If properly designed, one "standard" sensor module could be used at any measurement location.

Figure K-5.18 is a concept drawing of a candidate sensor module. Up to 4 individual eddy-current type transducers could be mounted in the module such that 3 different orthogonal target surfaces could be monitored. To properly install the sensor module and align it with the target, six adjustment degrees of freedom are required. These adjustments would be obtained as indicated in Figure K-5.18. Certain coarse alignment adjustments would be made during the initial installation of the support beam.

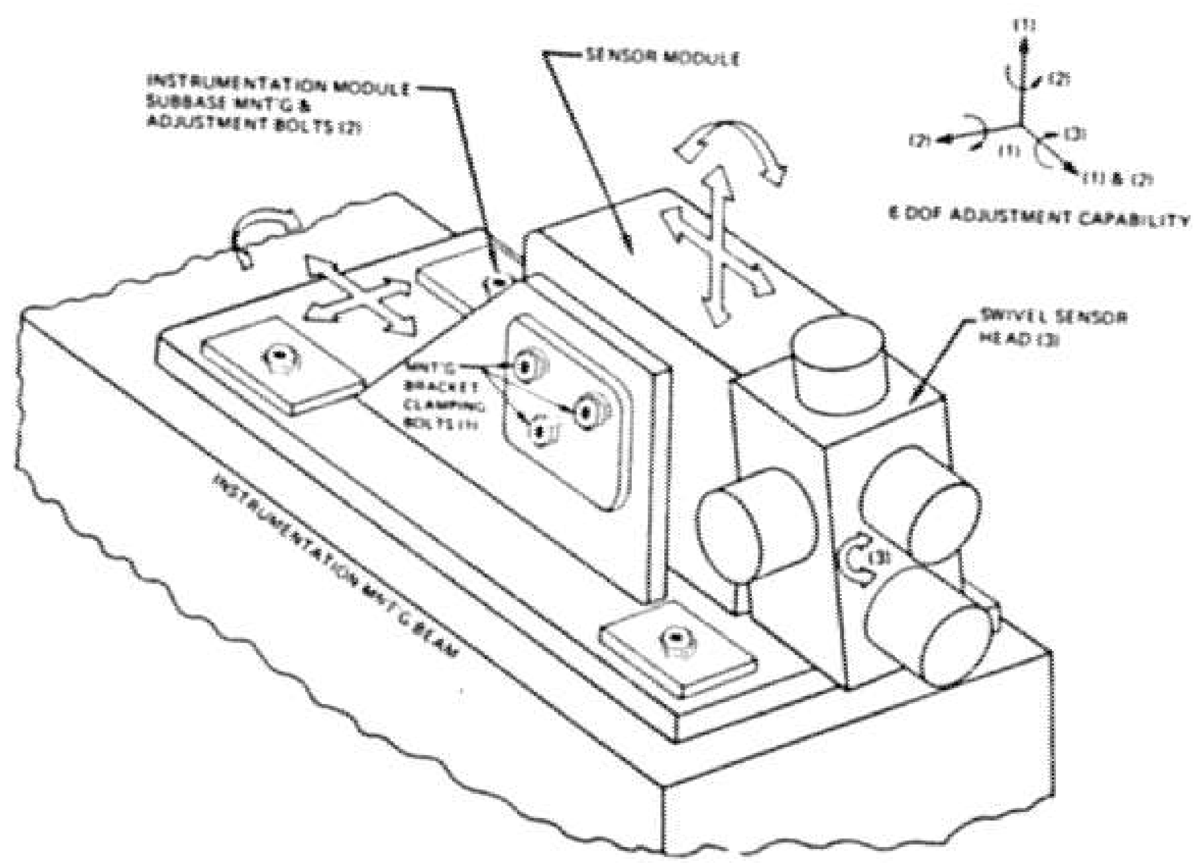


FIGURE K-5.18 SENSOR MODULE MOUNTING CONCEPT

K.5.3.4.4 Targets

Although these sensors can certainly operate under a wide variety of conditions, eliminating certain adverse affects due to target variations has several distinct advantages. One of these is the potential elimination of transducer calibration. If identical targets are utilized, a measurement system (i.e., transducer, cable, and electronics) can be initially calibrated and then successfully utilized in different test setups without recalibration as long as the same identical system components are used. Another significant advantage of course is the elimination of target geometry and surface irregularities.

Fortunately, a wayside measurement system lends itself quite nicely to the use of attached targets. In the case of rail measurements, a conceptual rail target such as shown in Figure K-5.19 would be used. The target would be designed to accommodate 115RE to 140RE rail. Such a target could be easily attached or removed from a rail in several minutes. For tie measurements, a simple 3-sided aluminum target such as shown in Figure K-5.20 would be used. The tie target would either be attached with screws or glued in place depending upon the type of the tie being measured (i.e., wood or concrete).

K.5.3.4.5 Support Pedestals

More detailed analysis and possibly some field testing is required to determine the optimum placement and design of the support pedestals. Basically two pedestal configurations can be considered, one for permanent type installations and another for portable installations. In terms of a permanent or semi-permanent installation, the following tradeoffs and design considerations need to be made:

- o Fabricate ("pour") on site or utilize pre-cast, "drop-in-place" pedestals

- o One piece design or a two piece design which could be partially removed to accommodate major track maintenance

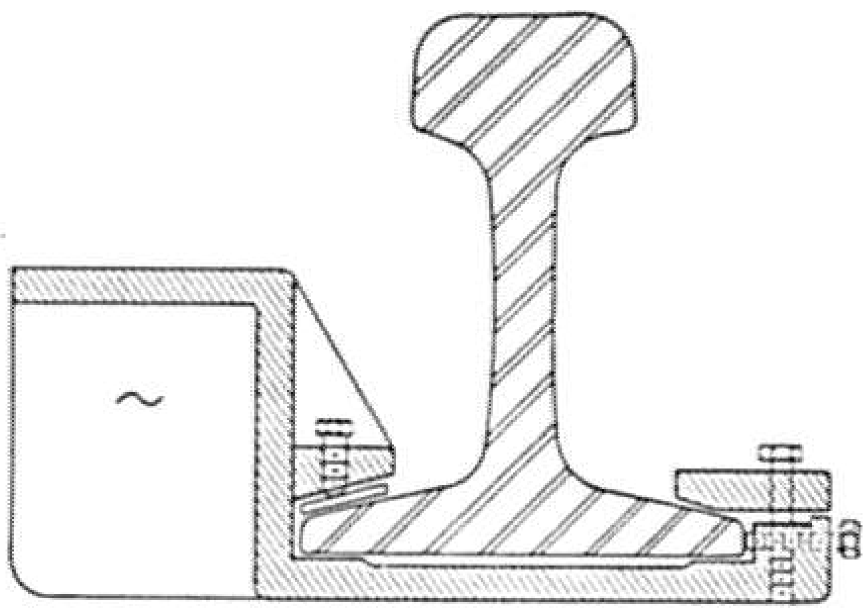


FIGURE K-5.19 CLAMP-ON RAIL TARGET (CONCEPT DWG)

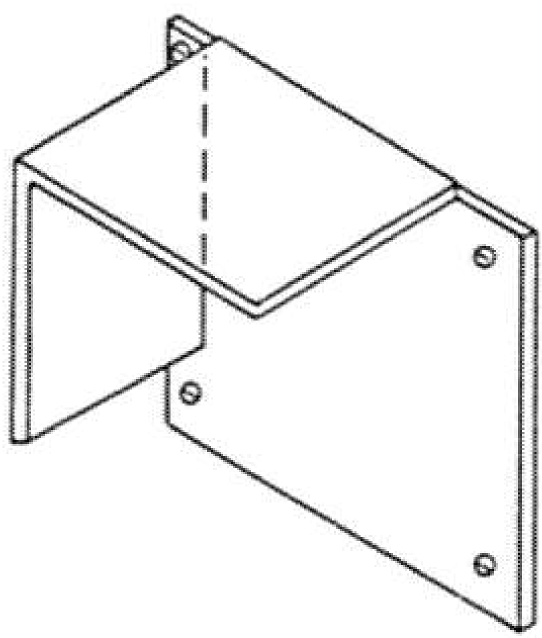


FIGURE K-5.20 TYPICAL CROSSTIE TARGET

- o Design techniques for vibration isolation (e.g., Styrofoam casing, shock mounts, etc.)

- o Optimum depth and placement relative to the rails

Figure K-5.21 shows a modular "building-block" approach which would result in a very portable instrumentation system. Each support pedestal would be comprised of a suitable stack of "building block" units which would interlock when assembled. Coarse height adjustment would be controlled by the number of pedestal modules utilized. Fine adjustment would be accommodated in the 4-DOF alignment unit as shown in Figures K-5.16 and K-5.17.

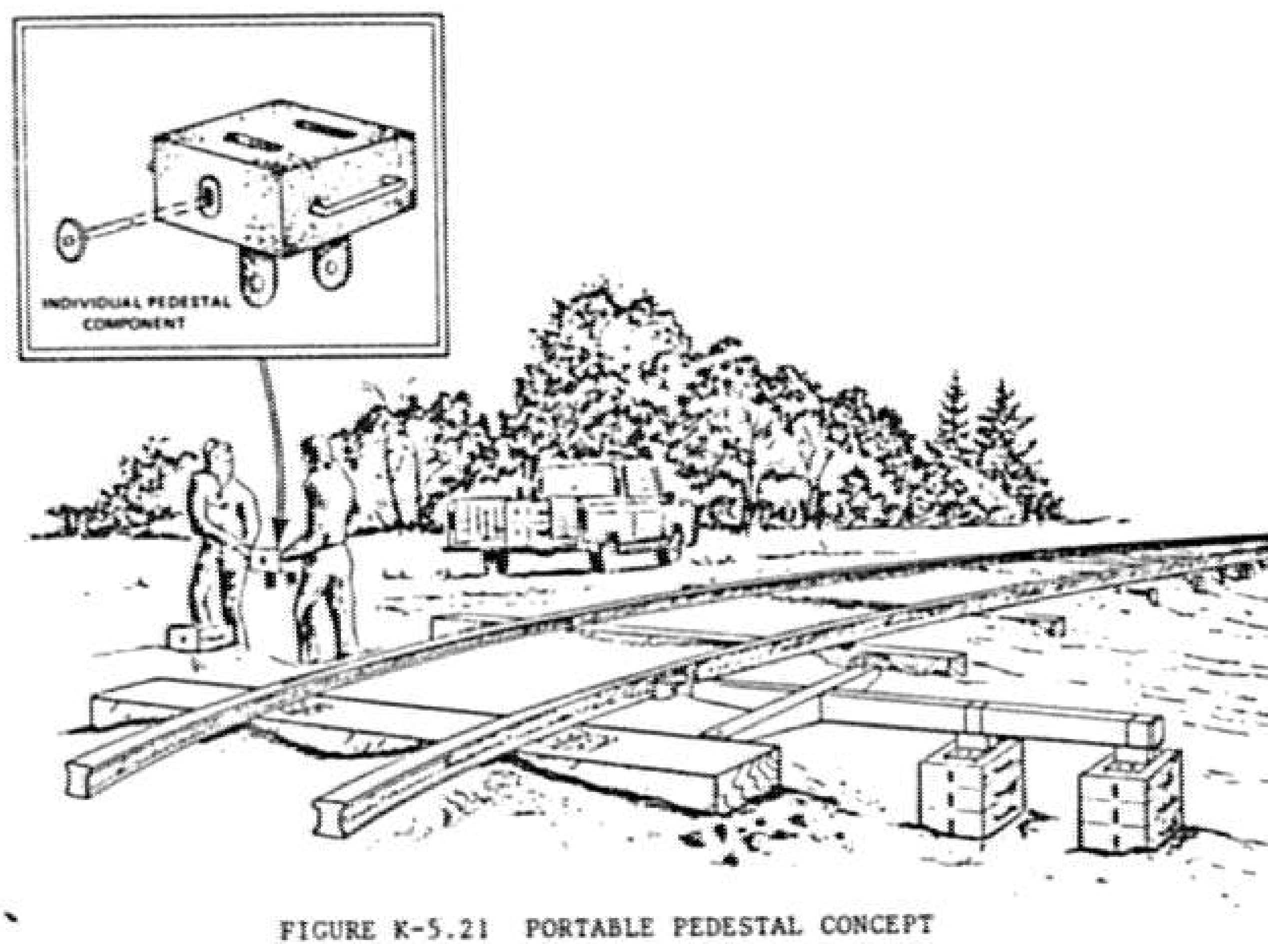


FIGURE K-5.21 PORTABLE PEDESTAL CONCEPT

K.5.3.4.6 Discussion of Installation and Calibration Procedures

Detailed installation and calibration requirements are quite dependent upon the final design configuration utilized and the particular maintenance procedures which would be associated with a given test site. However, some general procedures are discussed below.

K.5.3.4.6.1 Support Beam Installation

Assume a portable instrumentation system as depicted in Figure K-5.21. A general procedure for installing the support pedestals and instrumentation mounting beam would include the following:

1. Prepare "at-grade" pedestal locations.

2. Build-up suitable pedestals using interlocking pedestal block modules.

3. Place instrumentation support beam on pedestals and adjust alignment units to properly position the beam. Align each cantilevered mounting beam assembly with both the track and each other.

K.5.3.4.6.2 Sensor Module Installation/Calibration

Having installed and adjusted the support beams, the necessary sensor modules would be appropriately mounted and adjusted as follows.

1. Loosely install the sensor module/subbase units

2. Install suitable sensor targets (i.e., rail or tie)

3. Insert an installation gauge block(s) between the noncontact displacement gauge faces and the corresponding target surface.

4. Utilizing the 6-DOF adjustment capability obtained by loosening the sensor module mounting bracket clamping bolts, the subbase mounting bolts, and the sensor module swivel head (see Figure K-5.18), position the sensor module tightly against the installation gauge block(s) and tighten all the mounting and adjustment bolts.

5. As discussed in Section K.5.3.4.4, calibration of the sensor modules may not be necessary if the units have been previously calibrated with the identical electronics and cables being used. If it is necessary or desirable to calibrate the installed sensor modules, a complete end to end calibration can be quickly performed utilizing a set of aluminum calibration gauge blocks.

K.5.3.4.7 Measurement Methodology

In the design of a wayside instrumentation system, it is necessary to consider the measurement methodology which would be used for both short-term and long-term measurements. Basically the question to be addressed concerns the methods to be employed for obtaining both dynamic and static (long-term change) measurements. A proposed method for obtaining dynamic and static measurements follows.

K.5.3.4.7.1 Dynamic Measurements

Dynamic measurements would be made utilizing sub-arrays of noncontacting displacement sensors. Each sensor module would be appropriately mounted to a reference platform or beam and aimed so that each sensor in the module would see one of three orthogonal target surfaces such as shown in Figures K-5.19 and K-5.20.

The orthogonal plate targets would be affixed to each rail and to the ties as required. Since these sensors would be used primarily for dynamic test data, there is no need to reference the sensors to universal survey benchmarks.

K.5.3.4.7.2 Static (Long-Term) Measurements

A proposed method for making long-term static measurements is to utilize a precision dial depth gauge in conjunction with a survey-to-benchmark technique. The sensor modules could either be replaced with a gauge block device as shown in Figure K-5.22 or they may possibly be designed to incorporate the necessary calibration functions as part of the basic sensor module. Holes in the gauge block would provide guides for a dial depth gauge. The depth gauge would be used to determine orthogonal distances from the target surfaces to the gauge block reference face. The static measurement system would be designed to duplicate the measurement locations used for dynamic testing. Therefore, the same coordinate transformation or data reduction scheme developed for dynamic measurements could be used for the static measurements.

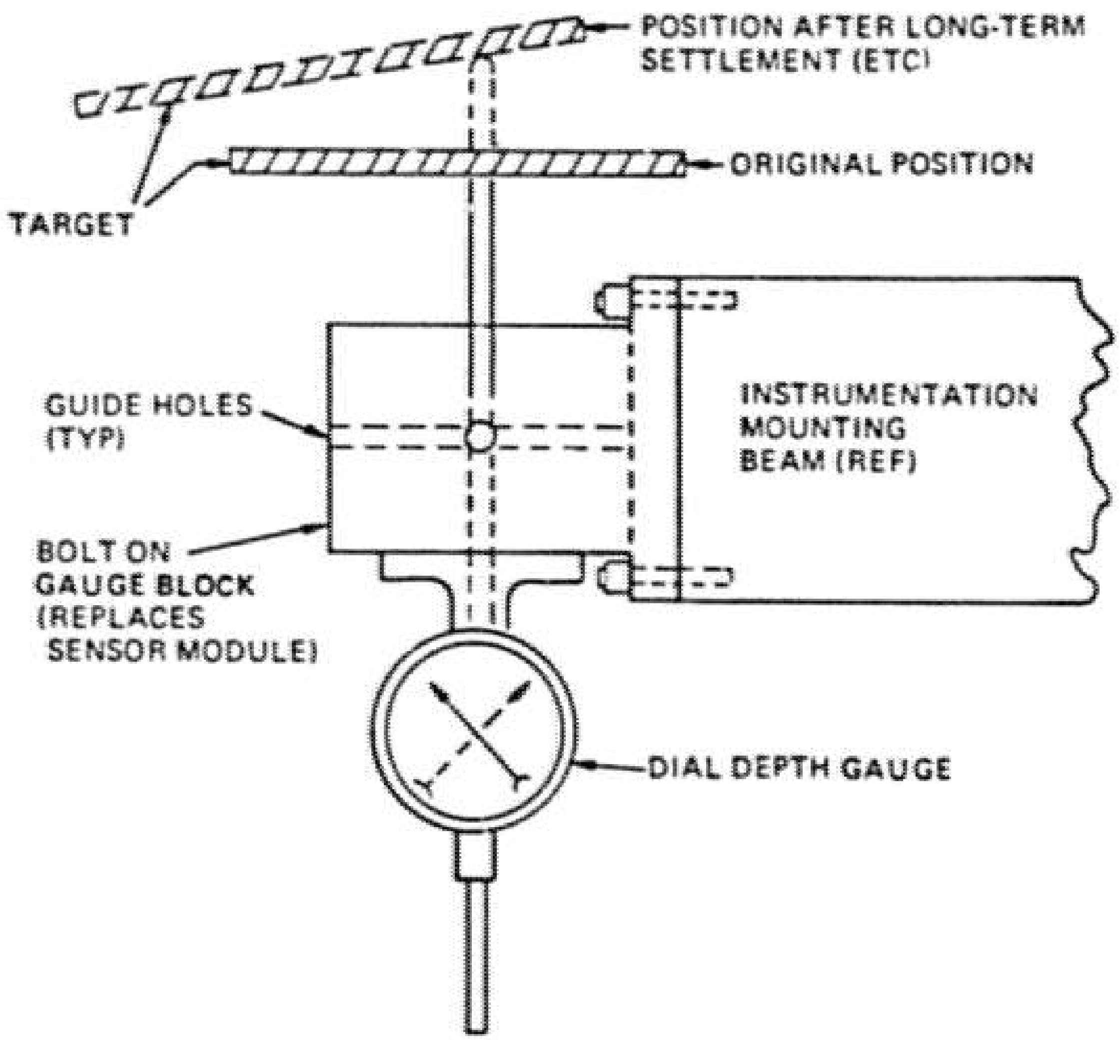


FIGURE K-5.22 CONCEPT DWG OF GAUGE BLOCK CONFIGURATION FOR LONG TERM MEASUREMENTS

To assure that repeatable long-term measurements can be made even with the removal and re-installation of the instrumentation mounting beam, suitable survey benchmarks would be incorporated in the design of the mounting beam or the sensor modules. If field benchmarks are provided, then survey-to-benchmark measurements can be made to provide accurate long-term measurement capability.

K.5.3.4.8 Conversion of Noncontact Sensor Outputs to Standardized Rail Measurements

When utilizing noncontacting displacement sensors, it is necessary to correlate the basic platform referenced transducer outputs into standardized rail displacement measurements. Although this conversion process may appear complex, it can be easily implemented as part of the data processing software and has some very distinct advantages. The measurement correlation technique as discussed below utilizes a sensor triad which allows the motion of any point on the rail cross section to be derived from only 3 fixed displacement measurements. Furthermore, this measurement scheme inherently compensates for cosine type kinematic errors. The measurement and analysis procedures for correlating noncontact sensor outputs to standardized rail measurements are discussed below.

K.5.3.4.8.1 Description of the Problem

The basic problem associated with correlating a set of noncontacting displacement transducer measurements into useful or standardized rail displacements can best be described by referring to Figure K-5.23. The bold arrow heads as shown in the figure denote the fixed noncontacting displacement sensor locations. Since these sensors are fixed to the reference platform, they can be assigned a set of "platform" coordinates as denoted by (Z, Y) in Figure K-5.23.

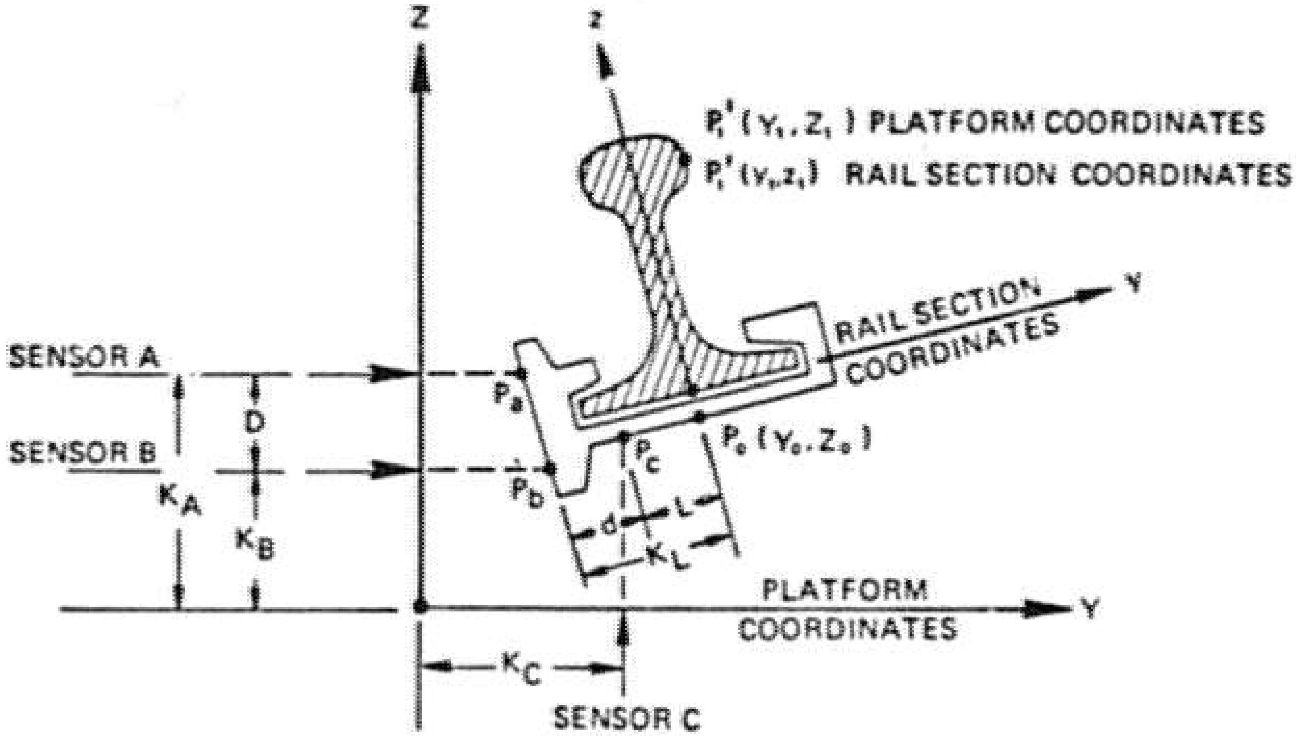


FIGURE K-5.23 COORDINATE SYSTEM FOR MEASUREMENT CORRELATION

The object or target being measured by the sensor triad shown in Figure K-5.23 is the rail section (or affixed rail target). Since the rail section is free to rotate and translate relative to the reference platform, it is convenient to assign it a separate coordinate system (Y, Z) as shown.

The correlation problem can now be stated as follows:

> Given a set of 3 displacement measurements in platform coordinates e.g. (Pa, Pb, Pc), determine the platform coordinates for an arbitrary point P' given in rail section coordinates.

A technique for monitoring any point on a rail section utilizing 3 noncontacting displacement sensors is presented below. A basic requirement associated with the sensor triad is that 2 of the 3 sensors be located relative to a target surface which is orthogonal to another target surface seen by the third sensor.

K.5.3.4.8.2 Derivation of Correlation Equations

The basic analysis steps are as follows:

Calulate Rail Rotation

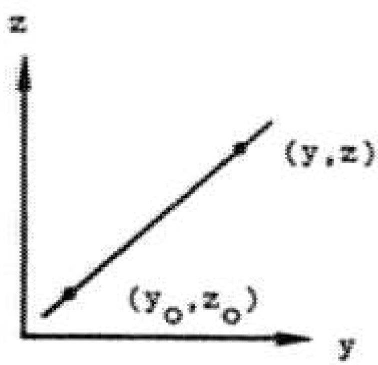
With reference to Figure K-5.23, rail rotation can be derived as below

$$\theta = \tan^{-1} \frac{A-B}{D}$$

Calculate the Perpendicular Distance Between a Vertical Target Plane and a Point on a Horizontal Target Surface

From the "point-slope" equation of a straight line:

$$z-z_o = m(y-y_o)$$



and the slope of the line is:

$$m = \frac{z-z_o}{y-y_o}$$

The equation for a straight line can also be written in the familiar form below:

$$Ay + Bz + C = 0$$

Hence it can be shown that the perpendicular distance (d) from any given point (y_o, z_o) to a line can be expressed in terms of y_o, z_o and the coefficients A, B and C as given below:

$$d = \frac{|Ay_o + Bz_o + C|}{\sqrt{A^2 + B^2}}$$

Then in terms of the rail base sensor triad, the following equations can be written with reference to Figure K-5.23.

The slope of the target vertical surface is:

$$m = \frac{K_A - K_B}{A - B}$$

where:

K_A = constant (fixed vertical reference - Sensor A)
K_B = constant (fixed vertical reference - Sensor B)
K_C = constant (fixed lateral reference - Sensor C)
A = Sensor A output
B = Sensor B output
C = Sensor C output

Taking (y_o, z_o) as the current target position as seen by Sensor B and (y,z) as the current target position seen by Sensor A, the equation for a line passing between the target intersections of Sensors A and B is:

$$z - K_B = \frac{K_A - K_B}{A-B} \quad (y - B)$$

or

$$(K_A-K_B)y + (B-A)z + (K_BA-K_AB) = 0$$

so

$A = K_A-K_B$

$B = B-A$

$C = K_BA-K_AB$

Now substituting the following constants into the equation for d using

$y_o = K_C$

$z_o = C$

$$d = \frac{|(K_A-K_B)K_C + (B-A)C + (K_BA-K_AB)|}{\sqrt{(K_A-K_B)^2 + (B-A)^2}}$$

or

$$d = \frac{K_AK_C - K_BK_C + BC - AC + K_BA - K_AB}{\sqrt{(K_A^2-2K_AK_B+K_B^2) + (B^2-2AB+A^2)}}$$

letting $K_1 = K_AK_C - K_BK_C$

and $K_2 = (K_A^2-2K_AK_B+K_B^2)$

We obtain an expression for d in terms of geometric constants and sensor outputs:

$$d = \frac{K_1 + C(B-A) + AK_B - BK_A}{\sqrt{K_2^2 + (B-A)^2}}$$

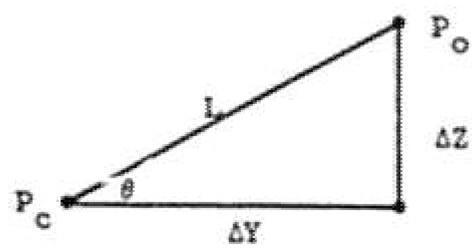
Calculate the Origin of the Rail Section Coordinate System

Let P_o denote the origin of the rail section coordinate system as shown in Figure K-5.23 and P_c the current target location for Sensor C.

By inspection:

$$P_o(Y_o, Z_o) = P_c(Y_c + \Delta Y, Z_c + \Delta Z)$$

where



From above

$L = K_L - d$ (K_L = fixed distance between side of rail target and vertical ℄ of rail)

then

$\Delta Y = L\cos\theta$

$\Delta Z = L\sin\theta$

so

$$P_o = P_c(Y_c + L\cos\theta, Z_c + L\sin\theta)$$

Determine the Location of any Selected Point on the Rail Section Formation

Once the rail section coordinate system origin is known, any point on the rail section can be located in platform coordinates by performing a simple rotation transformation as follows:

$$\begin{bmatrix} Y_1 \\ Z_1 \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & +\cos\theta \end{bmatrix} \begin{bmatrix} y_1 + Y_o \\ z_1 + Z_o \end{bmatrix}$$

where:

$P_1'(Y_1, Z_1)$ = Current postion (in platform coordinates) of a predesignated point on the rail section

$P_1'(y_1, z_1)$ = Location of predesignated point on rail section (in rail section coordinates). These would be "geometric constants" input prior to data processing.

$P_o(Y_o, Z_o)$ = Current location of the rail section coordinate system origin. ($Y_o = Y_c + L\cos\theta$), ($Z_o = Z_c + L\sin\theta$)

The above derivations result in easily implemented equations which will convert the platform mounted noncontacting sensor outputs into platform related deflection measurements for any pre-selected point on the rail section. Having obtained the platform coordinates for selected points on the rails, standard track displacements can be readily obtained either directly or by the sum and difference of appropriate measurements (e.g., dynamic gauge widening).

This correlation process could be done either directly on-line during data acquisition or off-line as a post-processing procedure. Figure K-5.24 shows a

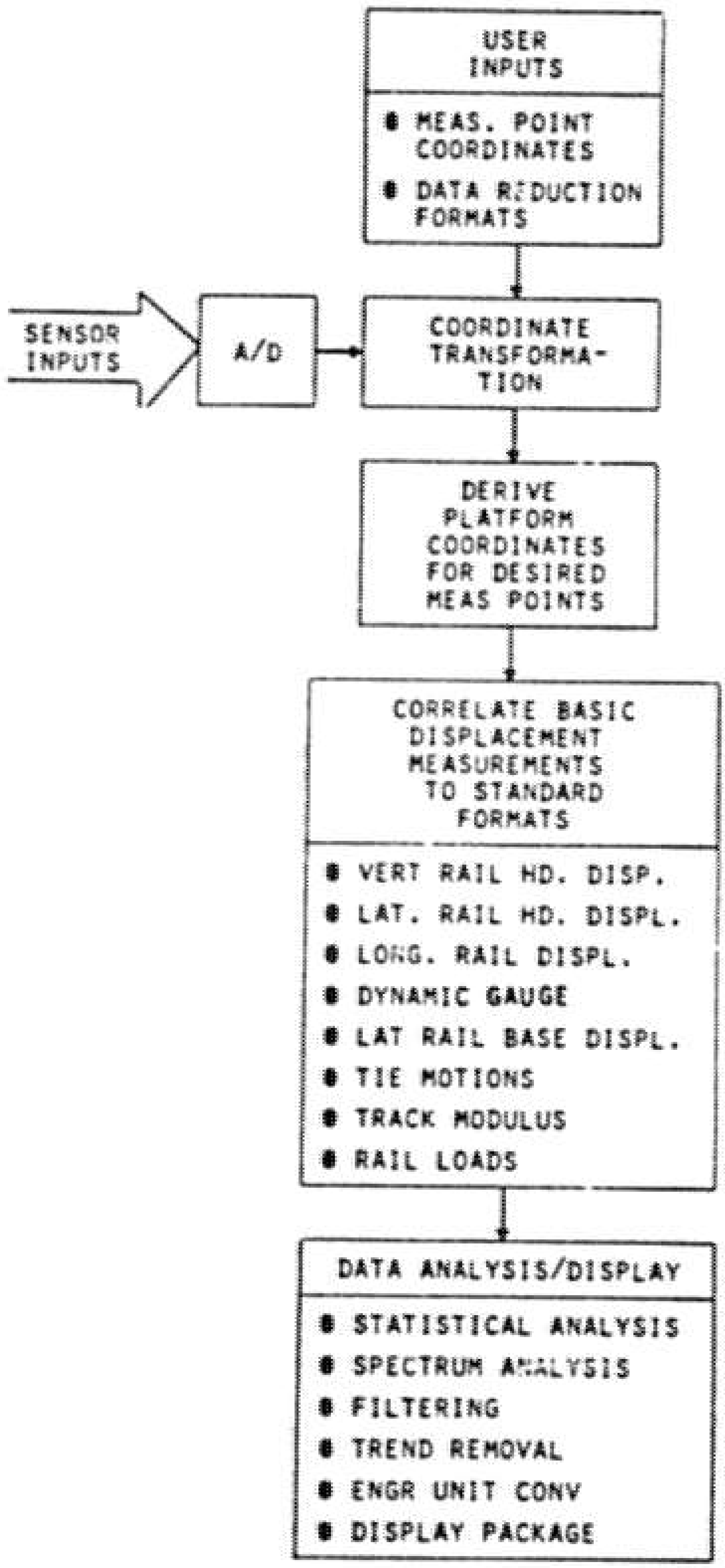


FIGURE K-5.24 TEST DATA PROCESSING & ANALYSIS block diagram of a typical data processing procedure which would be utilized with the wayside instrumentation concept under study.

K.5.3.4.9 Evaluation of Rail Loads Using Shear and Displacement Measurement Systems

The approach being taken to evaluate the feasibility of obtaining track loads from track displacement measurements includes a comparison with the conventional rail strain gauge technique. The problem under consideration therefore involves the prediction of vertical and horizontal rail forces using a rail shear strain measurement method and/or a rail displacement measuring method. In order to obtain a feeling for the significance of various track system variables upon these two response parameters, some initial analytic studies have been undertaken. Two analysis methods have been applied: (1) the classic beam on elastic foundation solutions, and (2) a linear elastic finite element model which includes discontinuous rail support effects.

K.5.3.4.9.1 Technical Discussion

The two measurement systems under consideration rely on two distinct rail response parameters: (1) rail shear strain, (2) rail displacement.

In the shear strain method, strain gauges are placed on the rail at locations where bending and torsional responses are either minimum or can be otherwise accounted for. The resultant shear strain measure, γ, is related to the rail shear force, Q, by the following linear relation (assuming elastic response):

$$Q = \alpha A G \gamma$$

where α = constant associated with the rail cross-section
A = area of rail cross section
G = shear modulus of rail material.

In practice, the Q,γ relationship is often determined by a field calibration of the track system subject to known shear forces.

In the rail displacement method, a series of noncontacting displacement gauges would be emplaced in suitable proximity to the rail and direct (absolute) measurement of rail deflection would be made. The relations between rail deflection and applied loading may be predicted analytically or by field calibration. The accuracy of this technique is of course dependent upon the gauge reference platform being representative of a ground reference. If it is not practical to build a reference platform which could suitably isolate ground vibrations directly, it may be possible to compensate for these vibrations analytically utilizing accelerometers.

In the following subsections, the sensitivities of both rail shear and rail displacement to variations in track parameters using both the beam on elastic foundation solution and a finite element track model are discussed.

K.5.3.4.9.2 Beam on Elastic Foundation

The vertical deflections and shear response of a rail foundation system based upon the classic beam on elastic foundation formulation is presented here for reference.

$$Z = \frac{P_v}{8\beta^3 EI} e^{-\beta X} (\cos\beta X + \sin \beta X)$$

$$Q = -\frac{P_v}{2} e^{-\beta X} \cos\beta X$$

where:

$$\beta = \sqrt[4]{\frac{U_v}{4EI}}$$

EI = rail stiffness parameter ($lb\text{-}in^2$)

Z = vertical deflection of rail at any point (in)

Q = shear response of rail (lbs)

P_v = single wheel load on rail (lbs)

X = distance from load point (in)

U_v = vertical track modulus (lb/in/in)

Consider first the vertical deflection of a rail subject to a one-wheel truck loading condition. Rail deflection under the wheel as a function of foundation modulus and rail stiffness is shown in Figure K-5.25. It may be observed that deflection is strongly affected by changes in foundation modulus but is relatively insensitive to changes in rail stiffness. The shear response in the rail is shown in Figure K-5.26. It can be seen that rail shear is invariant with both foundation modulus and rail stiffness.

Next consider the more realistic condition of a two-wheel truck loading. Rail deflection and shear may be obtained by superposition of the solutions presented above. The conditions studied assumed a constant wheel spacing of 68 inches, and a constant rail stiffness corresponding to a 132 RE rail ($EI=2.65 \times 10^9$). The rail deflections and shear as a function of track modulus are presented in Figures K-5.27 and K-5.28 respectively. Results are shown for two rail locations: (1) directly under one wheel, and (2) halfway between the two wheels.

Figure K-5.27 again indicates a strong sensitivity in rail deflections to change in track modulus. It is also noted that with vertical track modulus values less than about 6000 lb/in/in, the maximum rail deflection occurs midway between the wheels. At higher modulus values, the maximum deflection occurs under the wheels. Figure K-5.28 shows that the maximum shear occurs under the wheels and the shear halfway between the wheels is zero, as could be deduced from symmetry conditions. In addition, the induced rail shear under the wheel is no longer invariant with track modulus but shows a slight decrease in shear with increase in modulus.

The conclusion obtained from the one-wheel solution which pointed out the advantages of strain measurements versus deflection measurement should be modified somewhat based upon the two-wheel solution. Both strain and displacement measurements show sensitivity to track modulus; however, the strain method seems to be less sensitive than the displacement system, particularly at low track modulus values. At higher track modulus values, both methods show decreased sensitivity to modulus variation. It can also be concluded that rail stiffness variation has relatively little impact on induced deflection or shear.

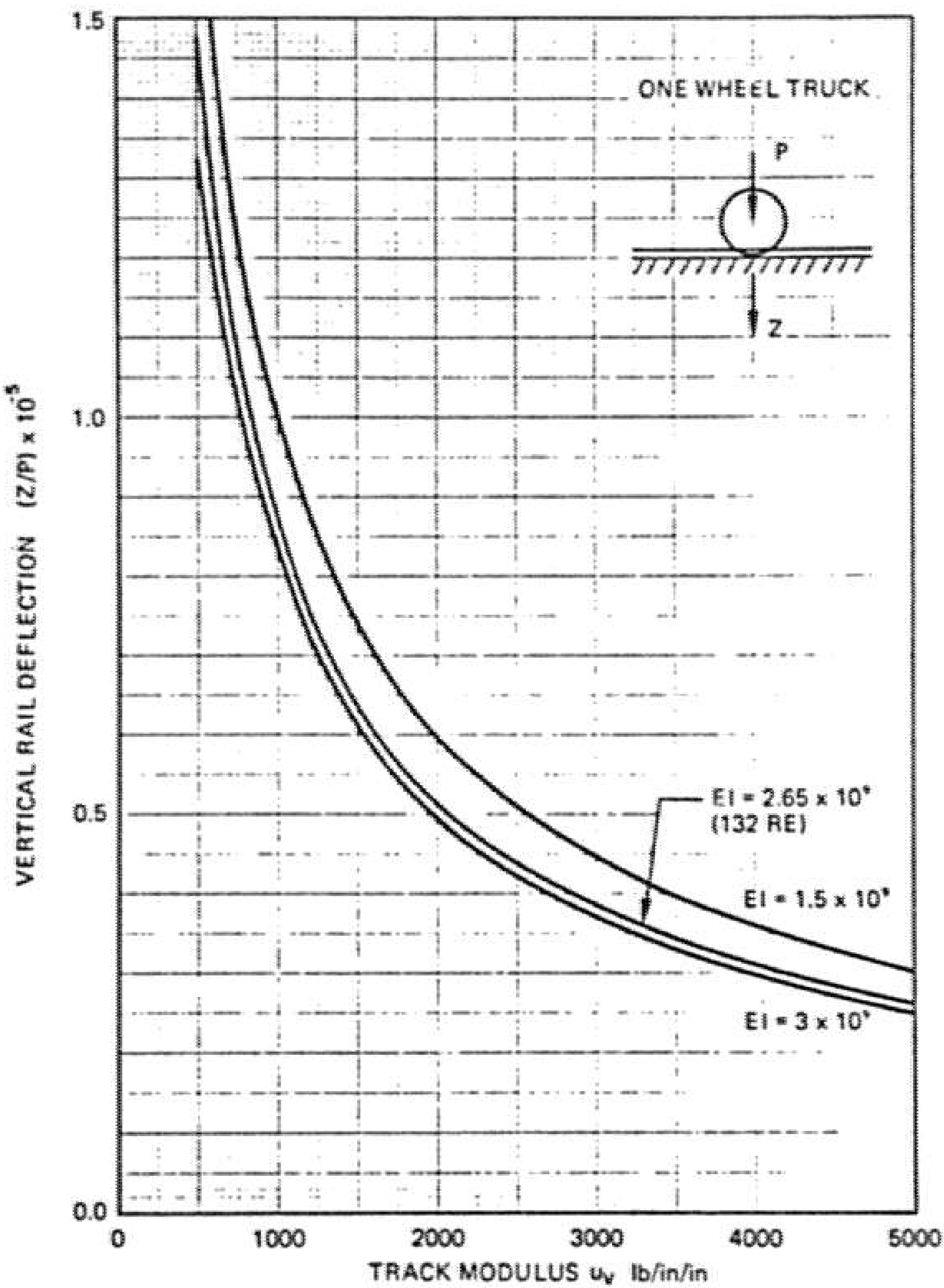


FIGURE K-5.25 VERTICAL RAIL DEFLECTION VS TRACK MODULUS AND RAIL STIFFNESS

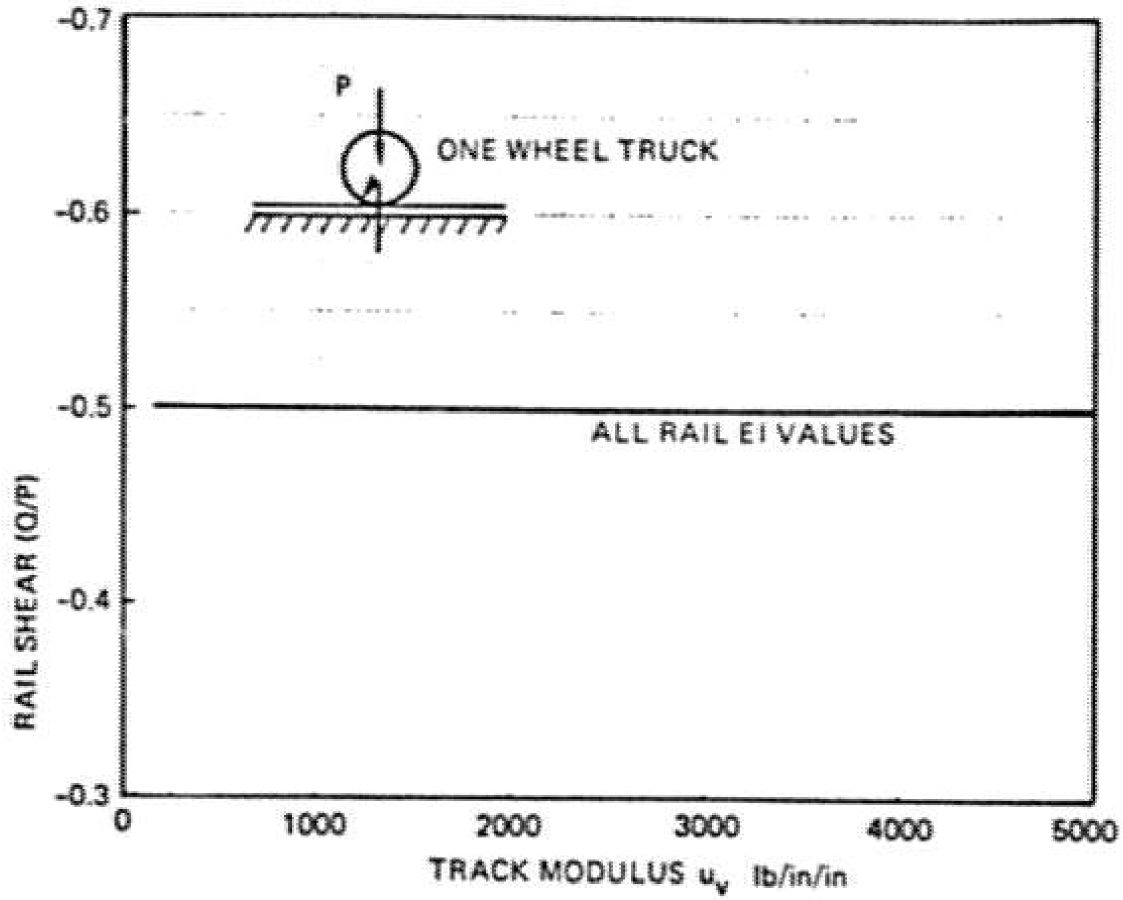


FIGURE K-5.26 RAIL SHEAR VS TRACK MODULUS AND RAIL STIFFNESS

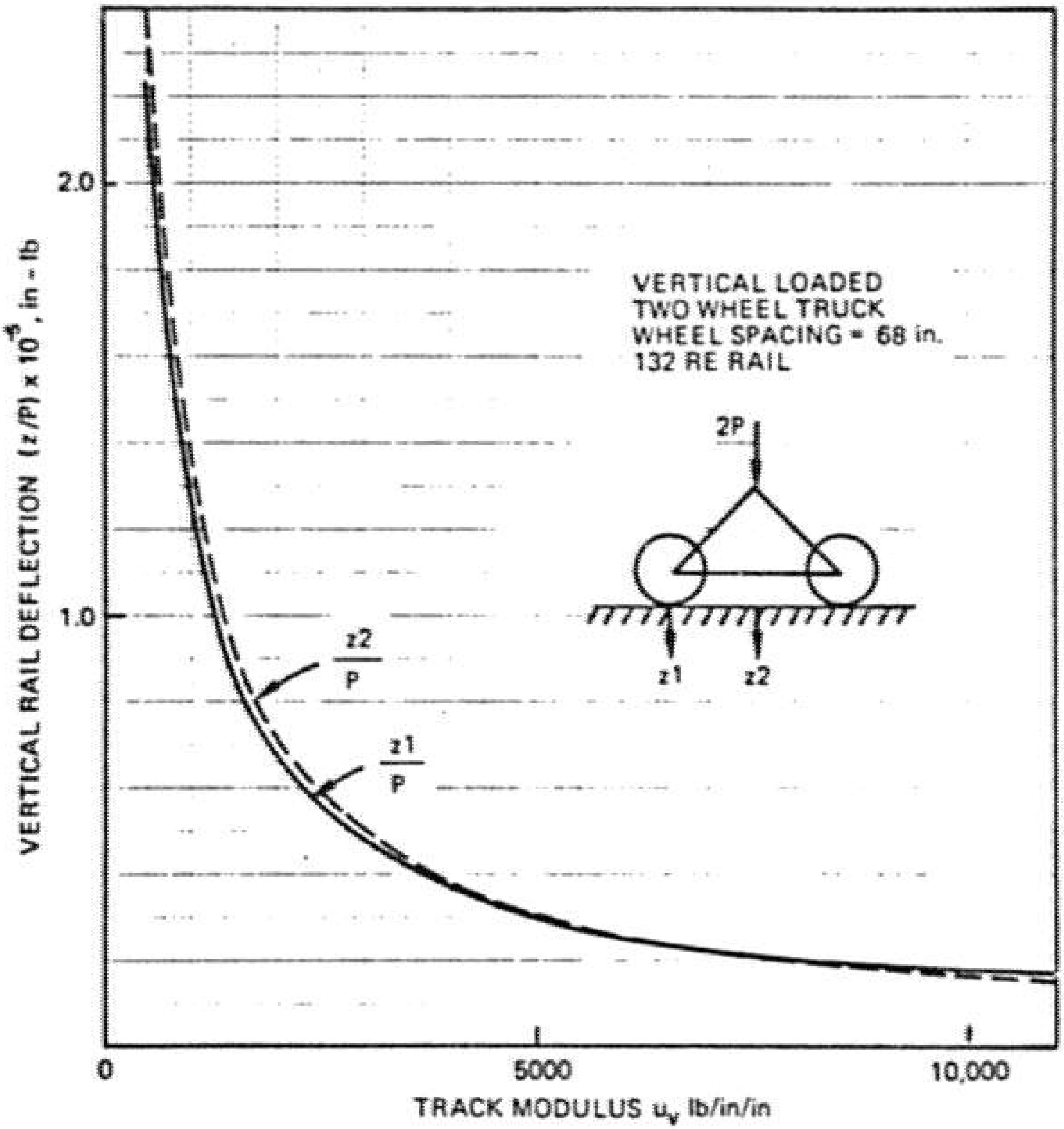


FIGURE K-5.27 VERTICAL RAIL DEFLECTION VS TRACK MODULUS

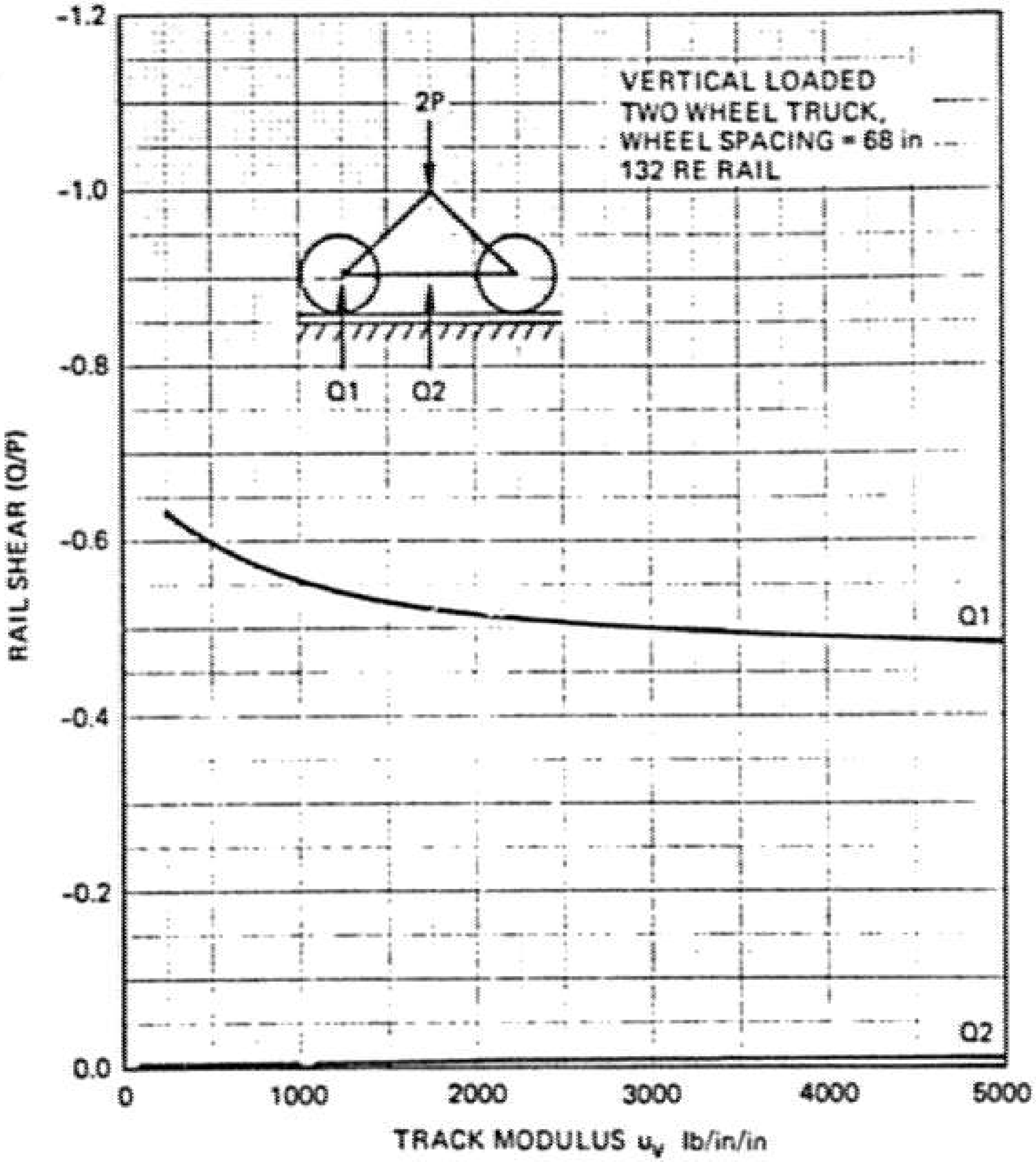


FIGURE K-5.28 RAIL SHEAR VS. TRACK MODULUS

Some initial studies have also been performed for lateral rail loading conditions using the beam on elastic foundation solution. The work accomplished to date is limited to sensitivity studies for a single wheel truck loading. The lateral rail loading model includes an additional effect afforded by rotational restraints from the rail fasteners. We define the rail tie down rotational stiffness by the parameter K_θ.

The displacement solutions for lateral loading takes the following form:

$$Y = \frac{Pe^{-\alpha X}}{4EI\beta\alpha} \; \frac{(\alpha \sin\beta X + \beta \cos\beta X)}{(\alpha^2 + \beta^2)}$$

where: $$\alpha = \sqrt{\sqrt{\frac{u_L}{4EI}} + \frac{K_\theta}{4EI}}$$

$$\beta = \sqrt{\sqrt{\frac{u_L}{4EI}} - \frac{K_\theta}{4EI}}$$

Y = lateral rail deflection (in)
P_L = lateral load (lbs)
X = distance from lateral load point (in)
EI = lateral rail stiffness parameter ($lb\text{-}in^2$)
u_L = lateral track modulus (lb/in/in)
K_θ = rail tie down rotational stiffness (lb/rad)

A corresponding equation for rail shear may also be derived.

The system parameters are as defined previously, however it should be remembered that the lateral track modulus u_L will in general have a much lower numerical value than the vertical track modulus. Similarly, the rail stiffness is in the lateral direction and includes the sum of both rail inertias.

Figure K-5.29 presents the lateral track deflection under the wheel for the one-wheel truck loading as a function of lateral track modulus (u_L), fastener rotational stiffness (K_θ), and two different rails; 132 RE and 115 RE. It is observed that the rail deflection again is strongly dependent upon lateral track modulus but is only weakly dependent upon rail lateral stiffness. In addition, the rail tie down rotational stiffness, K_θ, is also seen to have a strong influence on rail deflection. Rail shear is shown in Figure K-5.30. For the one-wheel truck loading, rail shear is seen to be invariant with lateral track modulus, tie down stiffness and rail stiffness. From this solution, we can draw the same tentative conclusion reached earlier -- rail shear appears to be a better response parameter than rail deflection since it shows much less sensitivity to the various system parameters. However, further studies involving two-wheel truck loading for lateral rail response are required to clarify these results.

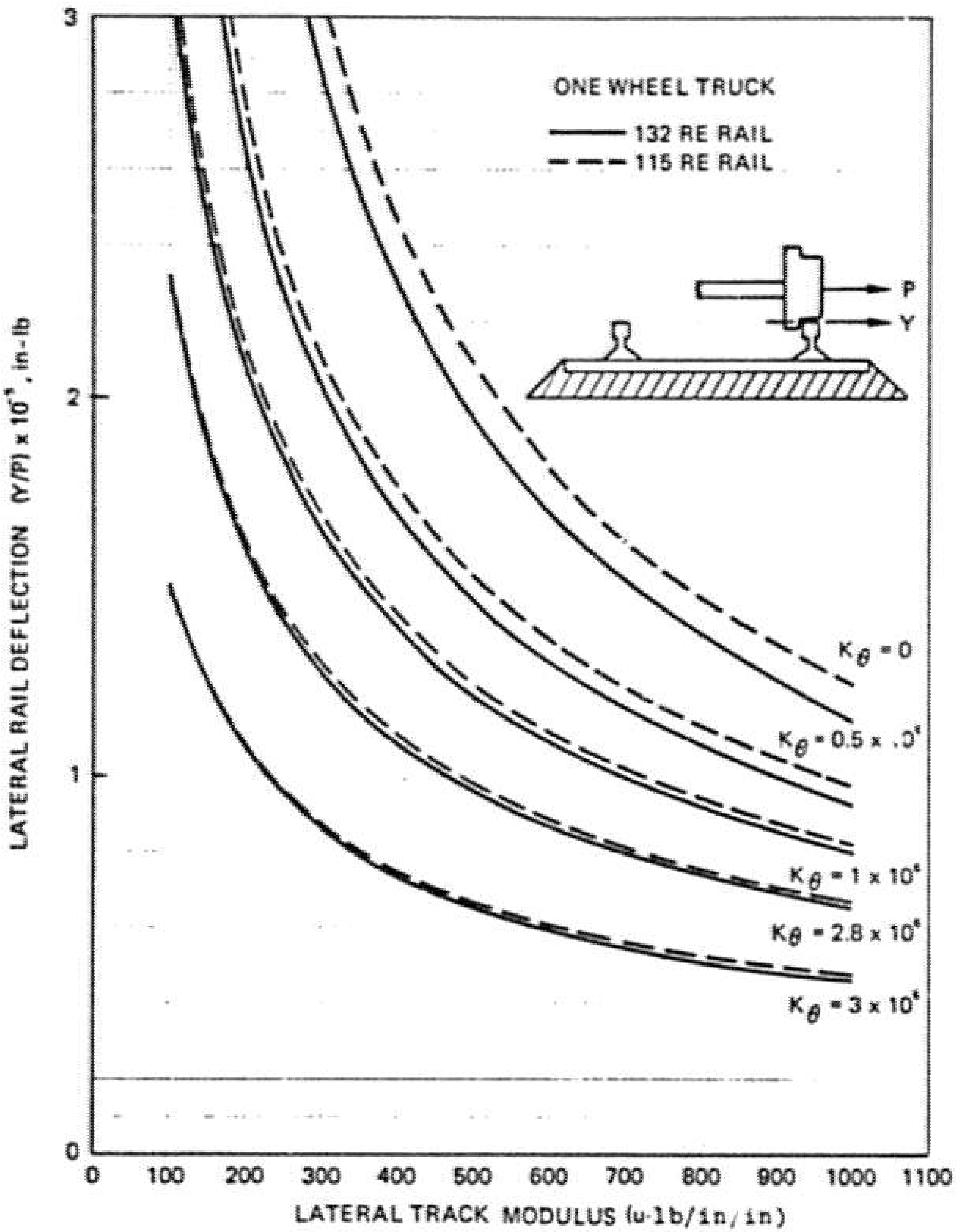


FIGURE K-5.29 LATERAL RAIL DEFLECTION VS LATERAL TRACK MODULUS, RAIL STIFFNESS, & TIE DOWN STIFFNESS

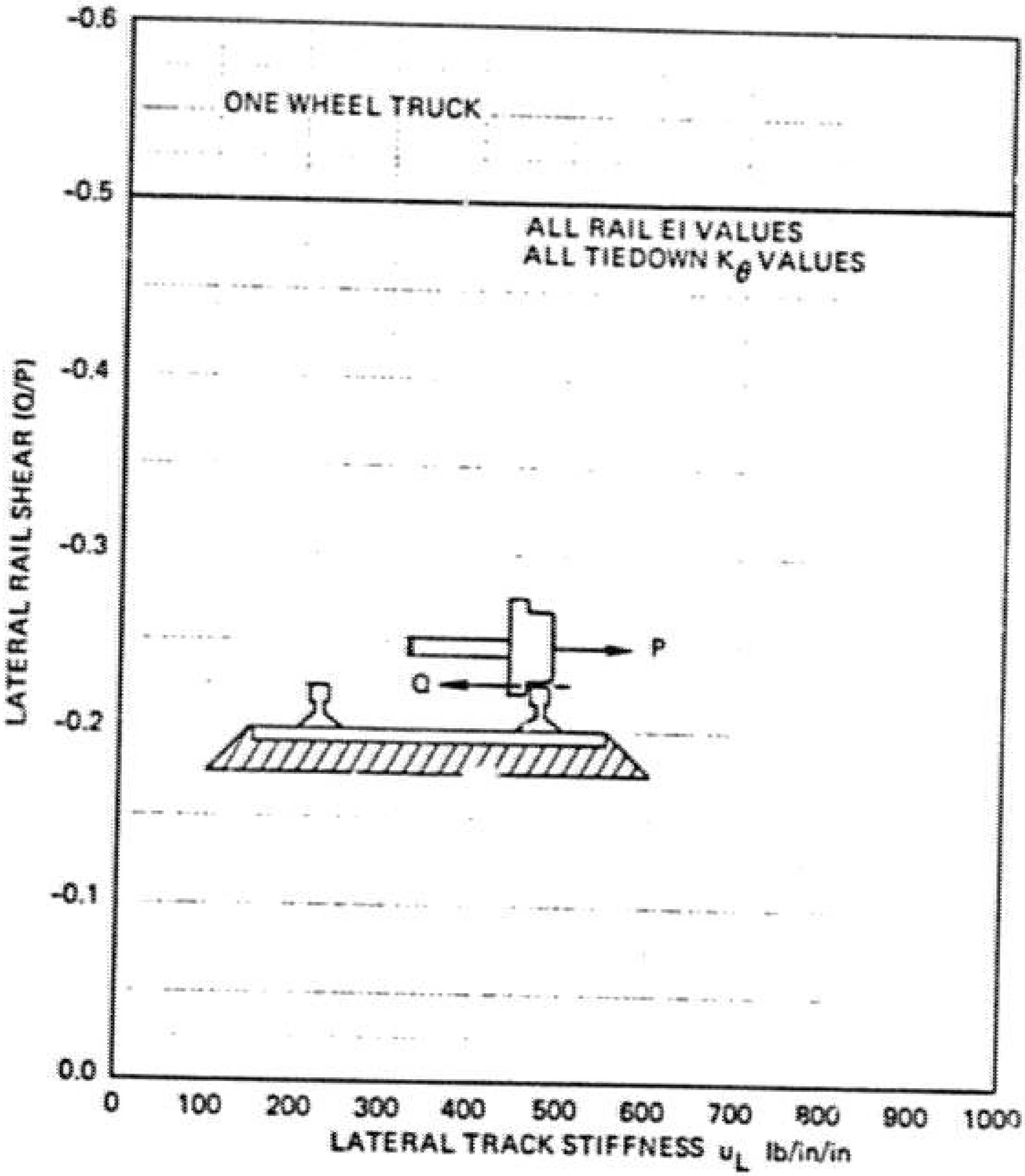


FIGURE K-5.30 LATERAL RAIL SHEAR VS LATERAL TRACK MODULUS, RAIL STIFFNESS & TIE DOWN STIFFNESS

K.6.0 DATA SYNCHRONIZATION AND RECORDING

K.6.1 Introduction

One of the prime requirements for the acquisition of test data is that sufficient information is recorded so that all recorded measurements can be correlated with each other in time and in position relative to the test site. In order to properly fulfill this requirement, special equipment and implementation schemes must be used. The type of equipment and scheme used for a particular test is dependent many factors including the speed of the test vehicles and precision requirements for the data.

The following section presents several synchronization and data recording schemes that can be used for a variety of test conditions.

K.6.2 General Method

The method recommended for recording and synchronizing all data recording instrumentation is based on correlating ground position and time simultaneously with the measurement data. The basic scheme is that ground location reference points are generated by automatic location detectors (ALD) and time reference points are generated by time generators. All data, reference information and measurements, are recorded simultaneously in real-time on chart paper or magnetic tape. The tape and/or chart paper speed is run at a constant known speed. The time and position reference data is entered on recorder channels dedicated specifically for data synchronization purposes. Figure K-6.1 shows an example of such a recording.

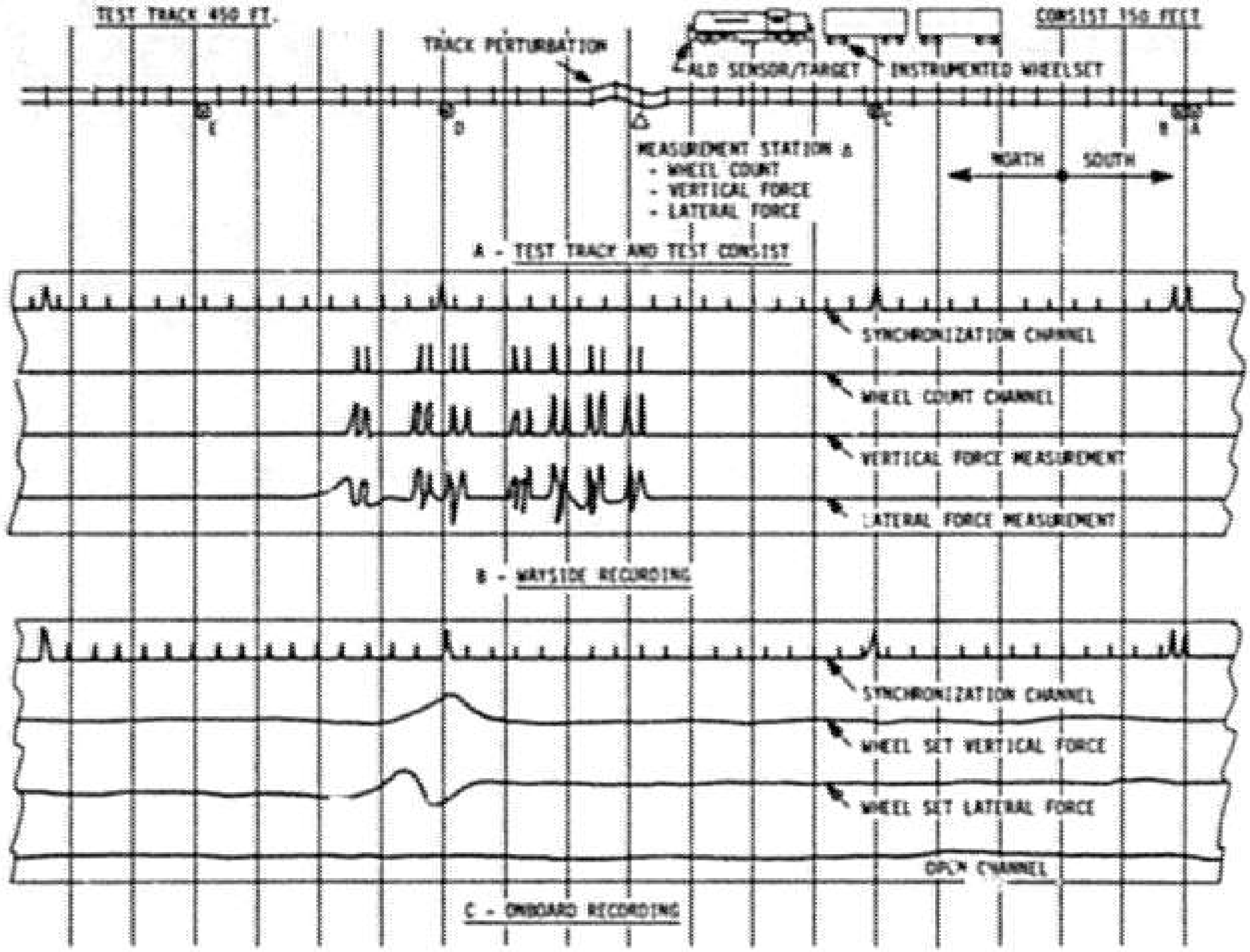


FIGURE K-6.1 TEST DATA EXAMPLE

Using the scheme described above, the following reference and synchronization information can be derived:

1. absolute ground position
2. relative positions of ground location and vehicle
3. distance between points within the test site
4. relative time between events
5. average speed between specified ground locations
6. average acceleration/deceleration between specified ground locations

K.6.2.1 Ground Location

The boundaries of test zones or specific instrumentation locations of the test track is marked using Automatic Location Detectors (ALDs). The location information generated by the ALDs is used to correlate reference position between wayside and onboard instrumentation. In test where only onboard data is recorded, onboard ALD sensors (receivers) and wayside targets are used. The passing of the vehicle (sensor) over the target attached to the track, generates a reference signal which is used to correlate data generated onboard with the ground location. In tests where only wayside data is collected, the targets are attached to the vehicle and sensors are installed at the ground location. In tests where both wayside and onboard data is recorded, a combination sensor/target station is used. (See figure K-6.2). Each sensor/target station contains a sensor and a target within the same unit. When two stations pass each other, simultaneous positions reference signals are generated at both the onboard and wayside recording stations.

In tests where only wheel position is required, wheel locators (counters) can be substituted for ALDs. In these tests the wheel counters are positioned at the exact position of the measurement location. The arrival time of the measurement data and the sensor position is then correlated, one to one.

K.6.2.2 Automatic Location Detection Devices

Two types of automatic location detection (ALD) devices are commonly used in vehicle/track field tests. These are, 1) electromagnetic devices and 2) optical devices. Each has characteristic performance features that best suit their used in specific type tests.

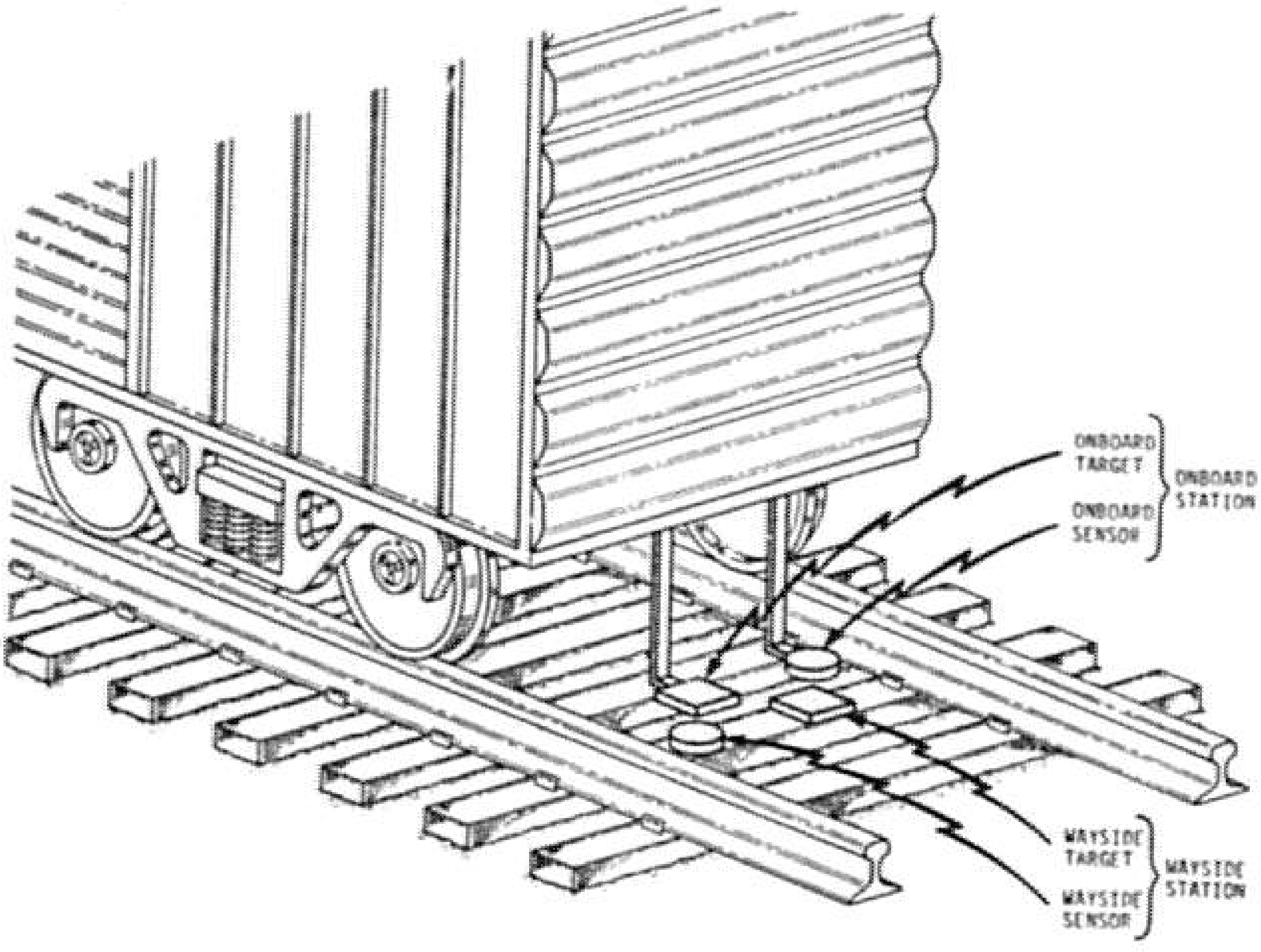


FIGURE K-6.2 ALD SENSOR/TARGET STATION

K.6.2.2.1 Electromagnetic ALD

The electromagnetic ALD is basically a metal detector. The ALD device is made up to two basic components, 1) a metal sensor and 2) a metal target. Conventionally, the sensor is installed on the test vehicle and the target is attached to a track location. This arrangement is used on tests where ground locations are recorded on onboard recording systems. In wayside tests where position of vehicle relative to ground position the target is attached tc the vehicle and the sensor is attached to the track.

The electromagnetic ALD can also detect certain types of track structures such as switches, crossing diamonds, etc. as well as metal test targets. For tests such as track geometry surveys covering long distances where track features (structures) provide good ground location marks, the electromagnetic ALD is commonly used.

K.6.2.2.2 Optical ALD

An optical ALD device is made up of an optical transmitter/receiver unit and a target(s) that reflects light. The transmitter and receiver are contained in a single enclosure and occupy adjacent locations. The basic method of operation for the device is that the transmitter sends out a continuous narrow beam of light that is reflected back to the receiver when the light beam intercepts the target.

The primary advantage of the optical ALD over the electromagnetic ALD is the time response of the technique. Optical ALDs are recommended for high speed tests where high time resolution are needed. Also the alignment of the sensor to target requirements is not as critical for optical ALDs. Electromagnetic units require that the sensor pass within a few inches of the target.

K.6.2.3 Time Reference

Three methods are recommended for generating time references for data synchonization and/or post data analysis. The method used is primarily determined by time response needed. These are: 1) time code generators, 2) time clock and, direct analysis of time markings on the recordings.

K.6.2.3.1 Time Code Generation

The use of time code generators is recommended for generating time references when a test requires the recording data from high speed tests where fast time response is needed. The basic function of a time code generator is to generate time reference signals at specified time intervals (frequencies) varying from functions of seconds to hours or even days. Each time signal is coded in a way that can be identified at a later date and the exact time at which the signal was generated can be determined. Another important function of the method is that specific time event can be found on a tape by passing the tape through a tape reader. The tape reader automatically scans the tape at high speeds and stops at the time position that has been entered into the reader. This function is particularly useful for post-test analysis of tapes that contain data from high speed test where large amounts of footage are generated.

K.6.2.3.2 Time Clocks

Time clocks are recommended to provide time reference signals for medium to low speed tests (0 to 35 mph). The recorder used for tests covered in this speed range is either magnetic tape or paper chart recorders. Time clocks generate time marks at selected intervals (frequencies) that are recorded, along with the in-coming measurement data, on the tape or chart paper. The time marks are single pulses and are not distinguishable from each other. In post analysis of data, time/location points are determined by counting the number of marks from a single reference point and multipling the number by the time rate of the marks.

K.6.3 Data Recorders

Two standard methods are used to record test data. These are multichannel paper chart and magnetic tape recorders. In general, magnetic tape recorders are used for recording data at all rates (slow and fast) where as chart recorders are limited to recording data at low rates. For both methods, the recording speed (inches/sec., mm/sec) is known and kept constant for each test run. It is important to calibrate the recording speed and to know it corresponds with the time resolution needed for the test. At least one channel is reserved for recording synchonization information. This information should include ALD marks and timing pulse which are recorded simultaneously with the measurement data.

K.6.3.1 Magnetic Tape Recorders

Magnetic tape recorders provide the widest range of utility of all recording devices. Tape recorders are manufactured by a number of companies and are available to cover a wide range of performance. In general, tape recorders can record at a high data rate and as a result have good time resolution characteristics. Recorders are available to record either analog or digital data. In most cases, analog data can be recorded directly from the sensor(s) whereas analog-to-digital converters are needed to make digital recordings.

One of the major disadvantages of tape recorders is that additional equipment is need to monitor test results in real-time and/or to calibrate sensor/amplifier combinations to insure that signals are within recording range. Chart recorders and oscilloscopes are typically used to monitor tape rec rder operations.

K.6.3.2 Chart Recorders

Chart recorders are manufactured with a wide range of performance characteristic and capabilities. In general, chart recorders are limited in data rate acquisiton and overall time response and are used for medium to slow speed tests. Chart recorders provide an good means for both real-time viewing and post-test data analysis.

K.6.4 Instrumentation Selection Guide

The following section provides guidelines to aid in the selection of instrumentation for the synchronization and acquisition of data generated in field tests. Several instrumentation schemes are presented and recommended for use with specific test scenarios. Table K-6.1 is presented for use in selecting instruments for various types of test performed at a variety of speeds and conditions. First the appropriate scheme is selected depending upon the users test requirements from the table. The user then goes to one of the following sections for detailed information to aid in the selection of equipment and general application.

TABLE K-6.1 INSTRUMENTATION SELECTION GUIDE

TEST RECORDING/ SYNCHRONIZATION MAKE-UP	HIGH SPEED 80-120 MPH	MEDIUM/ HIGH SPEED 55-80 MPH	MEDIUM SPEED 55-35 MPH	MEDIUM LOW SPEED 35-10 MPH	LOW SPEED 0-10 MPH	STATIC HIGH DATA RATE	STATIC LOW DATA RATE
WAYSIDE/ONBOARD (DATA GENERATED BY VEHICLE/TRACK INTERACTION)	Scheme 1	Scheme 1	Scheme 1	Scheme 1 or 2	Scheme 1,2 or 3	N/A	N/A
WAYSIDE (DATA GENERATED BY VEHICLE/TRACK INTERACTION)	Scheme 4	Scheme 4	Scheme 4	Scheme 4 or 5	Scheme 4,5 or 6	N/A	N/A
WAYSIDE (DATA GENERATED BY ENVIRONMENTAL CONDITIONS)	N/A	N/A	N/A	N/A	N/A	Scheme 7	Scheme 8
ONBOARD (DATA GENERATED BY VEHICLE/TRACK INTERACTIONS)	Scheme 9	Scheme 9	Scheme 1	Scheme 1 or 3	Scheme 3	N/A	N/A
ONBOARD (TRACK GEOMETRY SURVEY)	Scheme 9	Scheme 9	Scheme 9	Scheme 9	Scheme 9	N/A	N/A

K.6.4.1 Scheme #1 - High Speed Wayside/Onboard

Scheme #1 is a data recording and synchronization design for high speed tests where data is generated simultaneously at both onboard and wayside stations.

The time resolution for this scheme is in the range of one (1) millisecond and distance resolution of six (6) inches at 120 mph and three (3) inches at 60 mphs.

The time resolution is limited primarily by the bandwith of the recorder and the distance resolution is limited by the response of the ALD. The sensors recommended for measuring dynamic parameters have an upper limit frequency response of 100 Hz. Recorders with a bandwidth of 1 to 2 MHz are adequate for recording the sensor outputs and the ALD position devices. Recorders with wider bandwidth, are not needed.

A schematic of the instrumentation package is shown in Figure K-6.3. One complete instrumentation package is needed for both the onboard and wayside station. Only one time code reader is need for post-test analysis.

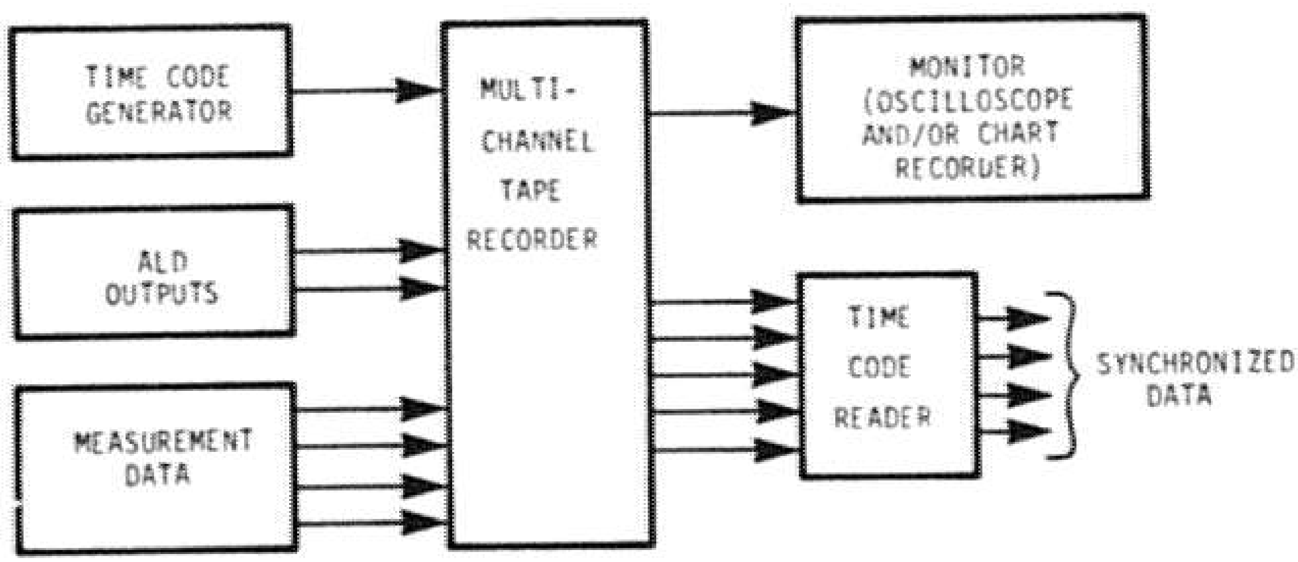


FIGURE K-6.3 SCHEME 1 - HIGH SPEED WAYSIDE/ONBOARD

K.6.4.2 Scheme #2 - Medium Speed Wayside/Onboard

Scheme #2 is designed to record and synchronize data at medium to low speed tests where data is generated simultaneously at both onboard and wayside stations.

The time resolution for this scheme is approximately ten (10) milliseconds and the distance resolution is approximately 2 inches using optical ALDs at 35 mph.

A schematic of the instrumentation package is shown in Figure K-6.4 One complete instrumentation package is needed for both the onboard and wayside station.

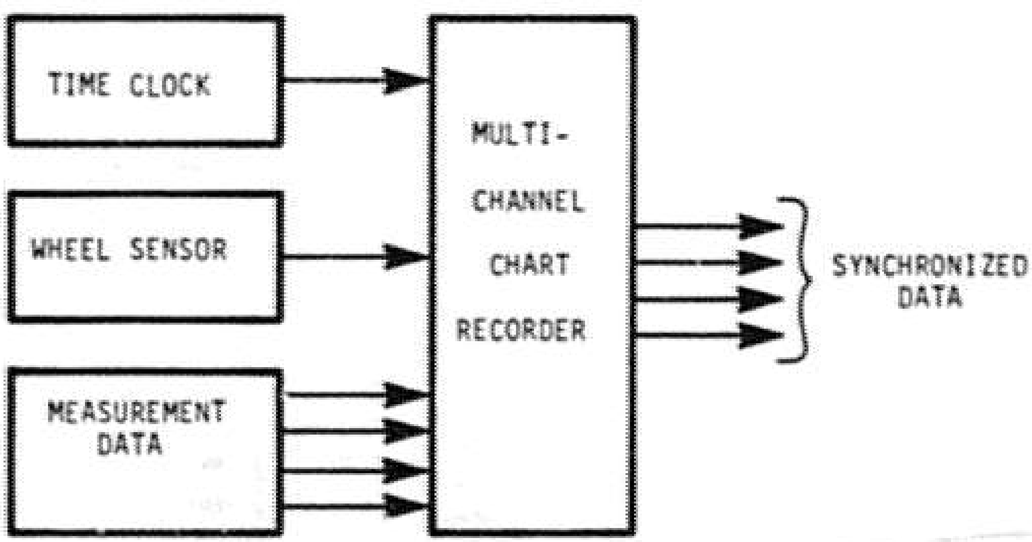


FIGURE K-6.4 SCHEME 2 - MEDIUM SPEED WAYSIDE/ONBOARD

K.6.4.3 Scheme 3 - Low Speed Wayside/Onboard

Scheme 3 is designed to record and synchonize data generated at low speeds. The time resolution is dependent on the response of the recorder and the distance resolution on the chart paper speed.

A schemetic of the instrumentation is shown in Figure K-6.5. One complete instrumentation each package is needed for both the onboard and wayside stations.

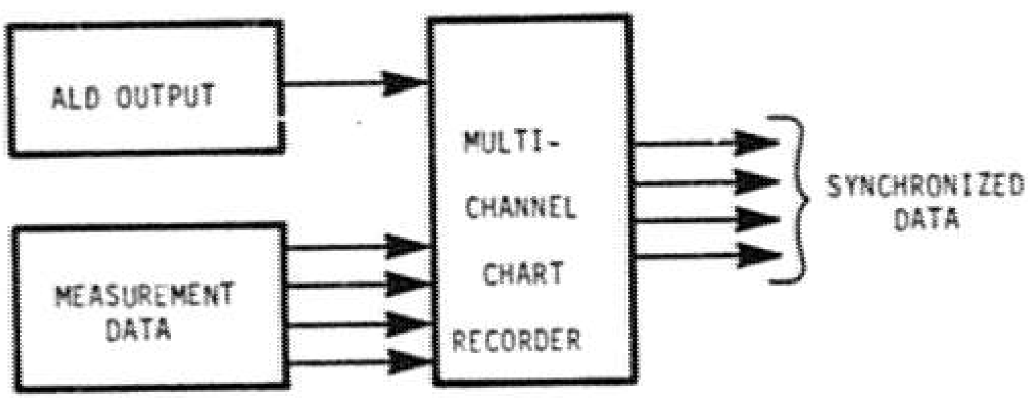


FIGURE K-6.5 SCHEME 3 - LOW SPEED WAYSIDE/ONBOARD

K.6.4.4 Scheme #4 - High Speed Wayside

Scheme #4 as shown in figure K-6.6 is the same as Scheme #1 except wheel sensors are used in place of optical ALDs.

ALDs can be used if they are more convenient, but wheel sensors are easier to install and adjust and are less expensive. The time response and location resolution are the same as those described for Scheme #1.

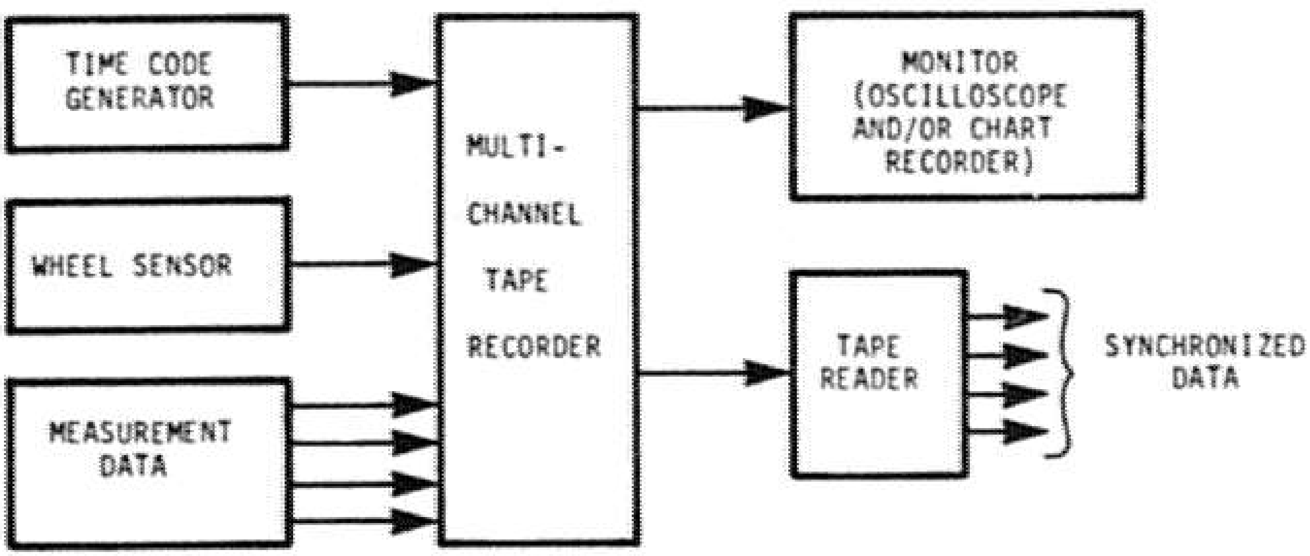


FIGURE K-6.6 SCHEME 4 - HIGH SPEED WAYSIDE

K.6.4.5 Scheme #5 - Medium Speed Wayside

Scheme #5 as shown in Figure K-6.7 is designed for use in tests where data is collected only at wayside at medium speeds. The design is similar to Scheme #2 except wheel sensors are recommended to replace ALDs to locate vehicle position. ALDs can be used, but are more difficult to operate and are more expensive. The time response and distance resolution is the same as that described in Scheme #2.

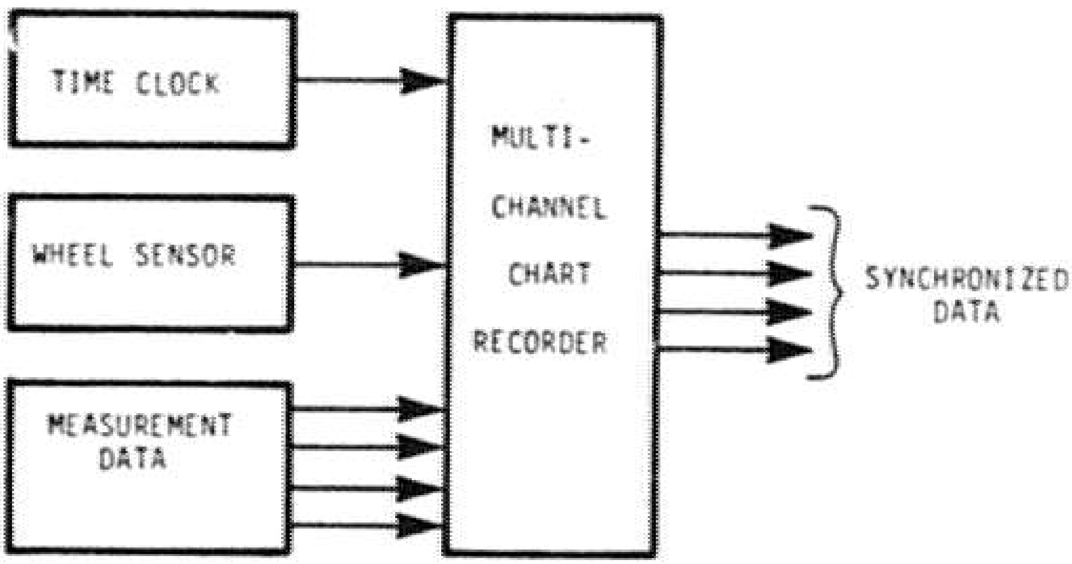


FIGURE K-6.7 SCHEME 5 - MEDIUM SPEED WAYSIDE

K.6.4.6 Sechme #6 - Low Speed Wayside

Scheme 6 as shown in Figure K-6.8 is designed for low speed, low data rate tests where data is recorded at a wayside station. The time resolution is dependent on the response of the recorder and the distance resolution on the chart paper speed.

The design is similar to Scheme #3 but wheel sensors are recommended in place of ALDs because they are easier to operate and less expensive to procure. ALDs can be used if it is more convenient.

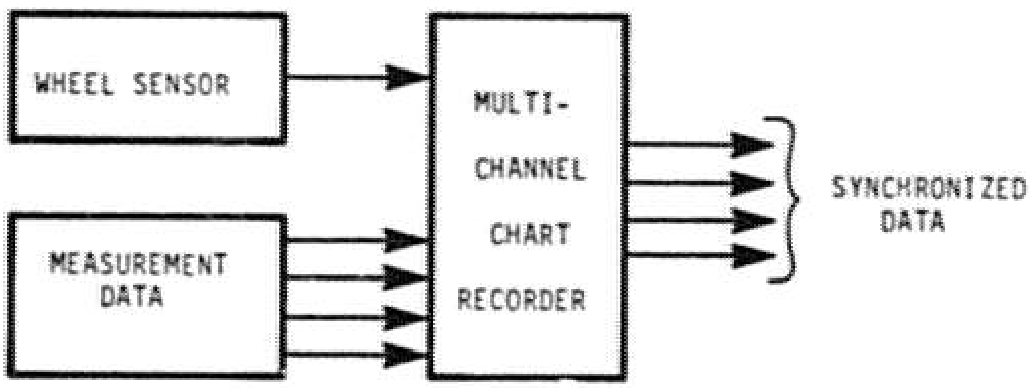


FIGURE K-6.8 SCHEME 6 - LOW SPEED WAYSIDE

K.6.4.7 Scheme #7 - Static High Data Rate Wayside

Scheme 7 as shown in in Figure K-6.9 is designed to record and synchronize data generated by changing environmental conditions or by applying forces at stationary points on the track. This instrumentation package is design to accept data at a high rate or in special conditions where a data recorder is used for technical convenience. In this scheme, the time resolution of the recordings is limited by the bandwidth of the magnetic tape recorder.

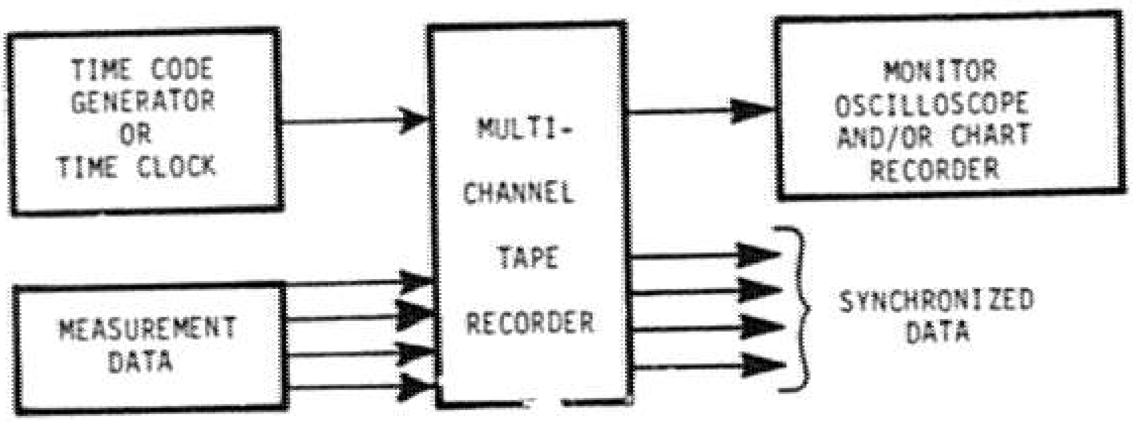


FIGURE K-6.9 SCHEME 7 - STATIC, HIGH DATA RATE WAYSIDE

K.6.4.8 Scheme #8 - Low Data Rate Wayside

The instrumentation recommended for Scheme #8 as shown in Figure K-6.10 is the basic essential for recording and synchronizing of data which is generated at slow rates. A time clock can be used as a time reference but is not necessary. Approximate time of events can be determined by simply measuring the distance on the paper chart from the start of the recording to the event and then dividing the chart paper speed into the measured distance.

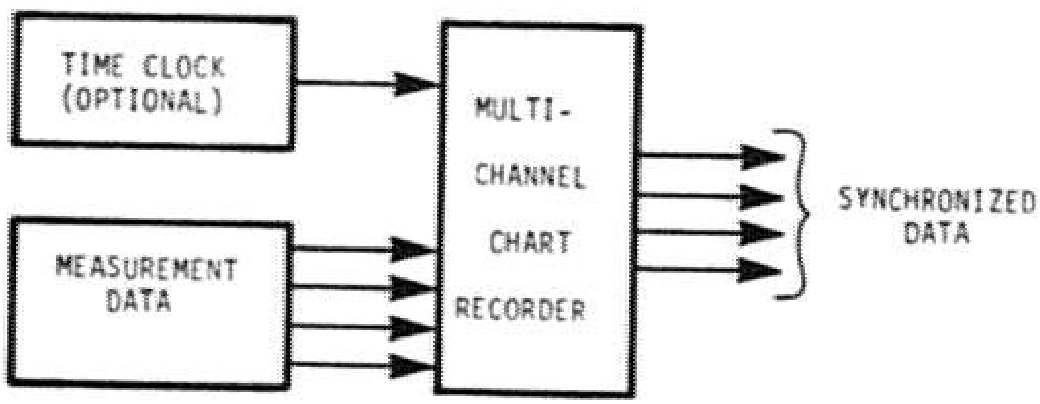


FIGURE K-6.10 SCHEME 8 - LOW DATA RATE WAYSIDE

K.6.4.9 Scheme #9 - High Speed Onboard

The instrumentation recommended in Scheme #9 as shown in Figure K-6.11 is for recording data generated by high data rate tests and track geometry survey systems. For this type of data recording and synchronization, it is important that a data event related to natural track geometry or man made anomalies can be correlated exactly to the track location where the anomaly actually exists. Elecromagnetic ALD sensors are commonly used to locate track features (switches, turnouts, test targets, etc.) that are frequently used to reference general locations on the track. Since the survey vehicles operate at speeds up to 80 mph, the data rates can be high and the time response of the sensors and data recorder must have a high frequency response.

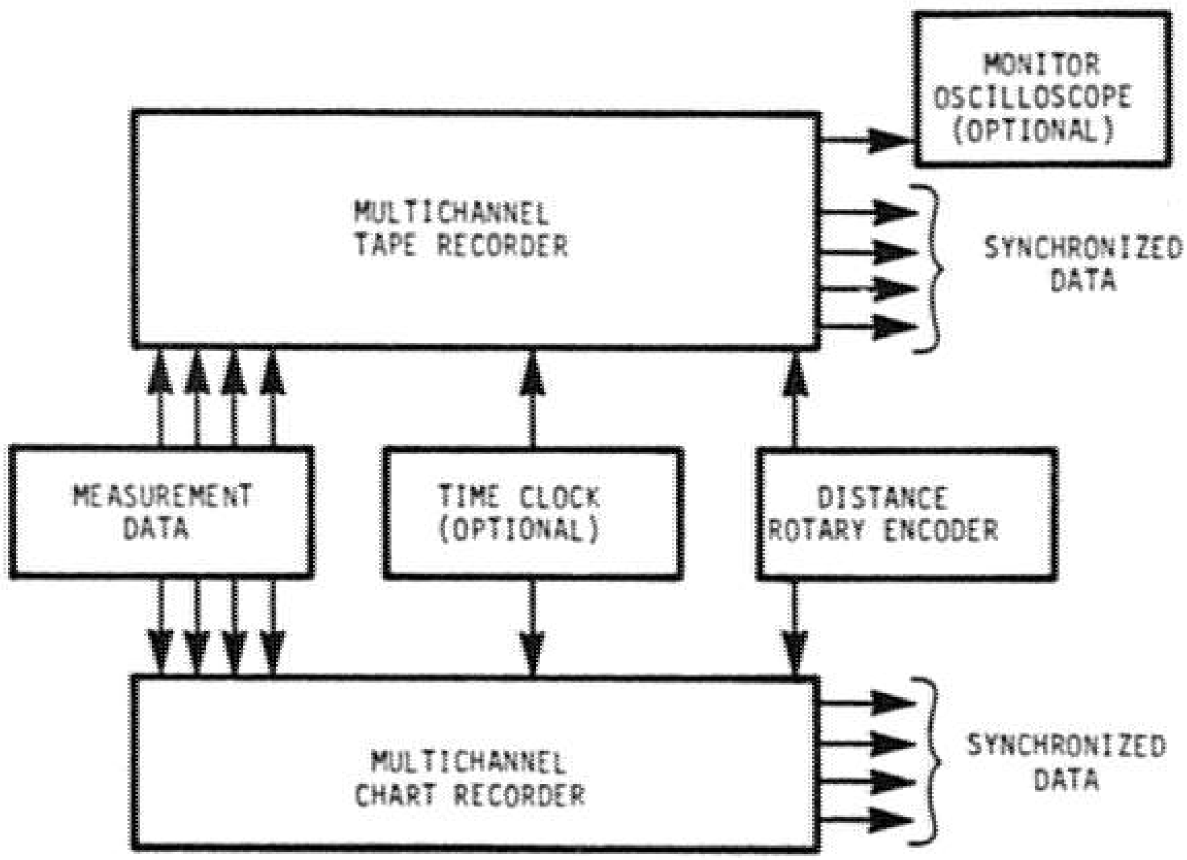


FIGURE K-6.11 SCHEME 9 - HIGH SPEED ONBOARD

K.7 SPECIAL EQUIPMENT AND TECHNIQUES

This section covers special equipment and techniques not conventionally used in the railroad industry due to their special application and/or recent development and, therefore limited use. Section K.7.1. describes the design and application of two portable track loading devices which are used to measure lateral rail restraint in track. Section K.7.2 describes a unique technique used to measure lateral truck forces indirectly by using intertial measurements.

K.7.1 TRACK LOADING FIXTURES

K.7.1.1 SYSTEM DESCRIPTION TRACK LOADING FIXTURE (TLF)

The Track loading fixture (TLF) is a loading device used to apply vertical load and a lateral gauge spreading load to the rail heads of track while measuring the resulting deflections. It is attached to a loaded hopper car, and load deflection characteristics of the track are measured using the hopper car to supply the required reactive forces. It is a portable system which can be transported by truck or air to site where tests are to be run. A modification is available to allow lateral loading at the rail shear center.

The TLF consists of three major subsystems. These are (1) the loading fixture, (2) the hydraulic system and (3) the electrical system. Figure K-7.1 is a basic layout showing the Loading Fixture and Figure K-7.2 shows the system with the modification installed.

K.7.1.1.1 LOADING FIXTURE

The load system has two 2-9/16 inch-diameter 10-1/4 inch stroke vertical loading cylinders which, with a 10,000 psi hydraulic system, can produce up to 51,000 lb of vertical load at each rail head. Inside of the loading fixture is another 2-9/16 inch-diameter cylinder which will also produce up to 51,000 lb of lateral load with the 10,000 psi hydraulic system. The available lateral stroke is approximately 6 inches.

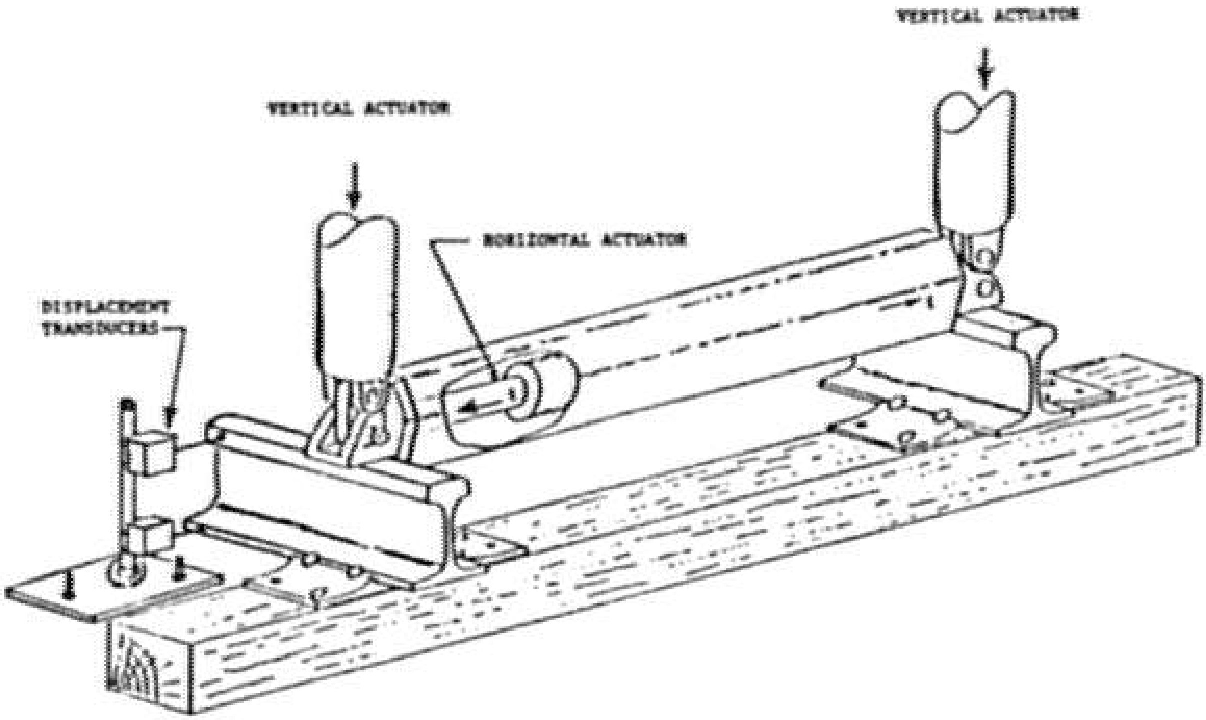


FIGURE K-7.1 BASIC LAYOUT OF TRACK LOADING FIXTURE

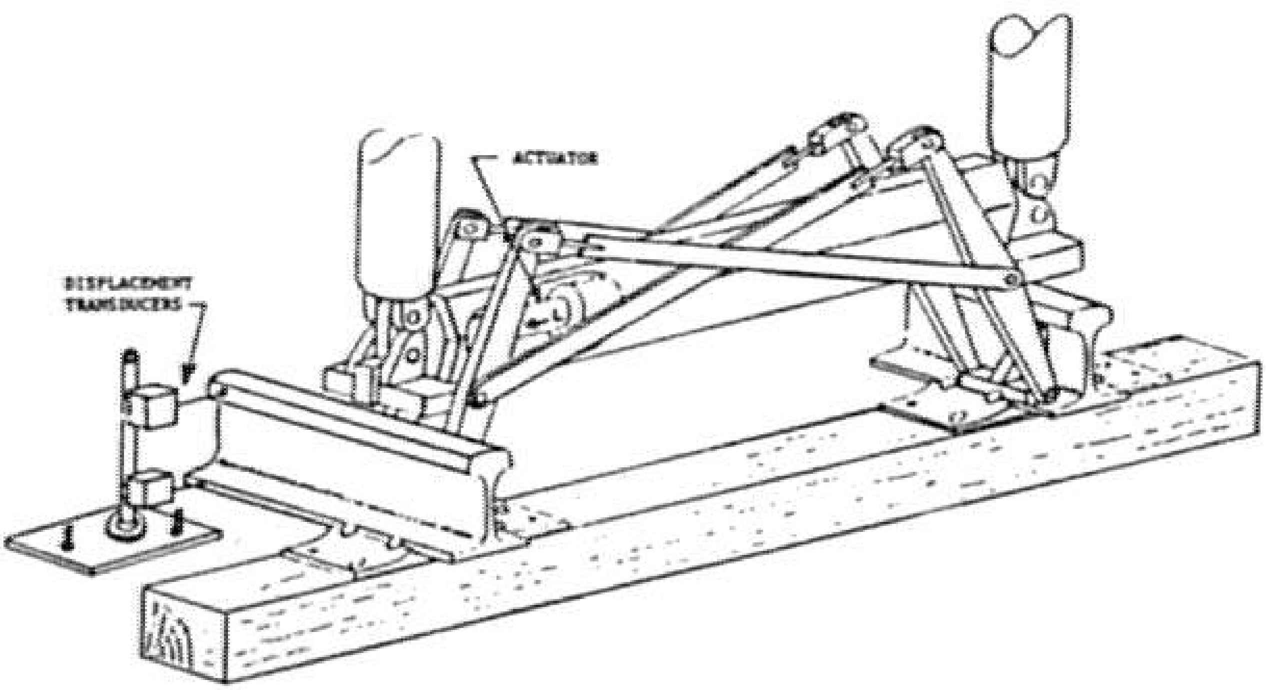


FIGURE K-7.2 MODIFIED BASIC LAYOUT OF TRACK LOADING FIXTURE

The clevis pins at each end of the loading fixture are strain gauge, pin-type load cells which are used to measure both the vertical and the lateral forces produced by the loading fixture. The orientation of these load cells is such that angular misalignment of the vertical cylinders does not cause errors in the indication of either the vertical or the lateral loads.

K.7.1.1.2 HYDRAULIC SYSTEM

The TLF system can be set up to operate with one or two hydraulic power supply pumps. To achieve optimum system performance, dual pump operation should be used. In the event that one pump/engine unit should become inoperable, the hydraulic system can be reconfigured to operate adequately from a single pump with reduced performance. The pump #1 unit incorporates and automobile alternator to supply electric power for the rest of the system and a manual 2-way valve for flow control. The pump #2 unit has a reservior-mounted, remote-controlled 3-way valve. If pump #2 fails, the system is operable using pump #1. If pump #1 fails,, pump #2 can be used, but an additional electrical energy source will be required to keep the battery charged. This electricity source can be a motor/generator set and battery charger or cable jumpers to an automobile charging system.

The dual pump hydraulic circuit includes the 4-way solenoid valve. This valve unloads the vertical cylinder hydraulic pump (pump #1) when no data are being taken and provides fast advance for the vertical cyclinders. The 3-way remote controlled solenoid valve mounted on the lateral cylinder hyraulic pump (pump #2) is used to control flow to the lateral cylinders. To control loads, two DC motor actuated relief valves are used. Other elements in the hydraulic system are check valves used for safety purposes to prevent rapid unloading in case of power failure and needle valves used to control and balance system flows.

Simple hose changes within the hydraulic control package allow change over to the single pump circuit. In this mode of operation, critical needle valve adjustments are required to balance system flows between the lateral and vertical cylinders. Since supply flows are reduced, the system speed performance will decrease.

K.7.1.1.3 ELECTRICAL SYSTEM

The electrical system consists of transducers, signal conditioning circuits, control circuits, logic circuits, and power circuits. Transducers included in the system are four strain gauge load cells to measure vertical and lateral loads, and five cable driven potentiometers to measure rail head, rail base, and gauge displacements. Signal conditioning for the strain gauge load cells is done using commercially available instrumentation amplifiers. Signal conditioning for the cable driven potentiometers is hard wired operational amplifier circuitry.

System loads are controlled by using the measured forces as indicated by the strain gage load cells in a feedback control system to drive the DC motors that actuate the relief valves in the hydraulic systems. Voltages are supplied to these motors in such a way that the relief valves operate until the desired load is obtained. Load commands are generated either manually with 10-turn potentiometers or automatically with integration circuits. Logic is provided so that with either the manual or automatic control mode the lateral command force cannot exceed the measured vertical force when in the normal operating mode. For operating in the modified mode (where up to 10,000 lb lateral loads can be produced with no vertical loads) an override switch is provided at the top of the control panel. Integrators and selector switches are provided to generate loads which can be increased and decreased in ramp type manner with loading and unloading rates of approximately 500 lb/per sec.

Other features of the electrical system are over-travel limits that stop system loading when rail motions exceed set limits, battery powered operation with recharging from the gasoline engine, and two X-Y-Y plotters to record forces and deflections.

The system is placed in shipping containers. To install the system the loading fixture is removed from its shipping container and attached to the hopper car. The system should be installed with the TLF mounted toward the end of the car with the brake rigging.

K.7.1.2 LIGHTWEIGHT TRACK LOADING FIXTURE (LTLF)

K.7.1.2.1 INTRODUCTION

Rail restraint is a critical factor which affects the safety or all vehicles. With inadequate rail restraint, wheel/rail loads can cause rail rollover and sudden gauge widening which can result in train derailment. In order to ensure that the lateral track strength is adequate, a means for measuring the rail lateral rail restraint characteristics is required.

The feasibility of making these measurements was demonstrated by the development and field tests with the Track Loading Fixture (TLF). The TLF was a research tool, and was not intended for frequent routine use by track inspectors. A "second generation" device was developed which was lightweight and more convenient to use that the TLF for routine track measurements. This device, called the Lightweight Track Loading Fixture (LTLF).

K.7.1.2.2 GENERAL DESCRIPTION

The function of the LTLF is to measure the lateral force applied at the rail shear center (i.e., center of "twist") and the corresponding change in track gauge. Lateral load is applied hydraulically with a hand pump and cylinder combination which is mounted to an aluminum structure. The load up to 10,000 prounds is applied to the rails through a pair of clevis-mounted loading shoes which are shaped to conform to the web area of the rail type under test. The magnitude of lateral load is indicated by a pressure gauge mounted to the pump, and calibrated to measure force. See figure K-7.3 for a layout of the device mounted between the rails.

Gauge widening and absolute gauge are measured with a telescoping gauge bar which is also attached to the aluminum structure. The gauge bar is spring-loaded so that it maintains contact with the rail heads at the gauge point throughtout the laoding excerise. An electonic gauge measurement system is included in the LTLF as shown in figure K-7.4.

The electronic gauge measurement system includes a linear potentiometer mounted on the gauge bar. The potentiometer is excited by 9V transistor batteries, and its output is signal conditioned through an adjustable voltage regulation circuit. The voltage output of the circuit is displayed on a digital multimeter which is provided.

The system includes a trimpot which can be used to adjust the output voltage to correspond to physical units (e.g. 1.75 volts = 1.75 inches). A convenient physical calibration is provided by the gauge bar, which was designed with a total range of 4.0 inches, and can be extended fully when the LTLF is not in the track by pumping the cylinder.

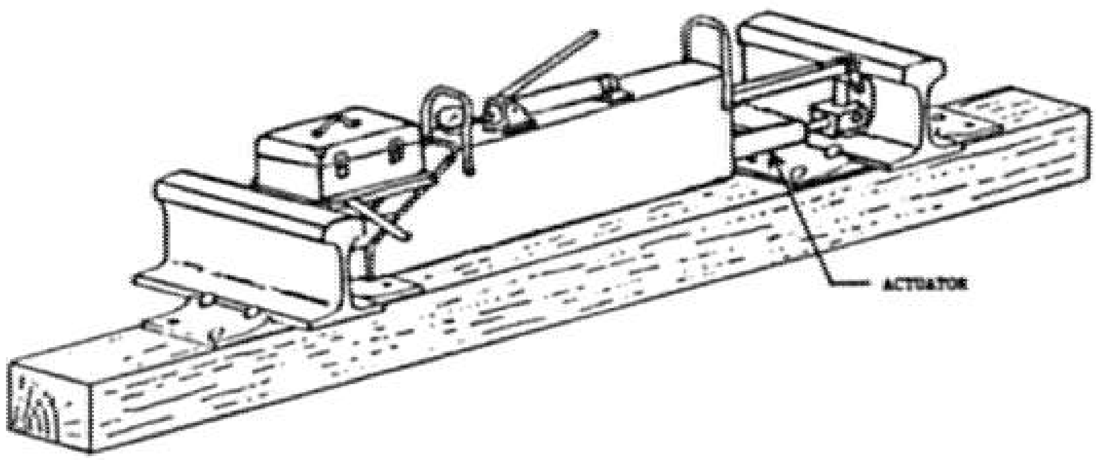


FIGURE K-7.3 LIGHTWEIGHT TRACK LOADING FIXTURE

The circuitry and multimeter are mounted in small sealed case, which in turn is mounted on the LTLF. An electrical schematic for the system is presented in Figure K-7.5.

A unique set of loading shoes is required for each rail type (shoes for 85, 100, and 132 lb RE rail are provided with the LTLF). Single acting ball-lock pins serve as the clevis pins for the LTLF, and provide a quick means for interchangind the shoes.

A custom shipping case is provided for the LTLF. This case is suitable for safe air-freight transfer of the device.

Safety features of the LTLF include protective bars, which were designed to prevent impact damage to the pressure gauge and electronics and nylon insulators, which eleminate the possibility of electrical "shorting" of the rail by the device.

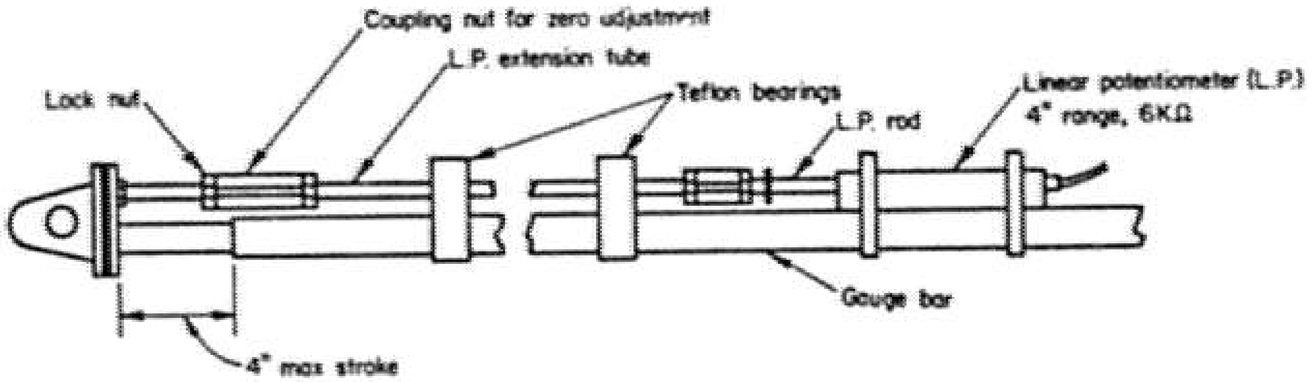


FIGURE K-7.4 SKETCH OF LTLF GAUGE BAR LAYOUT FOR ELECTRONIC GAUGE MEASUREMENT

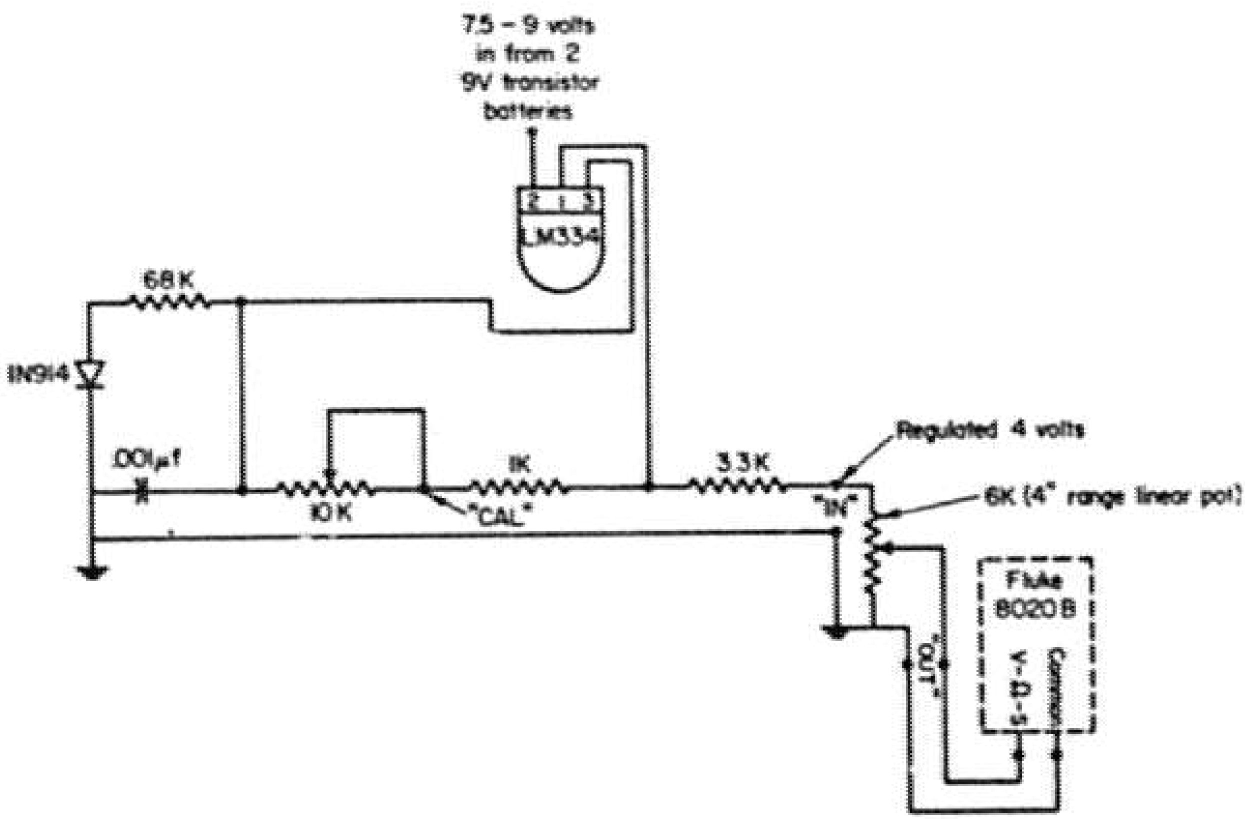


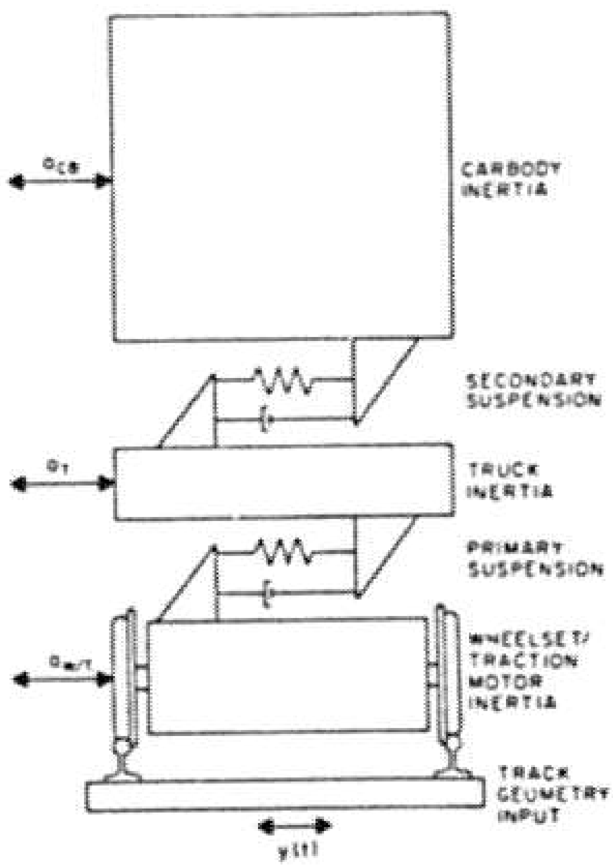
FIGURE K-7.5 ELECTRICAL CIRCUITRY FOR GAUGE MEASUREMENT WITH THE LTLF

K.7.2 ESTIMATING LATEPAL TRUCK FORCE FROM ACCELERATIONS

K.7.2.1 DESCRIPTION OF TECHNIQUE

An alternative to the direct measurement of lateral truck forces is their estimation using the inertial measurements. Data from an array of accelermeters placed on the axles, trucks and carbody of a rail vehicle, can be used, knowing the related masses and inertias, to calculate the dynamic (or inertial) forces of each component. The algebraic sum of the lateral component forces yields the net total truck force.

A simplified illustration of the approach is shown in Figure K-7.6



TRUCK FORCE $= M_{CB} \cdot a_{CB} + M_T \cdot a_T + M_{W/T} \cdot a_{W/T}$

FIGURE K-7.6 SCHEMATIC OF BASIC LOCOMOTIVE TRUCK FORCE MODEL

The major advantage of this technique is of course low cost, when compared with instrumented wheelsets and instrumented track for determining lateral dynamic truck forces. The technique is also valuable in evaluating suspension systems by identifying the contributions to lateral dynamic truck force from the carbody, truck and axle masses.

TABLE K-7.1 SUMMARY PROCEDURE FOR LATERAL TRUCK FORCE ESTIMATION

1. Measure and record carbody lateral, carbody yaw, truck lateral and axle lateral accelerations (note: 0-10Hz bandwidth and digital data acquisition are recommended.) Mechanical isolators for accelerometer mounting are recommended.
2. FFT filter at 10Hz (or equivalent) (pass 0-10Hz with no phase distoration, at least 25 db attenuation at 10 Hz and above with no phase distortion).
3. Calculate inertia forces from known masses and measured accelerations.
4. Sum forces to obtain net lateral dynamic truck force.
5. Plot time histories of component inertia forces and net truck force.
6. Identify contributions to peak and RMS truck force from carbody, truck frame and wheelsets.

K.7.2.2 SUMMARY PROCEDURES

The procedures for estimating net lateral truck force are fairly straight forward. (See Table K-7.1) The rigid body response modes of a typical rail vehicle are below 10 Hz, between 1g to 5g peak yet the environment on board a rail vehicle is filled with shock and vibration inputs of higher frequencies (100Hz and up) and higher force levels (100g and more). Only the rigid body accelerations are of interest in estimating dynamic forces. Therefore, all other accelerations are noise and must be filtered out. To overcome the noise problem, a 50Hz mechanical filter, or isolator mounting, is used to isolate the accelerometers from the major shock and vibration inputs. This reduces the dynamic range required for the transducers however it does not eliminate the noise. To eliminate it, the recorded output of the accelerometers must also be filtered. The best choice here is an FFT filter applied at 10Hz to a minimum of a 4 second time history. An FFT filter is applied by performing a Fast Fourier Transfer of the time series data. The real and imaginary components are retained. The coefficients for all frequencies above the desired cutoff are set to zero. An inverse FFT is performed using the remaining components. The result is an "ideally" filtered time series. An inverse FFT is performed using the remaining components. The result is an "Ideally" filtered time series. An FFT filter closely approximates an ideal filter in that it has no phase shift, it is flat in the pass band and zero everywhere else (nearly). (Alternative filtering should have about 25 db attenuation above 15 Hz, and have a flat response with little or no phase shift below 10Hz, to provide an acceptable signal to noise ratio). The interia forces are then calculated by multiplying the measured accelerations of the carbody, truck frame and axles by their respective masses and inertias as shown in Equation.

Net Truck Lateral Force--Equation

$$F_t = M_a \sum_{1}^{n} \ddot{X}_{a_i} + M_T \ddot{X}_T + \frac{\ell_{CG} M_c + I_c \ddot{\theta}_c}{\ell_{TC}}$$

where:

- F_t = Net Truck Lateral Force (lb)
- M_a = Mass of one axle (lb-sec^2/in)
- $\ddot{X}_{ai}$ = Axle "i" lateral acceleration (in/sec^2)
- n = Number of axles in truck
- M_T = Truck frame mass (lb-sec^2/in)
- X_T = Truck frame lateral acceleration (in/sec^2)
- ℓ_{CG} = Distance from carbody yaw center to truck center (ft)
- ℓ_{TC} = Truck center spacing (feet)
- M_C = Carbody mass (lb-sec^2/in)
- $\ddot{X}_C$ = Carbody lateral acceleration (in/sec^2)
- I_C = Carbody yaw inertia (lb-in-sec^2)
- $\ddot{\theta}$ = Carbody yaw acceleration (rad/sec^2)

The resultant forces are summed to obtain total net truck lateral force. Plots of the time histories of the total and component forces should be produced as an aid to analysis of the suspension system. The contributions of axle, truck and carbody inertia to peak truck force values can be readily identified from the plots. Calculations of the RMS values for each component inertia force and the total inertia force over the entire time history are also helpful in identifying suspension effectiveness.

K.7.2.3 LIMITATIONS AND SPECIAL REQUIREMENTS

Limitations and special requirements are summarized in Table K-7.2. The primary limitation of this approach is that friction forces are neglected. Therefore, wheel and axle forces cannot be resolved. Wheel and axle forces are significantly affected by creep forces and center plate friction whereas these effects are largely cancelled out when considering total truck forces.

Significant attention must be given to filtering to obtain the low-level low-frequency rigid body accelerations from the relatively high level-high frequency noise environment of a rail vehicle. For best results shock mounts with a flat response to 50Hz are recommended for the accelerometers and 10Hz FFT filtering is recommended in processing the data. As a result of the 10 Hz filtering, forces generated by wheel impact at misaligned joints are underestimated. However these forces are of very short duration and rarely contribute significantly to lateral truck force to rail rollover.

TABLE K-7.2 SUMMARY OF LIMITATIONS AND REQUIREMENTS
FOR LATERAL TRUCK FORCE ESTIMATION

1. Friction/creep forces neglected.
2. Wheel and axle forces cannot be resolved.
3. Shock mounts are required for the accelerometers.
4. Digital data acquisition and processing is recommended.
5. FFT filtering is recommended.
6. Impact forces are underestimated.

K.7.2.4 EXAMPLE

An application of this technique was performed during the perturbed track tests in 1978. The prescribed suite of accelerometers, with isolators, was installed on the carbody, truck and axles of an SDP-40F six axle locomotive. (See Figure K-7.7). The data was filtered and digitally recorded along with force data from three instrumented wheelsets in the same truck. (See Figure K-7.8). This direct measurement of net truck force enabled an evaluation of the accuracy of the estimation technique. Overall the results showed the technique to be up to 90% accurate in estimating filtered peak force levels. Also 4 second time histories of the estimated total truck force, from the perturbed track test zones, showed good agreement with those from the wheelset measurements. (See Figure K-7.9) the results are shown for several cycles of two alignment perturbations, one with a 78 foot fundamental wavelength and a second with a 39 foot fundamental wavelength.

One of the test objectives was to identify the factors contributing to excessive lateral truck forces which had resulted in a number of SDP-40F derailments. Figure K-7.10 shows the relative contributions of the carbody, axle and truck frame inertia forces to peak and RMS net lateral truck force. Within the test section, the carbody inertia force (as the result of carbody yaw activity) was found to significantly dominate the overall response. These results led to further investigation of the dynamic characteristics of the secondary suspension system.

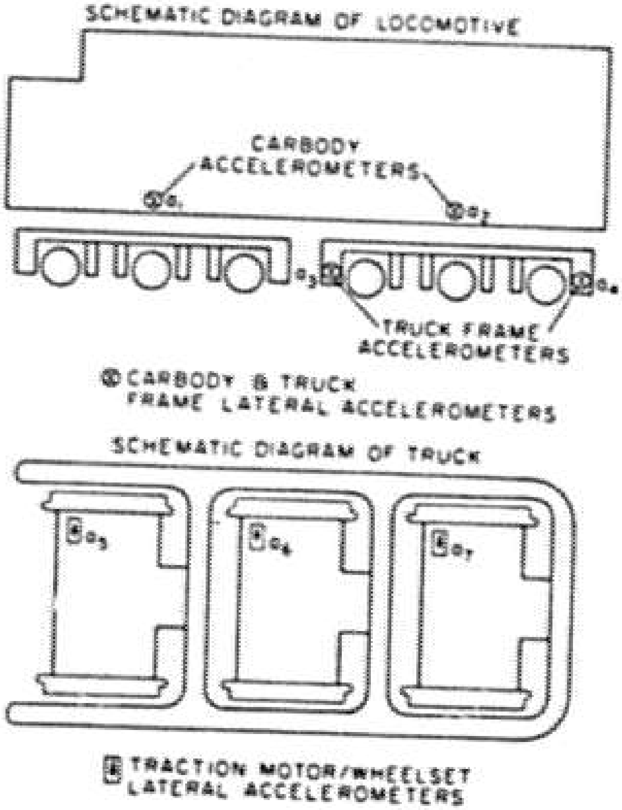


FIGURE K-7.7 LATERAL ACCLEROMETER LOCATIONS

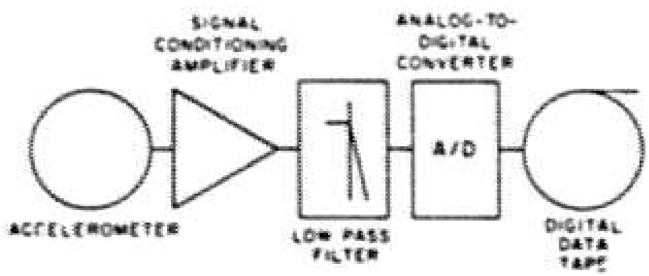
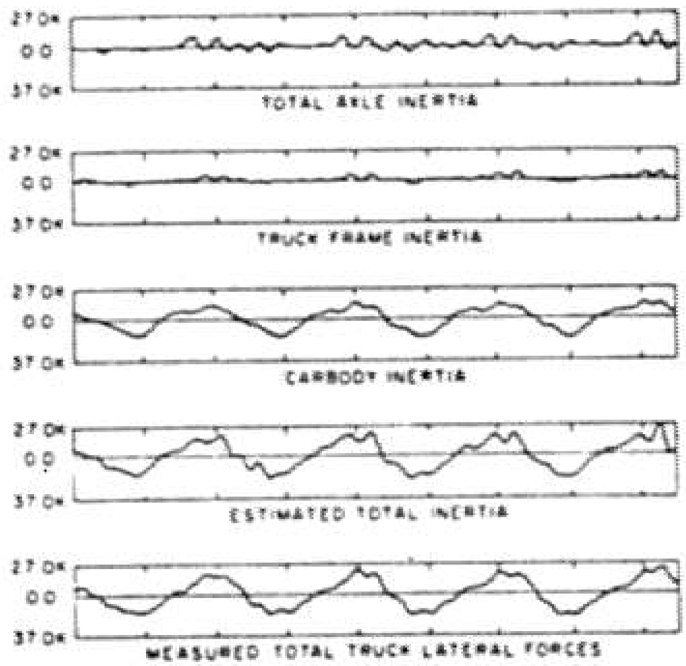
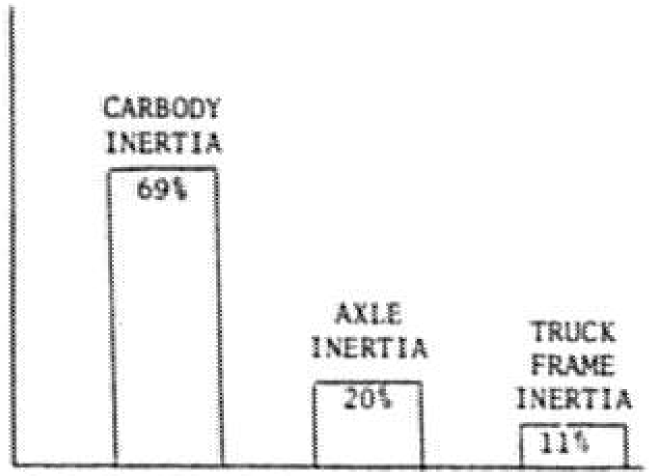


FIGURE K-7.8 INSTRUMENTATION FLOW CHART

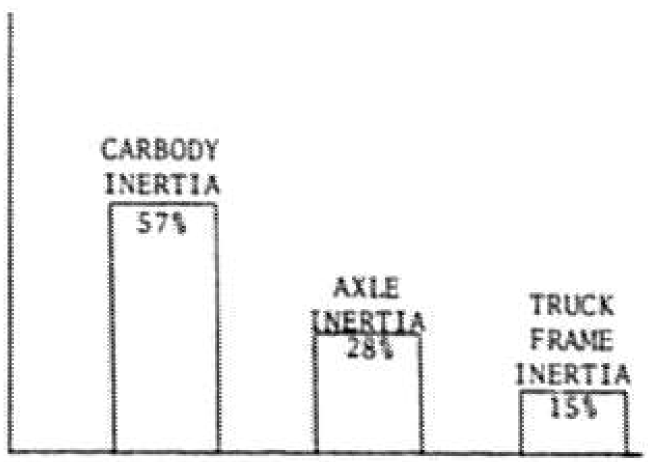


78-Foot Piecewise Linear @ 55 mph

FIGURE K-7.9 COMPARISONS OF ESTIMATED AND MEASURED TRUCK FORCES



RMS CONTRIBUTION OF INERTIA FORCES
(SPD-40F) 55 MPH



PEAK CONTRIBUTION OF INERTIA FORCES
(SPD-40F) 55 MPH

FIGURE K-7.10 RELATIVE CONTRIBUTIONS TO THE TOTAL TRUCK FORCE

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SECTION L
DATA MANAGEMENT

L.1 INTRODUCTION

There are many different approaches to data management for any particular combination of test requirements. This section, however, outlines the requirements for an overall data management concept for Vehicle/Track Interaction Assessment Techniques (IAT). This annotated outline will highlight the points needed for the user so that he can fill in the details of an approach which is optimized to the specific requirements, equipment, and facilities available to him.

L.1.1 Data Management

The management of data in any test is a critical element of the test. It must be taken into account from the earliest stages of planning and throughout the whole process of test planning, execution, and analysis. Data management provides for possible later use of test data in ways not considered until perhaps long after the test has been completed. Good data management practice is essential to assuring the validity and credibility of test results. Data management, if not practiced properly, can increase costs unnecessarily by requiring tests to be repeated because of lost, questionable, or unrecorded data or by requiring more data to be acquired and processed than is necessary.

Data management requires a seemingly inordinate attention to details but that attention will pay off by optimizing the validity of test results and cost and time for testing. Data management, then, is a process carried out by test engineers and planners and computer programmers in the planning stages of a test and by engineers, technicians, computer operators, machines (i.e., computer hardware), and programs (i.e., computer software) in the execution stages of a test. The combination of machines and programs, as put to use by a human operator, constitute a data management system.

L.1.2 Data Management System for IAT

A permanent or long-term facility using tests recommended by the IAT should include a data management system carefully designed and optimized to perform all the functions required of it in a standardized and efficient manner. However, IAT testing is likely to be performed often on one-time facilities by different users who have different computer equipment and facilities available to them. Each user must assemble a data management system, then, from available resources, optimizing and trading off features, performance, and cost while still providing an acceptable system for the tests to be performed. Software probably will be designed around "off-the-shelf" packages with little special programming and little automatic transfer from one step to the next in the processing. Hardware probably will utilize equipment already owned or leased by the user for other purposes and may include time on a machine owned by others, perhaps a time-share vendor or service bureau.

A data management system for IAT as outlined here is made up of the following subsystems, which may contain overlapping components and share certain personnel, software, hardware, and other resources.

A. Data Acquisition Subsystem.

B. Data Reduction/Analysis Subsystem.

C. Data Storage/Retrieval Subsystem.

D. Data Presentation Subsystem.

L.2 OBJECTIVES OF A DATA MANAGEMENT SYSTEM FOR IAT

The objectives of a data management system for IAT may be divided into three categories: user objectives, operational objectives, and analysis objectives.

L.2.1 User Objectives

These are key objectives important to a user of IAT. They include speed with which test results are obtained, security of proprietary data (if any), technical level required to interpret results, and cost of testing.

A. Easy to Use. The data management system must be able to be used by relatively inexperienced personnel without extensive training.

B. Rapid Results. The high value of equipment and personnel involved in testing, and time constraints on their availability, often will dictate that test results be available quickly.

1. Next Day Preliminary Results. Users of IAT should be able to review a selected set of reduced and processed data from individual runs in time to evaluate and potentially alter test parameters for the next day of testing.

2. Next Week Test Results. Equipment manufacturers and railroads will usually need test results promptly if those results are to be of use.

C. Multiple Data Access. Users should be able to withdraw data from the data management system at any reasonable stage in the processing.

D. Security of Proprietary Data. Users of a long-term test facility should be able to withdraw proprietary data from the data management system and be assured that it is not available to any other user.

E. Multi-Level Output Detail. Output formats should be provided which are convenient to users at multiple levels of expertise.

F. User-Supplied Personnel and Equipment. Users of a long-term test facility should be able to conduct tests and process the data with their own people and computer facilities.

G. Cost Effectiveness. The data management system chosen should provide the most performance above the minimum requirements for the lowest life-cycle cost. Maximum use of existing and off-the-shelf hardware and software should be used wherever practical, consistent with minimizing costs.

L.2.2 Operational Objectives

The objectives listed below are important to the safety of tests, the security of test data, and the operational efficiency of the IAT process.

A. Quick-Look Support. The data management system must support quick-look processing of key parameters in real time to assure that tests are conducted safely and that data is being properly recorded. Graphical displays and pre-established limit alarms should be used wherever appropriate. Related data should be available in engineering units and in tabular form to permit rapid manual plotting in the field when special conditions warrant such additional examination.

B. Backup Reduction/Analysis Subsystem. Ability to perform in-depth analysis either on-site (or at the user's computer system) or off-site (at another designated site, e.g., a contractor) to allow for unavailability due to system failure or maintenance.

C. Data Verification. The data management system should monitor the validity of the data (e.g., parity, range, etc.) and record verification statistics at all steps of data transfer.

   1. Calibration Data. Calibrations applied to signals to convert to engineering units.

   2. Bookkeeping. Counts of records and accounting for data (labeling, check sums, etc.).

   3. Recording the Verification. Verification data (e.g., number and type of possible errors found) should be transferred and recorded with the data itself.

D. Direct Data Transfer to Models. The data reduction/analysis subsystem should be able to support optional machine-readable output formats suitable for use as input to relevant (computerized) analytical models.

E. Flexible Graphical Output. Output graphics should include automatically a subset of plots for each test type or performance issue.

F. Remote-Site Testing. The data management system must be capable of receiving data from IAT tests performed at a variety of locations (e.g., revenue track) to accommodate the required track geometry or operating conditions which are conveniently and/or economically accessible at those locations.

L.2.3 Analysis Objectives

These objectives are important to assure that the analysis of test data can be performed with correct results.

A. Comparative Analyses. Test data should be maintained in a format which will permit various comparative analyses of performance of two or more vehicles to be made at any time after testing is completed on them.

B. Data Integration. Onboard and wayside data should be synchronized and combined into one data base along with dynamic track geometry data and pre-test and post-test track chacterization data.

C. Flexible Storage and Retrieval Formats. The data management system must include the capability for permanent storage and retrieval of data in a form or forms which will allow:

1. Comparative Analysis. Comparison of results of similar tests on different vehicles or components.

2. Specialized Analyses. Analyses by a researcher which would not normally be done as part of IAT testing.

3. Statistical Extracts. For administrative analyses such as measuring IAT performance over a long term.

D. Validation of Analytical Models. Model validation capability should be provided for as an integral part of the data management system (see IAT Section D).

E. Validation of Original Assumptions. Determination that original test assumptions, tolerances, error analyses, and distribution of data, etc., were reasonable and did not affect the results significantly.

L.3 DATA MANAGEMENT HANDLING REQUIREMENTS

The sampling rate and amount of data to be handled varies by the type of test and performance issue. This subsection categorizes and summarizes the requirements by location (onboard or wayside), test category, and performance issue.

L.3.1 Onboard Data Requirements

Onboard data handling requirements are summarized in Tables L-1, L-2, and L-3. Minimum number of channels, frequency range, and sampling rate are shown for each performance issue.

L.3.1.1 Real Time Data (Quick-Look & Safety) - Refer to the tables for the minimum number of channels required for each performance issue. They include principally the channels required to assure safe conduct of the test. See IAT Section E (Test Plan Summaries) for details on the safety channels. Most real time channels are duplicated for each performance issue, making the total real time channels for tests addressing multiple performance issues less than the sum of those for the individual performance issues.

L.3.1.2 Post Processing - Post processing data handling requirements are summarized in the tables. The data management system should perform the bulk of its various tasks upon the data after completion of a run or even a day of testing. This will require sufficient storage and retrieval systems and may mean non-prime time processing to reduce costs and reduce processing time.

L.3.2 Wayside Data Requirements

Wayside data handling requirements are summarized in Table L-4. Minimum number of channels, frequency range, and sampling rate are shown for each performance issue. The table is organized as for onboard data and contains the same categories of information for real time and post processing requirements. Many real time channels are duplicated across performance issues as in the onboard case, making the number of channels required less than their sum for tests addressing multiple performance issues.

TABLE L-1
ONBOARD DATA HANDLING REQUIREMENTS
FOR PROOF TEST

	PERFORMANCE ISSUES*									
	H	T&R	P&B	Y&S	SSC	SN	DC	SBD	LTA	LI
DATA CHANNELS:										
Speed	1	1	1	1	1	1	1	1	1	1
ALD	1	1	1	1	1	1	1	1	1	1
Environmental	3	3	3	3	3	3	3	3	3	3
Test Data	2	3	6	4	6	4	7	4	5	6
Total for Data	7	8	11	9	11	9	12	9	10	11
Quick-Look	4	3	5	5	4	3	6	4	4	7
Total Channels	11	11	16	14	15	12	18	13	14	18
FREQUENCY RANGE:										
Minimum (Hz)	0	0	0	0	0	0	0	0	0	0
Maximum (Hz)	50	10	10	10	100	100	100	100	100	50
Sampling Rate (Hz)	100	20	20	20	200	200	200	200	200	100

TABLE L-2
ONBOARD DATA HANDLING REQUIREMENTS
FOR DIAGNOSTIC TEST

	PERFORMANCE ISSUES*									
	H	T&R	P&B	Y&S	SSC	SN	DC	SBD	LTA	LI
DATA CHANNELS:										
Speed	1	1	1	1	1	1	1	1	1	1
ALD	1	1	1	1	1	1	1	1	1	1
Environmental	3	3	3	3	3	3	3	3	3	3
Test Data	14	9	7	8	8	21	17	16	17	20
Total for Data	19	14	12	13	13	26	22	21	22	25
Quick-Look	8	5	5	7	6	7	8	6	6	8
Total Channels	27	19	17	20	19	33	30	27	28	33
FREQUENCY RANGE:										
Minimum (Hz)	0	0	0	0	0	0	0	0	0	0
Maximum (Hz)	100	100	10	100	100	100	100	100	100	50
Sampling Rate (Hz)	200	200	20	200	200	200	200	200	200	100

* Symbols are described below Table L-4, next page.

TABLE L-3
ONBOARD DATA HANDLING REQUIREMENTS
FOR SERVICE ENVIRONMENT TEST

	PERFORMANCE ISSUES									
	H	T&R	P&B	Y&S	SSC	SN	DC	SBD	LTA	LI
DATA CHANNELS:										
Speed	1	1	1	1	1	1	1	1	1	1
ALD	1	1	1	1	1	1	1	1	1	1
Environmental	3	3	3	3	3	3	3	3	3	3
Structural Data	0	0	0	0	0	0	0	0	0	10
Test Data	17	10	7	16	13	25	26	16	17	22
Total for Data	22	15	12	21	18	30	31	21	22	37
Quick-Look	8	5	5	7	6	7	8	6	6	8
Total Channels	30	20	17	28	24	37	39	27	28	45
FREQUENCY RANGE:										
Minimum (Hz)	0	0	0	0	0	0	0	0	0	0
Maximum (Hz)	100	100	10	100	100	100	100	100	100	50
Sampling Rate (Hz)	200	200	20	200	200	200	200	200	200	100

TABLE L-4
WAYSIDE DATA HANDLING REQUIREMENTS
FOR SERVICE ENVIRONMENT TEST

	PERFORMANCE ISSUES						
	T&R	P&B	Y&S	SSC	SN	DC	SBD
DATA CHANNELS:							
Test Data	10	10	10	4	4	20	4
Quick-Look	6	6	6	4	4	8	4
Total Channels	16	16	16	8	8	28	8
FREQUENCY RANGE:							
Minimum (Hz)	0	0	0	0	0	0	0
Maximum (Hz)	100	100	100	100	100	100	100
Sampling Rate (Hz)	200	200	200	200	200	200	200

H = Hunting
T&R = Twist and Roll
P&B = Pitch and Bounce
Y&S = Yaw and Sway
SSC = Steady State Curving
SN = Spiral Negotiation
DC = Dynamic Curving
SBD = Steady State Buff and Draft
LTA = Longitudinal Train Action
LI = Longitudinal Impact

L.4 FUNCTIONS OF A DATA MANAGEMENT SYSTEM FOR IAT

Based upon preliminary assessment of the test requirements for IAT, the data management system, both hardware and software, is described in terms of its functional requirements in the following subsections. A data management system which performs these functions should meet the objectives outlined in Subsection L.2, above. A block diagram of the system is shown in Figure L-1.

L.4.1 Data Standardization

All test data should be formatted and transferred in a standardized manner to ensure proper cataloging and repeatability of analysis. Some of the issues to be resolved are:

A. Standard Channel Assignments (Analog). Channel assignments for raw analog data received from sensors should be consistent from test to test whenever possible. Assignments to be standardized are:

1. Unique Logical Channel Assignment.
2. Physical Channel Assignment.

B. Standard Record Formats (Digital). The format of data stored on magnetic or other machine-readable media should be carefully planned. Format may be different for data at various processing stages:

1. Unprocessed Data.
2. Processed Data.

C. Record Types to be Standardized.

1. Header Records. Information in text form concerning basic test parameters (e.g., description of test, date and time, number of channels recorded, description and value units of each channel, sample rate, etc.).

2. Calibration Records. Engineering unit conversion factors and offsets applicable to each channel.

3. Data Records. Since these make up most of the data, it is important that the format be chosen carefully with efficiency of storage use of prime importance. Some factors to be considered are:

   a. Record Length (in Bytes or Bits).
   b. Word Length (in Bytes or Bits).
   c. Resolution and Range of Values. Large range or large values may require more than one word for storage.
   d. Sign Convention.
   e. Bit Padding Convention.
   f. Multiplexing Technique.
   g. Number of Channels.
   h. Sample Rate.
   i. Characteristics of any Non-Standard Channels.

4. Trailing Records. Trailing records signal the end of a file of data and also may contain:

   a. Post-Test Calibration Data.

   b. Comments. These may describe unusual events during the test.

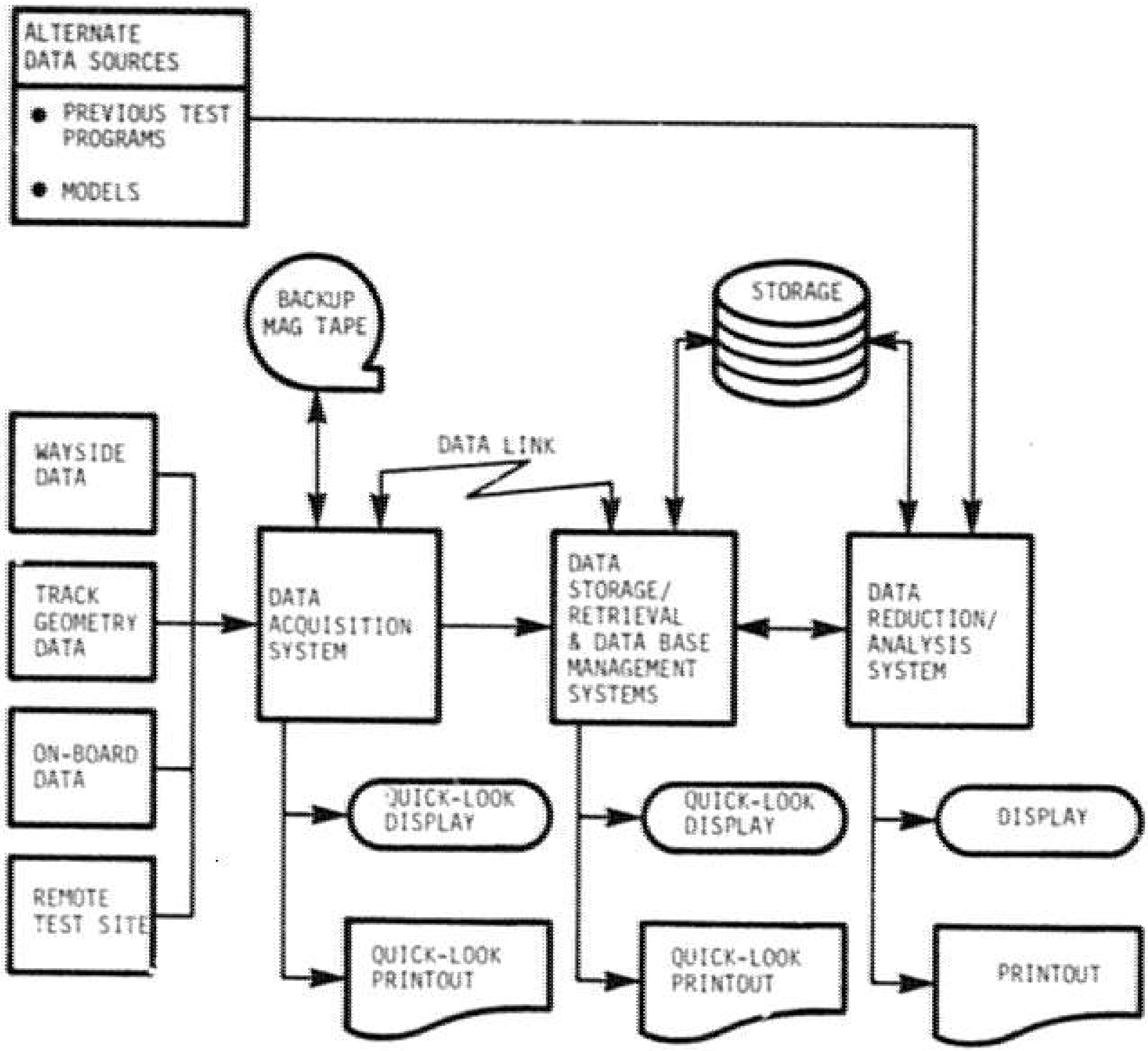


Figure L-1
Typical Data Management System for IAT

L.4.2 Data Acquisition

The data acquisition function may be performed in part by a pulse code modulation (PCM) system, probably located on-board the test train. Other techniques may be used instead, such as the more common frequency modulation (FM) multiplex systems. The principal data acquisition features are:

A. Input. Input data will be mostly in the form of analog electrical signals sampled at some fixed rate. Each signal will be assigned its own data channel.

B. Output. Output data will be in digital form and will be written onto magnetic or other machine-readable media for later retrieval. Data from all channels for each sample will be placed in a single record and placed serially onto the medium. Some multiplexing may occur, for efficiency of storage or speed of transfer, but distinct channel identification must be recoverable. Output from models may be required as well as from actual tests.

C. Functions to be Supported.

   1. Quick-Look. Conversion of quick-look parameters to engineering units will be required.

   2. Data Conversion (optional). If not provided here, it will be done under reduction/analysis.

   3. Time Synchronization. On-board and wayside data (if used) must be synchronized. A single output stream combining the two is preferred but if not practical the time codes must be matched to permit simplified synchronization later.

4. Pre-Test/Post-Test Acquisition. Pre-test and post-test acquisition of track geometry data will be necessary under some conditions.

5. Remote-Site Testing. The data acquisition subsystem may be required to function at a variety of test sites when special track geometry or operating conditions are required.

Typical data rate and capacity requirements are shown in Table L-5. Block diagrams of typical data acquisition systems are shown in Figures L-2 through L-4: Figure L-2 shows an analog-based system; Figure L-3 shows a computer-based system; and Figure L-4 shows a PCM system.

TABLE L-5

TYPICAL DATA ACQUISITION DATA REQUIREMENTS

	CHANNELS	SAMPLES PER SEC	RUN TIME	MEGABYTES OF DATA RAW SIG	MEGABYTES OF DATA ENG UNITS
Minimum	12	20	2 min.	0.6	1.2
Average	30	100	3 min.	1.1	2.2
Maximum	50	200	15 min.	20.0	40.0

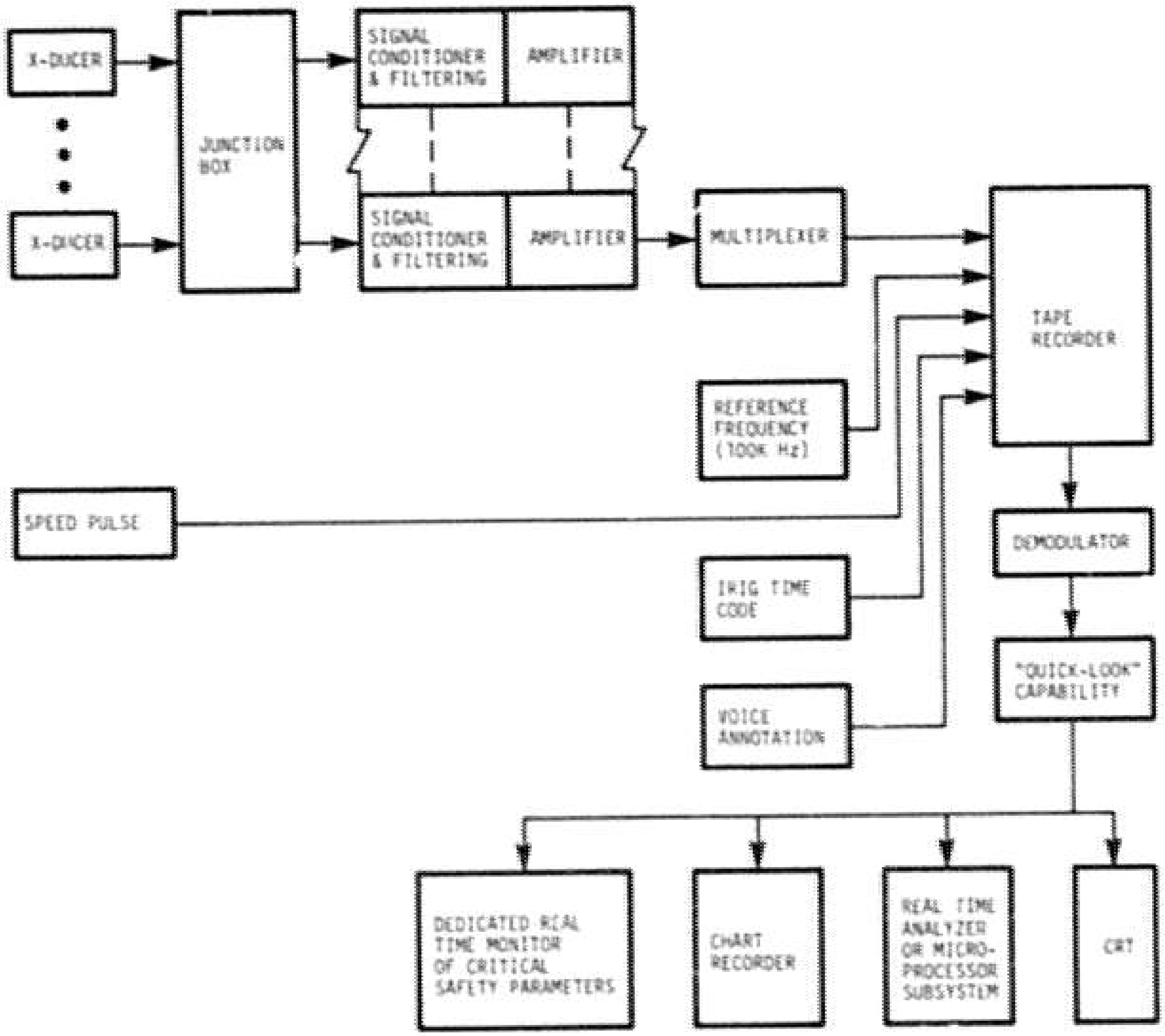


Figure L-2
Typical Analog-Based Data Acquisition System

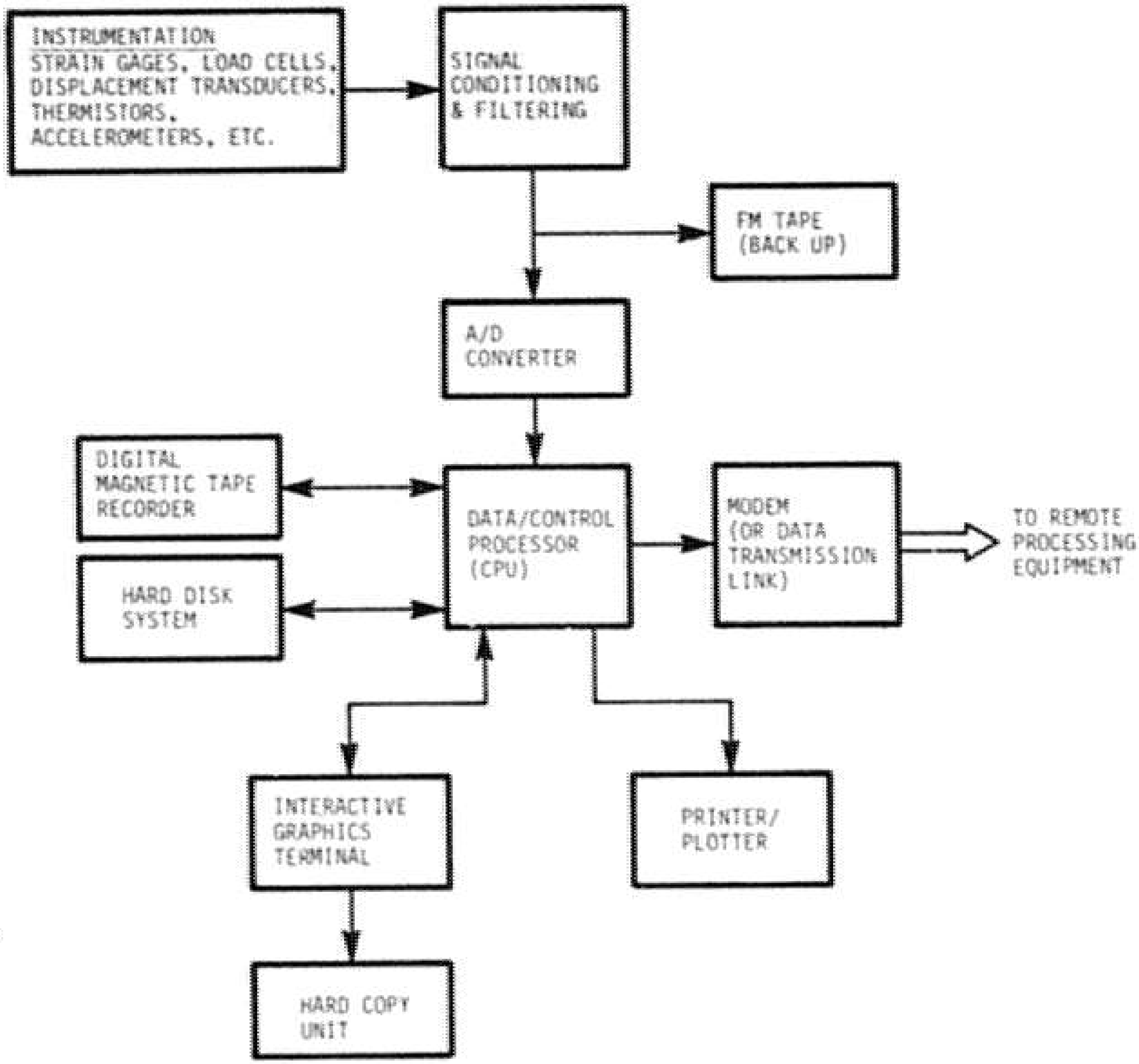


Figure L-3
Typical Computer-Based Data Acquisition System

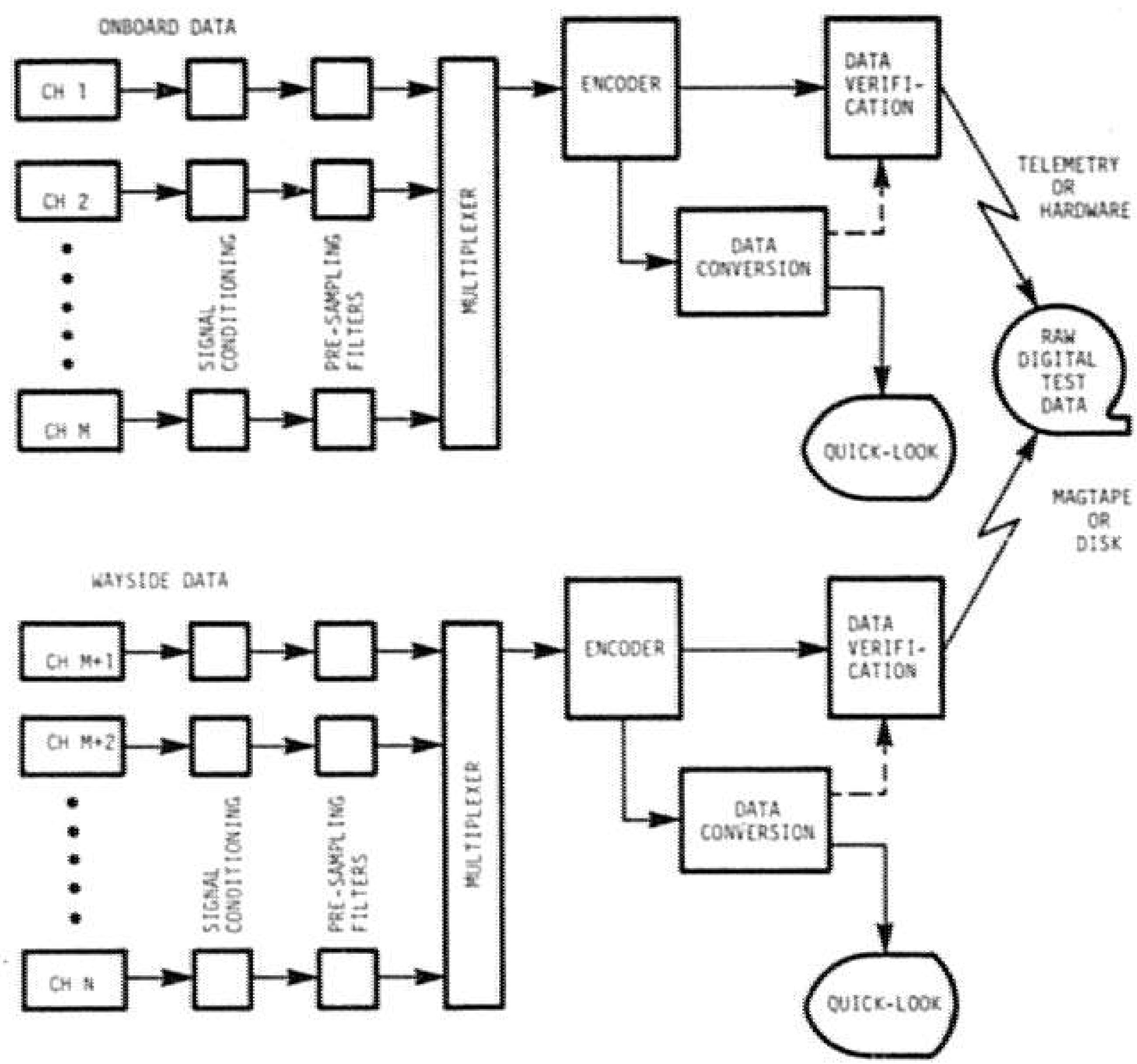


Figure L-4
Typical Pulse Code Modulation
Data Acquisition System

L.4.3 Data Conversion

If raw data are recorded on magnetic media in analog form they must first be converted to digital form with header and trailer information. The raw digital signal on each channel must be converted to calibrated engineering units. Conversion may be performed by either the data acquisition subsystem or by the data reduction/analysis subsystem. Possible conversion types to be considered are:

A. Digital to Analog.
B. Analog to Digital.
C. Raw Digital to Engineering Units.

L.4.4 Data Reduction/Analysis

A. Test Analysis. A block diagram of the data management system configured for test analysis is shown in Figure L-5. Typical functions required are:

   1. Time History and Simple Statistics.
   2. Statistical Analysis.
   3. Analytical Models. Extrapolation and ranging by using previously validated models.

B. Comparative Analysis. A block diagram of the data management system configured for comparative analysis is shown in Figure L-6. Typical functions required are:

   1. Statistical Analysis.
   2. Analytical Models. Use of previously validated models for comparison of different, but possibly untested, conditions or use of unvalidated models as part of the process of validating them.

C. Analysis Programs. A wide variety of analysis programs will be necessary for IAT. Many "canned" programs are available to run on virtually any computer. They will perform many general-purpose mathematical and statistical procedures on data properly formatted for them. A partial listing appears in the Bibliography of this Section L. However, the IAT analyses also require some very specialized mathematical procedures for which programs must be written. In either case, programs must format the data to be compatible with each analysis program. For a more thorough discussion of analysis programs see IAT Section C, Literature Search, and IAT Section D, Model Validation.

1. IAT-Specific. Programs written for IAT use and probably not usable for any other purpose.
2. Pre-Packaged Programs. Special-purpose programs and subroutines available for lease or purchase.
3. General-Purpose Packages. Large packages (e.g., statistical, data management, and analysis) available for lease or purchase. One or more of these may already reside on the user's computer system.
4. Utilities. Programs likely to be already available on the user's computer system to perform editing, file management, etc. These are often designed for specific models of computer system.

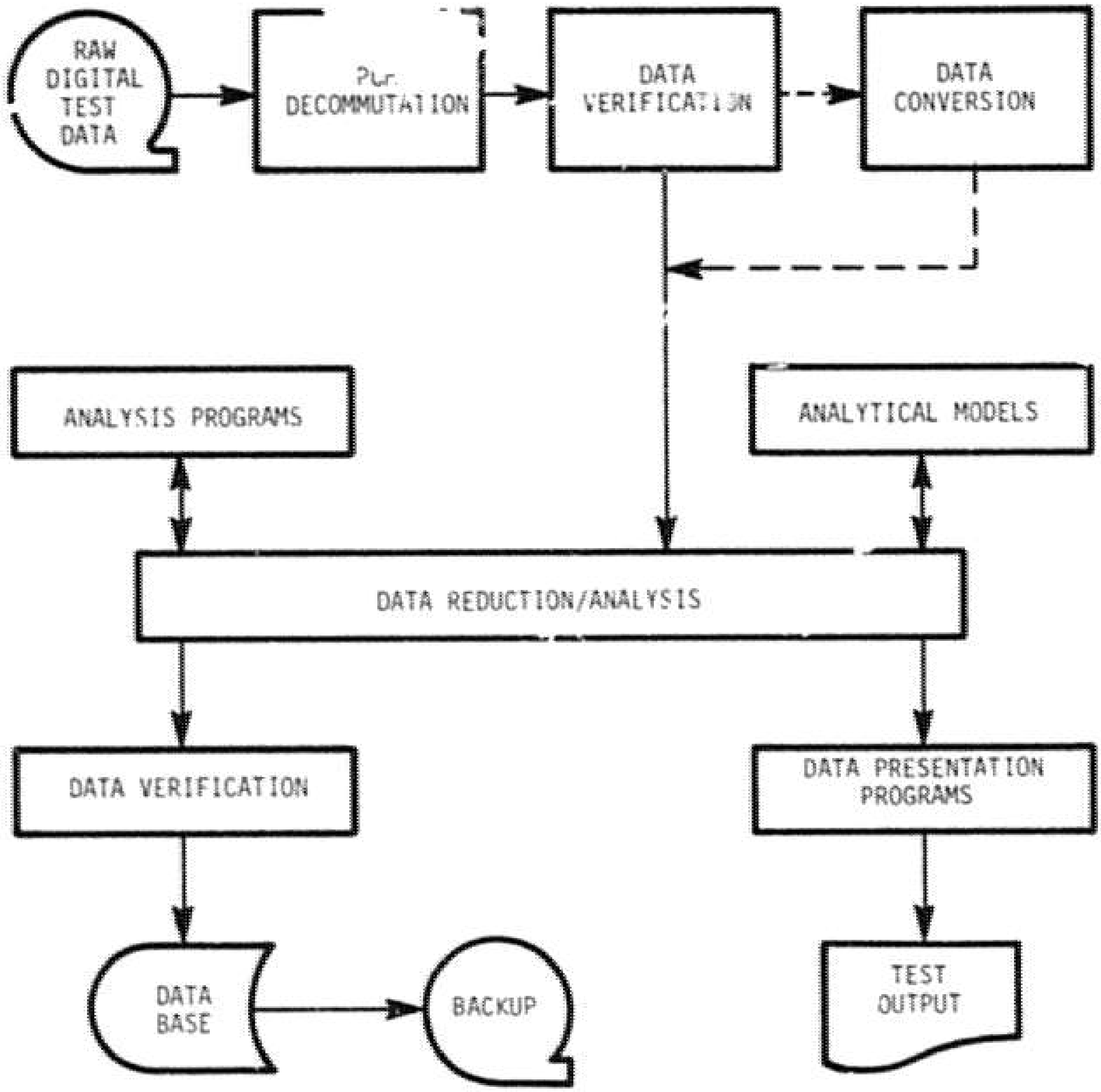


Figure L-5
Typical Data Management System
Configured for Test Analysis

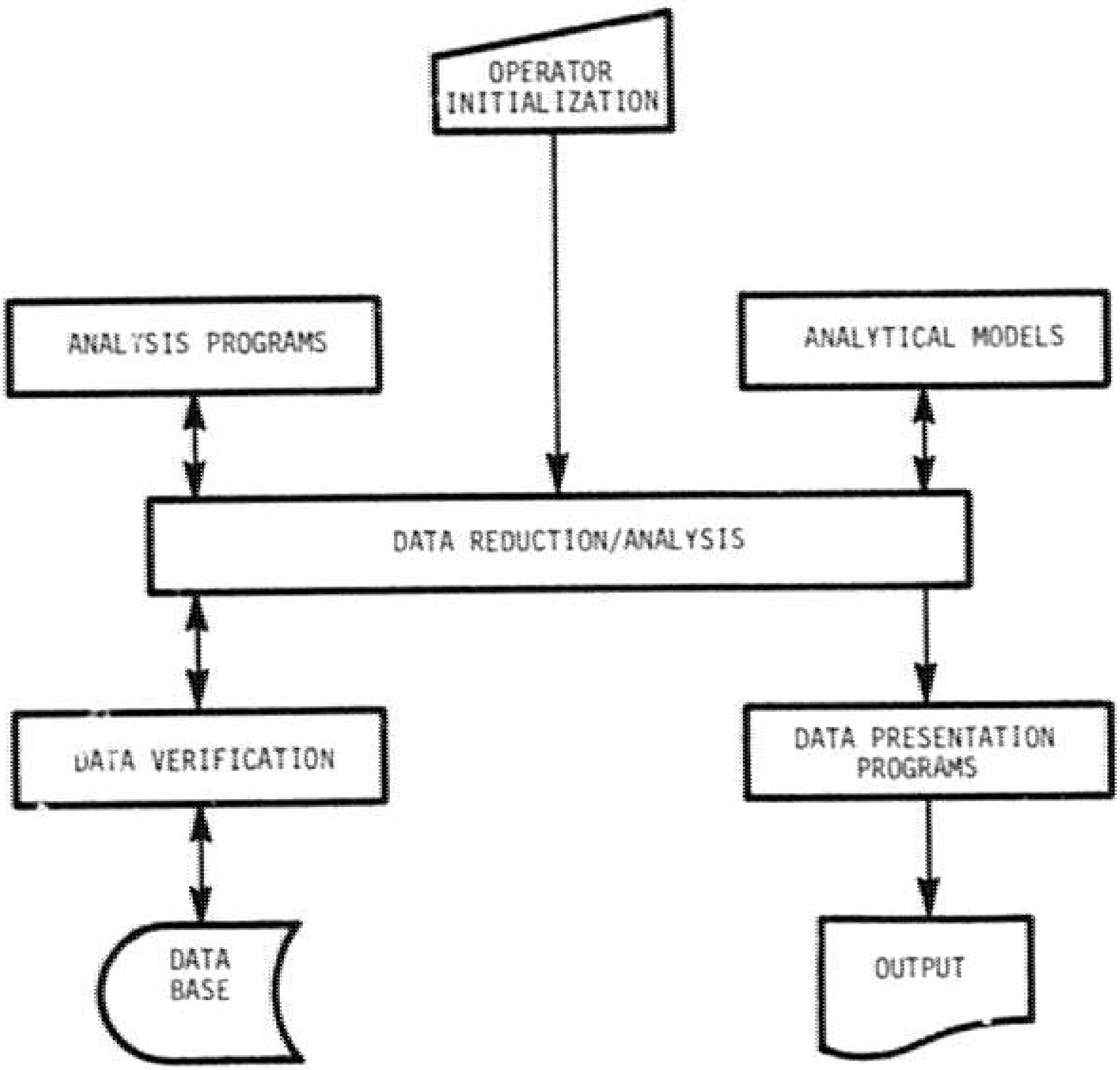


Figure L-6
Typical Data Management System
Configured for Comparative Analysis

L.4.5 <u>Data Storage/Retrieval</u>

All test data should be stored on some media as it is acquired so that it can be selectively retrieved later for processing and analysis. The rate of data acquisition, form of the data, and quantity of data to be stored will be principal factors in determining the media to use. Magnetic tape (magtape) has been common in the past but disk systems should be examined as a possible alternative for speed and capacity. As technology advances in this field, other systems may become available which are less expensive, more compact, and less susceptible to accidential erasure. Each user must determine which storage/ retrieval subsystem and media are appropriate for the tests to be run. Whatever system is chosen, however, the format of the stored data should be standardized insofar as possible to simplify the retrieval process.

A. Unprocessed Data. Raw data must be saved at least until it is stored in processed form and validated. This usually means at least until a test series is complete and the results are examined. Longer storage is preferred in case a post-analysis or comparison with a later test raises a question which can only be answered by re-examining the raw data. However, raw data for every test in a series of tests can take up many storage units so test planners must pre-determine the trade-offs involved and specify the storage duration requirements for raw data. Some characteristics of unprocessed data are:

1. Single Test Only.
2. Digitized.
3. Archived.

4. Write Once (no updates).
5. Large Amount of Data.
6. Synchronization With Track Geometry Data.

B. Processed Data. After the unprocessed data is reduced to processed form, it must again be stored on some media for retrieval by analysis programs. The reduction process will compress the data to a smaller number of words or bytes but more storage space will be needed because processed data from many, or all, tests in a series will need to be accessible simultaneously. A data base management system (DBMS) may be required if testing is extensive. It is suitable for large amounts of input/output, because it contains pointers to the location of the data. Header information should be included to permit complete analysis without the need to get these data from other sources. Some characteristics of processed data are:

1. Include All Tests.
2. Data Base Management System Probably Required.
3. Updated Frequently.
4. Allow for Future Additions and Modifications.
5. Availability of Track Geometry Data.
6. Backup Capability.
7. Accessible to Researchers.

L.4.6 Librarian Functions

Certain kinds of fixed data will be used in many tests, requiring them to reside in semi-permanent storage and be retrieved for use with various tests from time to time.

A. Track Data Library. Track characteristics, including geometry, modulus, and location identifiers, for all segments of the test track should be stored and cataloged for frequent retrieval for comparison with pre-test and post-test calibration measurements.

B. Model Library. All analytical models useful to IAT should be cataloged for use by the test planner and analyst. Update capabilities should be provided. See IAT Section C for listing and characteristics of available models.

1. Existing Analytical Models. Include procedures to acquire, add, modify, update, operate, and maintain. Preliminary concept provides for use of models on computer systems where they already exist. Some commonly used and readily available and trans-portable models may be installed on the user's computer but arrangements for use of the others for IAT analysis should be made with the organizations presently maintaining custody of them. A system to transfer test data in machine-readable form for input to the models should be designed as part of the IAT data analysis subsystem.

2. New Analytical Models. Include criteria and procedures for development. It is expected that IAT may be used to develop new models or identify needs for models to be developed. The International Government/Industry Research Program on Track Train Dynamics (TTD) and other researchers will continue to be the major source of new models for use by the railroad industry. An arrangement for exchange of information between researchers and TTD modeling personnel for IAT users will probably be required.

L.4.7 Model Validation

The model validation process is fully described in IAT Section D. The process is summarized in flow chart form in Figure L-7. Listed below are the principal features of model validation which affect the data management system. The model validation process may require either model-to-model comparisons or model-to-actual test data comparisons or both. For the latter, onboard and wayside data must be synchronized with each other and with track geometry and track characteristics data.

A. Accurate and Complete Data Required.

B. Significant (and costly) Processing Required.

   1. Reformatting of Data.
   2. Ensuring Compatibility Among Computers.
   3. Synchronizing Onboard, Wayside, and Track Data.
   4. Interpolating Synchronized Data.

C. Maximum Mechanization to Avoid Duplicate Effort.

D. Cannot Be Fully Mechanized.

E. Analyst Judgement Critical Throughout.

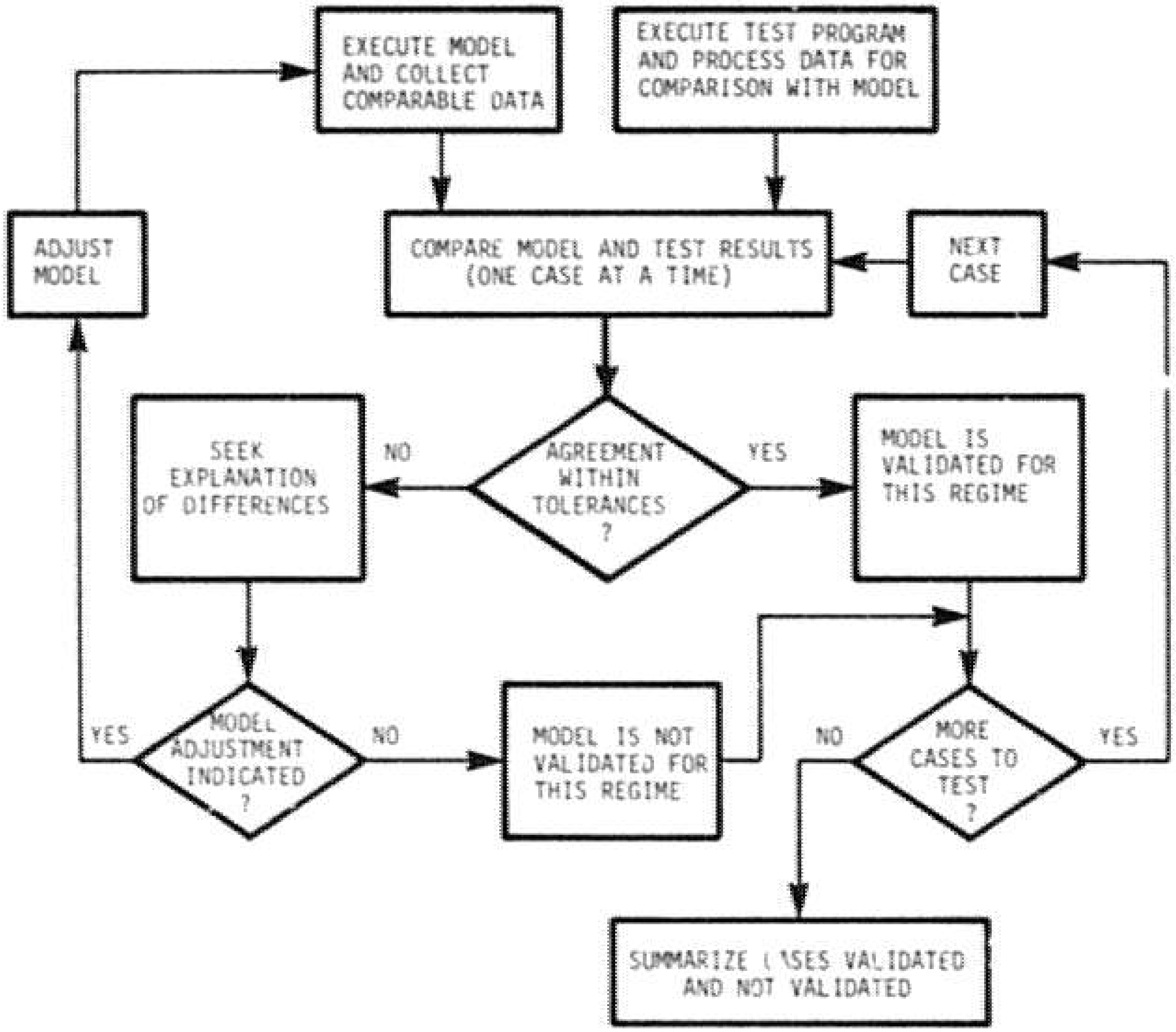


Figure L-7
Model Validation Process

L.4.8 Data Verification

IAT testing will collect a large amount of data which must be stored for later use and which will be difficult and expensive to re-generate. For these reasons it is important that the data be verified whenever a transfer between media and/or systems takes place. This verification should be as automatic as possible, utilizing verification data built in to every file or set of data. Some of the verification will be partly visual (e.g., verifying that a tape label date is the same as the date contained in the data itself), but most of it should be done automatically by programs which process the data. Examples of data verification are:

A. Automatic Label Generation. (e.g., visual labels for tapes, disk packs, etc.)
B. Automatic Label Cross-Referencing. (for data stored on more than one tape or disk, etc.)
C. Record Counts.
D. Channel Assignment Exceptions.
E. Calibration Constants.
F. Range and Limit Check.
G. Check Sums.
H. Parity Checks.

L.4.9 Data Presentation

Great care should be taken to design the data presentation subsystem as the perceived success or failure of the tests will rest upon the manner on which the results are presented. Test results should be presented at a number of levels of technical detail and in a set of formats matched to the various levels of understanding of the people to whom the results are directed. The results should be presented in a clear, concise manner without being obscured by many pages of tabular data. Graphical output is usually preferred over lengthy tables, except perhaps by the dynamicist who may need the numbers to perform manual calculations to verify a prediction or investigate an unpredicted result. Where appropriate, threshold or limit values should be plotted on the same graph as their companion test values so that a quick visual interpretation may be made. Tabular data extending beyond a single page usually should be available only as an option for the analyst to use in special cases. Some features of data presentation to be considered are:

A. Report Generation.
B. Concise Summary and Conclusions.
C. Graphical Output.
D. Threshold Overlays.
E. Multi-Level Technical Detail.
F. Optional Outputs for Special Use.

L.5 BIBLIOGRAPHY

L.5.1 Reports Related to IAT

1. "Safety Assessment Facility for Equipment (SAFE) Test and Analysis Methodology Options, Volume 1: Methodology Development", A.B. Boghani, P.R. Nayak, & D.W. Palmer, Arthur D. Little, Inc., October 1979.

2. "Perturbed Track Test Onboard Vehicle Response Data Base: User's Manual", D.W. Palmer, M.E. Hanson, & I. Sheikh, Arthur D. Little, Inc., September, 1980 (ADL 82919).

3. "Facility for Accelerated Service Testing Initial Data Base Design", Arthur D. Little, Inc., April, 1979 (ADL 82396 & 82787).

4. "Perturbed Track Test Program Wayside Instrumentation, Data Acquisition, and Data Reduction", H.D. Harrison, J.M. Tuten, & M. Forry, Battelle Columbus Labs, undated.

5. "Transportation Test Center PCM Implementation Plan", Dynalectron Corp., March 9, 1979 (TSD/IN-005-79).

6. "Perturbed Track Test: Results of Data Analysis", A.B. Boghani, D.W. Palmer, & P.R. Nayak, Arthur D. Little, Inc., April, 1981 (ADL 85102).

7. "Final Report on FAST Wheel/Rail Loads Wayside Data Reduction", J.M. Tuten & H.D. Harrison, Battelle Columbus Labs, September, 1980.

8. "Summary Report to Department of Transportation Transportation Systems Center on Vehicle/Track Interaction Tests - Wayside Test Data Summary", D.R. Ahlbeck, Battelle Columbus Labs, July, 1981.

L.5.2 Computer Software

A small sampling of available software packages is listed below. Not all packages will run on all computer systems. A current catalog should be consulted for an up-to-date list and applicability information.

A. Catalogs and Comparisons.

1. "A Comparative Review of Statistical Software", I. Francis (ed), The International Association for Statistical Computing, Voorburg, Netherlands, 1977.

2. "Introduction to the Use of Computer Packages for Statistical Analyses", R.W. Moore, Prentice-Hall, Englewood Cliffs, NJ, 1978.

3. "ICP Software Directory", International Computer Programs, Inc., Indianapolis, IN.

B. Large, General-Purpose Packages.

1. BMD "BMD Biomedical Computer Programs", University of California Press, 1973.

2. BMDP-77 "BMDP-77 Biomedical Computer Programs P-Series", M.B. Brown (ed), University of California Press, Los Angeles, CA, 1977.

3. DATATEXT

4. GENSTAT

5. MINITAB "MINITAB Student Handbook", T.A. Ryan, Jr., B.L. Joiner, & B.F. Ryan, Duxbury Press, No. Scituate, MA, 1976.

6. OMNITAB 78 "OMNITAB Users Reference Manual", National Bureau of Standards, US Govt. Printing Office, 1971.

7. OSIRIS III

8. PSTAT

9. SAS 76.5 "A User's Guide to SAS 76", A.J. Barr, et al, SAS Institute, Inc., Raleigh, NC 1976.

10. SCSS

11. SPSS "SPSS - Statistical Package for the Social Sciences", N.H. Nie, C.H. Hull, J.G. Jenkins, K. Steinbrenner, & D.H. Bent, McGraw Hill, New York, NY, 2nd ed., 1975.

12. SSP (Scientific Subroutine Package). Manual available from IBM Corp.

13. STATPACK "STATPACK Statistical Package", Lib. Prog. 1.1.4, R. Houchard, Western Michigan University Computer Center, Kalamazoo, MI, 1974.

14. SOUPAC

C. Data Management Packages.

1. BANK "BANK Data Management Package", Lib. Prog. 3.9.1, R. Houchard, Western Michigan University Computer Center, Kalamazoo, MI, 1974.

2. LEDA

3. SIR

4. WRAPS

D. Subroutine Libraries for Statistics.

1. IMSL FORTRAN Subroutines. Manual available from International Mathematics and Statistical Libraries, Inc.

2. NAG

E. Survey Analysis Packages.

1. RGSP

F. Signal Filtering and Processing Packages.

1. "Programs for Digital Signal Processing", Digital Signal Processing Committee, IEEE Acoustics, Speech, and Signal Processing Society, New York, NY, 1979.

2. ILS (Interactive Laboratory System). Signal technology, Inc., Goleta, CA.

SECTION M

FIELD TEST PLANNING

M.1 INTRODUCTION

Track testing required for investigating vehicle/track interactions may have broad and varied objectives. Since field testing typically requires significant expenditures of manpower, equipment and other resources, it is especially important that specific test objectives be well founded. If an efficient test program is to be carried out, it is then essential that the defined test objectives be systematically converted into appropriate test plans, track designs and test procedures. The primary purpose of this section is to provide the user with a methodology for effectively relating overall test objectives to specific field test design parameters and test procedures.

This section provides a detailed and systematic plan for designing and implementing vehicle/track interaction field test programs. The basic approach is to provide the user with a progressively detailed breakdown of constituent subtasks or test planning activities (i.e. starting with an overall flow diagram, the user will be able to quickly access the appropriate planning area and planning detail necessary). Where appropriate, specific examples of the type of information required for each planning stage are included.

M.2 USE OF FIELD TEST PLANNING SECTION

This section is intended to provide the user with a systematic and standardized approach for planning field test programs. The format is based upon a series of planning flowcharts. These flowcharts provide the user with a concise outline of activities or tasks to be considered when developing test plans and operations support for new test programs.

The primary purpose of this section is to enable a user to develop an overall planning structure needed to fulfill a set of test objectives. It is not proposed, however, that this document necessarily provides all the specific details needed to implement each planning task. Additional design details are covered in part one on "Vehicle/Track Interaction Assessment Techniques".

Use of this section should begin with the overall planning flow diagram as shown in Figure M-1. This flowchart (which is also provided at the end of the report for convenience) provides an overview of all the major planning tasks to be considered. The purpose of the overall planning diagram is to show the primary interrelationships between basic elements or activities. This procedure permits factoring out common elements, aids in assessing resource requirements, allows critical paths and decision points to be identified, and also provides the structure for a management plan through illumination of the major coordination requirements.

As part of the approach to developing a systematic plan for addressing vehicle/track interaction field testing, each of the larger tasks or basic blocks of the planning diagram are broken down into constituent subtasks (activities) which are more amenable to precise definition. Each block has been assigned a reference number which provides a mechanism for defining the interrelationships between subtasks. The detailed subtask breakdowns are presented in respective sections.

For each primary task, examples of the type of information to be developed or obtained are included as "planning aids" (where appropriate).

OVERALL GENERIC FLOW DIAGRAM FOR THE PREPARATION AND CONDUCT OF FIELD TEST PROGRAMS

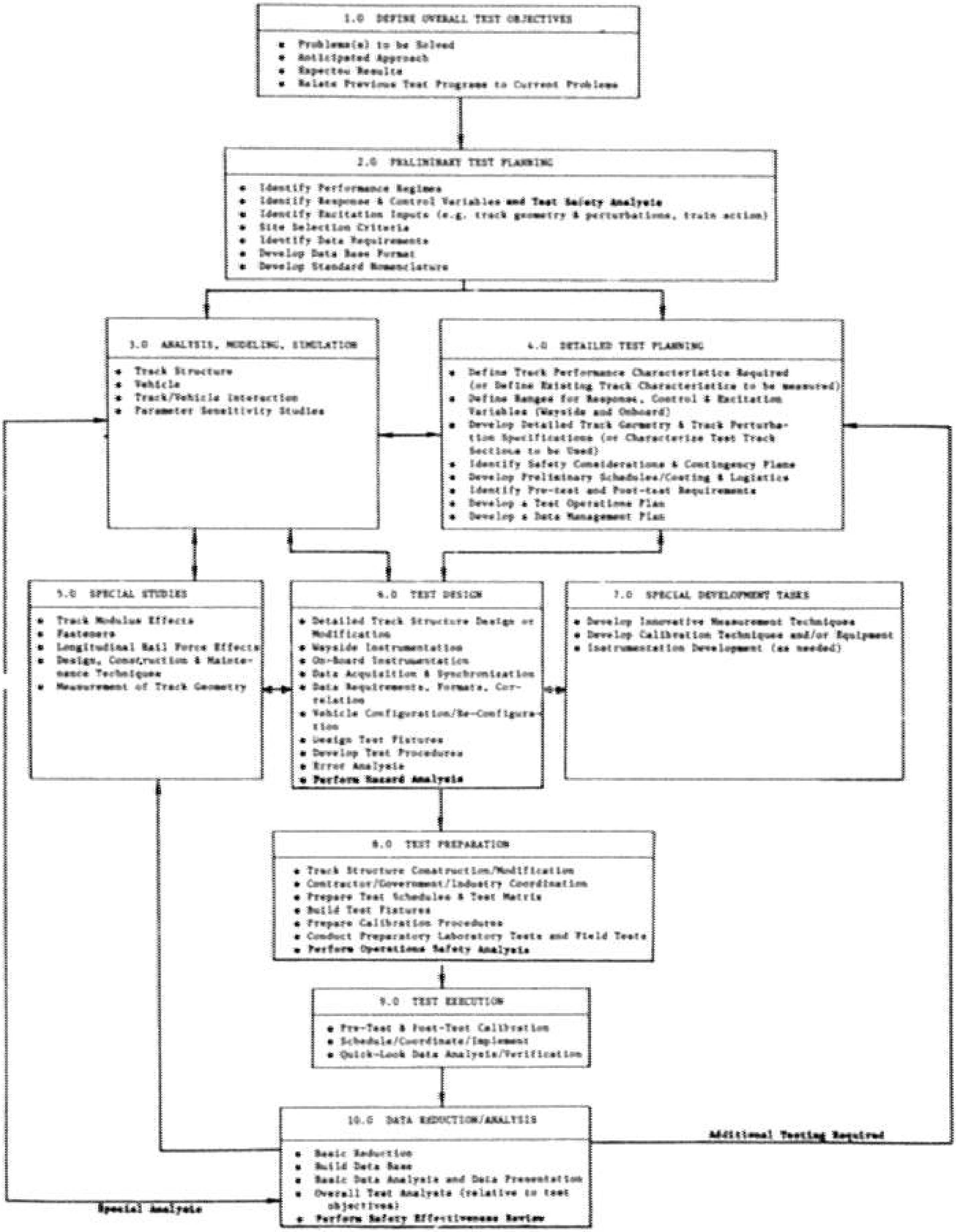


FIGURE M-1

Sections M.2.1 through M.2.10 of this report discuss each primary planning activity in detail and correspond to the block number identification used on the overall planning diagram (Figure M-1). This enables the user to quickly access a particular planning task as needed.

Sections M.3 and M.4 provide recommended sign conventions and consist configuration identification procedures to be used. It is strongly recommended that the suggested conventions be adhered to for the purpose of promoting a greater degree of standardization between test programs and test results.

M.2.1 DEFINE OVERALL TEST OBJECTIVES

The first step in planning a field test program is to clearly identify all of the objectives involved. These should include the overall program objectives associated with the basic engineering/research which establishes the need for testing. Once the basic program objectives have been defined, it is necessary to delineate the specific test objectives which are necessary to solve the identified problem(s).

The overall process of converting test objectives into engineering based conclusions requires an organized approach to coordinate needed analyses and associated support activities into cohesive and comprehensive solutions. Therefore it is essential that the problems or questions to be addressed, the anticipated approach and the expected results of a proposed test program be identified in as much detail as possible before proceeding with further test planning activities. A flowchart outlining this task is presented in Figure M-2.

1.0 DEFINE OVERALL TEST OBJECTIVES

1.1 IDENTIFY PROBLEM(S) TO BE SOLVED e.g.

- Investigate Vehicle Performance Characteristics
- Evaluate New Equipment Designs
- Conduct Acceptance Tests
- Evaluate Safety Standards (Vehicle & Track)
- Evaluate Vehicle/Track Interaction (i.e. Assess allowable maximum levels of dynamic response to assure vehicle safety and minimize track deterioration)
- Diagnose Known or Observed Problems
- Provide Basis for Equipment Re-Design
- Evaluate Advanced Designs
- Model Validation
- Conduct Comparative Characterizations of Vehicle Performance
- Predict Potential for Undesirable Dynamic Performance in Revenue Service

1.2 DEFINE SPECIFIC TEST OBJECTIVES AND THE ANTICIPATED APPROACH

- Conduct Pre-Test Analysis and Modeling
- Conduct Component Laboratory Tests (Vehicle and Track Structure)
- Conduct Field Tests
  - Single test, single site
  - Multiple tests, single site
  - Single test, multiple sites
  - Multiple tests, multiple sites
- Combinations of Above

1.3 EXPECTED RESULTS

1.3.1 Quantitative Results

- Observe if certain phenomenon occur under a specific set of conditions (e.g. hunting, pitch, bounce, yaw, sway, etc.)
- Observe (record) peak vehicle and/or track response levels for a specific set of conditions
- Establish Trends

1.3.2 Qualitative Results

- Record comprehensive test data for detailed data processing and analysis
- Obtain sufficient data to allow a statistical description of designated response parameters to be made

1.4 REVIEW PAST TEST PROGRAMS WITH REGARD TO PLANNED TEST ACTIVITY

- Have similar tests been conducted
- Identify test programs and available test results which would be useful for this program

FIGURE M-2

M.2.2 PRELIMINARY TEST PLANNING

During the preliminary test planning activity specific test objectives are transformed into basic test requirements. For example, given a specific test objective (i.e. investigate the derailment tendency of a given vehicle under specified operating conditions), a set of performance regimes can be defined. These performance regimes will in turn determine basic test requirements such as excitation inputs, response and control variables, type of track and track perturbations needed, etc.

Preliminary test planning identifies the engineering approach to be used in the test program. The results of this activity provide the basic framework for the remaining test preparation and design activities. Therefore it is essential that certain activities, procurements, safety, and critical decisions which affect subsequent planning activities or require long lead times be identified at this point. The flowchart shown in Figure M-3 outlines the preliminary planning activities which need to be addressed.

Planning Aids For Preliminary Test Planning

Table M-1 provides an example of the type of information which is to be developed during this planning task. As shown in the table and on the flow chart (Figure M-3), the first requirement is to identify the performance regime(s) to be addressed relative to the previously defined test objectives. Once the performance regimes have been defined, it is then necessary to identify the associated excitation inputs, response variables and control variables as shown in Table M-1. It is also necessary to develop a preliminary estimate for the anticipated control variable ranges. This will provide guidelines for selecting a test site or designing a section of test track. More refined estimates for the required excitation levels, control variables and expected response levels will be developed during the detailed test planning and test design activities.

Performance of the Preliminary Test Safety Analysis will aid in establishing preliminary estimates through evaluation of associated risks. Table M-2 presents a format for the preliminary Safety Assessment information to be developed.

2.0 PRELIMINARY TEST PLANNING

2.1 IDENTIFY PERFORMANCE REGIMES TO BE ADDRESSED

- Hunting
- Twist and Roll
- Pitch and Bounce
- Yaw and Sway
- Steady State Curving
- Spiral Negotiation
- Dynamic Curving
- Steady Buff and Draft
- Longitudinal Train Action
- Longitudinal Impact

2.2 IDENTIFY LEVEL OF ASSESSMENT REQUIRED TO MEET TEST OBJECTIVES

2.2.1 <u>Limited Assessment:</u>
Compare the response characteristics of a vehicle with a performance reference or with the characteristics of another vehicle.

2.2.2 <u>Limited Assessment With Diagnosis:</u>
Observe and compare response variables and if a problem exists, determine why, and what can be done about it.

2.2.3 <u>Comprehensive Assessment With Diagnosis:</u>
Evaluate and compare test response, predict response in revenue service, diagnose and solve any identified problems.

2.3 IDENTIFY GENERAL RESPONSE VARIABLES

- Define the response variables (both vehicle and track) which are required to adequately investigate the performance regimes to be addressed for a desired assessment level.
  - displacements (relative, absolute)
  - forces
  - accelerations
  - pressures

2.4 IDENTIFY EXCITATION INPUTS AND CONTROL PARAMETERS

- Define the track structure excitation & control variables required to investigate the performance regimes of interest
  - Perturbation characteristics
  - Track geometry characteristics
  - Rail friction
  - Rail size and type
- Define vehicle excitation & control variables required to investigate the performance regimes of interest
  - Operational parameters (speed, buff, draft)
  - Physical parameters (lading conditions, spring rates, damping coefficients, design parameters, wheel profiles, truck types, car body type, etc.)

2.5 DEFINE TEST SITE SELECTION CRITERIA

- Track construction
- Track geometry
- Track condition
- Track class
- Revenue traffic conditions and density
- Accessibility (both wayside and track access for special train consists)
- Train operating characteristics (speed, weather & terrain conditions, site logistics)

2.6 TEST SAFETY

Perform Preliminary Test Safety Analysis

2. DEFINE PRELIMINARY DATA REQUIREMENTS

- Identify approximate number of data channels expected
- Define real time data monitoring requirements
- Define Quick-Look requirements
- Identify which critical safety issues must be carefully monitored
- Identify <u>basic</u> data base format
- Establish standard nomenclature as appropriate

2.8 DEVELOP PRELIMINARY LOGISTICS

- Prepare a preliminary test planning and preparation schedule showing major activities, procurements, critical coordination points and delegation of responsibilities.
- Prepare a preliminary table of major events and activities chronologically sequenced. Delegate areas of responsibility as appropriate

FIGURE M-3

TABLE M-1

CANDIDATE PERFORMANCE REGIMES AND TEST PARAMETERS TO BE ADDRESSED

PERFORMANCE REGIMES	REQUIRED EXCITATION INPUTS	REQUIRED RESPONSE VARIABLES	CONTROL VARIABLES	* ANTICIPATED RANGES OF CONTROL VARIABLES
1. Hunting	Tangent Lateral Transient	L/V; Wheel, Truck and Body Motions	Speed Lateral Displacement Amplitude; Rail Friction	
2. Twist and Roll	Tangent Crosslevel Perturbations	Vertical Wheel Force; Roll Motion of Truck and Body	Wavelength of Perturbations; Amplitude of Perturbations; Phase of Perturbations; Speed	
3. Pitch and Bounce	Tangent Vertical Perturbations	Vertical Wheel Force; Pitch and Bounce Motion of Truck and Body	Wavelength of Perturbations; Amplitude of Perturbations; Phase of Perturbations; Speed	
4. Yaw and Sway	Tangent Lateral Perturbations	L/V; Yaw and Sway Motion of Truck and Body	Wavelength of Perturbations; Amplitude of Perturbations; Phase of Perturbations; Speed	
5. Steady State Curving	Uniform Curves	L/V	Curvature; Superelevation; Speed; Rail Friction	
6. Spiral Negotiation	Uniform Spirals	L/V; Truck and Body Motions	Rate of Change of Curvature; Rate of Change of Superelevation; Speed; Rail Friction	
7. Dynamic Curving	Curves With Lateral and Crosslevel Perturbations	L/V; Truck and Body Motions	Curvature; Superelevation; Type of Perturbations; Wavelength of Perturbations; Amplitude of Perturbations; Phase of Perturbations; Speed; Rail Friction	
8. Steady Buff and Draft	Uniform Curves and Steady Coupler Force	L/V; Coupler Angles	Curvature; Coupler Force Magnitude; Speed	
9. Longitudinal Train Action	Uniform Tangent and Curves and Dynamic Coupler Force	L/V; Coupler Forces and Angles; Longitudinal and Lateral Motion of Body	Curvature; Locomotive Acceleration and Deceleration Rates	
10. Longitudinal Impact	Tangent Impact Force	Coupler Forces; Structural Stresses and Deformation; Body Longitudinal Motion	Impact Momentum	

* Will be developed during the detailed test planning activity

Performance Issue ______________

Activity ______________

TABLE M-2

PRELIMINARY TEST SAFETY MATRIX

Item/ Function	Mode	Hazardous Aspect	Hazard Category	Safety Provisions Needed	Action Priority

By ______________

____

Date ______ Page ______

M.2.3 ANALYSIS, MODELING, SIMULATION

The analysis, modeling and simulation task addresses the steps necessary to utilize mathematical tools for the purpose of solving problems encountered in either the planning stages or as a result of data reduction and analysis. For example, during one of the planning stages it may be necessary to quantify the range and sensitivity of specified transducers. Assuming an absence of prior empirical data, the analysis, modeling and simulation phase would be used to describe the activities required to obtain transducer range and sensitivity estimates.

As can be seen in the overall planning flow diagram (Figure M-1) Analysis, Modeling and Simulation should really be considered as a support activity for many of the pre-test preparation tasks as well as for post-test analysis and data reduction.

The main objective of this task is to identify the basic analysis tools which will be required to resolve problems or provide supportive information for tests. Having identified the needs, an assessment of available tools must be made to determine whether suitable capabilities are available and operational. If not, deficiencies need to be identified and a recommended approach defined. Figure M-4 provides a flowchart of planning activities which should be addressed. A partial listing of analytical tools or models which have been developed within the railroad community are included in the planning aids.

Planning Aids For Analysis, Modeling, Simulation

Tables M-3 through M-11 present a partial compilation of "analytical tools" or mathematical models which can be considered when planning the analytical support activities required for a specific test program. A more comprehensive compendium of vehicle/track simulation models is presented in Section C, Part II of this document.

3.0 ANALYSIS, MODELING, SIMULATION

↓

3.1 DEFINE THE TYPE OF ANALYSIS FUNCTIONS WHICH WILL BE NEEDED

- Parameter Sensitivity Studies
- Predictive analysis (e.g. estimate expected parameter response levels, catastrophic disturbance levels i.e. derailment conditions, safety limit, etc.)
- Design analysis (track structure, vehicle components, vehicle/track interaction)
- Establish accuracy requirements for instrumentation and data acquisition

↓

3.2 ESTABLISH ANALYSIS REQUIREMENTS CONSIDERED NECESSARY TO SUPPORT DEFINED TEST OBJECTIVES

- Simple analytical computations and qualitative engineering models
- Combinations of simple analytic models
- Linearized models of track structure and vehicles
- Detailed nonlinear subsystem models (track and vehicle)
- Complete "system" models

↓

3.3 SELECT OR DEVELOP APPROPRIATE SOFTWARE AS NEEDED

↓

3.4 ASSEMBLE DATA BASE AS APPROPRIATE FOR DEFINED TEST OBJECTIVES

- Track Parameters
- Vehicle Parameters
- Special Site Conditions

↓

3.5 PERFORM ANALYSIS UTILIZING SOFTWARE AS NEEDED FOR TEST PLANNING AND DESIGN

↓

3.6 PROVIDE ANALYTICAL RESULTS AS NEEDED TO FORMULATE TEST REQUIREMENTS OR RESOLVE PROBLEM AREAS

Figure M-4

TABLE M-3

COMPILATION OF EXISTING ANALYTICAL MODELS FOR INVESTIGATING VEHICLE DYNAMICS

(REFERENCE 1)

NO.	SOURCE	TYPE	NAME/DESCRIPTION	COMMENTS
1	AAR	Steady State	2, 3, 4 Axle Rigid Truck Curve Negotiation Model	Program designed for rigid locomotive truck analysis. Not suitable for the more flexible freight car trucks, especially Type II. Does not model wheel conicity or gravitational effects.
2	AAR	Dynamic Time Domain	Nonlinear Time Domain Curving Program	Modified version of Smith's Illinois Institute of Technology Masters Thesis Program.
3	Battelle	Steady State	SSCUR2-2 Axle Steady State Curve Negotiation	Similar to Law and Cooper-rider steady state program. Models Metroliner.
4	Battelle	Steady State	SSCUR3-3 Axle Locomotive Steady State Curve Negotiation	
5	Battelle	Dynamic Time Domain	Nonlinear Curve Entry for 9 degrees of freedom (dof) Half Car Model	Similar to a Law and Cooper-rider program. Models Metroliner.
6	Battelle	Dynamic Time Domain	Full Car Curving Model	Same as Law and Cooperrider program. Models Metroliner.
7	Law/ Cooper-rider	Steady State	Nonlinear Steady State Curving of a 9 dof Rail Vehicle	Suitable for Type I freight car trucks.
8	Law/ Cooper-rider	Steady State	Nonlinear Steady State Curving of a 17 dof Rail Vehicle	Suitable for Type I and some Type II freight car trucks. Similar to the 9 dof with the addition of primary suspension elements.
9	Law/ Cooper-rider	Dynamic Time Domain	Nonlinear Curve Entry for 11 dof Half Car Model	Same as 6. Models Metroliner.

TABLE M-3 (Continued)
COMPILATION OF EXISTING ANALYTICAL MODELS FOR INVESTIGATING
VEHICLE DYNAMICS
(REFERENCE 1)

NO.	SOURCE	TYPE	NAME/DESCRIPTION	COMMENTS
10	Law/ Cooper-rider	Dynamic Time Domain	Nonlinear Curve Entry for 9 dof Full Car Model	Same as 7. Presently models Metroliner. Is being modified at Clemson to Model freight car.
11	Law/ Cooper-rider	Dynamic Time Domain	CURVELOCO - 27 dof Nonlinear 6 Axle Locomotive on Tangent, Spiral, Curved Track	
12	AAR	Dynamic Time Domain	Dynamic Curving Model of 6 Axle Locomotive	
13	Japanese Rail	Steady State	Side Thrust of Curving Wheels	
14	British Rail	Steady State	Steady State Curving, Flexible Trucks	
15	Nichio-Japan	Steady State	Steady State Curving	
16	AAR-TTD	Eigen-value	Freight Car Hunting Model	
17	AAR-TTD	Non-Linear Time Domain	Lateral-Vertical Model	Detailed modeling of truck masses, wheel and rail profiles defined mathematically, 2 dof reserved for carbody.
18	AAR-TTD	Time Domain Solution, Numerical Integration	Nonlinear Hunting Model	Similar to lateral-vertical model with more complexity and degrees of freedom in the math model.
19	AAR-TTD	Force Balance at Equilibrium	Quasi-Static Lateral Train Stability	Cannot be used to directly evaluate truck performance. Ignores all internal forces.

TABLE M-3 (Continued)

COMPILATION OF EXISTING ANALYTICAL MODELS FOR INVESTIGATING VEHICLE DYNAMICS

(REFERENCE 1)

NO.	SOURCE	TYPE	NAME/DESCRIPTION	COMMENTS
20	Arizona State	Sub-routine to Support Time Domain Lateral Stability Program	WHRAIL, a Wheel/Rail Contact Geometric Constraint Subroutine	Utilized in HUNTCT. One of the best available subroutines for calculating wheel/rail interaction effects.
21	SPTCo. TDOP Phase 1	Frequency Domain, Time Domain Optional	Graphical Output Oriented Computer Model (Frequency Domain Model)	Documentation indicates some unconventional trucks cannot be modeled. Limited to linear analysis with describing function techniques used to handle Coulomb friction.
22	Clemson U.	Time Domain Solution, Numerical integration	Nonlinear Wheelset Dynamic Response to Random Lateral Rail Irregularities	Good for studying the nonlinear dynamics of a single wheelset.
23	TSC	Frequency Domain	LATERAL	Includes creep effects, but no detailed description of wheel/rail interaction. Designed for lateral, roll, and yaw only, no vertical.
24	Wyle	Time Domain Solution	HUNTCT	Truck hunting program which includes detailed carbody/lading modeling. Many non-linear capabilities. Easily adaptable to Type II trucks. Some validation with Phase I data performed by comparing calculated and observed kinematic frequency.

TABLE M-3 (Continued)

COMPILATION OF EXISTING ANALYTICAL MODELS FOR INVESTIGATING VEHICLE DYNAMICS

(REFERENCE 1)

NO.	SOURCE	TYPE	NAME/DESCRIPTION	COMMENTS
25	AAR	Time Domain Solution, Numerical Integration	Detailed Lateral Stability Model for a Consist	Overall train models cannot be used directly to evaluate truck performance.
26	Law/ Cooperrider	Eigenvalue	Linear 9 dof Freight Car	Linear 9 dof (lateral, yaw, and warp of each truck; and lateral, yaw, and roll of car) spin and lateral spin creep effects and gyroscopic effects. Allows wheelset and suspension asymmetries.
27	Law/ Cooperrider	Eigenvalue	Linear 17 dof Rail Car	Lateral and yaw of each wheelset; lateral, warp, and yaw of each truck, and lateral, yaw, and roll of body. Provides for modeling radial trucks. Spin creep and gyroscopic terms included. Allows for wheelset and suspension asymmetries.
28	Law/ Cooperrider	Eigenvalue	Linear 19 dof Rail Car	Modification of 17 dof model with two additional degrees of freedom representing body bending and torsion.
29	Law/ Cooperrider	Eigenvalue	Linear 23 dof Freight Car	Modification of 19 dof model with four additional degrees of freedom representing torsional flexibility of each wheelset.

TABLE M-3 (Continued)

COMPILATION OF EXISTING ANALYTICAL MODELS FOR INVESTIGATING VEHICLE DYNAMICS

(REFERENCE 1)

NO.	SOURCE	TYPE	NAME/DESCRIPTION	COMMENTS
30	Law/ Cooper-rider	Describing Function Analysis with Iterative Search for Limit Cycle Conditions	Quasi-Linear 9 dof Freight Car	Model of linear 9 dof freight car model with nonlinear wheel/rail geometry and Coulomb friction at wear plate, center plate, and bearing adapters.
31	J. H. Wiggins	Eigenvalue Time Domain Response to Periodic Input	DYNALIST II	General linear systems modeling capability. Allows up to 50 degrees of freedom and 25 system components. Response to sinusoidal or stationary random rail irregularities. Limited to linear system analysis. Readily adaptable to Type II trucks.
32	MELPAR	Time Domain Numerical Integration	Dynamic Rail Car Simulation Program	Variable degrees of freedom, nonlinear analysis. High run costs and great complexity makes use and validation impractical.
33	IIT	Time Domain Solution Includes Non-linear Effects	Dynamics of a Freight Element in a Railroad Freight Car	Other models which operate with similar capability are available. Adaptability to to Type II trucks is difficult due to Lagrangian derivation.
34	MITRE	Time Domain Simulation	FRATE	Program is based on FRATE 11 with improved input-output capabilities. Currently set up for modeling the 89-foot flat car, but can be used for other vehicles as well by changing input parameters.

TABLE M-3 (Continued)

COMPILATION OF EXISTING ANALYTICAL MODELS FOR INVESTIGATING VEHICLE DYNAMICS

(REFERENCE 1)

NO.	SOURCE	TYPE	NAME/DESCRIPTION	COMMENTS
35	AAR-TTD	Time Domain Simulation	Flexible Body Railroad Freight Car Model	20 dof. Not easily modified to simulate Type II trucks. Some validation in terms of wheel lift-off test data.
36	MIT	Combination of Numerical Integration and Force Balance at Equilibrium	Response to Track Cross Level Variations	Nonlinear capabilities. Adaptability to Type II trucks unknown. Alternative models for the same purpose available.
37	MIT	Time Domain Solution Numerical Integration	General Vehicle Dynamic Model	
38	Battelle	Frequency Domain Solution	TRKVEH	Limited to linear analysis. Lateral model has only partial representation of wheel rail kinematics. No evidence of prior validation.
39	Battelle	Frequency Domain Solution	TRKVPSD	Limited to linear analysis. Lateral model has only partial representation of wheel/rail kinematics. No evidence of prior validation. Appears to differ from TRKVEH in that output is in form of power spectral density. 7 dof model.

TABLE M-3 (Continued)

COMPILATION OF EXISTING ANALYTICAL MODELS FOR INVESTIGATING VEHICLE DYNAMICS

(REFERENCE 1)

NO.	SOURCE	TYPE	NAME/DESCRIPTION	COMMENTS
40	Wyle	Time Domain Solution	FRATE 11	Nonlinear 11 dof. Easily adaptable to Type II trucks. Evidence of prior validation exists.
41	Wyle	Time Domain Solution	FRATE 17	Nonlinear 17 dof. Easily adaptable to Type II trucks. Evidence of prior validation exists.
42	Battelle	Eigenvalue	CARHNT	Calculates eigenvalues and eigenvectors of the characteristic equations in lateral stability regime.
43	Battelle	Eigenvalue	TRKHNT	Similar to #6 except emphasizes truck as opposed to entire vehicle.
44	TSC	Frequency Domain	FULL	Linear model for vehicle pitch and vertical responses.
45	TSC	Frequency Domain	HALF	Linear model for rock and roll responses. Includes compliant track structure.
46	TSC	Frequency Domain	FLEX	Linear model for rock and roll responses. Includes one mode for car flexibility.
47	Japanese Railways	Unknown	Vehicle on a Bridge	
48	British Rail	Numerical Integration	Wheel-Rail Force	Investigates interaction between wheel and rail in vertical plane in detail.
49	Japanese Rail	Unknown	Variation of Wheel Load	Investigates wheel/rail forces at rail discontinuities.

TABLE M-3 (Continued)

COMPILATION OF EXISTING ANALYTICAL MODELS FOR INVESTIGATING VEHICLE DYNAMICS

(REFERENCE 1)

NO.	SOURCE	TYPE	NAME/DESCRIPTION	COMMENTS
50	British Rail	Unknown	Dynamic Loading of Rail Joints	Investigates rail forces at rail discontinuities.
51	Battelle	Solves Beam Equation	Rail on Elastic Foundation	Investigates rail foundation (ballast) forces.
52	AAR/TTD	Eigenvalue	Locomotive Hunting Model	Generates critical speeds of locomotives.
53	Chang. Carg	Time Domain	6 Axle Locomotive Response	Written specifically for 6-axle locomotive.
54	AAR-TTD	Numerical Integration Time Domain	Detailed Vertical Train Stability Model	Emphasis on car interactions, does not separate truck modeling.
55	TRW	Frequency Domain	Rail Vehicle Roadbed Study	Developed for high speed, mass transit application. Apparently has not been used for some time.
56	MITRE	Eigenvalue	MITRE Random Process	Perlman[4] calls program "unsuitable for dynamic stability analysis". Primary applications elsewhere.
57	Battelle	Time Domain Numerical Integration	Nonlinear Freight Car Model	Emphasis on rail foundation stresses, rail discontinuities, wheel/rail forces.

TABLE M-3 (Continued)

COMPILATION OF EXISTING ANALYTICAL MODELS FOR INVESTIGATING VEHICLE DYNAMICS

(REFERENCE 1)

NO.	SOURCE	TYPE	NAME/DESCRIPTION	COMMENTS
58	United Aircraft	Critical Speed	UAC-4	Written specifically for the single turbotrain application.
59	United Aircraft	Critical Speed	UAC-6	Perlman[4] notes "not documented in any detail".

TABLE M-4

GENERAL TYPE OF ANALYTICAL MODELS AVAILABLE FOR

INVESTIGATING TRACK STRUCTURE

(Reference 2)

1. Vertical Track Models

   - Beam on Elastic Foundation
   - Finite Element Model

2. Lateral Track Models

   - Beam on Elastic Foundation
   - Finite Element Model

3. Tie Models

   - Classical Simple Beam
   - Finite Element Model

4. Rail-Fastener Model

5. Ballast-Subgrade Models

   - Talbot's Equation
   - Pyramid of Stress
   - Boussinesq's Equations
   - Westergaard's Equations
   - Cerruti's Equations
   - Burmister's Multi-Layer Elastic System

6. Three-Dimensional Track Models

   - Finite Element Model With Prismatic Elements
   - Finite Element Model With Member Representation

TABLE M-5

APPLICATION OF TRACK MODELS FOR

INVESTIGATING VERTICAL TRACK SETTLEMENT

(Reference 2)

Model Type	Model	Intended Use: Continuous Track	Intended Use: Missing Ties	Intended Use: Loss of Joint Efficiency	Intended Use: Off-Loading
Vertical Track Models	Beam on Elastic Foundation Model	x		x	
	Finite Element Model	x	x	x	
Tie Models	Classical Simple Beam Model	x	x	x	
	Finite Element Model	x	x	x	x
Ballast-Subgrade Models	Talbot's Equation	x	x	x	x
	Pyramid of Stress Model	x	x	x	x
	Boussinesq's Equations	x	x	x	x
	Westergaard's Equations	x	x	x	x
	Burmister's Multi-layer Elastic System	x	x	x	x
Three-Dimensional Track Models	Finite Element Model With Prismatic Elements	x			x
	Finite Element Model with Member Representation			x	x

x indicates intended use

TABLE M-6

COMPARISON OF VERTICAL

TRACK MODEL CAPABILITIES

(Reference 2)

CAPABILITIES	MODELS	
	Beam on Elastic Foundation Model	Finite Element Model
Multiple Wheel Loads	x	x
Rail Bending and Shear Stresses	x	x
Rail Deflections	x	x
Rail-Tie Reactions	x	x
Joint Incorporation	x	x
Missing Ties and Fasteners		x
Non-Linear Foundation		x

x indicates capability

TABLE M-7

COMPARISON OF LATERAL

TRACK MODEL CAPABILITIES

(Reference 2)

CAPABILITIES	MODELS	
	Beam on Elastic Foundation Model	Finite Element Model
Multiple Wheel Loads	x	x
Rail Bending and Shear Stresses	x	x
Rail Deflections	x	x
Rail-Tie Reactions	x	x
Joint Incorporation	x	x
Missing Ties and Fasteners		x
Non-Linear Foundation		x

x indicates capability

TABLE M-8

COMPARISON OF TIE MODEL CAPABILITIES

(Reference 2)

CAPABILITIES	MODELS	
	Classical Simple Beam Model	Finite Element Model
Tie Bending Stresses	x	x
Tie Deflections		x
Tie-Ballast Reactions	x	x
Off-Loading		x[1]
Non-Linear Ballast-Subgrade		x

x indicates capability

1 indicated rail-tie loads to be obtained from three-dimensional track models

TABLE M-9

COMPARISON OF RAIL

FASTENER MODEL CAPABILITIES

(Reference 2)

CAPABILITIES	RAIL FASTENER MODEL
Fastener Loads	x
Fastener Deflections	x
Joint Incorporation	x
Missing Ties and Fasteners	x
Off-Loading	x
Staggered Joints	x
Multiple Wheel Loads	x
Non-Linear Fastener and Foundation	x

x indicates capability

TABLE M-10
COMPARISON OF BALLAST AND
SUBGRADE MODEL CAPABILITIES
(Reference 2)

CAPABILITIES	MODELS					
	Talbot's Equation	Pyramid of Stress Model	Boussinesq's Equations	Westergaard's Equations	Cerruti's Equations	Burmister's Multi-layer Elastic System
Stresses	x	x	x	x	x	x
Deflections			x		x	x
Off-Loading			x	x	x	x
Multi-Layers		x				x
Vertical Load	x	x	x	x		x
Lateral Load					x	

x indicates capability

TABLE M-11

COMPARISON OF THREE-DIMENSIONAL TRACK MODEL CAPABILITIES

(Reference 2)

CAPABILITIES			MODELS: Member Representation	MODELS: Prismatic Elements
Loading	Vertical Load		x	x
Loading	Lateral Load		x	
Loading	Multiple Wheel Loads	V	x	x
Loading	Multiple Wheel Loads	L	x	
Loading	Off-Loading	V	x	x
Loading	Off-Loading	L	x	
Rail	Bending and Shear Stresses	V	x	
Rail	Bending and Shear Stresses	L	x	
Rail	Deflections	V	x	x
Rail	Deflections	L	x	
Rail	Rail-Tie Reactions	V	x	x
Rail	Rail-Tie Reactions	L	x	
Rail	Joint Incorporation	V	x	
Rail	Joint Incorporation	L	x	
Rail	Staggered Joints	V	x	
Rail	Staggered Joints	L	x	
Rail	Missing Fasteners	V	x	
Rail	Missing Fasteners	L	x	
Tie	Bending Stresses	V	x	
Tie	Deflections	V	x	x
Tie	Tie-Ballast Reactions	V	x	x
Tie	Missing Ties	V	x	
Ballast-Subgrade	Stresses			x
Ballast-Subgrade	Multi-Layers			x
Ballast-Subgrade	Material Non-Linearity		x	

x indicates capability
V indicates vertical direction
L indicates lateral direction

M.2.4 DETAILED TEST PLANNING

The primary purpose of this planning task is to convert the previously identified test objectives into detailed test requirements. Therefore both planning tasks 1 and 2 (DEFINE OVERALL TEST OBJECTIVES, PRELIMINARY TEST PLANNING) should be essentially complete before initiating the detailed test planning activity as outlined here.

The level of detail to be developed during this task should be sufficient to allow the test design task to proceed. For example before suitable wayside or onboard instrumentation can be selected or developed, test parameter ranges must be known. In the absence of suitable empirical data, it will be necessary to provide estimates of expected test parameter ranges and critical limits of risk. The degree of confidence associated with various parameter response levels will be somewhat dependent upon the level of analytical support expended.

As shown on the flow chart in Figure M-5, it is anticipated that some level of analytical support activity will typically be necessary to complete task 4.0.

Planning Aids For Detailed Test Planning

Several planning aids are presented as an example of the type of information to be developed for test operations. Figure M-6 shows a typical test organization chart. Depending upon the size and complexity of the specific test program being addressed, it may be desirable to expand or condense such an organization chart. However it should be sufficiently detailed to enable all participants involved to clearly identify their respective areas of responsibility and authority.

Table M-12 provides an example of the type of detail to be considered when addressing contingency plans.

4.0 DETAILED TEST PLANNING

4.1 ESTABLISH RISK CRITERIA FOR TEST

- Identify key performance parameters associated with each performance issue to be addressed (vehicle characteristics and consist characteristics)
- Define "quantitative" risk levels for key parameters or indices
- Establish track perturbation extremes which are compatible with established levels of risk

4.2 DEFINE (OR CHARACTERIZE) BASIC TRACK GEOMETRY PARAMETERS & TRACKWORK

(5.0) →

- Geometric Track Class
- Curvature & Superelevation
- Grade
- Special Trackwork (turnouts, switches, etc.)
- Perturbation Type
  - crosslevel
  - profile
  - alignment
  - gauge
- Perturbation Shape
  - cusp
  - rectified sine
- Perturbation Amplitude
- Perturbation Wavelength
- Perturbation Phase
- Perturbation Cycles
- Transition lengths between perturbations
- Prepare a table which identifies specific track section details needed (new track or existing) to accommodate defined performance issues.
- Convert Track section details into preliminary cost, construction, and schedule estimates.

4.3 DEFINE (OR CHARACTERIZE) TRACK PERFORMANCE PARAMETERS

(5.0) →

- Track Modulus (Vertical Stiffness)
- Track Lateral Stiffness
- Dynamic Strength/Compliance
- Track Resistance to Transverse and Longitudinal Displacement
- Allowable Track Displacement
- Allowable Rail Bending Stress
- Allowable Tie Bending Stress
- Allowable Ballast/Subgrade Pressure and Strain

Define requirements for uniformity, stability, repeatability and maintainability of essential track response characteristics

4.5 ESTABLISH EXPECTED "NOMINAL" TEST PARAMETER RANGES AND CRITICAL PARAMETER LIMITS COMMENSURATE WITH THE ESTABLISHED LIMITS OF RISK

Track Structure Response Parameters

- Wheel/Rail Loads
- Rail Deflections
- Tie Strain
- Tie Motion
- Track Modulus

(5.0) → Vehicle Response Parameters

- Displacements
- Accelerations
- Forces

Control/Excitation Parameters

- Track Geometry Parameters
- Track Performance Parameters (e.g. Vertical Track Modulus)
- Operational Parameters

(1.0) → Review Past Test Data (If Available) to Help Establish Test Parameter Ranges

4.6 PREPARE A TEST OPERATIONS PLAN

Develop a "Manual" for setting up and running each identified test

- Scope of test
- Test Schedule
- Logistics
- Test Sequences
  - Setup
  - Pre-test
  - Operations
  - Post Test

4.7 DEVELOP A DATA MANAGEMENT PLAN

- Identify Data Management Objectives
- Define Basic Functions
  - Data Standardization
  - Data Acquisition
  - Data Conversion
  - Data Storage/Retrieval
  - Librarian Functions
  - Model Validation
  - Data Validation
  - Data Presentation
- Identify Critical Test Parameters to be Monitored for Safety Purposes

4.8 IDENTIFY SAFETY CONSIDERATIONS

- Safety Procedures
- Personnel Safety
- Vehicle Safety Inspections
- Track Safety Standards
- Special Considerations

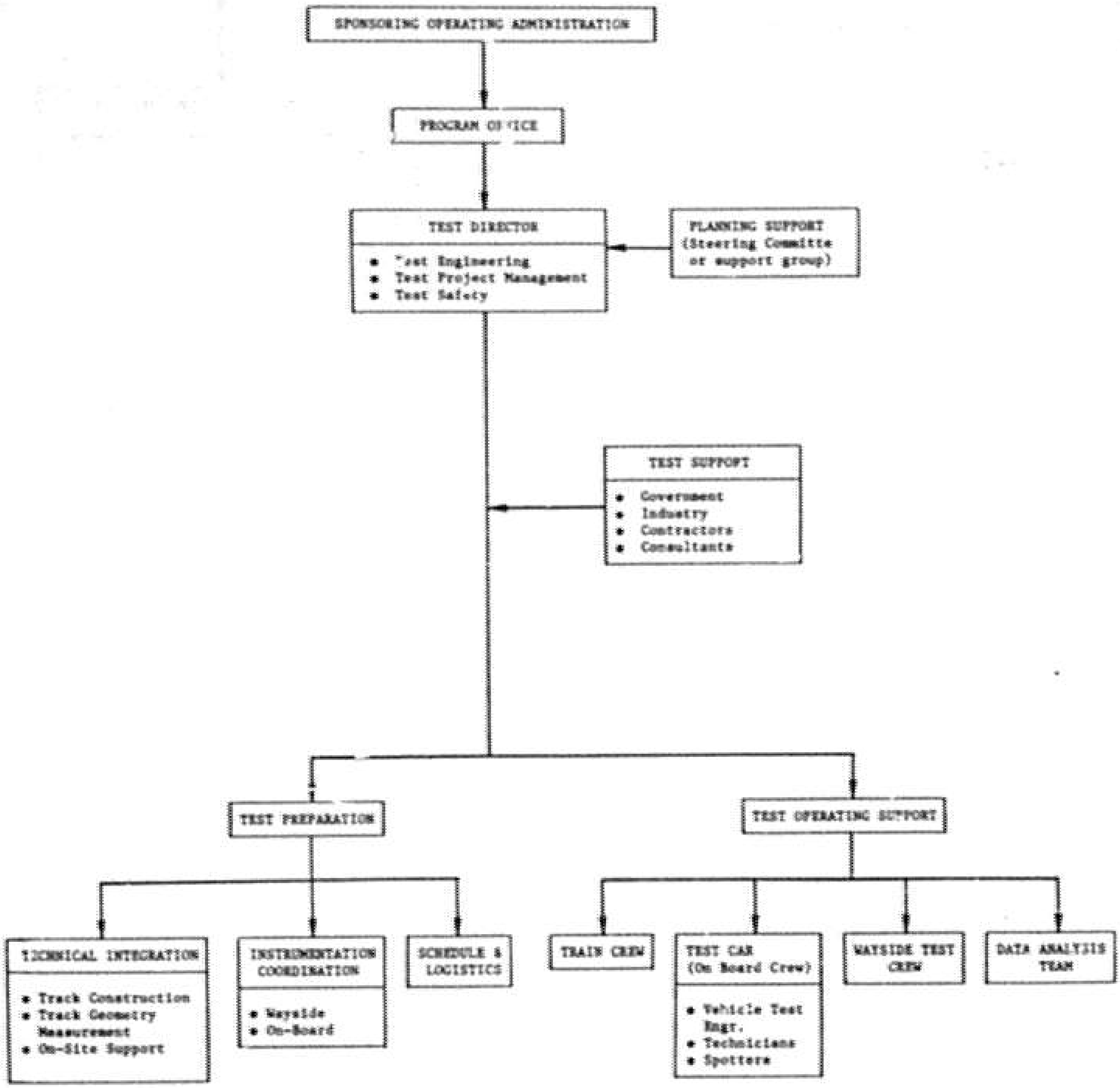
4.9 IDENTIFY CONTINGENCY PLANS (See Planning Aid Example)

- Alternate Test Sites
- Consist Make-up
- Abbreviated or Extended Test Schedules
- Alternate Instrumentation Schemes

Note:

(.0) → refers to inputs or outputs from the other major tasks.

FIGURE M-5



TYPICAL TEST ORGANIZATION CHART

FIGURE M-6

TABLE M-12

EXAMPLE CONTINGENCY PLAN
(Reference 3)

NO.	EVENT	POSSIBLE ACTION	REMARKS
	PRE-TEST PHASE		
1	Track Access Delayed	• Delay Test • Find Alternate Site	Dependent on expected delay.
2	Onboard Instrumentation not Available	• Delay Test • Continue Test with Track Instruments Only • Substitute Instruments • Reduce Scope of Test	Dependent on expected delay. If schedule is crucial. If substitutes are available.
3	Track Fixture Not Available	• Delay Test • Use Substitute Calibration • Calibrate Post-Test	If schedule is crucial.
4	Track Geometry Measurement Car not Available	• Delay Test • Stringline Survey • Continue Tests with Track Instruments Only • Substitute Instruments • Reduce Scope of Test	
5	Originally Designated Cars for Consist Make-up not Available	• Delay Test • Use Alternate Cars and Revise Test to Fit Available Cars	
6	Onboard Instrumentation not Ready on Schedule	• Delay Test • Complete Partial Instrumentation and Proceed with Test	
7	Site Reconstruction is Delayed	• Delay Test • Conduct Abridged Test on Available Track	
8	Site Reconstruction Track Characteristics	• Run Traffic to Settle Track • Rebuild Track • Proceed with the Altered Track	

TABLE M-12 (Continued)

EXAMPLE CONTINGENCY PLAN
(Reference 3)

NO.	EVENT	POSSIBLE ACTION	REMARKS
9	Track Instruments not Available (or Partially Available)	• Delay Test • Conduct Test using On-board Instrumentation Only • Reduce Test Scope to Available Instrument	
10	Survey Consist not Available	• Delay Test • Survey After Test • Survey Manually	Some information is lost. Track not loaded.
	TEST PHASE		
11	Track Instrument Fails	• Delay Testing • Do without the Failed Instruments • Provide Redundancies	Depends on the extent of the delay and the importance of the failed instrument.
12	Onboard Instrument Fails	• Delay Testing • Do Without the Failed Instruments • Provide Redundancies	Depends on the extent of the delay and the importance of the failed instrument.
13	Track Panel Shifts	• Rework Track • Do not Rework Track	Depends on safety assessment.
14	Vehicle Component Fails	• Delay Testing • Test Alternate Vehicle	
15	Severe Weather Interferes	• Delay Testing • Compensate for Change in Track Characteristics	
16	Track Seems Unsafe	• Repair Track	
17	Safety Criteria Close to Being Exceeded	• Do not Test at Faster Speed • Make Perturbations Less Severe	Depends on the speed and the test section at which this happens.
18	Total Data Loss	• Repeat Tests	
19	Partial Data Loss	• Repeat Tests • Do Without the Missing Data	

M.2.5 SPECIAL STUDIES

"Special Studies" are not necessarily a planning item to be considered for all test programs. However due to the diversity of test objectives which typically are encountered in field testing, there will be test programs that have unique problem areas which require special attention. The primary purpose for considering a "Special Studies" phase during test planning is to provide a systematic approach for handling special problem areas. If done in a timely manner, the results of such "Special Studies" can be integrated into the test planning design phase (task 6.0). Such an approach would minimize potential problems during actual testing and provide good assurance that the final test results will fulfill the original test objectives.

As implied above, a "Special Studies" task should be considered on a "as needed" basis depending upon the particular test program being addressed. The flowchart shown on Figure M-7 provides an example of the type of planning activity which should be considered when a special study task is necessary.

5.0 SPECIAL STUDIES

5.1 IDENTIFY SPECIAL PROBLEM AREAS

Identify special problem areas and special studies required to meet the test program objectives as defined in Task 1.

- Evaluate the affects of track modulus variations upon expected test results.
- Evaluate the affects of fastener types and condition upon test results
- Determine the required frequency of track geometry measurements with regard to specific test programs.

5.2 IDENTIFY AN APPROACH FOR RESOLVING THE IDENTIFIED PROBLEM AREAS

- Define important parameters
- Identify analysis/simulation requirements
- Identify test requirements
- Develop correlation techniques between special study results and expected experimental test data

5.3 DEVELOP A STUDY PLAN

5.4 CONDUCT STUDY

5.5 REVIEW STUDY RESULTS AND PREPARE "TEST DESIGN RECOMMENDATIONS" (WITH REGARD TO THE SPECIAL PROBLEM AREAS)

FIGURE M-7

M.2.5 TEST DESIGN

Test design considers all those activities or functions which are required to convert detailed planning requirements into actual specifications or procedures needed to implement a productive, safe and efficient test. For example, during the test planning phase, certain track perturbations needed to fulfill identified test objectives would be defined. Construction techniques and specifications for implementing these perturbations would then be defined and developed during the TEST DESIGN activity.

As can be seen from the overall planning diagram, the TEST DESIGN task is really a focal point for the entire test planning activity. Because of the importance of this task, it has been broken down into seven different subtasks. The completion of this task will typically require interaction and feedback from several other tasks as shown. Flow charts and planning aids for the TEST DESIGN subtasks follow on Figures M-8, M-9, M-14, M-18, M-22, M-23, and M-25.

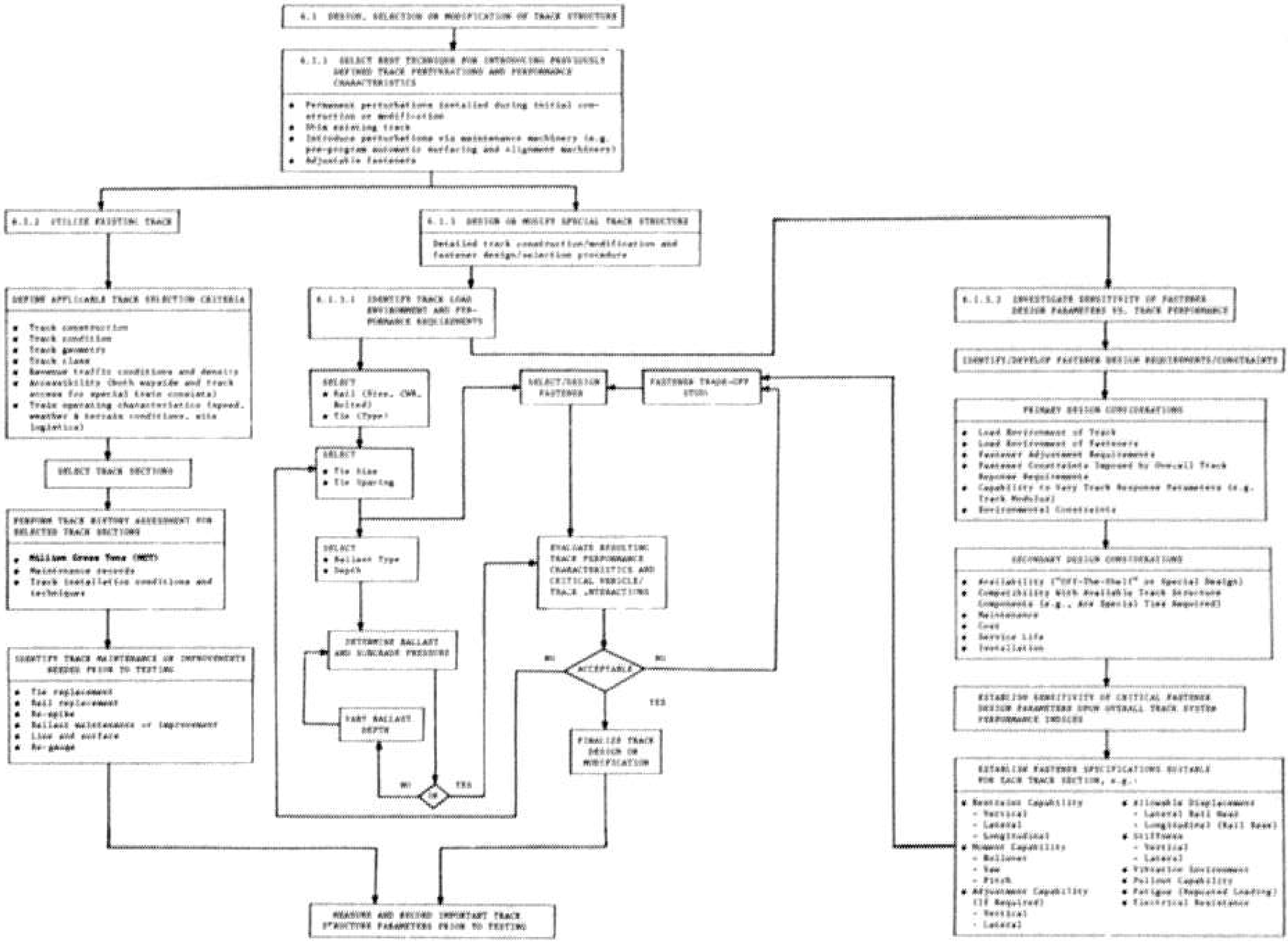
Included with most of the subtasks are some planning aids which serve to exemplify the type of information to be developed.

Planning Aids For Track Structure Design

Table M-13 presents a list of track structure parameters which may need to be identified and/or measured prior to testing.

Planning Aids For Wayside Instrumentation

Table M-14 provides a planning worksheet to be used when designing the wayside instrumentation system. Figures M-10 through M-13 provide an example of the type of identification diagrams which should be developed for wayside instrumentation.



4.1 DESIGN, SELECTION OR MODIFICATION OF TRACK STRUCTURE
4.1.1 SELECT BEST TECHNIQUE FOR INTRODUCING PREVIOUSLY DEFINED TRACK PERTURBATIONS AND PERFORMANCE CHARACTERISTICS
• Permanent perturbations (installed during initial construction or modification
• Shim existing track
• Introduce perturbations via maintenance machinery (e.g. pre-program automatic surfacing and alignment machines)
• Adjustable fasteners
4.1.2 UTILIZE EXISTING TRACK
DEFINE APPLICABLE TRACK SELECTION CRITERIA
• Track construction
• Track condition
• Track geometry
• Track class
• Revenue traffic conditions and density
• Accessibility (both wayside and track access for special train consists)
• Train operating characteristics (speed, weather & terrain conditions, site logistics)
SELECT TRACK SECTIONS
PERFORM TRACK HISTORY ASSESSMENT FOR SELECTED TRACK SECTIONS
• Million Gross Tons (MGT)
• Maintenance records
• Track installation conditions and techniques
IDENTIFY TRACK MAINTENANCE OR IMPROVEMENTS NEEDED PRIOR TO TESTING
• Tie replacement
• Rail replacement
• Re-spike
• Ballast maintenance or improvement
• Line and surface
• Re-gauge
4.1.3 DESIGN OR MODIFY SPECIAL TRACK STRUCTURE
Detailed track construction/modification and fastener design/selection procedure
4.1.3.1 IDENTIFY TRACK LOAD ENVIRONMENT AND PERFORMANCE REQUIREMENTS
SELECT
• Rail (Size, CWR, Bolted)
• Tie (Type)
SELECT
• Tie Size
• Tie Spacing
SELECT
• Ballast Type
• Depth
DETERMINE BALLAST AND SUBGRADE PRESSURE
VARY BALLAST DEPTH
OK
NO
YES
SELECT/DESIGN FASTENER
FASTENER TRADE-OFF STUDY
EVALUATE RESULTING TRACK PERFORMANCE CHARACTERISTICS AND CRITICAL VEHICLE/TRACK INTERACTIONS
ACCEPTABLE
NO
NO
YES
FINALIZE TRACK DESIGN OR MODIFICATION
MEASURE AND RECORD IMPORTANT TRACK STRUCTURE PARAMETERS PRIOR TO TESTING
4.1.3.2 INVESTIGATE SENSITIVITY OF FASTENER DESIGN PARAMETERS VS. TRACK PERFORMANCE
IDENTIFY/DEVELOP FASTENER DESIGN REQUIREMENTS/CONSTRAINTS
PRIMARY DESIGN CONSIDERATIONS
• Load Environment of Track
• Load Environment of Fasteners
• Fastener Adjustment Requirements
• Fastener Constraints Imposed by Overall Track Response Requirements
• Capability to Vary Track Response Parameters (e.g. Track Modulus)
• Environmental Constraints
SECONDARY DESIGN CONSIDERATIONS
• Availability ("Off-The-Shelf" or Special Design)
• Compatibility With Available Track Structure Components (e.g., Are Special Ties Required)
• Maintenance
• Cost
• Service Life
• Installation
ESTABLISH SENSITIVITY OF CRITICAL FASTENER DESIGN PARAMETERS UPON OVERALL TRACK SYSTEM PERFORMANCE INDICES
ESTABLISH FASTENER SPECIFICATIONS SUITABLE FOR EACH TRACK SECTION, e.g.:
• Restraint Capability
- Vertical
- Lateral
- Longitudinal
• Moment Capability
- Rollover
- Yaw
- Pitch
• Adjustment Capability (If Required)
- Vertical
- Lateral
• Allowable Displacement
- Lateral Rail Head
- Longitudinal (Rail Base)
• Stiffness
- Vertical
- Lateral
• Vibration Environment
• Pullout Capability
• Fatigue (Repeated Loading)
• Electrical Resistance

FIGURE M-8

TABLE M-13

TRACK STRUCTURE DESCRIPTION AND CANDIDATE TRACK PARAMETERS TO BE IDENTIFIED OR MEASURED

GENERAL INFORMATION

DESCRIPTION OF TRACK SECTION __________

TRACK CLASSIFICATION __________ APPROXIMATE GRADE __________

MILEPOST START __________ CURVE __________

MILEPOST STOP __________ TYPE OF FASTENER __________

RAIL WEIGHT __________

RAIL TYPE __________ TYPE OF BALLAST __________

RAIL LAID IN __________ BALLAST GRADATION __________

RAIL JOINT SPACING __________ OTHER: __________

TRACK STRUCTURE	SYMBOL	PARAMETER DESCRIPTION	PARAMETER VALUE	UNITS
RAIL	I_R	rail moment of inertia		in^4
	A_R	rail cross sectional area		in^2
	E_R	rail modulus of elasticity		psi
TIES	W	tie width		in
	T	tie thickness		in
	L	tie length		ft
	S	tie spacing		in
	E_T	compressive modulus		psi
	L_B	effective bearing length under each rail		in
BALLAST/ SUBBALLAST	K_{RB}	resilient response modulus		--
	μ_B	Poisson's ratio		--
	h_B	ballast depth		in
	E_B	Young's modulus		psi
SUBGRADE	K_{RSG}	resilient response modulus		--
	μ_{SG}	Poisson's ratio		--
FASTENER	K_ϕ	fastener rotational stiffness		lb-in/rad

6.2 WAYSIDE INSTRUMENTATION

6.2.1 SELECT PARAMETERS TO BE MEASURED TO MEET TEST OBJECTIVES

(3.0) ↔ (4.0)

- Rail Displacement (Vertical, Lateral, Longitudinal)
- Rail Strain (Vertical, Lateral, Longitudinal)
- Fastener Strain
- Rail Seat Loads
- Tie Bending
- Tie Displacement (Vertical, Lateral, Longitudinal)
- Ballast Compression
- Track System Settlement
- Track System Lateral Shift
- Dynamic Gauge Widening
- Rail Rollover
- Ballast Gradation
- Ballast Moisture Content
- Wind Speed/Direction
- Temperature/Humidity
- Consist Speed
- Consist Location and Direction Detection
- Rail Temperature vs. Time
- Parameters Required to Adequately Cover Critical Safety Issues

6.2.2 DEFINE SITE SPECIFIC MEASUREMENT IDENTIFICATION, LOCATION AND CONSTRAINTS

Includes the Identification and Location of Relative Data Points

- Rail Flaw Locations
- Tie Numbering
- Benchmark Locations
- Fasteners to be Instrumented
- Rail Seat Load Points
- Gauge Widening Locations (Wayside)
- Ballast Parameter Measurement Locations
- Rail Vertical Strain Bridge
- Rail Lateral Strain Bridge
- Rail Longitudinal Strain Bridge
- Site Test Segments
- Critical Measurement Points for Monitoring Key Safety Issues

6.2.3 DETERMINE SENSOR REQUIREMENTS

- Type
- Quantity
- Range
- Frequency
- Resolution
- Stability
- Environmental Constraints
- Cost Constraints
- Lead Time Needed
- Spares Required
- Noise/EMI Immunity

6.2.4 DESIGN WAYSIDE INSTRUMENTATION SYSTEM

- Select Transducers
- Select Signal Conditioning
- Power Requirements
- Instrumentation Synchronization
  - On-board vs. On-board
  - Wayside vs. Wayside
  - Combination of Above
- Identify Signal Processing Methodology Required to Address Performance Issues

6.2.5 DESIGN SENSOR/DATA ACQUISITION SYSTEM (DAS) INTERFACE

- Conductor Routing
- Cable Protection From Environment
- Common Tie Point (J-Box, Etc.)
- Grounding/Shielding Requirements
- Patch Capability
- Channel Assignments
- Spares Requirements

Note:

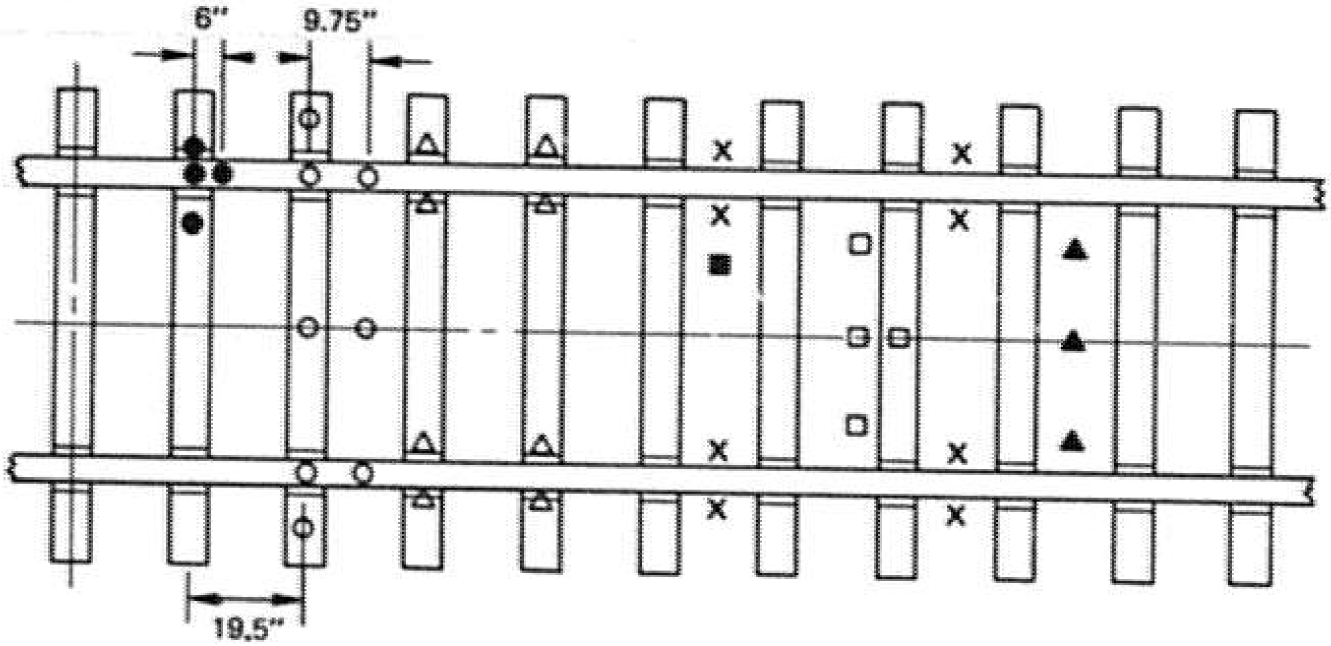
(3.0)→ refers to inputs or outputs from the other major tasks.

FIGURE M-9

TABLE M-14

WAYSIDE MEASUREMENT REQUIREMENTS WORKSHEET

MEAS. I.D.	MEAS. DESCRIPTION	PURPOSE OF MEASUREMENT	MEAS. RANGE	UNITS	MEAS. ACCURACY	MEAS. LOCATION	SPECIAL REQUIREMENTS	ANALYSIS REQUIREMENTS				SELECTED TRANSDUCER (MFG, MODEL #)
								QUICK LOOK	POST PROCESSING	PRE-TEST CALIBRATION	POST-TEST CALIBRATION	

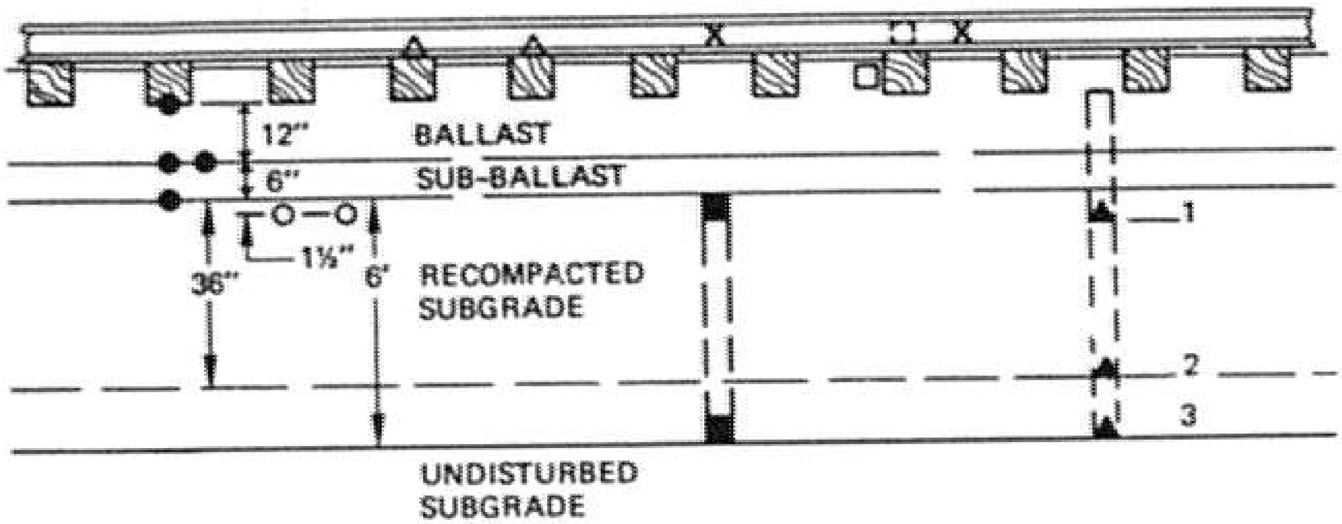


J-BOX □

MEASUREMENT	SYMBOL
W/R LOADS	×
TIE BENDING STRAINS	□
FASTENER STRAINS	△
PRESSURES	○
SOIL STRAINS	●
EXTENSOMETER (STRAIN)	■
SOIL SAMPLES	▲

TYPICAL INSTRUMENTATION IDENTIFICATION (PLAN VIEW)

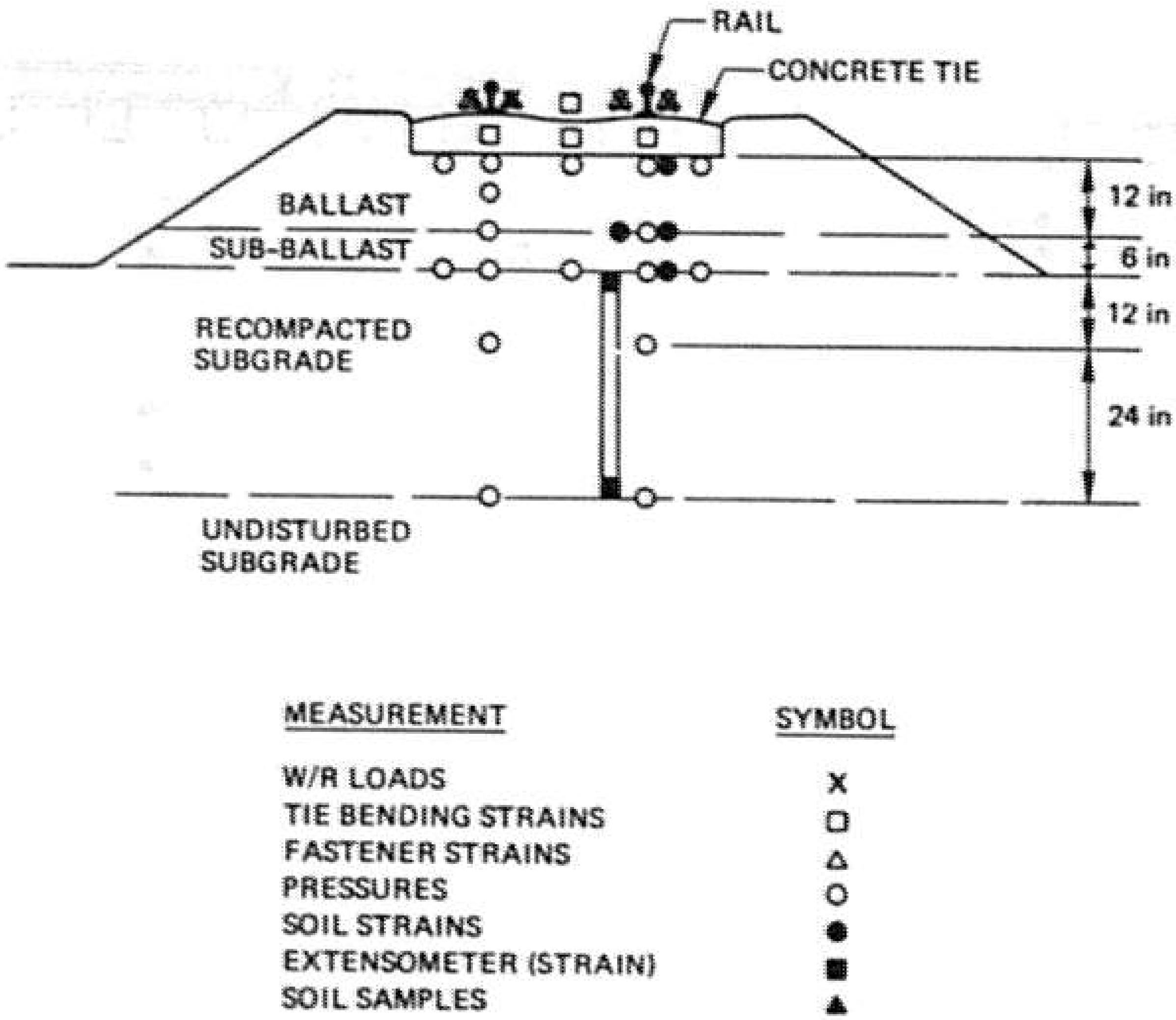
FIGURE M-10



MEASUREMENT	SYMBOL
W/R/ LOADS	X
TIE BENDING STRAINS	◻
FASTENER STRAINS	△
PRESSURES	○
SOIL STRAINS	●
EXTENSOMETER (STRAIN)	■
SOIL SAMPLES	▲

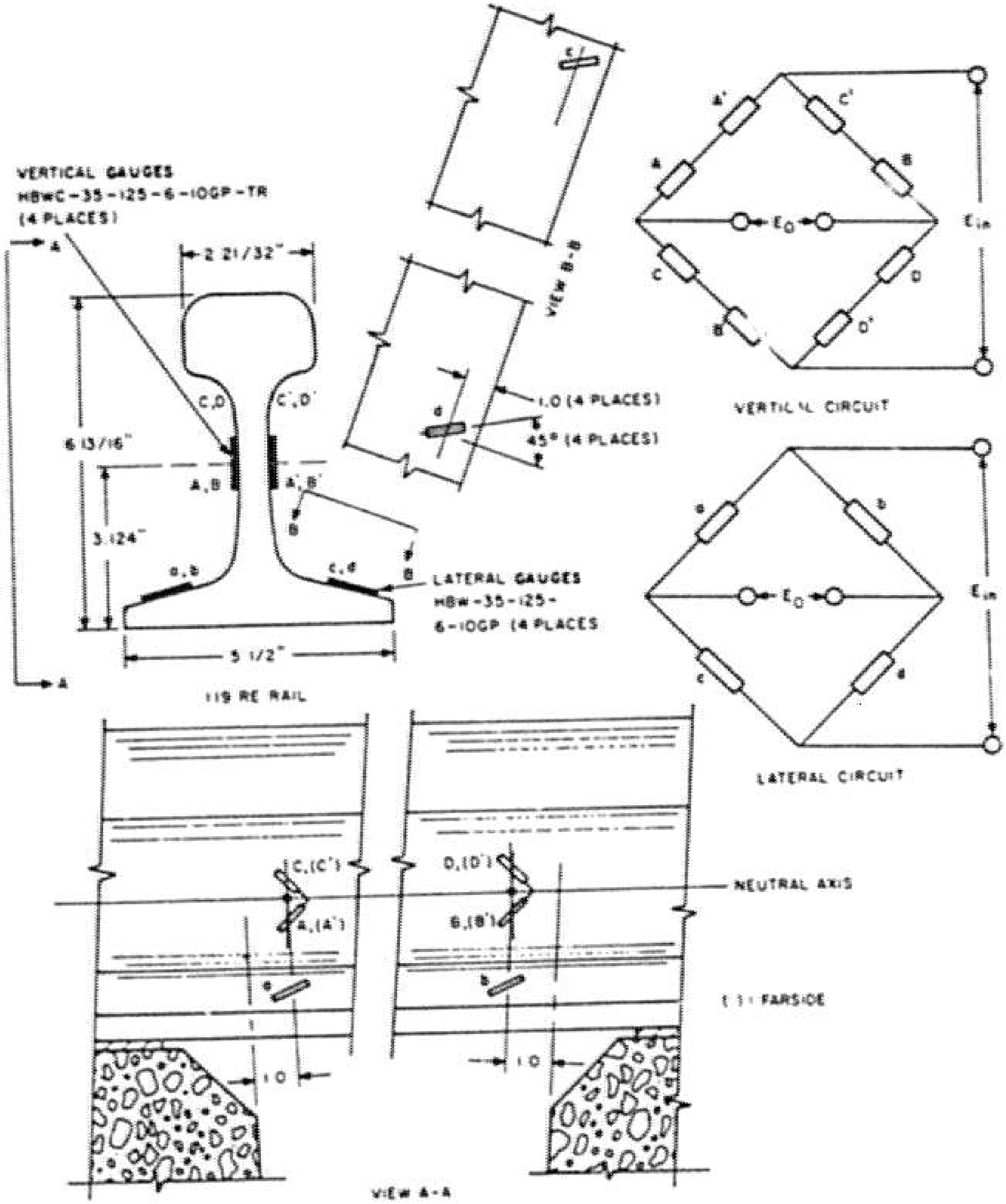
TYPICAL INSTRUMENTATION IDENTIFICATION (SIDE VIEW)

FIGURE M-11



TYPICAL INSTRUMENTATION IDENTIFICATION (END VIEW)

FIGURE M-12



TYPICAL IDENTIFICATION OF SPECIAL INSTRUMENTATION
(L/V WHEEL-RAIL LOAD STRAIN GAUGE LOCATIONS AND
CIRCUIT CONNECTIONS)

FIGURE M-13

6.3 ON-BOARD INSTRUMENTATION

↓

6.3.1 SELECT PARAMETERS TO BE MEASURED TO MEET TEST OBJECTIVES

- Relative vertical journal displacement.
- Relative lateral displacement between truck and axle.
- Relative lateral motion between bolster and truck frame.
- Truck yaw.
- Pitch, roll, yaw, and vertical, lateral, and bending acceleration of carbody.
- Lateral and vertical wheel force.
- Raw wheel strain gage data.
- Wheel L/V ratio.
- Truck L/V ratio.
- Axle vertical and lateral acceleration.
- Truck frame lateral acceleration.
- Wind velocity and direction.
- Vertical, lateral, and longitudinal coupler force.
- Coupler angle (lateral and vertical).
- Lateral and vertical wheel load.
- Vertical, lateral, roll, pitch, and yaw acceleration.
- Location and distance information.
- Time Reference
- Speed
- Brake pressure.
- Traction Motor Current.
- Axle yaw.
- Parameters required to adequately cover critical safety issues.

↓

6.3.2 PREPARE ON-BOARD MEASUREMENT MATRIX, FINALIZE PARAMETER RANGES AND MEASUREMENT ACCURACIES

- Measurement Description
- Measurement Range
- Measurement Accuracy
- Measurement Location
- Data Usage/Analysis Requirements

↓

6.3.3 DEFINE INSTRUMENTATION LOCATION DETAILS

- Establish Location Standards and Sign Conventions (See Section C)
- Define Special Mounting Requirements
- Determine Available Mounting Envelop (If Critical)
- Critical Measurement Points for Monitoring Key Safety Issues

↓

6.3.4 ESTABLISH DETAILED INSTRUMENTATION SPECIFICATIONS AND SELECT HARDWARE

- Identify Detailed Specs
  - Frequency Response
  - Resolution
  - Environmental Tolerance
  - Noise Immunity
  - Zero Stability With Time
  - Gain Stability With Time (Repeatability)
  - Linearity
  - Hysteresis
  - Ripple (For Wheelsets)
  - Temperature Coefficient of Zero
  - Temperature Coefficient of Gain
- Power Requirements
- Identify Signal Processing Methodology

↓

6.3.5 DESIGN SENSOR/DATA ACQUISITION SYSTEM (DAS) INTERFACE

- Conductor Routing
- Cable Protection From Environment
- Common Tie Point (J-Box, Etc.)
- Grounding/Shielding Requirements
- Patch Capability
- Channel Assignments
- Spares Requirements

FIGURE M-14

Planning Aids For On-Board Instrumentation

Table M-15 provides a planning worksheet to be used when designing the on-board instrumentation system. Figures M-15 through M-17 represent examples of on-board instrumentation identification diagrams which should be developed.

Planning Aids For Data Acquisition and Management

A block diagram of the defined data acquisition system(s) should be developed as the requirements are finalized. Figures M-19 through M-21 are typical of the type of diagrams which should be developed.

Planning Aids For Vehicle Preparation

Table M-16 provides a "shopping list" of vehicle parameters which may need to be identified or measured for a specific test program.

Planning Aids To Support Test Series Development

Figure M-24 represents a diagram of the type of information which should be identified for each selected test zone.

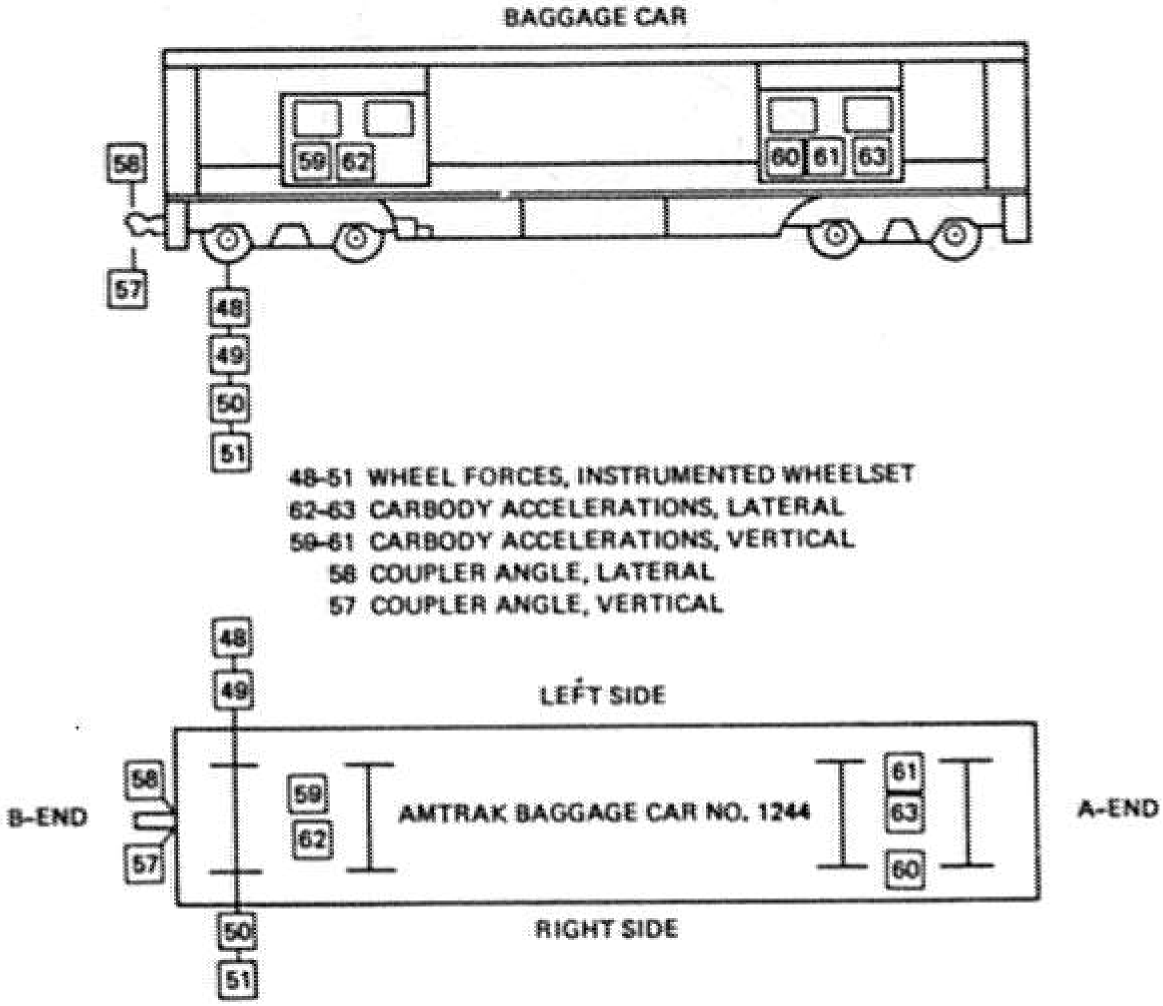
Test Design Hazard Matrix

Table M-17 presents a format for evaluating the test design for safety hazards.

TABLE M-15

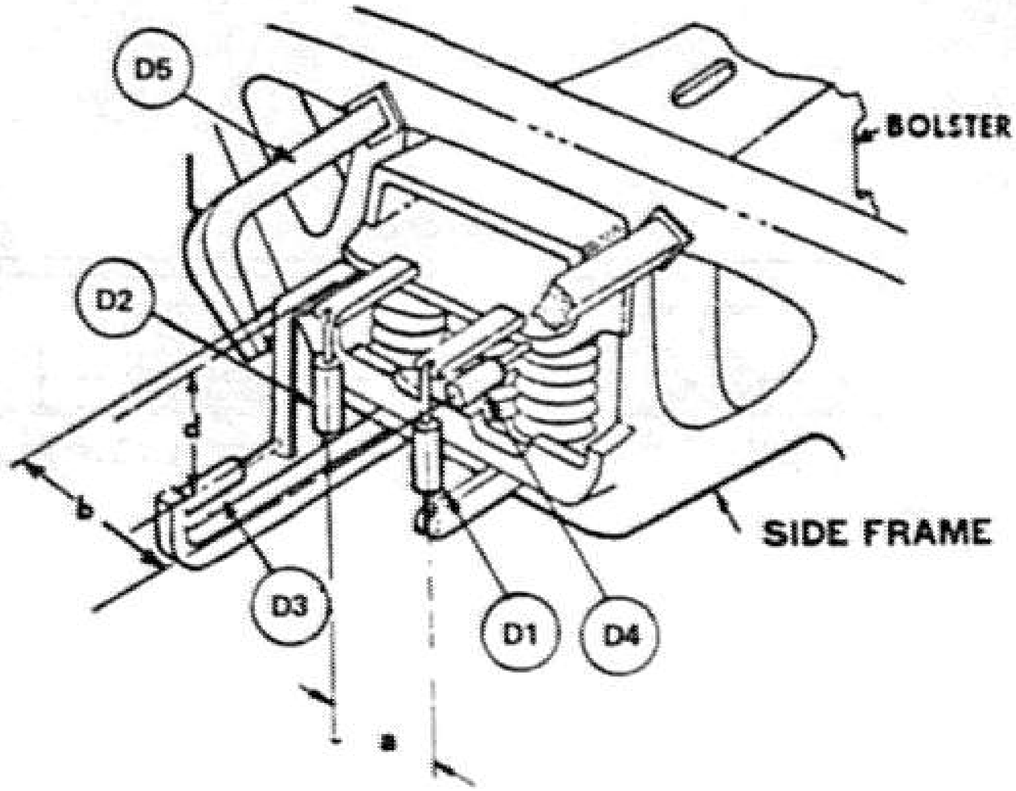
ON-BOARD MEASUREMENT REQUIREMENTS WORKSHEET

MEAS. I.D.	MEAS. DESCRIPTION	PURPOSE OF MEASUREMENT	MEAS. RANGE	UNITS	MEAS. ACCURACY	MEAS. LOCATION	SPECIAL REQUIREMENTS	ANALYSIS REQUIREMENTS				SELECTED TRANSDUCER (MFG, MODEL #)
								QUICK LOOK	POST PROCESSING	PRE-TEST CALIBRATION	POST-TEST CALIBRATION	



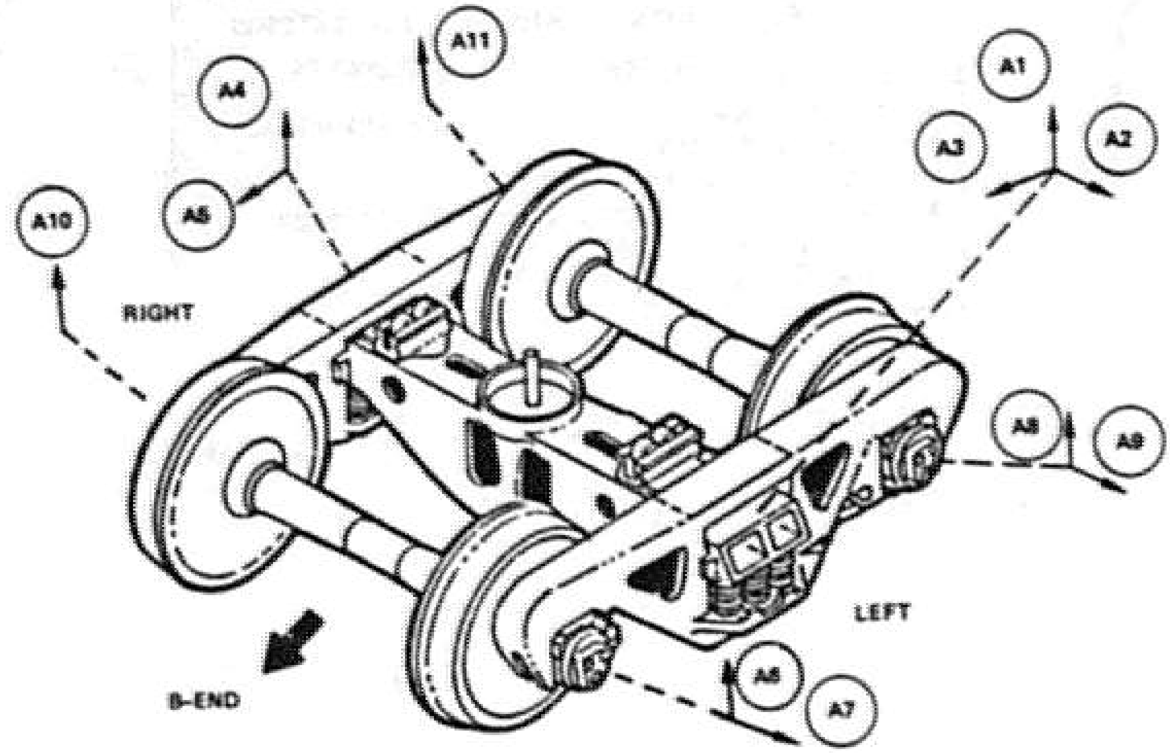
TYPICAL CAR BODY INSTRUMENTATION IDENTIFICATION

FIGURE M-15



CHANNEL NO.	MEAS. TYPE
D1	Spring Group Vert. Disp. Rear
D2	Spring Group Vert. Disp. Front
D3	Truck Bolster to Sideframe Lat. Disp. Bottom
D4	Truck Bolster to Sideframe Lat. Disp. Rear
D5	Truck Bolster to Sideframe Lat. Disp.

TYPICAL IDENTIFICATION OF SPECIAL INSTRUMENTATION
(SPECIAL BOLSTER INSTRUMENTATION)
FIGURE M-16



CHANNEL NO.	MEAS. TYPE	CHANNEL NO.	MEAS. TYPE
A1	Truck Bolster Vert. Accel.	A7	Fore Axle Brg. Pocket Lat. Accel.
A2	Truck Bolster Lat. Accel.	A8	Rear Axle Brg. Pocket Vert. Accel.
A3	Truck Bolster Long. Accel.		
A4	Truck Bolster Vert. Accel.	A9	Rear Axle Brg. Pocket Lat. Accel.
A5	Truck Bolster Long. Accel.	A10	Fore Axle Brg. Pocket Vert. Accel.
A6	Fore Axle Brg. Pocket Vert. Accel.	A11	Rear Axle Brg. Pocket Vert. Accel.

TYPICAL TRUCK INSTRUMENTATION IDENTIFICATION

FIGURE M-17

6.4 DATA ACQUISTION & MANAGEMENT

↓

6.4.1 DEFINE BASIC DATA ACQUISITION SYSTEM (DAS) REQUIREMENTS

- Inputs (Number & Type of Data Channels)
- Data Bandwidth
- Data Storage Required
- Type of Transducers (i.e. strain gage, accelerometer, LVDT, etc.) (See Table M-14 and M-15)

↓

6.4.2 CONFIGURE DAS TO MEET DEFINED REQUIREMENTS

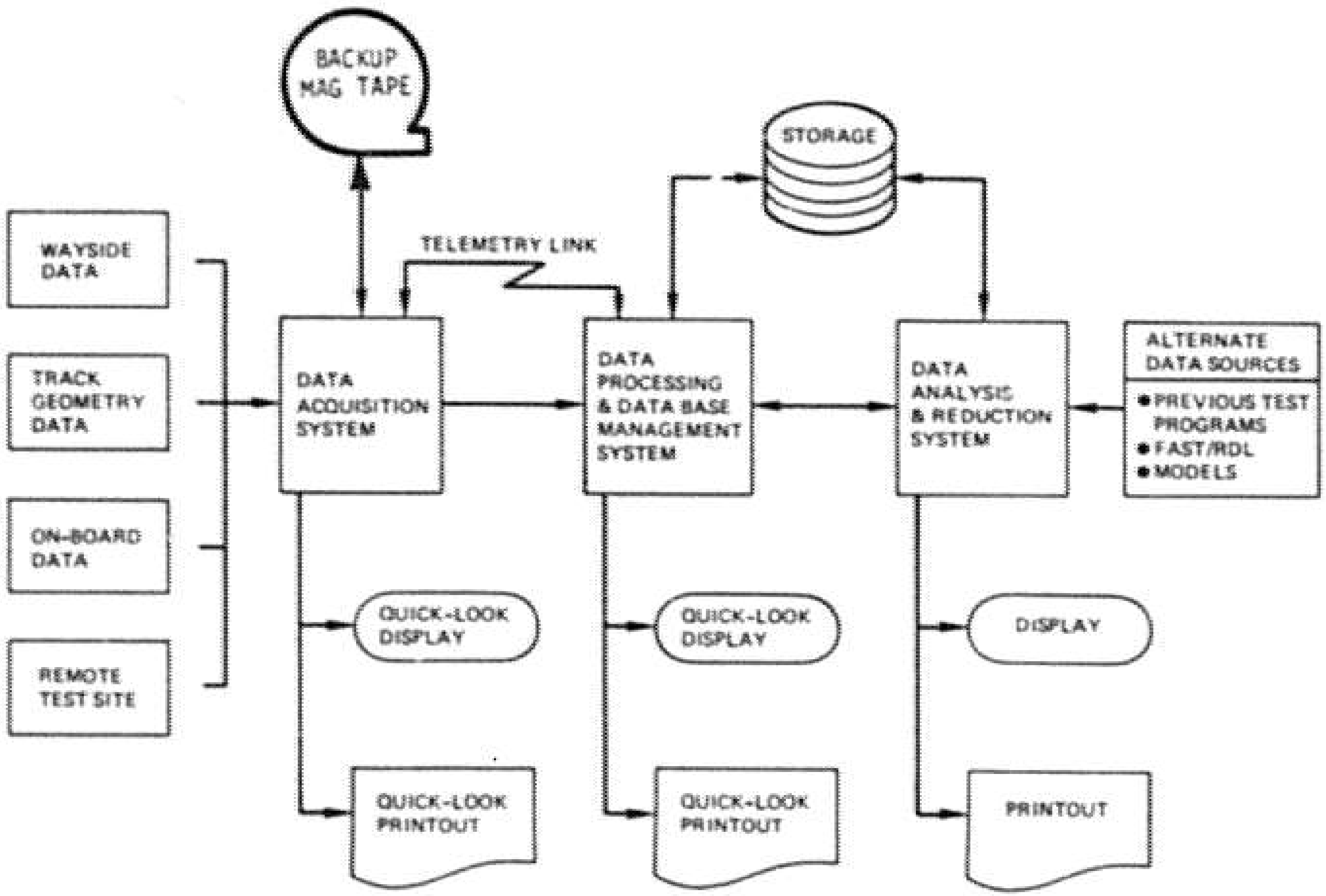
- Select Signal Conditioning (Remote or Data Van)
- Select Data Recording Technique and Equipment (F.M. Tape, Digital Magnetic Tape, Hard Disk)
- Select A/D Converters and/or Multiplex-De-Multiplex Equipment
- Time Reference, Wayside/On-Board Data Correlation
- Quick Look Analysis
- Real Time Display
- Select Peripherals (Hard Copy, Graphics Display Terminal, Line Printer, etc.)
- Telemetry Data Link(s)
- Field Communication System
- Prepare DAS Block Diagram (see Figure M-20 and M-21)
- Develop a Data Synchronization System
- Establish Critical "Alarm" Values Associated With Key Safety Issues.

↓

6.4.3 DEVELOP DATA MANAGEMENT DETAILS

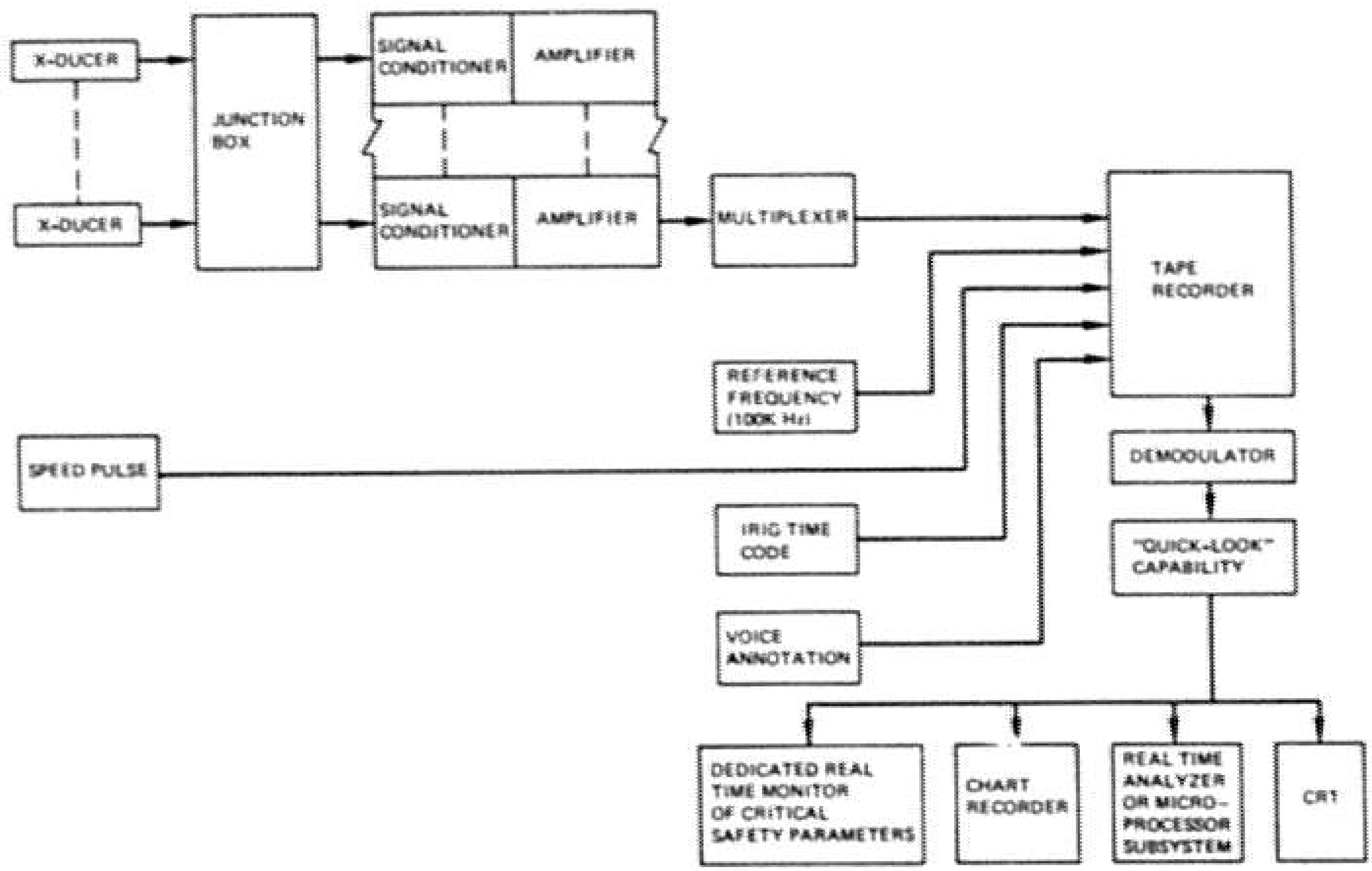
- Establish Data Input Rate
- Define Data Management/Manipulation Requirements
- Define Data Formats (Header Information, Data File Organization, Calibration Files, Channel Description File)
- Define Sensor Identification System
- Define Channel Identification System
- Develop Data Base Storage Algorithms
- Define Processing Methodology Required to Properly Format Data as Needed to Investigate Performance Regimes

FIGURE M-18



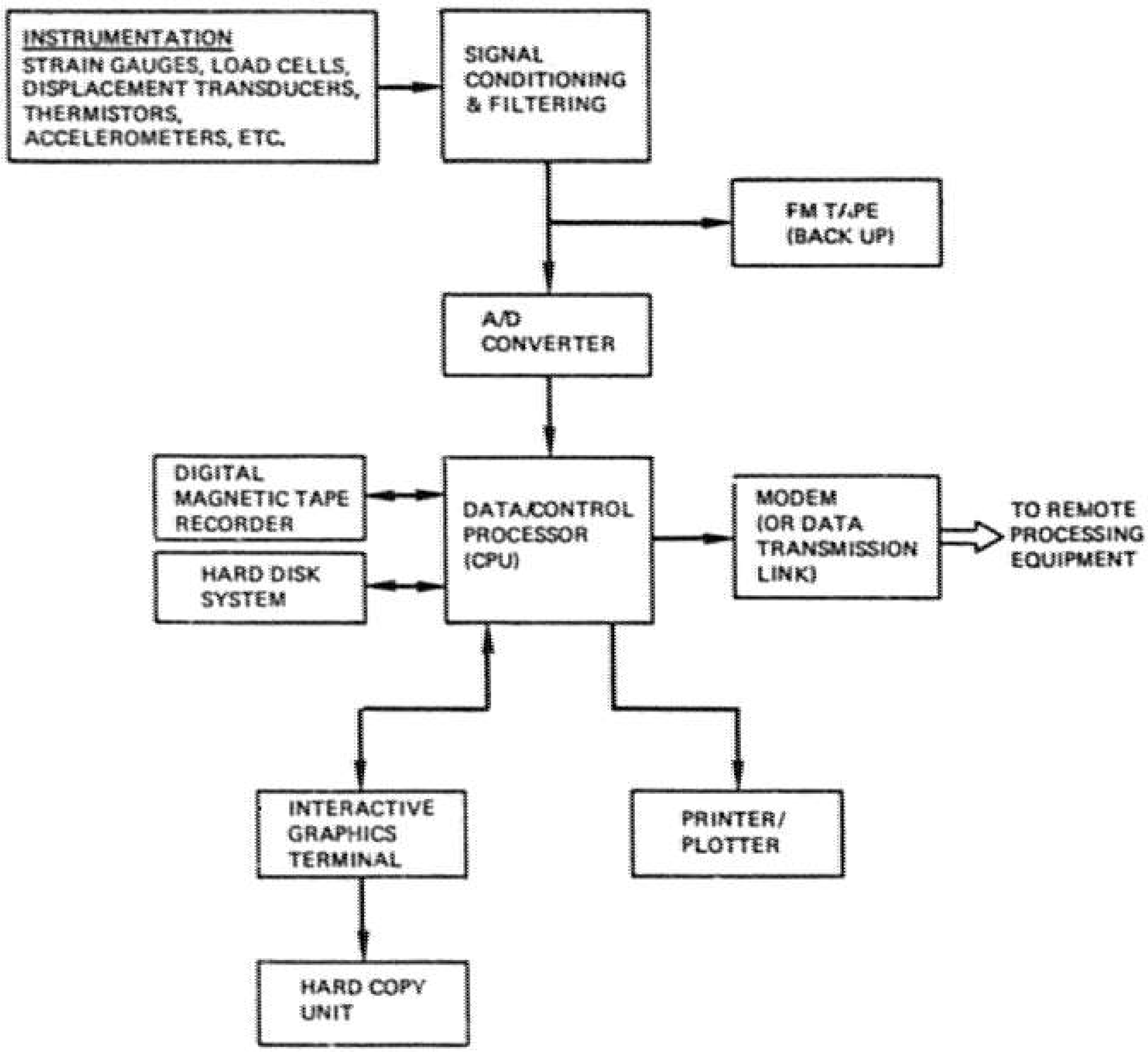
TYPICAL OVERALL FLOW CHART FOR THE DATA MANAGEMENT SYSTEM

FIGURE M-19



BLOCK DIAGRAM FOR THE DATA ACQUISITION SYSTEM
(EXAMPLE OF A TYPICAL ANALOG BASED SYSTEM)

FIGURE M-20



BLOCK DIAGRAM FOR THE DATA ACQUISITION SYSTEM
(EXAMPLE OF A TYPICAL COMPUTER BASED SYSTEM)

FIGURE M-21

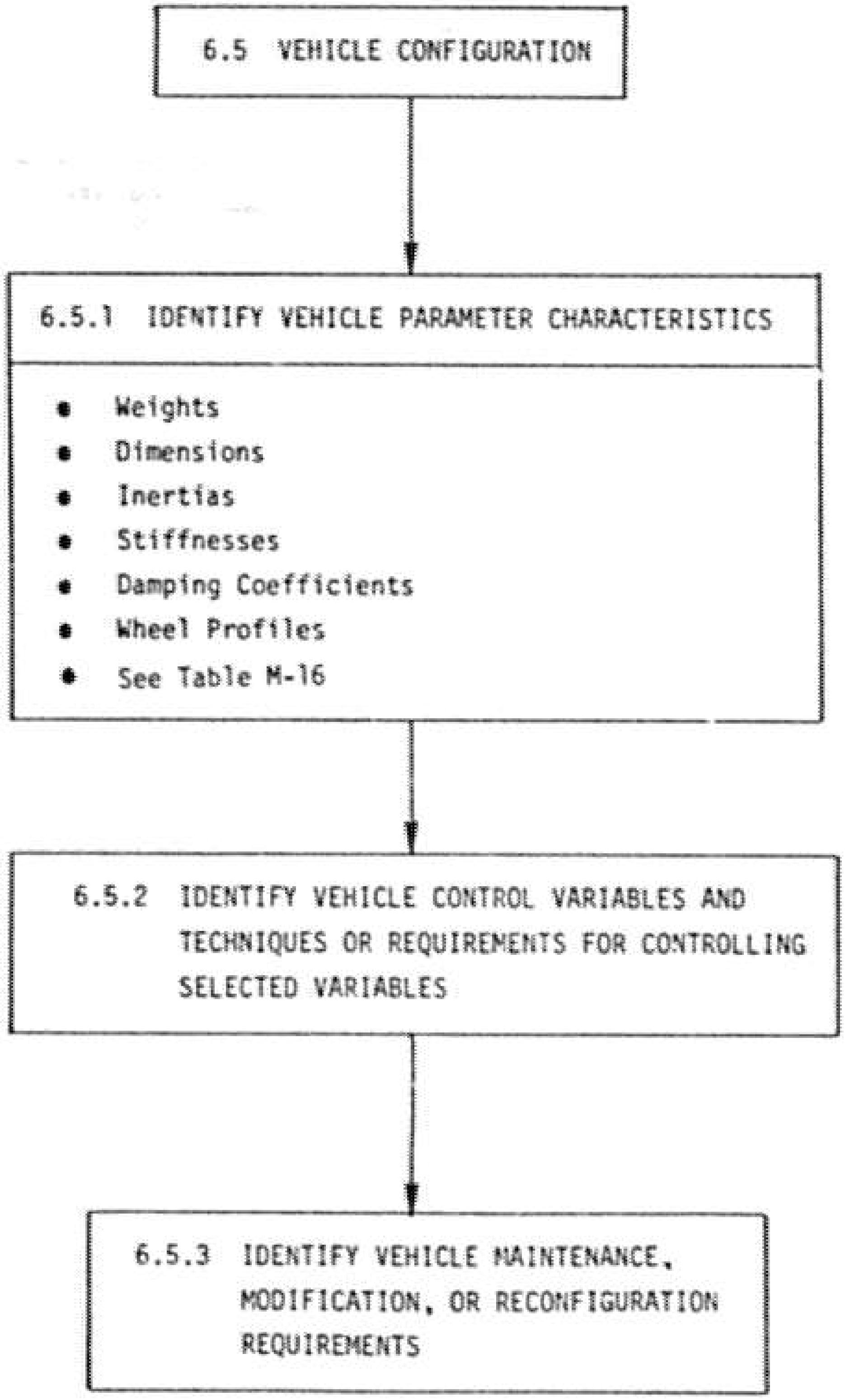

6.5 VEHICLE CONFIGURATION
6.5.1 IDENTIFY VEHICLE PARAMETER CHARACTERISTICS
• Weights
• Dimensions
• Inertias
• Stiffnesses
• Damping Coefficients
• Wheel Profiles
• See Table M-16
6.5.2 IDENTIFY VEHICLE CONTROL VARIABLES AND TECHNIQUES OR REQUIREMENTS FOR CONTROLLING SELECTED VARIABLES
6.5.3 IDENTIFY VEHICLE MAINTENANCE, MODIFICATION, OR RECONFIGURATION REQUIREMENTS

FIGURE M-22

TABLE M-16

CANDIDATE VEHICLE PARAMETERS TO BE IDENTIFIED

GENERAL INFORMATION

Vehicle Number ________
Vehicle Initials ________
Vehicle Type ________
Car Capacity ________
Car Tare Weight ________
Tare Weight ________

Vehicle Manufacturer ________
Truck Type ________

I.D. NUMBER	SYMBOL	PARAMETER DESCRIPTION	PARAMETER VALUE	UNITS	PHYSICAL LIMITS (IF APPLICABLE)
	L	car overall length			
	L_a	truck axle spacing			
	L_o	end of car to truck center			
	L_t	truck spacing, center-to-center			
	M_a	effective unsprung mass per truck			
	M_c	total car body mass			
	M_t	truck sprung mass, per truck			
	m	car body effective mass			
	n_{axle}	number of axles per truck			
	q	first body-bending mode displacement, center of car, vertical			
	W_a	unsprung weight (wheels, axles, etc.), per truck			
	W_c	car body total weight (including suspended mass)			
	W_t	truck suspended weight (frame, etc.), per truck			
	h_1	height of unsprung mass c.g. above rail			
	h_2	height of primary lateral suspension above rail			
	h_3	height of sprung mass c.g. above rail			
	h_4	height of secondary lateral suspension above rail			
	h_5	height of car body c.g. above rail			

TABLE M-16 (continued)
CANDIDATE VEHICLE PARAMETERS TO BE IDENTIFIED

VEHICLE I.D. NUMBER ________

I.D. NUMBER	SYMBOL	PARAMETER DESCRIPTION	PARAMETER VALUE	UNITS	PHYSICAL LIMITS (IF APPLICABLE)
	I_c	car body mass moment of inertia (pitch, yaw)			
	J_w	truck unsprung mass moment of inertia, per truck			
	J_c	car body mass moment of inertia in roll, total			
	K	linear spring rate, per truck			
	K	torsional spring rate, per truck			
	K_{sw}	swing hanger effective lateral stiffness, per truck			
	$\bar{K}_x$	overall lateral truck stiffness			
	$\bar{K}_a$	overall torsional truck stiffness			
	$\bar{K}'_x$	lateral/torsional truck cross coupling stiffness			
	$\bar{K}'_a$	torsional/lateral truck cross coupling stiffness			
	b_1	lateral separation of primary vertical suspension springs			
	b_{1c}	lateral separation of primary vertical suspension dampers			

6.6 DEFINE REQUIRED TEST SERIES AND DEVELOP TEST PROCEDURES

↓

6.6.1 DEFINE OVERALL TEST PROGRAM REQUIRED TO MEET IDENTIFIED TEST OBJECTIVES

(1.0) →
(4.0) →

- Identify a test series required to meet the defined test objectives
- Develop a test sequence (e.g. test zones, speed profiles, lading conditions, wheel profiles, Train Direction, Consist make-up, etc.)

↓

6.6.2 DEVELOP DETAILED TEST PROCEDURES

Prepare a detailed, step-by-step, test procedures document which will be used to actually conduct each individual test sequence.

- Identify individual responsibilities for each test
- Identify individual actions to be taken during each step
- Provide a sequential "checklist" format for the test procedures
- Identify general test rules

↓

6.6.3 DEVELOP PROCEDURES FOR MISCELLANEOUS ACTIVITIES

- Field Inspection of Test Site
  - Tie numbering system
  - Identify track super structure and its condition
  - Ballast Design & Condition (type, depth, profile, fouling or degradation, drainage)
  - Tie Installation (Re-work, Spot installation, etc.)
  - Subgrade Conditions
- Develop test procedures as needed to conform to railroad and/or laboratory safety standards
- Soil Sample Acquisition
- Soil Sample Testing
- Monitoring of Environmental Conditions
  - Subsurface moisture, temperature
  - Weather information and history
- Track Geometry Measurement
- Track Structure Location (survey to benchmark)
- Data Acquisition Procedure
- Perform Test Design Hazard Analysis

↓

6.6.4 PREPARE CALIBRATION PROCEDURES

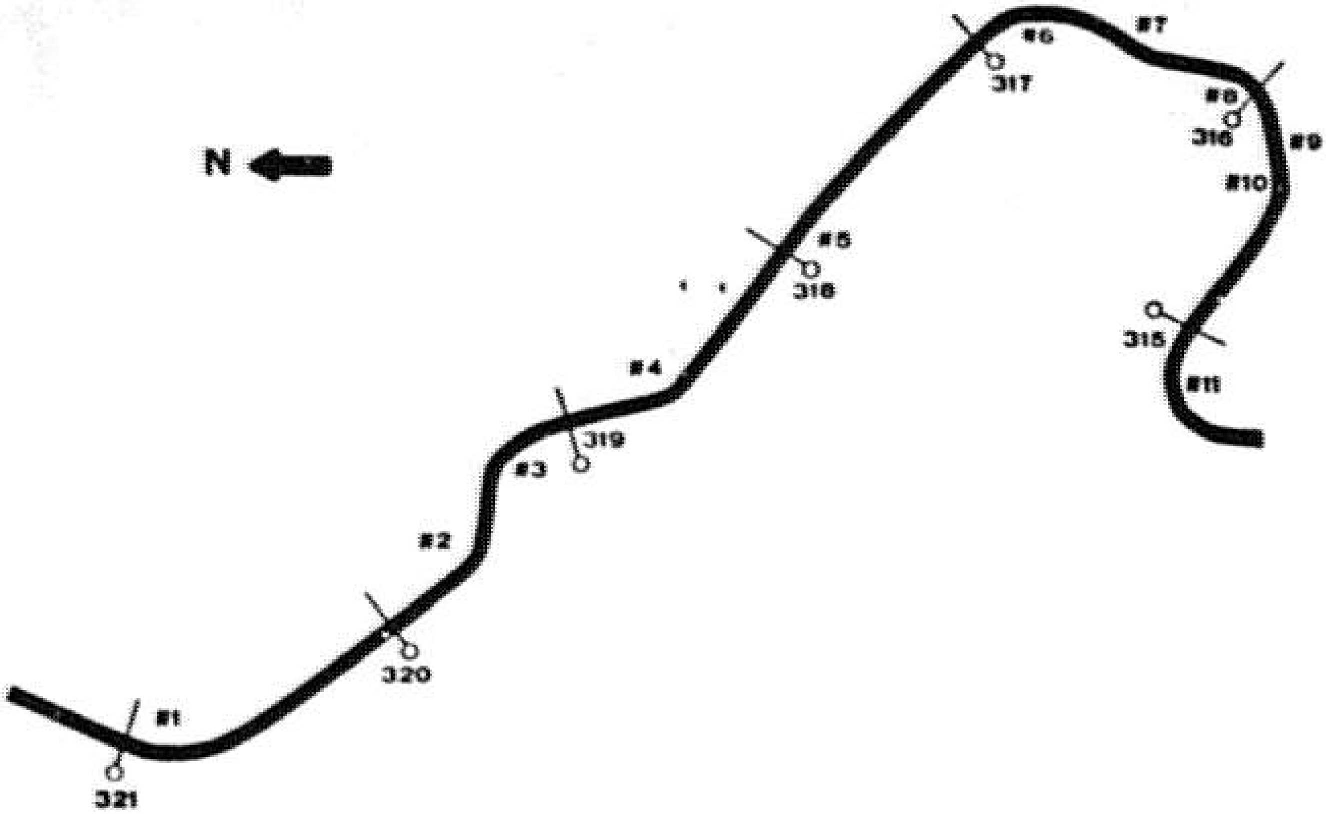
- Wheel/Rail Lateral, Vertical and Longitudinal Load Circuits
- Displacement Measurements
- Tie Bending Strains
- Fastener Instrumentation
- Vehicle Weight
- Vehicle Properties

Note:

(3.0)→ refers to inputs or outputs from the other major tasks.

FIGURE M-23

TEST ZONE 1 (CURVE DATA)



CURVE NO.	DEGREE OF CURV.	CURVE DIRECTION	LENGTH (ft.)	SUPER ELEVATION (in)	START MP	STOP MP	EQUILIBRIUM SPEED
1	2.6	Right hand	2736	4.07	321.1	320.6	47.5
2	6.2	Right hand	1080	5.19	319.7	319.5	34.7
3	6.1	Left hand	1386	4.80	319.4	319.1	33.7
4	5.3	Right hand	1136	5 10	318.7	318.5	37.2
5	1.2	Left hand	934	1.42	318.0	317.8	41.3
6	3.2	Left hand	3118	3.13	317.1	316.5	37.6
7	5.1	Right hand	961	5.06	316.5	316.3	37.8
8	3.0	Left hand	2070	4.55	316.2	315.8	36.2
9	3.7	Right hand	491	3.72	315.8	315.7	38.1
10	6.3	Left hand	1037	4.90	315.7	315.5	33.5
11	6.1	Right hand	2420	4.92	315.0	314.6	34.1

TYPICAL TEST SITE DESCRIPTION

FIGURE M-24

Performance Issue ____________

Activity ____________

TABLE M-17

TEST DESIGN HAZARD MATRIX

Hazard or Failure	Effect	Hazard Category	Exposure	Hazard Duration Period	Known Quantifying Data or Procedure	Likelihood of Occurrence	Hazard Control Options	Corrective Action and Priority

By ____________

____

Date ________ Page ________

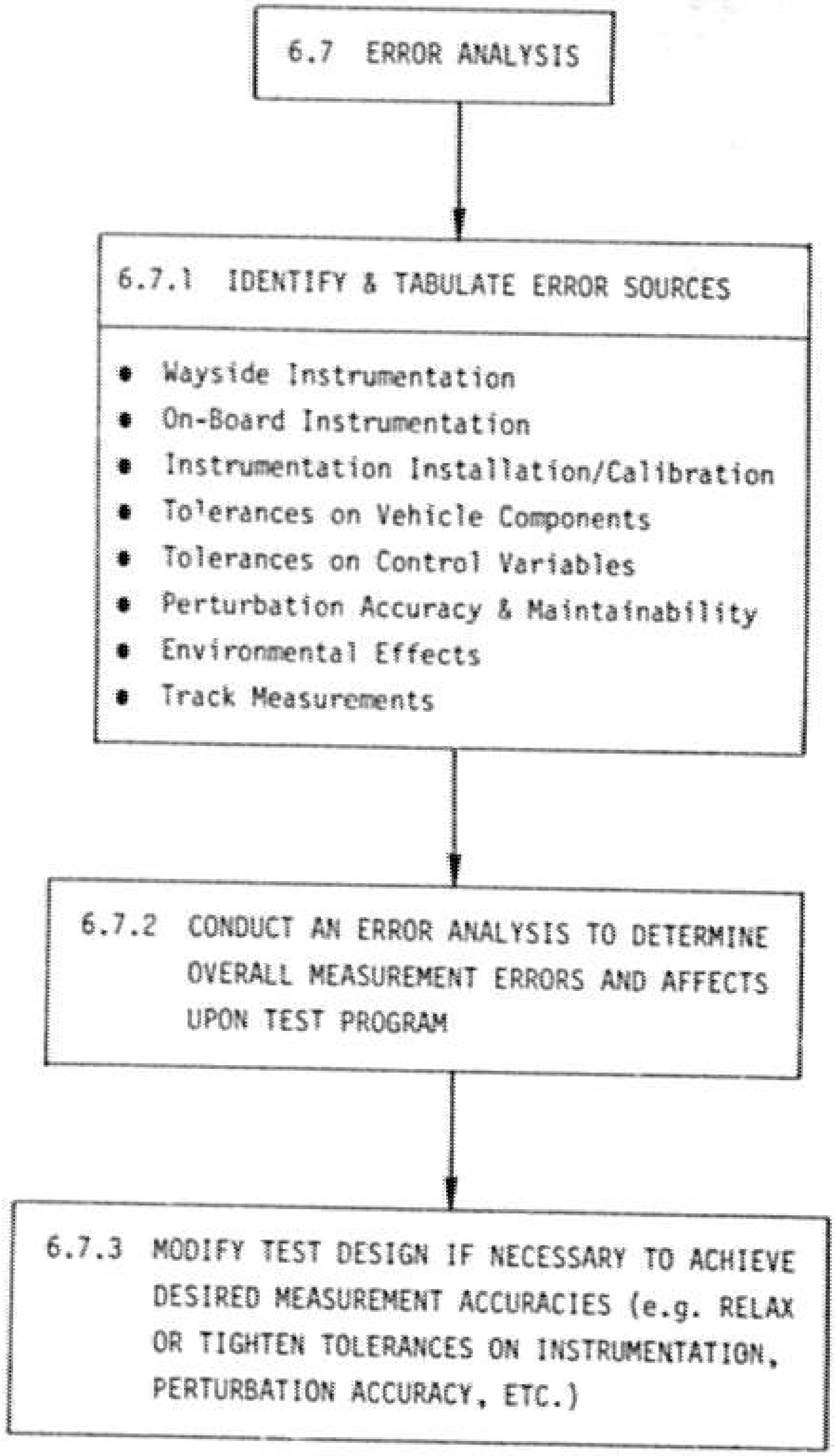

6.7 ERROR ANALYSIS
6.7.1 IDENTIFY & TABULATE ERROR SOURCES
• Wayside Instrumentation
• On-Board Instrumentation
• Instrumentation Installation/Calibration
• Tolerances on Vehicle Components
• Tolerances on Control Variables
• Perturbation Accuracy & Maintainability
• Environmental Effects
• Track Measurements
6.7.2 CONDUCT AN ERROR ANALYSIS TO DETERMINE OVERALL MEASUREMENT ERRORS AND AFFECTS UPON TEST PROGRAM
6.7.3 MODIFY TEST DESIGN IF NECESSARY TO ACHIEVE DESIRED MEASUREMENT ACCURACIES (e.g. RELAX OR TIGHTEN TOLERANCES ON INSTRUMENTATION, PERTURBATION ACCURACY, ETC.)

FIGURE M-25

M.2.7 SPECIAL DEVELOPMENT TASKS

Special development tasks, while not an integral part of the mainstream test planning methodology, are tasks which are considered either necessary or very desirable for the conduct of a specific test program. These development tasks should be performed in parallel with the overall test planning activities as requirements evolve. A planning flow diagram is presented in Figure M-26.

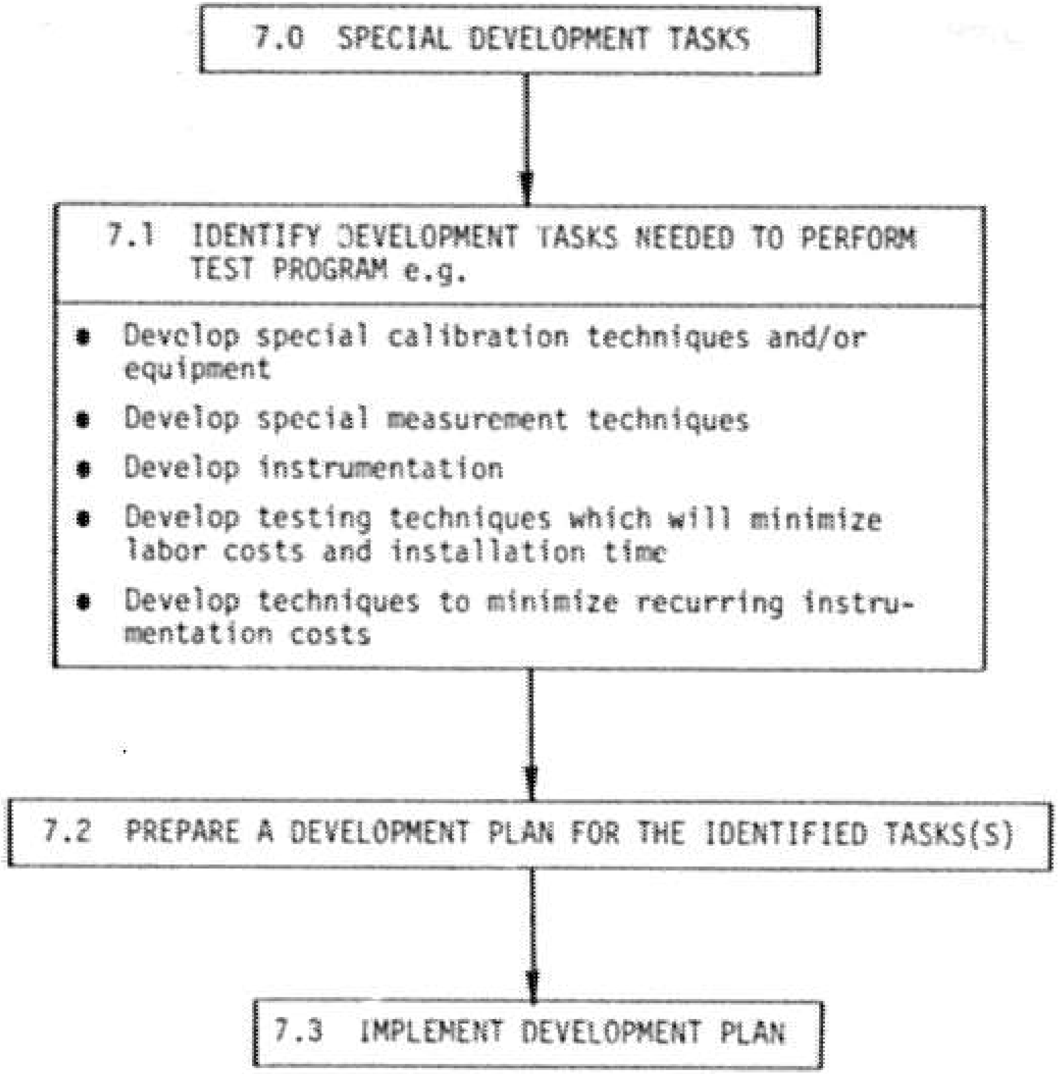

7.0 SPECIAL DEVELOPMENT TASKS
7.1 IDENTIFY DEVELOPMENT TASKS NEEDED TO PERFORM TEST PROGRAM e.g.
• Develop special calibration techniques and/or equipment
• Develop special measurement techniques
• Develop instrumentation
• Develop testing techniques which will minimize labor costs and installation time
• Develop techniques to minimize recurring instrumentation costs
7.2 PREPARE A DEVELOPMENT PLAN FOR THE IDENTIFIED TASKS(S)
7.3 IMPLEMENT DEVELOPMENT PLAN

FIGURE M-26

M.2.8 TEST PREPARATION

The "TEST PREPARATION" planning task should identify all of the procedures and activities which are necessary to prepare the test site, test consist and the associated test equipment prior to testing (see Figure M-27). Any changes or revisions to the previously identified test schedule and the associated logistics involved should be made at this time. Procedures and schedules for fabricating and/or procuring special equipment (e.g. test fixtures) or supplies should be defined.

Planning Aids For Test Preparation

A checklist for vehicle preparation (Table M-18) is included as an aid for documenting vehicle condition and identifying required maintenance or modification. As noted in the table, it will most likely be necessary to measure and record certain previously identified vehicle parameters prior to testing. Table M-19 provides a brief checklist of design considerations which may be useful when developing test fixtures. Table M-20 presents a "shopping list" of test equipment which may be required for a specific test. As part of this planning task a specific list of required equipment should be made.

Table M-21 presents some general considerations for personnel health and safety. A table of "miscellaneous site preparation activities" is presented in Table M-22. Such preparation can be easily overlooked but can be potentially very critical to a successful test program.

Table M-23 presents a format for the Test Operations Safety Analysis Matrix which will provide assurance that previous hazard analysis are met and safety requirements satisfied.

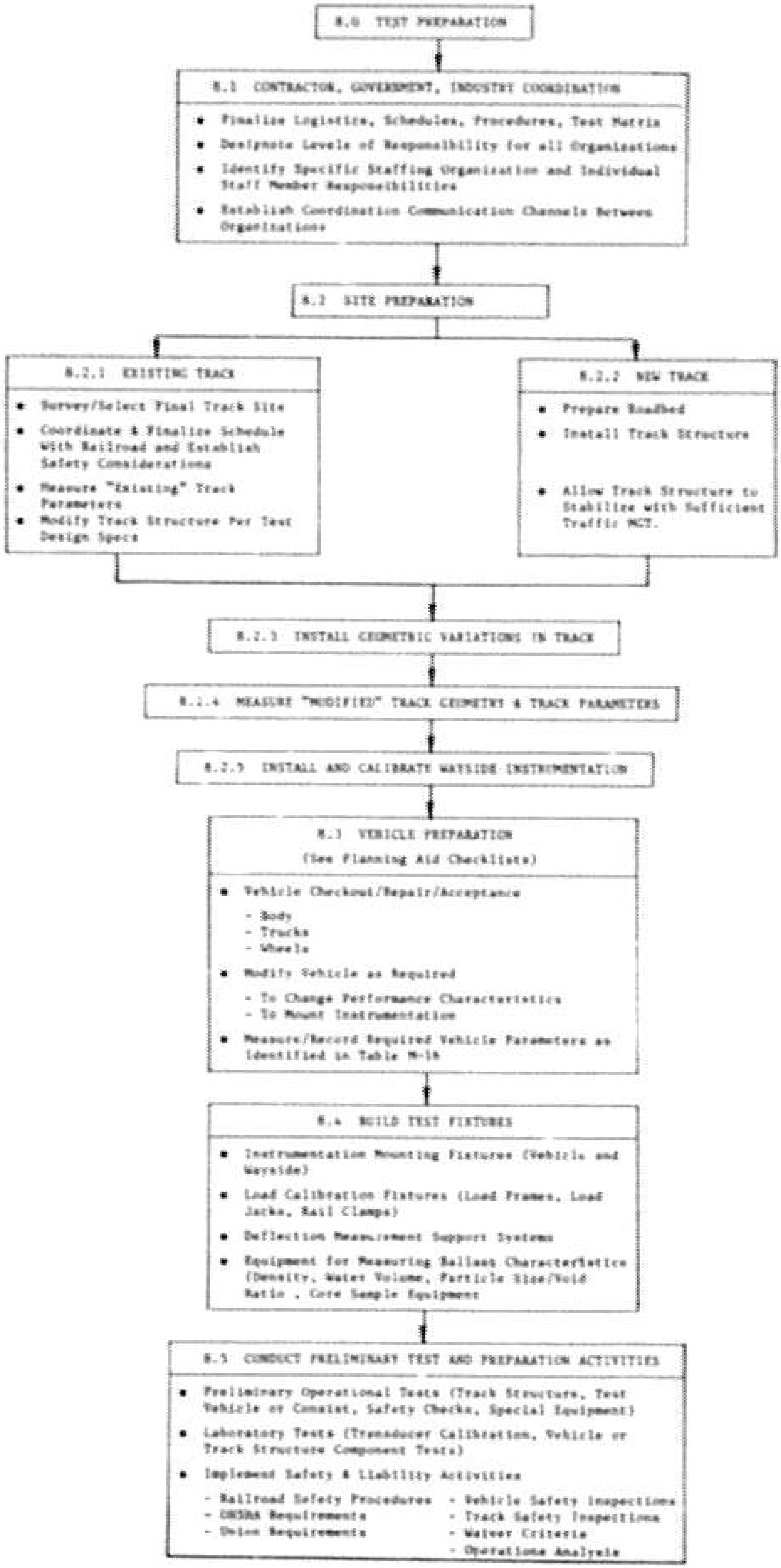

8.0 TEST PREPARATION
8.1 CONTRACTOR, GOVERNMENT, INDUSTRY COORDINATION
• Finalize Logistics, Schedules, Procedures, Test Matrix
• Designate Levels of Responsibility for all Organizations
• Identify Specific Staffing Organization and Individual Staff Member Responsibilities
• Establish Coordination Communication Channels Between Organizations
8.2 SITE PREPARATION
8.2.1 EXISTING TRACK
• Survey/Select Final Track Site
• Coordinate & Finalize Schedule With Railroad and Establish Safety Considerations
• Measure "Existing" Track Parameters
• Modify Track Structure Per Test Design Specs
8.2.2 NEW TRACK
• Prepare Roadbed
• Install Track Structure
• Allow Track Structure to Stabilize with Sufficient Traffic MGT.
8.2.3 INSTALL GEOMETRIC VARIATIONS IN TRACK
8.2.4 MEASURE "MODIFIED" TRACK GEOMETRY & TRACK PARAMETERS
8.2.5 INSTALL AND CALIBRATE WAYSIDE INSTRUMENTATION
8.3 VEHICLE PREPARATION
(See Planning Aid Checklists)
• Vehicle Checkout/Repair/Acceptance
- Body
- Trucks
- Wheels
• Modify Vehicle as Required
- To Change Performance Characteristics
- To Mount Instrumentation
• Measure/Record Required Vehicle Parameters as Identified in Table M-16
8.4 BUILD TEST FIXTURES
• Instrumentation Mounting Fixtures (Vehicle and Wayside)
• Load Calibration Fixtures (Load Frames, Load Jacks, Rail Clamps)
• Deflection Measurement Support Systems
• Equipment for Measuring Ballast Characteristics (Density, Water Volume, Particle Size/Void Ratio , Core Sample Equipment
8.5 CONDUCT PRELIMINARY TEST AND PREPARATION ACTIVITIES
• Preliminary Operational Tests (Track Structure, Test Vehicle or Consist, Safety Checks, Special Equipment)
• Laboratory Tests (Transducer Calibration, Vehicle or Track Structure Component Tests)
• Implement Safety & Liability Activities
- Railroad Safety Procedures
- OHSRA Requirements
- Union Requirements
- Vehicle Safety Inspections
- Track Safety Inspections
- Waiver Criteria
- Operations Analysis

FIGURE M-27

TABLE M-18

VEHICLE PREPARATION CHECKLISTS

1.0 Vehicle Checkout and Documentation of Vehicle Condition

(Body)

- Check for bent or twisted center sill (does car sit level?)
- Rust thru, cracked or broken body welds
- Cracked corner castings on box car doors
- Operational hand brake and slack adjuster
- Safety appliances (ladders, stirrups, hand rails, etc.)
- Worn, dragging, cracked brake hoses
- Check for broken center plate wear ring
- Perform air test
- Check for existence of retainer line if required

(Wheels)

- Excessive tread or flange wear
- Cracked wheel
- Spalled tread
- Wheel flats
- Over heated (thermal or herring bone cracks, color or rust on wheel plate)
- Loose wheel
- Leaky wheel bearing seals
- All wheels of same diameter
- Document and record flats, spalls (size, dimensions, location, depth)
- Check for roller bearing frame keys
- Check for wheelset separation (flange back-to-back dimensions)

TABLE M-18 (Continued)

VEHICLE PREPARATION CHECKLISTS

(Trucks)

- Worn brake shoes
- Improper shoes (cast vs. composition)
- Burned in beams
- Broken, misaligned springs
- Worn friction blocks
- Bolster gib wear (inner and outer)
- Number of buttons on opposite sideframes
- Side frame integrity

(Draft Gear)

- Proper couplers (type E, F, shelf, interlocking) if required for test
- Cracked pocket or coupler shank
- Note special draft gear (Freightmaster, Hydracushion, etc.)

(Check for Evidence of Derailment)

- Dirt and gravel in spring group
- Sling marks on carbody
- New air reservoir and brake cylinder
- Blue gouges on field side of wheel tread
- Flange marks on underside of car
- Missing side bearings
- Damaged bearing cap

2.0 Measure and record physical vehicle parameters as identified under planning task (see Figure M-22).

TABLE M-18 (Continued)

VEHICLE PREPARATION CHECKLISTS

Typically it will be necessary to obtain or measure certain vehicle parameters which will be required for a specified test program. These parameters may include those presented in Table M-16.

3.0 Vehicle Modification As Required For Test

- Attach transducer fixtures, J-boxes, conduits and cable hangers, etc.
- Load vehicle, locate c.g.
- Modify jack pads
- Change couplers
- Change center plate
- Check shocks or change as necessary
- Check side bearings
- Change brake forces (levers, clevices, rod lengths)
- Disconnect brakes, block cylinder
- Retrofit w/retainer line
- Tap train line air supply
- Wire down cut levers to prevent uncoupling

TABLE M-19

TEST FIXTURE DESIGN/FABRICATION CONSIDERATIONS

- Convenience and ease of use
- Accuracy and repeatability
- Ruggedness
- Method of attachment (bolted, welded, clamped)
- Adjustment capability
- Will not cause interference problems or affect vehicle performance or safety
- Susceptibility to contamination and weather
- Ease and cost of fabrication
- Coordinate actual fabrication w/machine shop
- Arrange for transportation to test site
- Provide time in schedule for field installation and possible modification or re-work
- Electro Magnetic Interference (EMI) considerations as appropriate

TABLE M-20

EQUIPMENT CHECKLIST

NO	ITEM	I.D.	QUANTITY	CHECKOFF
GENERAL PURPOSE HAND TOOLS				
1	Flat Head Screw Drivers			
2	Phillips Head Screw Drivers			
3	Offset Screw Driver (Phillips & Flat)			
4	Set of Jeweler's Screw Drivers			
5	Hammers (Machinist, Claw, Sledge)			
6	Adjustable Wrenches			
7	Vise Grips			
8	Punch Set (Center, Drift)			
9	Chisel Set			
10	Pliers			
	Slip Joint			
	Needle Nose (Midget and Std)			
	Adjustable (Pump)			
	Diagonal Cutters (Midget & Std)			
	Snap Ring			
	Tin Snips			
11	Hydraulic Jack and Jack Stands			
12	Sharp and Dull Knives			
13	Dry Bars and "Cheater" Pipe			
14	Lights			
	Flash Light and Batteries			
	Trouble Light (Ext. Cord)			
	Flood Lights (Ext. Cord)			

TABLE M-20 (Continued)

EQUIPMENT CHECKLIST

NO	ITEM	I.D.	QUANTITY	CHECKOFF
GENERAL PURPOSE HAND TOOLS				
15	C-Clamps			
16	Spring Clamps			
17	Screen Door Springs			
18	String			
19	Rope			
20	Chain w/Hooks			
21	Saws			
	Hack Saw and Blades			
	Carpenter's Saw			
	Keyhole Saw			
22	Hydraulic Jacks w/Handles			
	2 Ton			
	5 Ton			
23	Wire Brush			
24	Fox Tail Brush			
25	Scissors			
26	Putty Knife			
27	Allen Wrench Set			
28	Complete Socket Sets			
	Ratchet Handle			
	Extensions			
	U-Joint			

TABLE M-20 (Continued)

EQUIPMENT CHECKLIST

NO	ITEM	I.D.	QUANTITY	CHECKOFF
GENERAL PURPOSE HAND TOOLS				
	Deep Well Sockets			
	Regular Sockets			
	Metric Sockets			
29	Drill Bit Index Set			
30	Open End Wrench Set			
31	Box End Wrench Set			
32	Torque Wrenches			
33	Shovel			
34	Pick			
35	Posthole Digger			
36	Complete Tap and Die Set w/Wrenches			
37	Spare Taps			
38	Cutting Oil			
39	Bench Vise			
40	Files			
	- Flat (Fine and Coarse)			
	- Half-Round (Fine and Coarse)			
	- Rat Tail (Fine and Coarse)			
	- Triangular (Fine)			
	- Square (Fine)			
41	File Card			
42	Handles			
43	Swiss Needle File Set			
44	Pop-Riverter and Pop Rivets			
45	Rerailing Blocks/Wedge			

TABLE M-20 (Continued)

EQUIPMENT CHECKLIST

NO	ITEM	I.D.	QUANTITY	CHECKOFF
ELECTRICAL SUPPLIES				
1	Hook Up Wire (assorted sizes)			
2	Spade Lugs and Connectors			
3	Solder and Flux			
4	Jumper Wires			
5	Electrical Technician's tool kit			
6	Assortment of Electrical Components - resistors - capacitors - diodes - integrated circuits and amplifiers			
7	Heat Shrink Tubing			
8	Soldering Iron or Torch			
MEASURING TOOLS				
1	Machinist Rule 12"			
2	Carpenter's Level 3 Ft.			
3	Square			
4	Tapes 25' 100'			
5	Micrometer Set 0-6"			

TABLE M-20 (Continued)

EQUIPMENT CHECKLIST

NO	ITEM	I.D.	QUANTITY	CHECKOFF
MEASURING TOOLS				
6	Caliper 0-6"			
7	Plumb Bob			
8	Chalk Line			
9	Transit			
10	Ultra-Sonic Unit and Coupling Fluid			
11	Depth Gage			
POWER TOOLS & EQUIPMENT				
1	Variable Speed Reversible Electric Drill (3/8")		1	
2	1/2 Inch Heavy Duty Electric Drill		1	
3	Disc Grinder and Assorted Discs		1	
4	Die Grinder and Assorted Discs and Bits		1	
5	Saber Saw			
6	Heat Gun			

TABLE M-20 (Continued)

EQUIPMENT CHECKLIST

NO	ITEM	I.D.	QUANTITY	CHECKOFF
ELECTRICAL EQUIPMENT				
1	Digital Volt/Ohm Meter			
2	Frequency Counter			
3	Function Generator			
4	Portable Oscilloscope			
5	Regulated Power Supply			
CONSUMABLES				
1	Tape			
	Scotch			
	Duct			
	Filament			
	Electrician's			
	Masking			
2	Solvent			
3	Grease			
4	Rags			
5	Sand Paper			
6	Emory Cloth			
7	Glue:			
	Paper			
	Wood			
	Metal			
	Plastic			
	Rubber			

TABLE M-20 (Continued)

EQUIPMENT CHECKLIST

NO	ITEM	I.D.	QUANTITY	CHECKOFF
CONSUMABLES				
8	Temperature Sticks (100°F - 200°F range)			
9	Spray Paint			
STATIONERY SUPPLIES				
1	Pencils			
2	Pencil Sharpener			
3	Pens			
4	Paper (Lined and Graph)			
5	Clip Board			
6	Chalk			
7	Paint Stick			
8	Magic Marker			
9	Sticky Labels			
10	Loose Leaf Binders			

TABLE M-20 (Continued)

EQUIPMENT CHECKLIST

NO	ITEM	I.D.	QUANTITY	CHECKOFF
PHOTOGRAPHIC EQUIPMENT				
1	Camera			
2	Light Meter			
3	Film			
4	Tripod			
5	Batteries			
6	Lenses			
MISC. ITEMS				
1	Gloves			
2	First Aid Kit			
3	Snake Bite Kit			
4	Insect Repellant			
5	Calculator			
6	Fire Extinguisher			
7	Keys (for equipment and lockers, etc)			
8	Wire			
9	Dust Masks			
10	Safety Glasses			
11	Stool			
12	Small Table			
13	Canvas Tarp, Drop Cloths			
14	Broom			
15	Brush			

TABLE M-20 (Continued)

EQUIPMENT CHECKLIST

NO	ITEM	I.D.	QUANTITY	CHECKOFF
MISC. ITEMS				
16	Coveralls			
17	Rain Gear			
18	Complete Supply of assorted nuts, bolts, screws, washers, etc.			
19	Raw Materials - sheet metal - sheet plastic - gasket material - card board			
20	Tie Wraps			
21	Hose Clamps			
22	Cotter Keys			
23	Turn Buckles			
24	Wire Cable			
25	Water Container			
26	Hard Hats			

TABLE M-21

TYPICAL PERSONNEL HEALTH AND SAFETY CONSIDERATIONS

- Fire protection on equipment, buildings, and storage areas.
- Evacuation procedures, emergency service routes, and posting of emergency plans, radio calls and phone numbers.
- Alerting and communications systems.
- Protective devices, barricades, warning signs, ropes, railways, railroad equipment safety appliances.
- Trained and instructed personnel as required by regulations.
- Personal protective devices and protective clothing, personnel restraints, cushions, padding.
- On-site medical supplies, first aid, evacuation litters.
- Safe drinking water supply and sanitary facilities.
- Copies of Book of Rules, applicable safety manuals.
- Gang watchmen, flagmen, crossing protection, public protection.
- Accident/injury reporting system.
- Poisonous plants, vermin, insects, caustic protection.
- Crane, high lift and fire apparatus inspection forms and schedules.
- Procedures and equipment for work on or near electrified track or signal systems.
- Equipment, procedures, and instructed personnel for work on hazardous or safe-critical operations.
- Housekeeping and waste/disposal equipment.

Note: Health and safety planning should span the interface between railroad, construction, industrial, and laboratory rules, practices, and regulations which pertain to test operations.

TABLE M-22

MISCELLANEOUS SITE PREPARATION ACTIVITIES

1. Identify the closest source for both routine and emergency medical services (e.g. hospitals, clinics, paramedics, drugstores, fire department). Develop a list of phone numbers.

2. Identify local sources for typical personnel services (e.g. motels, restaurants, grocery stores, etc.).

3. Identify local sources for test equipment and their business hours (e.g. hardware stores, electrical supplies, tool rentals, fuel supplies, car rental, etc.).

Performance Issue ____________

Activity ____________

By ____________

Date ____________

TABLE M-23

TEST OPERATIONS SAFETY MATRIX

Task Description or Test Operation	Hazard or Condition	Hazard Duration Period	Likelihood of Occurrence	Effect	Hazard Class	Safety Requirements	Actions to Control Hazard

M.2.9 TEST EXECUTION

The planning task for "TEST EXECUTION" should identify all of the activities and procedures which are necessary to actually implement a test. The flowchart shown in Figure M-28 summarizes the type of activities which should be addressed during this test planning task.

A review of the test procedures, results, and deficiencies should be made to verify data retrieved and permit future test efficiency including a review of test safety procedures effectiveness. Table M-24 shows a format for review of test safety procedures. Table M-25 summarizes some of the pre-test coordination activities or topics which should be dealt with prior to actual test execution.

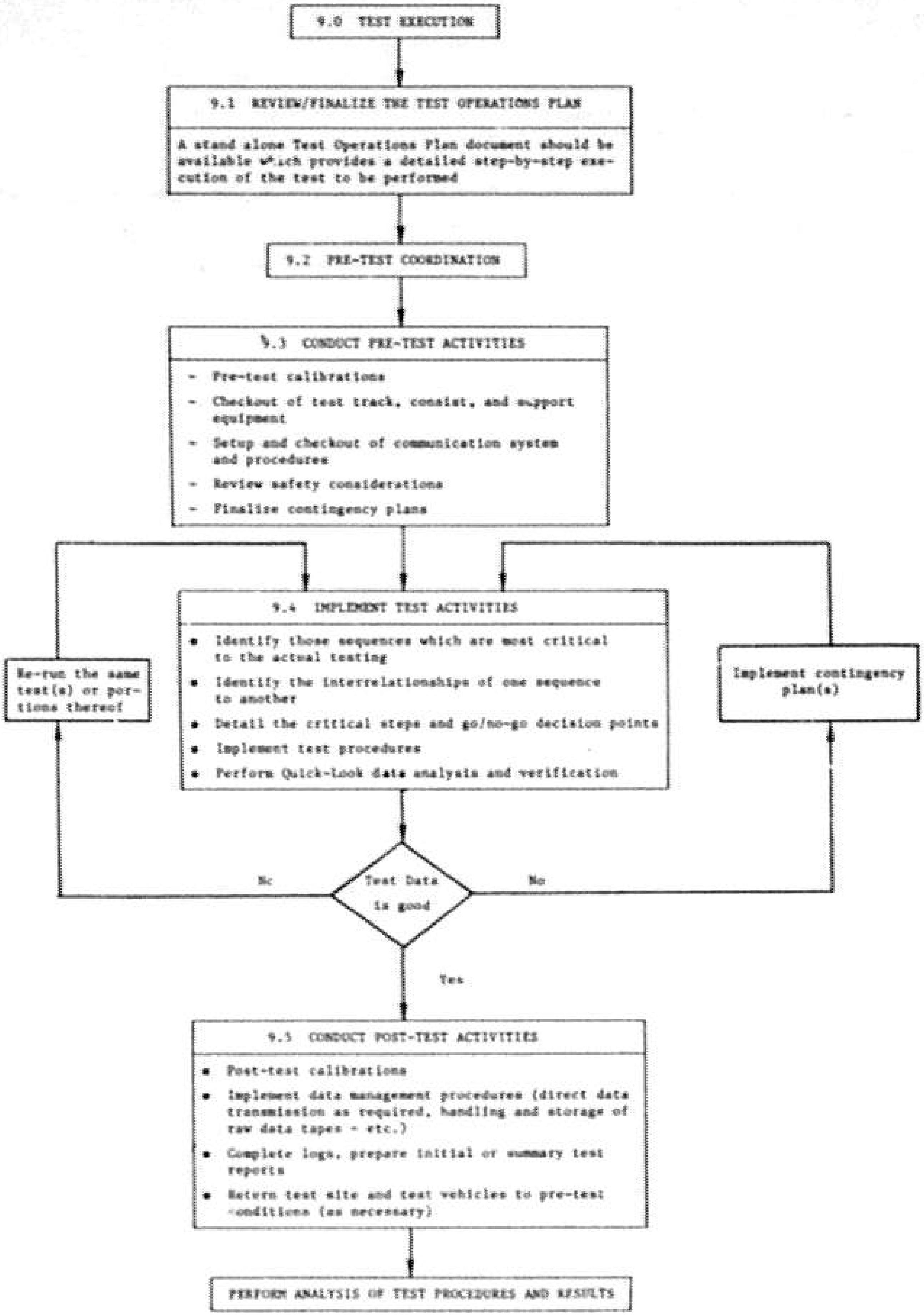

9.0 TEST EXECUTION
9.1 REVIEW/FINALIZE THE TEST OPERATIONS PLAN
A stand alone Test Operations Plan document should be available which provides a detailed step-by-step execution of the test to be performed
9.2 PRE-TEST COORDINATION
9.3 CONDUCT PRE-TEST ACTIVITIES
- Pre-test calibrations
- Checkout of test track, consist, and support equipment
- Setup and checkout of communication system and procedures
- Review safety considerations
- Finalize contingency plans
9.4 IMPLEMENT TEST ACTIVITIES
• Identify those sequences which are most critical to the actual testing
• Identify the interrelationships of one sequence to another
• Detail the critical steps and go/no-go decision points
• Implement test procedures
• Perform Quick-Look data analysis and verification
Re-run the same test(s) or portions thereof
Implement contingency plan(s)
Test Data is good
No
No
Yes
9.5 CONDUCT POST-TEST ACTIVITIES
• Post-test calibrations
• Implement data management procedures (direct data transmission as required, handling and storage of raw data tapes - etc.)
• Complete logs, prepare initial or summary test reports
• Return test site and test vehicles to pre-test conditions (as necessary)
PERFORM ANALYSIS OF TEST PROCEDURES AND RESULTS

FIGURE M-28

Performance Index ______________

Activity ______________

By ______________

Date ______________

TABLE M-24

TEST SAFETY PROCEDURE EFFECTIVENESS REVIEW MATRIX

Accident or Incident	Effect or Loss Suffered	Likelihood and Exposure Evaluation	Noted on Previous Analysis (Y) (N)	Possible Means of Future Avoidance	Remarks

TABLE M-25

PRE-TEST COORDINATION TOPICS

- Review of security procedures
- Establish a hierarchy of authorities in case of an emergency
- Announce the location of emergency fire and safety personnel
- Review the test schedule for the day emphasizing any special conditions such as sanding or vehicle maintenance.
- Note operational requirements such as use of brakes, speed tolerances, etc.
- Coordinate the days visual track inspection requirements
- Announce the radio channels to be used
- Identify the groups to be in the test area.
- Identify group leaders and all expected communications.
- Announce the run numbering sequence to be used by all groups.
- Identify thresholds requiring a report from wayside and onboard instrumentation and from track inspection.

M.2.10 DATA REDUCTION AND ANALYSIS

Data reduction and analysis includes the process of identifying the format of the raw data; converting it to a form easily accessed by a data analysis software package and presenting the results of the analysis in an attractive and readily useable manner.

M.2.10.1 Basic Reduction

For purposes of this discussion, it has been assumed that the raw test data has been previously assembled on a machine readable storage medium. Some of the more common storage mediums used are digital magnetic tapes, analog magnetic tapes and disc files. The data may be the result of a test or it can be the output of an analytic model. The first phase of data reduction involves identifying the type of data storage medium to be used.

M.2.10.1.1 Digital Magnetic Tape

The format of data stored on digital tape must be identified, either by having previous knowledge of how it was recorded or by deciphering the tape once it has been received. A typical format for digital test tapes would include the following records:

1) Header Record

Header records contain information in text form (7 or 8 bit ASCII, BCD RADIX 50 or EBCDIC) concerning basic test parameters such as a description of the test, the number of channels being recorded, a description of each channel, the sample rate, engineering units and so forth.

2) Calibration Records

Calibration records are recorded just prior to the start of a test for the purpose of obtaining the engineering unit conversion factors applicable to the forthcoming test.

3) Data Records

Data records comprise the majority of the tape. The formats of the recorded data vary widely from test to test. Some of the factors which must be considered are:

a) Record length in Bytes;
b) Word length in bits (12 or 16), resolution, sign convention, bit padding;
c) How the data is multiplexed, number of channels, number of samples per record, any odd word length channels or irregularities in the multiplexing scheme.

4) Trailing Records

Trailing records may contain post-test calibration and more comments describing any anomalies which were observed during the test.

M.2.10.1.2 Analog Magnetic Tape

Test data may be recorded on analog tape. If this is the case, the information must be digitized prior to data reduction and analysis. Header information may have to be added to the digital copy of the test data.

Test data gathered onto a disc file may or may not require demultiplexing since random access write is available.

M.2.10.2 Build Data Base

A data base is required for data reduction to minimize access time for the reduction of software which, by the nature of the task, involves large amounts of Input/Output (I/O). This is accomplished by a combination of pointers to disc sectors and by placing the information on a disc in such a way that the sector number of a desired piece of information is a function of the channel number and the time into the test. Besides containing the test data, the data base should contain all the other information necessary to perform analysis and generate the output. Examples of this information include channel descriptions, engineering unit conversion factors and maximum or minimum values.

Building a data base is accomplished by copying and manipulating the raw information while re-ordering it to a random access device. Depending on the type of peripherals, the input of data to be reduced, and memory limitations, the process of building a data base may involve several different algorithms. The format of the data base will also depend heavily on these limitations. It may also be appropriate at this stage of data reduction and analysis to include necessary pointers and perform range checks on the data.

M.2.10.3 Basic Analysis and Data Presentation

The software actually responsible for accessing the data base and performing the analysis should provide a high degree of flexibility as well as being very efficient and easy to use. The software should be written in such a manner as to facilitate future additions and modifications so as to readily accommodate future changes or demands. A flow chart showing the basic data reduction and analysis functions is presented on Figure M-29.

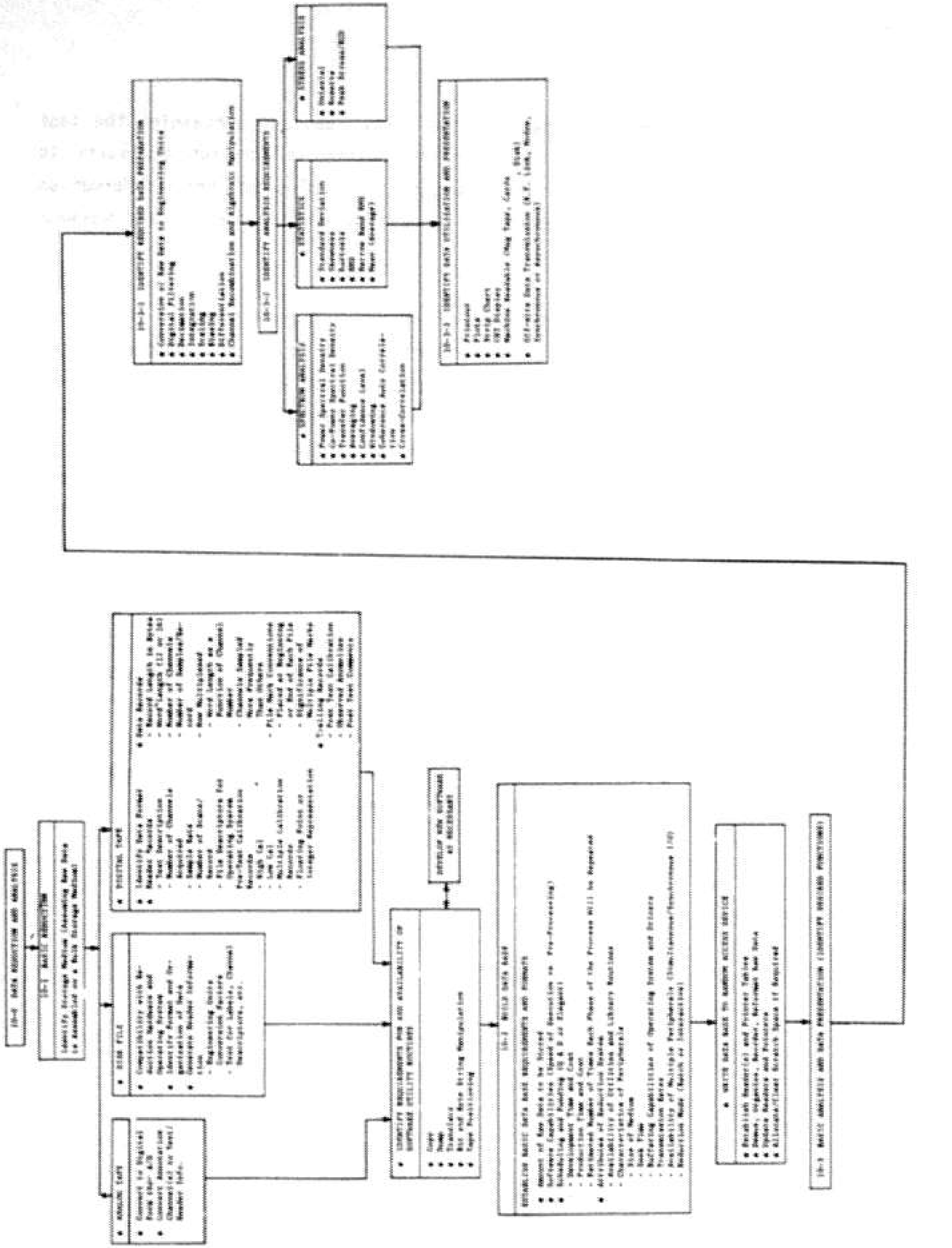


FIGURE M-29

M.3 STANDARD SIGN CONVENTIONS

When planning a field test program, standard sign conventions should be used whenever possible. This will promote continuity of the test results from test to test as well as between different test programs. If standard sign conventions can not be used, it is imperative that the convention be clearly identified and flagged on the test data involved.

Standard sign conventions are presented below for wayside instrumentation and vehicle borne instrumentation.

M.3.1 WAYSIDE SIGN CONVENTIONS

Wayside sign conventions apply to all of the instrumentation associated with the track structure. Typical measurements include displacements, forces and accelerations. In addition, conventions are helpful for identifying direction of travel relative to the track structure as well as the "right" and "left" rails. The suggested sign conventions are presented in Figure M-30.

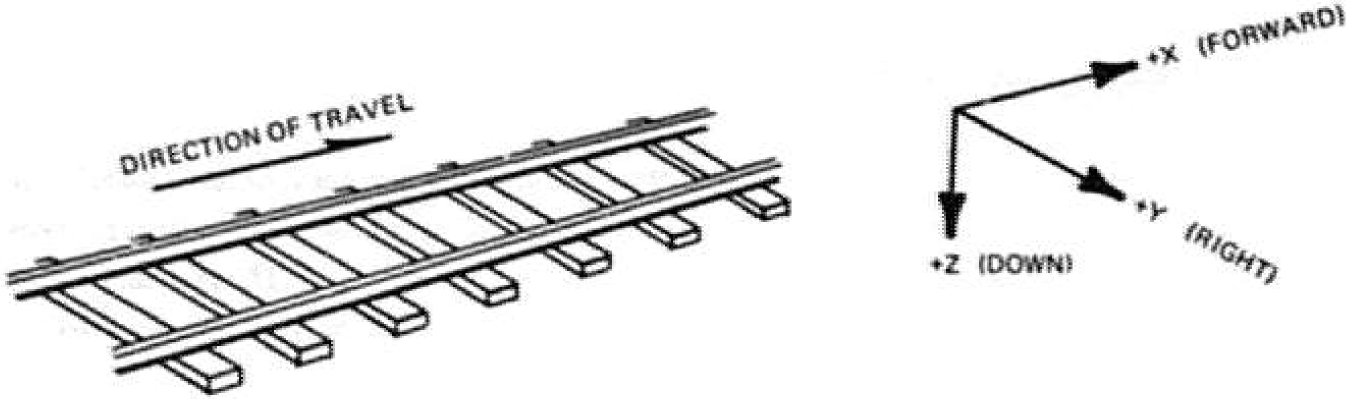
M.3.2 VEHICLE BORNE SIGN CONVENTIONS

Sign conventions for vehicle borne measurements are presented in Figure M-31.

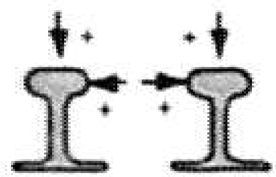
M.3.3 CONSIST CONFIGURATION IDENTIFICATION

A consist configuration should be clearly and uniquely identified such that both vehicle and component locations and orientations can always be traced from test to test. Proper identification should include a side view schematic of each configuration showing vehicle I.D. numbers, vehicle orientation, axle numbers, and direction of travel.

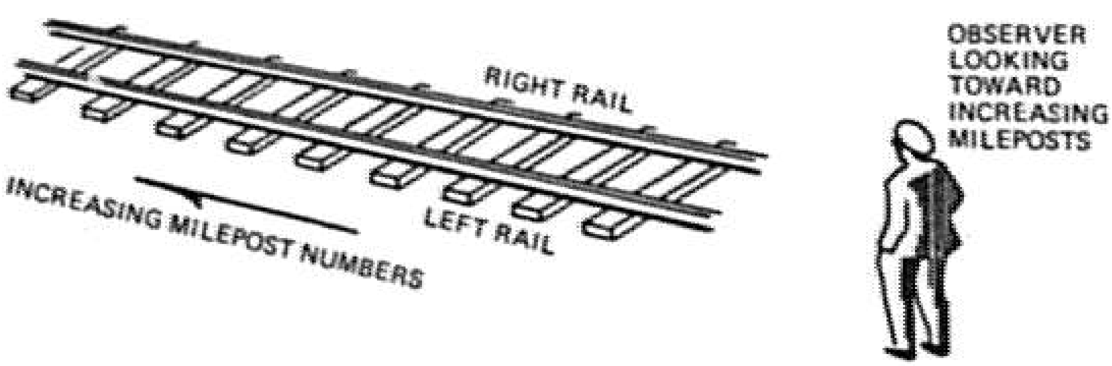
The following guidelines are suggested to standardize consist configuration identification:



STANDARD COORDINATE SYSTEM



RAIL FORCES AND DISPLACEMENT

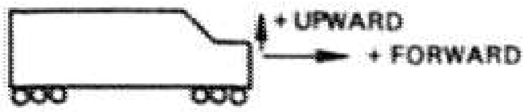


RIGHT AND LEFT RAIL

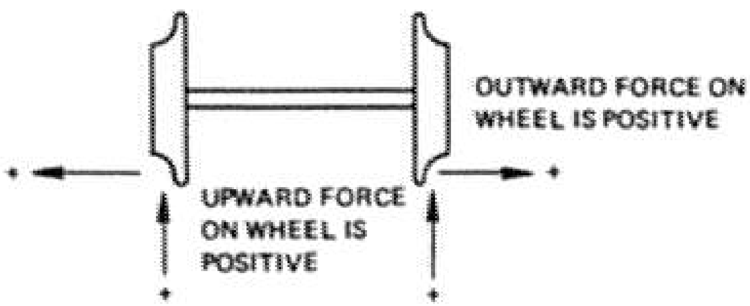
WAYSIDE SIGN CONVENTIONS
FIGURE M-30

GENERAL MEASUREMENT CONVENTIONS

ACCELERATIONS, DISPLACEMENTS, FORCES

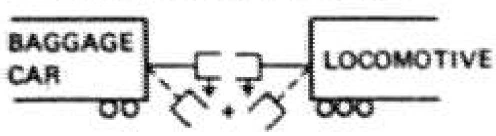


WHEEL FORCES



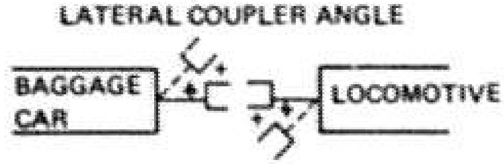
COUPLER FORCES

VERTICAL COUPLER ANGLE



DOWNWARD MOTIONS ARE POSITIVE

LATERAL COUPLER ANGLE



COUNTERCLOCKWISE ROTATIONS ARE POSITIVE

MISCELLANEOUS

- BUFF FORCE IS POSITIVE
- SPRING EXTENSION IS POSITIVE

VEHICLE BORNE SIGN CONVENTIONS

FIGURE M-31

1. For <u>each</u> test run, axle count will be sequential starting from the head-end of the consist with respect to the direction of travel for the respective test run.

2. Axles/wheelsets will be <u>uniquely</u> identified based upon their <u>initial</u> location in the consist. Car axles/wheelsets will be identified in accordance with the AAR designation specified by AAR interchange rule number 83 (Field Manual of the AAR Interchange Rules). The following excerpt defines this rule:

<u>RULE 83 (excerpt)</u>

15. For designation of locations on car at which damage occurred or repairs made, the following will govern:

    a. Cars equipped with four wheel trucks.

        (1) The end of car upon which the brake shaft is located shall be known as B end and the opposite end shall be known as A end. If the car has two brake shafts, the owner shall have the respective ends, A and B, stenciled on car, on both sides, near each end.

        (2) Facing the B end of car in their order on the right side, wheels, journal boxes, brake beams and other truck parts shall be known as R1, R2, R3 and R4. The main structure of car is divided into four sections known as BR, BL, AR and AL. See Figure M-32.

    b. Cars equipped with six or eight wheel trucks.

        (1) The same principle applies as given above for four wheel trucks.

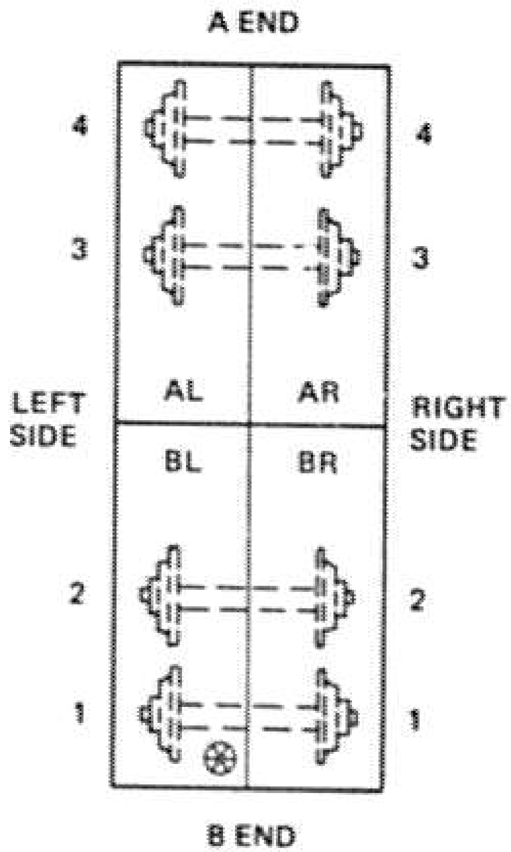
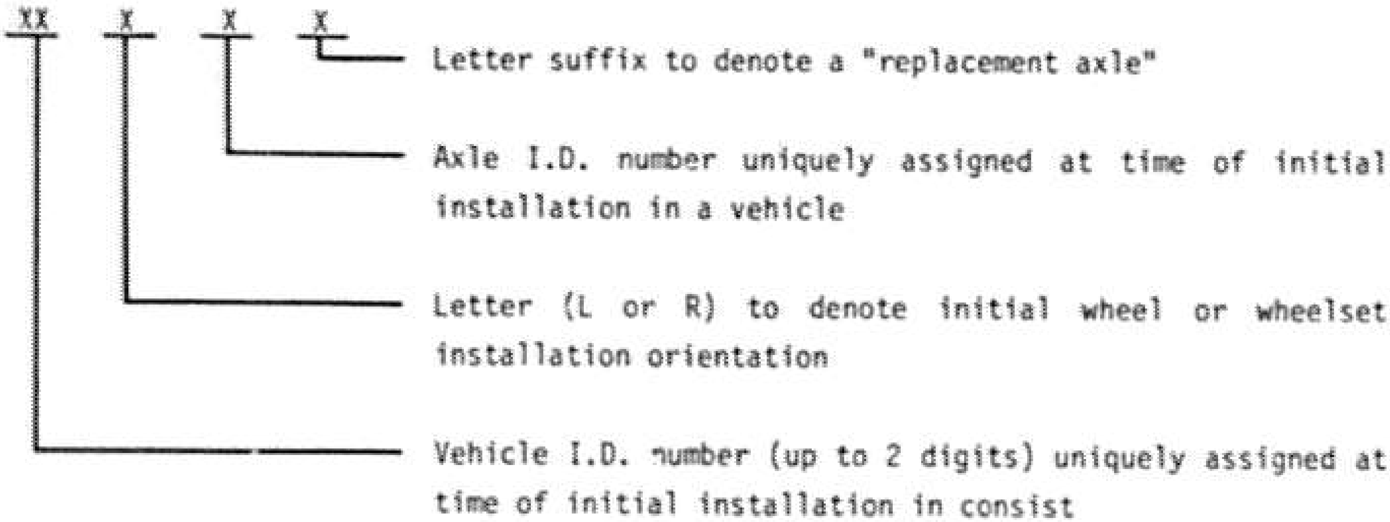
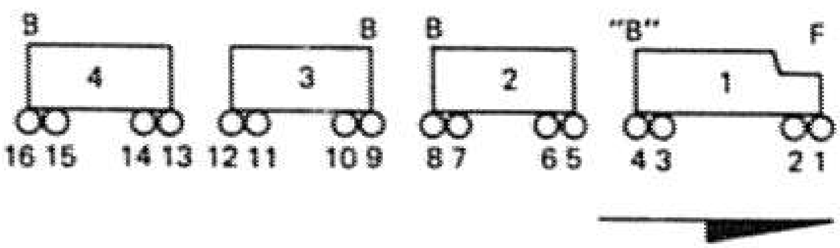


FIGURE M-32. CAR WHEELSET IDENTIFICATION

Using the above AAR designation, wheels will be uniquely defined using an identifier word of up to 5 characters as follows:



As an example, consider an initial consist configuration of a test series as shown below:

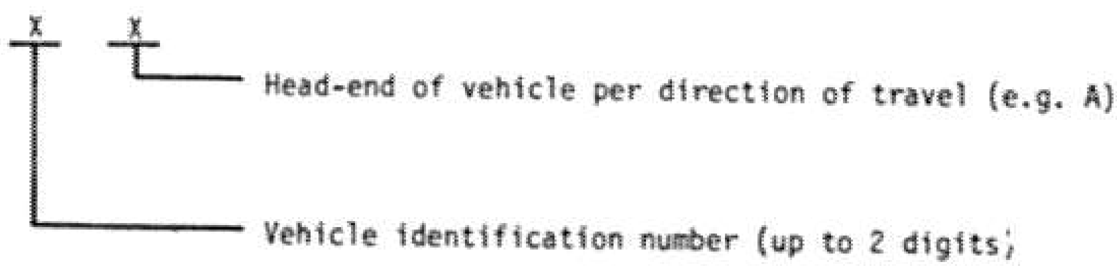


The axle identification associated with axle count number 7 would be 2-2 (i.e. vehicle 2, axle number 2). The wheel identification associated with the above side view would be 2R2 (i.e. the right side of vehicle #2, axle #2). If the same car happened to be number 15 in the consist, the equivalent car wheel identification would be 15R2. Now assume that the number 2 wheelset for car 2 is replaced during the next test run. The corresponding wheel identification associated with axle count #7 for test 2 would be denoted by the following identifier 2R2A (i.e. the suffix A denotes a replacement wheelset).

If a wheelset from one vehicle is changed out and swapped with another vehicle, each wheelset will retain its original identification as established by its initial installation orientation and location in the test consist. Using the above figure as an example, assume that wheelset number 3 of vehicle 3 (axle count #11) and wheelset number 1 of vehicle 4 (axle count #16) are swapped. Furthermore, assume that the wheelset from vehicle 3 is directly transposed to vehicle 4 but that the wheelset from vehicle 4 is rotated 180° before installation in vehicle 3. The wheel identifications for the next test (per the above figure) would then be 4L1 for axle count 11 and 3L3 for axle count 16.

Axles/wheelsets for locomotives will be identified using a nomenclature similar to that used for cars. In the case of locomotives, the "B" end will equate to the long end of the cab or the back of the locomotive as specified by manufacturer in conformance with FRA regulations. The opposite end or short cab end will be designated the "F" end. Similar to freight cars with two brake shafts, locomotives with cabs on both ends or in the middle shall be appropriately marked F or B by the owner. The right and left sides will be established facing the "B" end of the locomotive. However it should be noted that axles will be numbered in reverse order from the "B" end (or conversely in sequential order from the "F" end). This identification scheme is illustrated in Figure M-33.

The following sample test log sheets illustrate the suggested consist configuration identification scheme. As noted on the log sheet, there is a column labeled "VEHICLE I.D.". This column relates axle count to a current vehicle number and orientation i.e.



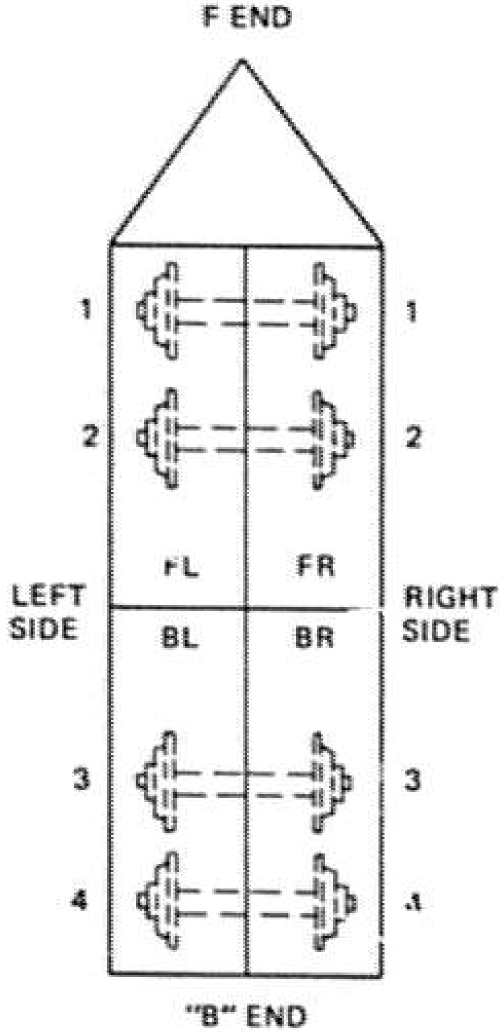


FIGURE M-33. LOCOMOTIVE WHEELSET IDENTIFICATION

M.4 TEST HAZARD ANALYSIS DEFINITIONS

The following definitions are provided as an aid for preparing Tables [illegible], M-23 and M-24. These definitions should also assist in determining safety aspects of the test design, test operations and post review of the procedures under which the overall testing objectives were accomplished.

M.4.1 Hazard Categories

Category I - Negligible - Will not result in personal injury or system damage.

Category II - Marginal - Can be counteracted or controlled without injury to personnel or major system damage.

Category III - Critical - Will cause personnel injury or major system damage, or will require immediate corrective action for personnel or system survival.

Category IV - Catastrophic - Will cause severe injury or fatality to personnel or major system loss.

M.4.2 Action Priority Ranking

Routine - Can be adequately handled through routine channels for corrective action.

Special - Requires special follow-on action because of unique aspects which might prove to be a problem.

Critical - Requires special management attention due to extent of test program impact.

Urgent - Requires special management attention due to test program impact and time constraint.

M.4.3 Likelihood of Occurrence

Frequent - May be expected continuously.

Reasonably Probable - Will occur frequently during test.

Occasional - Will occur several times during test.

Remote - Unlikely but possible.

Extremely Improbable - So unlikely, can assume will not be experienced.

Impossible - Physically impossible to occur.

M.4.4 Hazard Duration Period

The period of time through which the hazard has effect on the test program. Estimates for establishing a hazard duration period may be based upon known data, or methods to arrive at quantitative data, concerning the likelihood of occurrence of a hazard. These may include probabilities, failure experience, reliability estimates, accident experience, or other numeric data describing or aiding in understanding the hazard or key contributors to the hazard.

M.4.5 Exposure

An estimate of factors leading to understanding the effect of a hazard such as: number of persons in the hazard area, frequency of interface with the hazard during the test, length of time of effect, type or critical nature of the potential loss.

OVERALL GENERIC FLOW DIAGRAM FOR THE PREPARATION AND CONDUCT OF FIELD TEST PROGRAMS

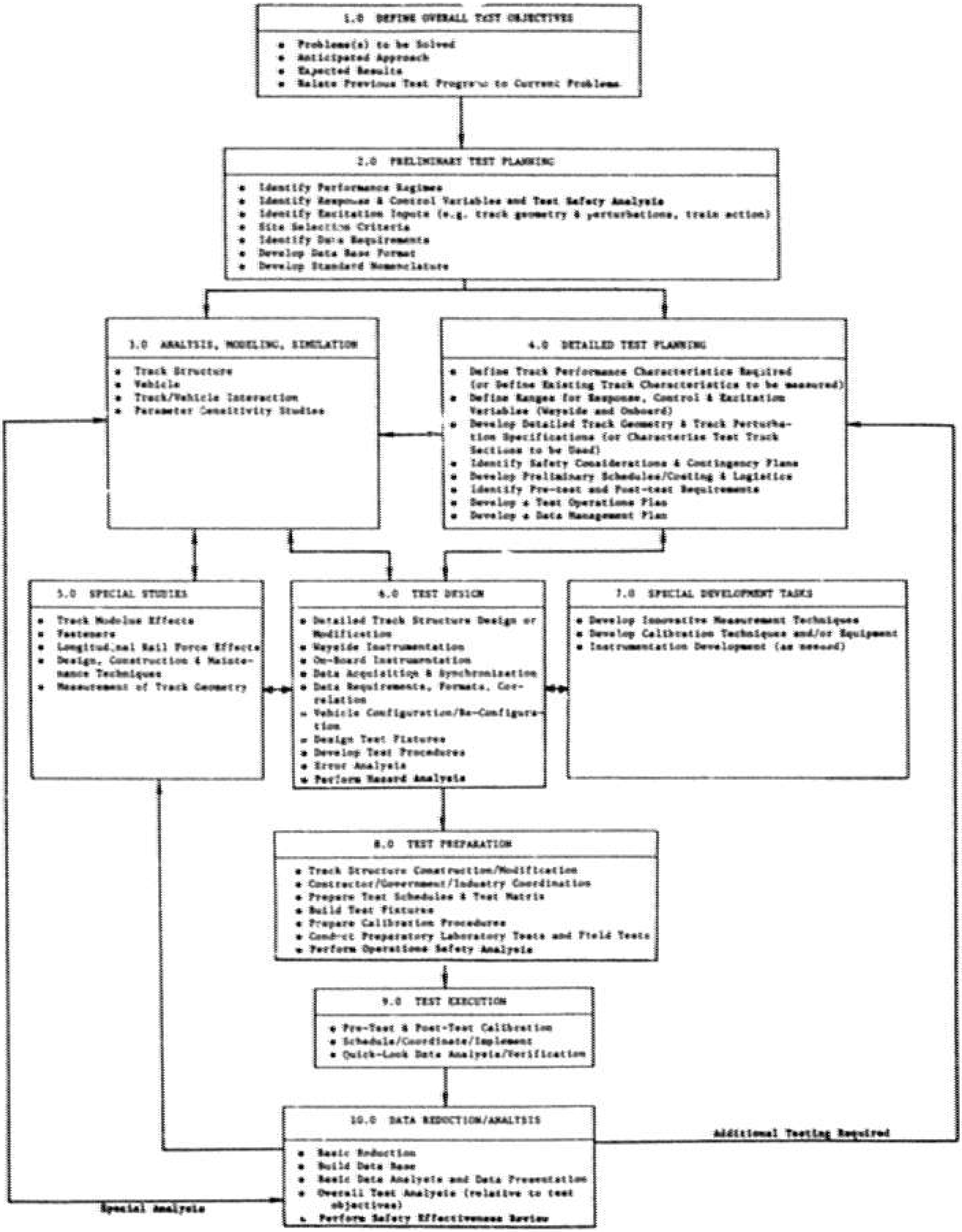


FIGURE M-1 (Spare)

REFERENCES

1. Truck Design Optimization Project Phase II, Analytical Tool Assessment Report, Report No. FRA/ORD-79/36, August 1979.

2. Mathematical Models For Track Structures, AAR Report No. R-262, April 1977.

3. V/T INTERACTION TEST, Test Plan, Prepared by Arthur D. Little, Inc., May 15, 1981.

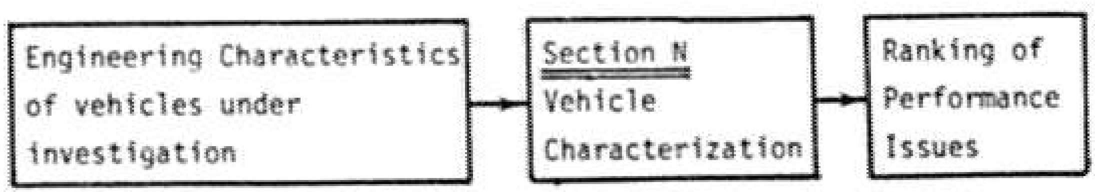
4. An Evaluation of Computer Programs for the Analysis, Prediction, and Simulation of Rail Vehicle Dynamics, TSC Task memorandum RR-515, Rail System Dynamics Program, August 1974.

SECTION N
VEHICLE CHARACTERIZATION

N.1 Introduction

Once a vehicle problem has been determined and the assessment objectives have been set, as described in Part I, Section 2 of this report, an Assessment Plan should be developed using the procedures outlined in Section A (Resources Available for Literature Search), Section B (Accident History Investigation), Section C (Computer Modeling), and this section, Section N (Vehicle Characterization). Section N should be accessed first to provide the initial selection of significant Performance Issues to guide subsequent research. The information in this section is called for by the Assessment Procedures shown in Figures 2-2, 2-3, and 2-4.

The primary objective of this section is to identify the sensitivity of each Performance Issue to specific, relevant vehicle characteristics. Section N requires, as input, engineering characteristics of the vehicle under investigation and provides, as output, a ranking of the ten performance issues. This is shown schematically below:



No inputs from other sections are required although findings from other sections may clarify some of the engineering characteristics of the vehicle being investigated and, therefore, suggest a supplementary use of Section N.

N.2 Nomenclature

The text, tables, and figures in this section include references to the design and dynamic behavior of freight cars, passenger cars, and locomotives. The definitions of all terms used are consistent with the rest of this report. In most cases, figures are included to illustrate the components and dimensions referenced.

N.3 Technical Discussion

A vehicle's proclivity toward each of the ten Performance Issues (outlined in Subsection 2.4) can be estimated parametrically from the conditions of certain specific characteristics of that vehicle. These characteristics are engineering descriptions of a vehicle which relate to its dynamic response to track geometry inputs or inputs from adjoining vehicles. For instance, a vehicle characteristic of truck center spacing is particularly relevant to that vehicle's car body roll response to staggered 39 ft. rail joints.

The purpose of this section is as follows:

- to isolate, define, and quantify principal vehicle characteristics which affect each Performance Issue;
- to present these characteristics in such a format that any rail vehicle under investigation can be quantified in these terms,
- to show the relative importance of each characteristic to each Performance Issue; and
- to rank the Performance Issues showing those which would most likely be of interest for further investigation.

In formulating this approach, a great deal of approximation has been necessary in developing the quantitative ranges for the conditions of each characteristic and in assigning the weighting values comparing the effects of the characteristics. This approach will nonetheless be useful in assisting in the identification of relevant dynamic Performance Issues for a vehicle or vehicle design being investigated.

The vehicle characteristics are listed in Table N-1. These are the characteristics which must be quantified or estimated using the definitions and sample cases provided in Appendix N-A.

TABLE N-1: VEHICLE CHARACTERISTICS WHICH AFFECT VEHICLE DYNAMIC PERFORMANCE

Wheel

- Wheel Profile

Truck

- Total Shear Stiffness
- Total Axle Yaw Bending Stiffness
- Wheel Base
- Static Yaw Friction
- Number of Axles
- Yaw Moment of Inertia
- Wheelset Weight
- Net Braking Ratio

Coupler

- Draft Gear Longitudinal Energy Absorption
- Draft Gear Compressive Energy

Car Body

- Truck Center Spacing
- Bounce Natural Frequency
- Pitch Natural Frequency
- Roll Natural Frequency
- Yaw Natural Frequency
- Sway Natural Frequency
- Bounce Damping Ratio
- Pitch Damping Ratio
- Roll Damping Ratio
- Yaw Damping Ratio
- Sway Damping Ratio
- Torsional Stiffness
- Overall Length
- Center of Gravity Height

The vehicle characteristics can apply to any rail vehicle in any configuration, such as locomotives, passenger cars, or freight cars with weight variations due to lading, passengers, or fuel/water. The particular vehicle condition chosen may be based upon accident history investigations or mathematical analysis or, if no guidelines are available from other sources, an evaluation of each Performance issue should be made for the extremes of all possible operational configurations.

N.3.1 Details of Vehicle Characteristics

N.3.1.1 Wheel Profile

The geometry of the wheel/rail contacting surfaces is of particular importance to Performance Issues involving curving and hunting. Generally, two segments of a wheel profile are defined, the tread conicity and flange angle. It seems that the tread angle is most significant to the initiation of hunting or curving problems and that the flange angle affects the severity of the resultant wheel/rail forces. The evaluation of the wheel profile is relevant only in connection with common rail profiles. Special cases of rail vehicles regularly running on rail profiles not common to U.S. interchange service must be considered analytically. For use of this section only the tread angle is required.

The three conditions of conicity are; less than 2%, from 2 to 10%, and greater than 10%. The middle range includes the predominant AAR 1-in-20 (5%) and 1-in-40 (2.5%) new freight and passenger wheel profiles, as well as most moderately worn wheels. Higher conicity wheels are often used on the new radial or self-steering trucks.

N.3.1.2 Total Truck Shear Stiffness

Truck shear stiffness is a measure of a truck's resistance to the parallel displacement of its wheelsets. In general, increasing the shear stiffness of a truck will improve its hunting performance. This is especially significant for conventional (non-radial) truck designs. Radial truck designs are likely to be relatively rigid in shear due to structural elements present, such as cross-bracing. Curving performance may be reduced slightly by increases in shear stiffness.

Truck dynamic curving and hunting behavior vary inversely in many truck designs and are highly dependent upon two characteristics, shear stiffness and axle yaw bending stiffness (described in Section N.3.1.3). Substantial analytical modeling efforts have been devoted to this area. Of particular relevance is the work performed at the Vehicle Dynamics Laboratory at the Massachusetts Institute of Technology [Ref. 1 and 2]. An approximate formula, developed by Wickens, is qualitatively useful to show the influence of these parameters on the critical hunting speed, V_{cr}:

$$V_{cr} = \frac{C}{m\lambda a}\left[K_{BT} + (a^2+b^2)K_{ST} - ((K_{BT}+(a^2+b^2)K_{ST})^2 - 4b^2K_{ST}K_{BT})^{\frac{1}{2}}\right]^{\frac{1}{2}}$$

where C is a constant

m is the effective hunting mass, which is, in general, the mass of the wheelsets

a is the track semi-gauge

b is one-half of the wheel base

λ is an effective wheel/rail contact conicity

K_{BT} is the truck axle yaw bending stiffness

K_{ST} is the truck shear stiffness

Using typical values, shear stiffnesses were calculated for several sample cases, as noted in the appendix to this Section, Appendix N-A. Since dynamic truck performance is not solely a function of shear stiffness, but includes the effects of the overall truck design, major groups of designs are defined and ranges for shear stiffness established within each. These groups are steerable and non-steerable passenger trucks and freight trucks. The typical values of trucks in each group have been set with "conditions" of shear stiffness (low, medium, or high) as befits the design, even though the absolute value ranges are not the same for each group.

N.3.1.3 Total Truck Axle Yaw Bending Stiffness

Truck axle yaw bending stiffness is a measure of the truck's resistance to relative yaw between two wheelsets. This is shown schematically in Appendix N-A. Bending stiffness is particularly relevant to curving performance. Low bending stiffness allows the wheelsets of a truck to take positions radial to a curve, thereby reducing the wheelset-to-rail angle of attack. Steerable, or radial, truck designs allow low bending stiffness through the structural interconnections of the wheelsets, such as cross-bracing or special shear pads. Lower bending stiffness allows sharper curving before lateral forces, due to the angle of attack, become a problem. Conversely, low bending stiffness can increase the tendency for wheelset hunting.

As with shear stiffness, the absolute value of bending stiffness is useful only within the prescribed design groups of steerable and non-steerable passenger and freight trucks.

N.3.1.4 Wheel Base

Wheel base, the distance between the centers of the outside axles of a truck, can have a substantial effect on curving performance, especially on tight curves. Long wheel bases increase the lateral forces required to move through a curve or spiral. In operation on tangent track, a long wheel base can reduce the probability of truck hunting, as shown by Parameter b in the equation for critical hunting speed in Section N.3.1.2.

N.3.1.5 Truck Yaw Friction

Truck yaw friction, or break-away torque, is defined as the peak torque required to initiate rotation of the truck relative to the car body. A high level of yaw friction can increase the probability of problems with Spiral Negotiation and Dynamic Curving. However, the effects of high yaw friction will decrease the probability of truck hunting. Most trucks will fall into the medium or low categories, as defined in Appendix N-A.

N.3.1.6 Number of Axles per Truck

Although the number of axles per truck will usually be directly correlated with the wheel base, the addition of a third or fourth axle to a truck greatly increases the geometric constraints imposed during curve or spiral negotiation.

Conversely, a truck with three or more axles will be less prone to truck hunting than one-or-two axle trucks, all other factors being constant.

N.3.1.7 Yaw Moment of Inertia

The yaw moment of inertia of a truck is measured about a vertical axis through its center plate. The quantity of this parameter is determined by the weight of the truck and by the weight distribution about the center of yaw rotation. A high yaw moment of inertia will increase the dynamic wheel/rail forces during dynamic curving or spiral negotiation and will slightly reduce the tendency toward truck hunting.

N.3.1.8 Wheelset Weight (Effective Lateral Wheelset Mass)

The inertial mass or weight of an individual wheelset is relevant to the lateral wheel/rail forces generated during the negotiation of relatively short alignment perturbations. In many truck designs, there is sufficient lateral clearance between the axle and other components, such as side frames and journal boxes, to allow rapid accelerations of the wheelset without immediate coupling to the larger truck or car body masses. Traction motors may often be excluded from the effective lateral wheelset mass. In other cases, tight lateral clearances, such as those in tapered roller bearings, make the effective lateral dynamic wheelset mass substantially greater than that of the wheelset alone. Most freight and passenger trucks will fall into the "light" category, as shown in Appendix N-A. A low wheelset effective mass is generally beneficial for all Performance Issues.

N.3.1.9 Net Braking Ratio

With respect to the Performance Issues considered in this report, the interest in braking is only in determining circumstances in which a vehicle under investigation has a braking rate substantially different from the rest of a typical consist. Substantially different braking rates in a consist may initiate excessive buff or draft forces during braking.

For use in U.S. interchange service, specific AAR rules must be met regarding braking ratios. These are summarized in Appendix N-A with additional terms for non-tread brakes, novel brake shoes, and weight equalization braking systems.

Vehicles used in a unit train consist, in which all net braking ratios are equal, will not be prone to Performance Issues of interest here due to their braking system's equality of braking rates.

N.3.1.10 Coupler/Draft Gear Longitudinal Energy Absorption

The spring-mass system of a train composed of cars (mass) and couplers with draft gear (spring) can undergo longitudinal oscillations under certain conditions of braking and/or gravitational input. The Performance Issue, "Longitudinal Train Action," investigates this situation. The primary deterrent to oscillations is the damping afforded by the consist, including that of the draft gear. Some of the energy absorbed during a cycle of compression and extension is converted into heat and not returned to the oscillating system. This vehicle characteristic is measured by laboratory or field tests in which the forces generated during one quasi-static cycle of the draft gear are measured. The energy returned during extension is subtracted from the energy required for compression. This difference is the energy absorbed due to damping.

N.3.1.11 Coupler/Draft Gear Compressive Energy

During longitudinal impact, such as during coupling in classification yards, the amount of energy which can be stored by the draft gear during compression is dependent on the longitudinal stiffness of the coupler/draft gear and the amount of deflection allowed. If the coupler/draft gear, even when deflected to its limit, cannot absorb the kinetic energy of the impacting car, a high longitudinal force can result, which may cause the car to pitch significantly and be susceptible to damage. For the purpose of evaluating the coupler/draft gear performance in impact, we can compare the total compressive energy which can be absorbed by the draft gear with the energy required to decelerate a 100 ton vehicle from 3 mph to standstill. During laboratory or field testing, the loads may be applied slowly, if necessary, to establish a conservative estimate.

N.3.1.12 <u>Truck Center Spacing</u>

Track geometry inputs to the car body are filtered, spatially, by the truck center spacing. Specifically, track geometry alignment and profile perturbations which have wavelengths close to the truck center spacing (or one-half multiples of it) will have particularly strong effects on car body dynamics compared to other wavelength inputs. Typical revenue track geometry contains a spectrum of wavelengths and amplitudes. However, the most severe inputs for car body response are those with regular repeated cycles. On U.S. railroads, the common use of 39 foot staggered jointed rail segments make vehicles with truck center spacings of about 39 feet and 58 feet (1½ rail lengths) particularly sensitive to track geometry inputs.

N.3.1.13 <u>Car Body Resonant Frequencies</u>

Railroad vehicles are often modeled as simple "spring-mass" systems, with the mass being the car body mass and the spring being the lateral or vertical suspension system between the car body and the rail. Such a spring-mass system will have displacement-amplitude gains dependent on the frequency of the input. The greatest gain comes at the resonant frequency. The frequency of the input is determined by the wavelength of the repeated track geometry perturbation and the vehicle speed. Although there is a continuum of perturbation wavelengths in typical trackage, the most common are due to the use of 39 ft. rail. Vehicles with resonant frequencies in the range encountered during normal operating speeds over typical trackage will be especially susceptible to Performance Issues of twist and roll, pitch and bounce, and yaw and sway. Appendix N-A contains the cutoff frequencies for the ranges of interest as well as suggestions for measuring the resonant frequency of a car body, if the ranges are not known.

N.3.1.14 Car Body Damping Ratio

Car body damping reduces the displacement amplitude response of a car body due to any frequency input. Low damping can allow large car body displacements to occur, especially due to repeated inputs. Appendix N-A, gives the conditions of the damping ratio and suggested techniques for its measurement, if the condition is not already known.

N.3.1.15 Car Body Torsional Stiffness

A torsionally stiff car body can have problems with wheel lift when negotiating a sharp spiral or any other track geometry with relatively large differences in crosslevel. Torsional stiffness can be measured as the amount of torque on the car body necessary to produce a certain amount of twist.

N.3.1.16 Overall Length

The overall length of a vehicle affects spiral negotiation, due to the continuously increasing warp over increasing lengths of spiral, and steady state buff and draft, due to the lateral forces converted from axial forces on a curve.

N.3.1.17 Center of Gravity Height

The height of a vehicle's center of gravity has a significant effect on its response to roll inputs. Dynamic roll inputs can be achieved by crosslevel variations on tangent or curved track and are related to Performance Issues of twist and roll, dynamic curving, and spiral negotiation. Static roll inputs due to operation on curved track at other than balance speed affects the Steady State Curving Performance Issue.

N.3.2 Parameter Estimation Techniques for Vehicle Characterization

Appendix N-A "Potential Techniques for Vehicle Characterization" contains summary descriptions of the vehicle characteristics which are considered most relevant to dynamic performance. The appendix provides typical ranges and examples for each parameter as well as simple techniques for their measurement. However, for the most accurate assessment of a vehicles' characteristics under dynamic conditions, parameter estimation is recommended. Parameter estimation involves the empirical determination of a systems' characteristics by monitoring its input and output.

N.3.2.1 Description

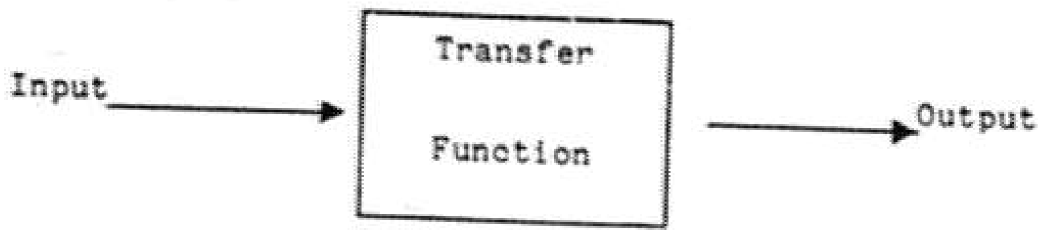
This section describes the application of parameter estimation techniques to the evaluation of a rail vehicle. Although the example presented involves estimating the parameters of the secondary lateral suspension of a vehicle, the technique is general and can be used for other applications.

An accurate knowledge of a rail vehicle's physical parameters is needed for simulation and modeling of vehicle dynamics. Parameters such as spring rates and viscous dynamic coefficients must be known precisely in order to produce reliable models.

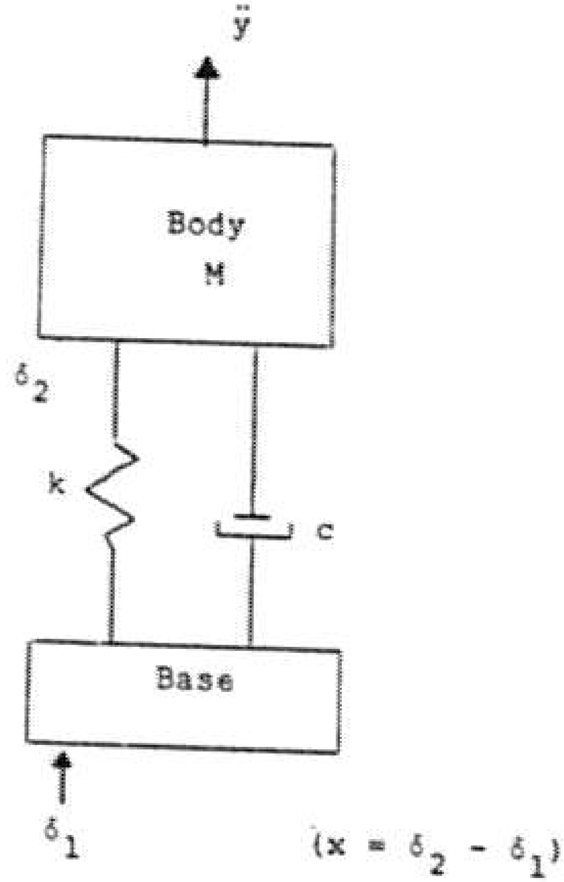
A field measurement technique is described here for estimating vehicle suspension parameters, i.e., spring rate and damping coefficient. The concept of parameter estimation is given in Figure N-1. As opposed to the laboratory methods, this technique provides measurements under dynamic loading conditions. Another advantage of the technique is the extraction of both linear and nonlinear components.

N.3.2.2 Procedure

Table N-2 outlines the procedure for the parameter estimation technique. The first step in the parameter estimation technique involves the collection of input/output data. The number and locations



a) Relationship between input and output



b) Determine parameters c and k of equation:

$$m\ddot{y} + c(\dot{x}) + k(x) = 0$$

FIGURE N-1: PARAMETER ESTIMATION TECHNIQUE

TABLE N-2: SUMMARY PROCEDURE FOR PARAMETER ESTIMATION

1. Measure and record input/output data such as displacements and accelerations.

2. Hypothesize the model explaining the relationship between input/output (Figure N-1).

3. Condition data for analysis. This includes filtering and numerical differentiation.

4. Estimate parameters using least squares method.

5. Analyze and interpret results.

of transducers should be selected carefully to measure the required inputs and outputs. Figure N-2 shows a schematic diagram of instrumentation arrays to characterize the secondary lateral suspension of a locomotive. This includes two accelerometers to measure the lateral acceleration directly above the center plates of each truck and two displacement transducers to measure the relative lateral displacement between the truck bolster and frame.

The next step in the parameter estimation is hypothesizing the model which defines the relationship between input and output. As shown in Reference [1]. The pure yaw response mode can be isolated from sway mode using the model of the form:

$$M\ddot{z} + c(\dot{x}) + k(x) = 0 \tag{2}$$

where

$M = I/2\ell^2$

I = moment of inertia

2ℓ = distance between accelerometers placed symmetrically with respect to the carbody center of gravity

$z = \ddot{y}_1 - \ddot{y}_2$

$x = \delta_1 - \delta_2$

$c(x)$ and $k(x)$ may represent either linear or nonlinear viscous damping and spring forces respectively. Thus, assuming linear function for both elements, the moment balance equation can be written as:

$$M\ddot{z} + c_1\dot{x} + c_3\dot{x}^3 + k_1x + k_3x^3 = 0 \tag{3}$$

The parameter estimation technique now involves the estimation of coefficients c_1, c_3, k_1, and k_3.

Before proceeding with the estimation of the parameters, c_1, c_3, k_1, and k_3, it is necessary to derive the relative velocity, $\dot{x}$, from

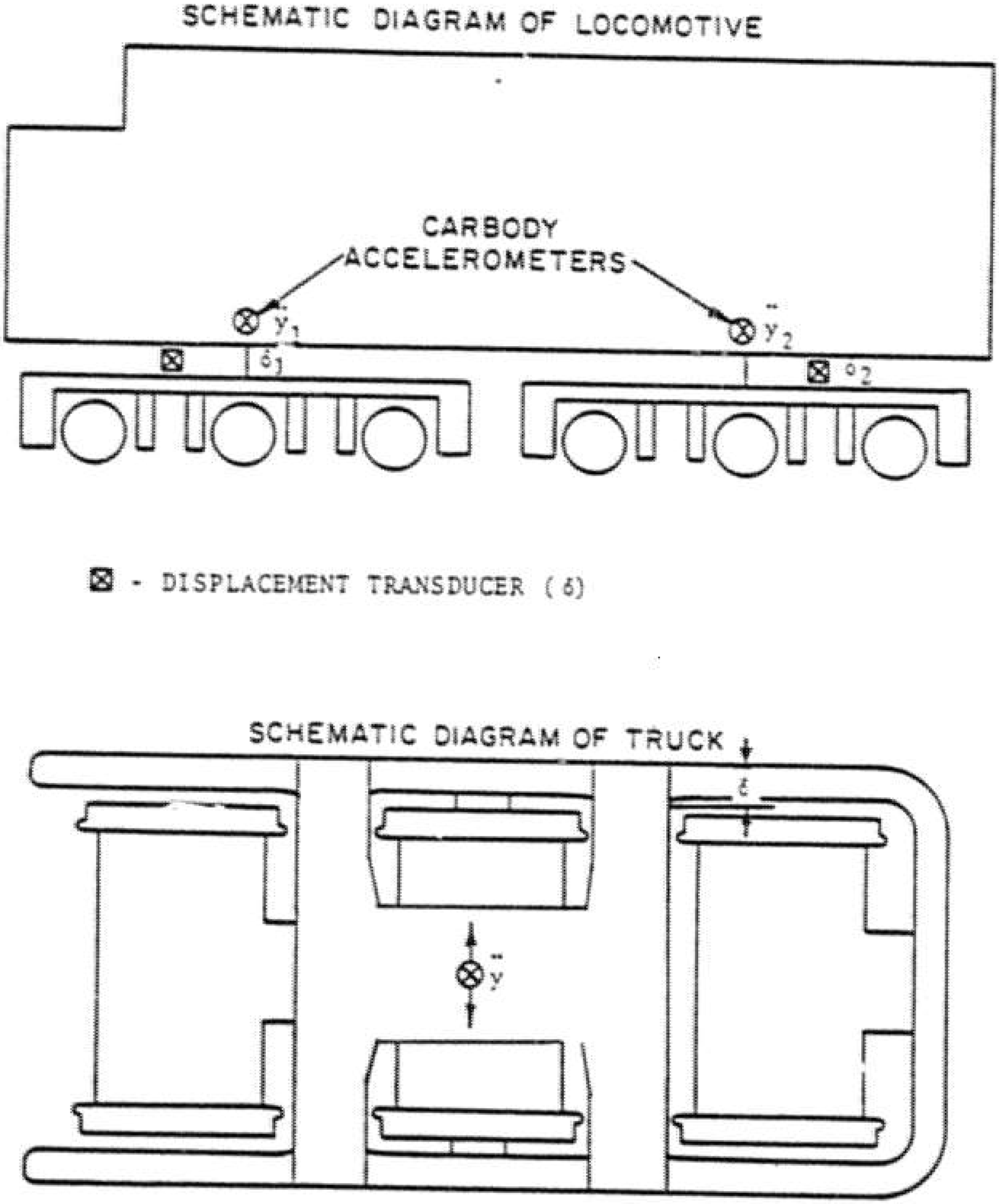


FIGURE N-2: THE INSTRUMENTATION ARRAY

the measurement of relative displacement. Conceptually, this involves taking the first derivative which in this instance is the first finite difference divided by the sample interval. However, care must be exercised in numerical differentiation because of the tendency to introduce errors which appear as noise at the sampling frequency or at the frequency of instrumentation noise.

The rigid body yaw response mode of a typical rail vehicle is below 5Hz, and the high frequency inputs are not of interest and should be filtered out. An FFT filter is recommended for this purpose. This filter has a unity gain in the pass band and zero gain elsewhere. This filter also has no phase shift.

The implementation of an FFT filter is a straight forward application of the use of Fourier Transform pairs. The raw signal is Fourier Transformed. The Fourier Transform is an array of vectors with each vector specifying the magnitude and phase angle of a given frequency. All vectors above the desired frequency are set to zero. The modified array is then inverse transformed into the time domain giving the desired filtered signal.

Once the relative displacement is filtered, the velocity can be computed by taking the first finite difference divided by the sample interval. This signal is again filtered using the same corner frequency used to filter the relative displacement. The next step is selecting a suitable means to fit the four unknown parameters to the data. One of the most convenient methods to accomplish this is the least squares technique. Detail of this technique is given in Reference [12].

One final step is the analysis and interpretation of results. Standard statistical techniques are available to test the adequacy of regression models [12]. The coefficients of determination, R^2 provides an indication of what portion of output variations are explained by the model. T values can be used to test the hypothesis that the individual coefficients are not zero.

N.3.2.3 Limitations/Requirements for Application

Limitations and requirements are summarized in Table N-3. The primary requirements for the technique is the prior knowledge of the candidate system model. A classical second order system has been assumed for the purpose of this discussion. It is further assumed that the rigid body equations are applicable.

Instrumentation errors can be difficult to account for. Therefore, test planning and collection of good quality data can not be over emphasized. Transducers should be located so that the yaw and sway modes can be easily isolated. The values of parameters c and k are sensitive to temperature and environmental conditions and test conditions should thus be clearly defined.

Numerical differentiation introduces errors and is very sensitive to signal noise. Therefore, special attention must be given to filter the data to retain only the frequencies of interest. An FFT filter with a corner frequency of 5 Hz is recommended for this purpose.

Parameters are estimated using the least squares method. Therefore, it is important that the assumptions underlying this method be met. Furthermore, results are valid only with the test range and should not be extrapolated beyond this range.

N.3.2.4 Example

The parameter estimation technique was applied to characterize the High Traction Coefficient (HTC) truck secondary lateral suspension used on an SDP-40F locomotive. Data collected during the Perturbed Track Test conducted in 1978 were used for this purpose. This offered an excellent example of the use of parameter estimation while at the same time delineating the mechanics of its application. The estimated values of spring rate and damping coefficient were compared with laboratory measurements and a good agreement was found between the two.

A schematic of instrumentation array is given in Figure N-2. The test zone was a tangent zone designed with piecew linear alignment

TABLE N-3: SUMMARY OF LIMITATIONS AND REQUIREMENTS FOR PARAMETERS ESTIMATION TECHNIQUE

1. Candidate system model must be developed prior to analysis.

2. Requires careful planning for selection and collection of data.

3. Digital data acquisition and processing is recommended.

4. Data should be filtered to include only specific frequencies of interest.

5. Numerical differentiation can introduce significant noise.

6. Results should not be extrapolated beyond test conditions.

perturbations as shown in Figure N-3. These perturbations were specifically designed to excite the yaw mode of the locomotive.

The instrumented vehicles were run over the test zone at speeds between 40 mph and 70 mph. In all, eleven runs were made at the speeds given in Table N-4.

TABLE N-4: TEST MATRIX

Run Number	1	2	3	4	5	6	7	8	9	10	11
Test Speed (mph)	40	55	70	40	55	43	63	47	60	50	70

The sample rate used to digitize the data was 256 Hz per channel. Thus, a 40 mph run was 6.6 seconds long and the related data stream was 1,700 samples per channel. A 60 mph run would create just less than 1,000 samples per channel.

Data were filtered using an FFT filter with a cut-off frequency of 5 Hz. The velocity was computed by taking the first finite difference divided by the sample interval. Estimation was then sought of the parameter; of Equation (3).

Table N-5 gives the representative results for a 63 mph test. In addition to the values of the suspension characteristics are given the F value, the coefficient of determination R^2 and the standard error s^2 for the estimate.

The F value confirms that the indicated results are not just by chance and that the hypothesized model does explain the observations. The R^2 value of 0.99 indicates that the model accounts for rather a significant portion of variations.

The results indicate that the suspension has a "softening" spring since the k_3 coefficient is negative. This means that the natural frequency of the system would be slightly lower for large displacements than it is for small displacements. This result is typical for

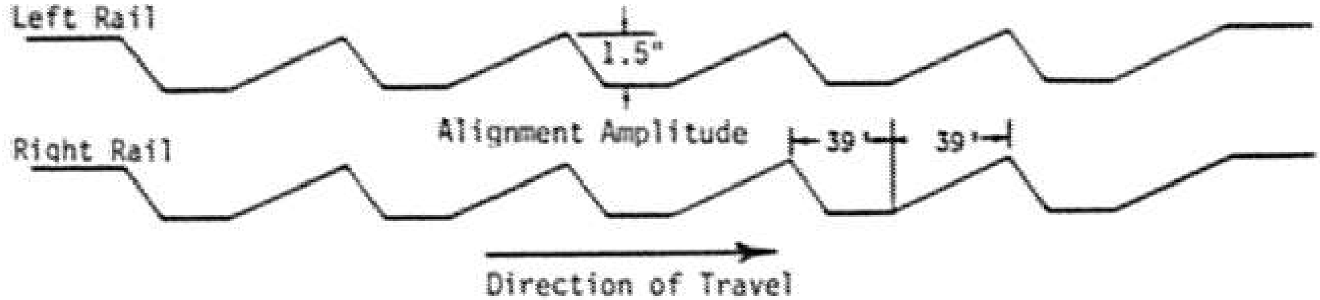


FIGURE N-3: PLAN VIEW OF PTT TEST SECTION 8

k_1 lb/in	k_3 lb/in³	c_1 lb sec/in	c_3 lb sec³/in³	F	R^2	s^2
3.5×10^4	-6.3×10^2	1.0×10^3	-1.1	2.9×10^5	0.9994	0.0001

TABLE N-5: SUSPENSION CHARACTERISTICS

elastomeric shear springs of the type in this locomotive. The damping coefficient is similarly nonlinear. As the suspension velocity increases, the effective damping decreases slightly. This is typical of the force limited type dampers installed on the SDP-40F. The dampers have a pressure relief which limits the maximum damping force to 1,800 pounds.

The above results are extremely difficult, if not impossible to obtain from laboratory or static suspension tests. Only by exciting the system under actual conditions can the effects of vertical loading, large displacements, and high velocities under dynamic conditions be observed. Parameter estimation can then be used to accurately determine vehicle characteristics from the dynamic response data.

N.4 Evaluation of Performance Issues Due to Vehicle Characteristics

Once a vehicle's characteristics are known, at least to a degree which allows the selection of an appropriate range for each characteristic (as defined in Appendix N-A), Table N-6 may be used to evaluate that vehicle's susceptibility to each Performance Issue. The condition of each parameter is marked manually on the table under the heading "Test Vehicle Condition." Then, for the column under each Performance Issue, accumulate the quantities for each condition of a vehicle characteristic which is marked. Write the total of each column in the space provided at the bottom of the table. This number can be used for relative ranking of each Performance Issue. The weighting quantities have been adjusted so that a ranking of 100 or more is an indication that the Performance Issue should definitely be considered for investigation. A minimum value of zero indicates that it is very unlikely that the Performance Issue would be worth investigating. A final display of the use of this table is to list the Performance Issues, in descending order of their rankings, in the space provided on the lower left side of the table. The Performance Issues with a ranking of about 70 or more should be considered for further investigation. If the condition of a vehicle characteristic is not known confidently, the user can, perhaps, estimate two possible

TABLE N-6: PERFORMANCE ISSUE EVALUATION THROUGH VEHICLE CHARACTERIZATION

VEHICLE CHARACTERISTICS

TEST VEHICLE ________

PARAMETER[1]	RANGE	TEST VEHICLE CONDITION (✓)	Hunting	Twist and Roll	Pitch and Bounce	Yaw and Sway	Steady State Curving	Spiral Negotiation	Dynamic Curving	Steady State Buff and Draft	Longitudinal Train Action	Longitudinal Impact
WHEEL												
Profile, Conicity												
Low	< 2%	☐	0				20	10	10			
Medium	2 - 10%	☐	20				10	5	5			
High	> 10%	☐	30				0	0	0			
TRUCK												
Total Shear Stiffness												
Low	(See Note 2)	☐	20				20	8	5			
Medium		☐	10				10	5	5			
High		☐	0				0	0	0			
Tot. Axle Yaw Bending Stiff.												
Low	(See Note 3)	☐	20				0	0	0			
Medium		☐	10				10	5	5			
High		☐	5				20	10	10			
Wheel Base												
Short	< 7.0 ft	☐	5				0	0	0			
Long	> 7.0 ft	☐	0				10	10	10			
Yaw Friction												
Low	< 1.5 inlb/lb	☐	10					0	0			
Medium	1.5 - 3.0 inlb/lb	☐	5					5	5			
High	> 3.0 inlb/lb	☐	0					10	10			
Number of Axles/Truck												
Low	1 or 2	☐	5				0	0	0			
High	3 or more	☐	0				10	15	15			
Yaw Moment of Inertia												
Low	< 30,000 lbsec²in	☐	5					0	0			
Medium	30,000 - 45,000 lbsec²in	☐	5					1	5			
High	> 45,000 lbsec²in	☐	0					2	5			
Wheelset Weight												
Light	< 5,000 lb	☐	0					0	0			
Heavy	> 5,000 lb	☐	5					2	5			
Net Braking Ratio												
Standard/Unit Train	(See Note 4)	☐								10	0	
High/Low (Interchange)		☐								30	20	
COUPLER/DRAFT GEAR												
Long. Compressive Energy												
Low	< 61,000 ft. pounds	☐										20
High	> 61,000 ft. pounds	☐										10
Long. Energy Absorption												
Low	< 40,000 ft. pounds	☐									10	
High	> 40,000 ft. pounds	☐									30	
		SUMMARY BY ISSUE (ADD QUANTITIES ✓)										
		SUBTOTAL (Page 1)										

TABLE N-6: PERFORMANCE ISSUE EVALUATION THROUGH VEHICLE CHARACTERIZATION (continued)

PARAMETER	RANGE	TEST VEHICLE CONDITION (✓)	Hunting	Twist and Roll	Pitch and Bounce	Yaw and Sway	Steady State Curving	Spiral Negotiation	Dynamic Curving	Steady State Buff and Draft	Longitudinal Train Action	Longitudinal Impact
BODY												
Truck Center Spacing												
33 Feet	36 - 42 Ft.	☐		20	40	40			10	0		
58 Feet	55 - 61 Ft.	☐		10	40	40			40	10		
Other	Other	☐		5	10	10			5	10		
Bounce Natural Frequency												
Low	≤ 6 Hz	☐			10				2			
High	> 6 Hz	☐			5				1			
Bounce Damping												
Low	≤ 0.20	☐			20				5		0	
High	> 0.20	☐			5				1		0	
Pitch Natural Frequency												
Low	≤ 6 Hz	☐			10				3			
High	> 6 Hz	☐			5				1			
Pitch Damping												
Low	≤ 0.20	☐			20				5		20	30
High	> 0.20	☐			5				1		5	10
Roll Natural Frequency												
Low	≤ 3 Hz	☐		20					2			
High	> 3 Hz	☐		10					1			
Roll Damping												
Low	≤ 0.20	☐		20					5			
High	> 0.20	☐		10					1			
Yaw Natural Frequency												
Low	≤ 3 Hz	☐				10			3			
High	> 3 Hz	☐				5			1			
Yaw Damping												
Low	≤ 0.20	☐				20			5		20	
High	> 0.20	☐				5			1		5	
Sway Natural Frequency												
Low	≤ 3 Hz	☐				10			3			
High	> 3 Hz	☐				5			2			
Sway Damping												
Low	≤ 0.20	☐				20			6		20	
High	> 0.20	☐				5			1		5	
Torsional Stiffness												
Low	≤ 10^8 ft-lb/rad	☐						10				
High	> 10^9 ft-lb/rad	☐						30				
Overall Length												
Short	≤ 75 Ft.	☐						10		20		
Long	> 75 Ft.	☐						20		40		
Center of Gravity Height												
Low	≤ 90.0 in	☐		10			10	0	2			10
High	> 90.0 in	☐		30			20	3	6			40
		SUMMARY BY ISSUE (ADD QUANTITIES ✓)										
		SUBTOTAL (Page 2)										
		TOTAL (Page 1 & Page 2)										

TABLE N-6: PERFORMANCE ISSUE EVALUATION THROUGH VEHICLE CHARACTERIZATION (continued)

PERFORMANCE ISSUE RANKING

1 ______________________

2 ______________________

3 ______________________

4 ______________________

5 ______________________

6 ______________________

7 ______________________

8 ______________________

9 ______________________

10 ______________________

NOTES:

1. See Appendix N-A for parameter definitions.

2. Total Shear Stiffness (refer to Appendix N-A, for the ranges of each parameter).

3. Truck Axle Yaw Bending Stiffness (refer to Appendix N-A, for the ranges of each parameter).

4. Net Braking Ratio (refer to Appendix N-A, for the ranges of eacn parameter).

conditions for that characteristic and note a range of rankings which apply to that vehicle.

Note that all Performance Issues are weighted about an arbitrary value of 1.0. This does not judge the relative severity of a Performance Issue, just the relative probability of the vehicle being sensitive to that Performance Issue.

After using Table N-6, return to the main body of this report, Part I, and use this information along with the results of the Accident History Investigations and Literature Searches to select Performance Issues for further investigation and for possible field testing or computer simulation.

N.4.1 Examples of Performance Issue Evaluation

Two examples of the use of Table N-6 are given in Tables N-7 and N-8.

Table N-7 applies the characteristics of a loaded 100 ton coal hopper to the matrix of Table N-6. The parameter conditions are supplied by using the sample cases in Appendix N-A. The results suggest that for this car the rigid car body dynamics, (i.e., Performance Issues twist and roll, pitch and bounce, and yaw and sway), are of primary importance, along with longitudinal impact. Next, with values greater than 70, are longitudinal train action, steady state curving, and dynamic curving. The user must combine this evaluation with other research into accident history and literature reviews to select Performance Issues for further investigations.

Table N-8 considers a six-axle locomotive in the same fashion. The results suggest a closer examination of the rigid car body dynamics, plus longitudinal train action, dynamic curving, and spiral negotiation.

TABLE N-7: EXAMPLE OF PERFORMANCE ISSUE EVALUATION OF A 100-TON HOPPER CAR

VEHICLE CHARACTERISTICS

TEST VEHICLE: *100 TON HOPPER*

PARAMETER[1]	RANGE	TEST VEHICLE CONDITION (	Hunting	Twist and Roll	Pitch and Bounce	Yaw and Sway	Steady State Curving	Spiral Negotiation	Dynamic Curving	Steady State Buff and Draft	Longitudinal Train Action	Longitudinal Impact
WHEEL												
Profile, Conicity Low Medium High	< 2% 2 - 10% > 10%	*1/10*	0 20 30				20 10 0	10 5 0	10 5 0			
TRUCK												
Total Shear Stiffness Low Medium High	(See Note 2)	*FRT. NONSTEER*	20 10 0				20 10 0	8 5 0	5 5 3			
Tot. Axle Yaw Bending Stiff. Low Medium High	(See Note 3)	*FRT NONSTEER*	20 10 0				0 10 20	0 5 10	0 5 10			
Wheel Base Short Long	< 7.0 ft > 7.0 ft	*6 FT.*	5 3				0 10	0 10	0 10			
Yaw Friction Low Medium High	< 1.5 inlb/lb 1.5 - 3.0 inlb/lb > 3.0 inlb/lb	*MEDIUM*	10 5 0					0 5 10	0 5 10			
Number of Axles/Truck Low High	1 or 2 3 or more	*2*	5 0				0 15	0 15	0 15			
Yaw Moment of Inertia Low Medium High	< 30,000 lbsec²in 30,000 - 45,000 lbsec²in > 45,000 lbsec²in	*MEDIUM*	5 [illegible] 0					0 1 2	0 5 5			
Wheelset weight Light Heavy	< 5,000 lb > 5,000 lb	*LIGHT*	0 5					0 2	0 5			
Net Braking Ratio Standard/Unit Train High/Low (Interchange)	(See Note 4)	*STANDARD*								10 30	0 20	
COUPLER/DRAFT GEAR												
Long. Compressive Energy Low High	< 61,000 ft. pounds > 61,000 ft. pounds	*LOW*										20 10
Long. Energy Absorption Low High	< 40,000 ft. pounds > 40,000 ft. pounds	*LOW*									10 30	
		SUMMARY BY ISSUE (ADD QUANTITIES ✓)										
		SUBTOTAL (Page 1)	*60*	*0*	*0*	*0*	*60*	*29*	*30*	*19*	*10*	*20*

TABLE N-7: EXAMPLE OF PERFORMANCE ISSUE EVALUATION OF A 100 TON HOPPER CAR (continued)

PARAMETER	RANGE	TEST VEHICLE CONDITION (✓)	Hunting	Twist and Roll	Pitch and Bounce	Yaw and Sway	Steady State Curving	Spiral Negotiation	Dynamic Curving	Steady State Buff and Draft	Longitudinal Train Action	Longitudinal Impact
BODY												
Truck Center Spacing 33 feet 58 feet Other	 36 - 42 ft. 55 - 61 ft. Other	40 FT. ✓		30 10 5	40 40 10	40 40 10			10 10 5	0 10 10		
Bounce Natural Frequency Low High	 ≤ 6 Hz > 6 Hz	LOW ✓			10 5				2 1			
Bounce Damping Low High	 ≤ 0.20 > 0.20	LOW ✓			20 5				5 1		0 0	
Pitch Natural Frequency Low High	 ≤ 6 Hz > 6 Hz	LOW ✓			10 5				3 1			
Pitch Damping Low High	 ≤ 0.20 > 0.20	LOW ✓			20 5				5 1		20 5	10 10
Roll Natural Frequency Low High	 ≤ 3 Hz > 3 Hz	LOW ✓		20 10					2 1			
Roll Damping Low High	 ≤ 0.20 > 0.20	LOW ✓		20 10					5 1			
Yaw Natural Frequency Low High	 ≤ 3 Hz > 3 Hz	LOW ✓				10 5			3 1			
Yaw Damping Low High	 ≤ 0.20 > 0.20	LOW ✓				20 5			5 1		20 5	
Sway Natural Frequency Low High	 ≤ 3 Hz > 3 Hz	LOW ✓				10 5			3 1			
Sway Damping Low High	 ≤ 0.20 > 0.20	LOW ✓				20 5			5 1		20 5	
Torsional Stiffness Low High	 ≤ 10^9 in-lb/rad > 10^9 in-lb/rad	LOW ✓						10 30				
Overall Length Short Long	 ≤ 75 ft. > 75 ft.	SHORT ✓						10 20		20 60		
Center of Gravity Height Low High	 ≤ 90.0 in > 90.0 in	HIGH ✓		15 30			10 20	3 3	2 5			10 40
SUMMARY BY ISSUE (ADD QUANTITIES ✓) SUBTOTAL (Page 2)			0	100	100	100	20	25	53	20	60	70
TOTAL (Page 1 & Page 2)			60	100	100	100	80	52	83	30	80	80

TABLE N-8: EXAMPLE OF PERFORMANCE ISSUE EVALUATION OF A 6-AXLE LOCOMOTIVE

VEHICLE CHARACTERISTICS — TEST VEHICLE: *6-AXLE LOCO*

PARAMETER[1]	RANGE	TEST VEHICLE CONDITION (✓)	Hunting	Twist and Roll	Pitch and Bounce	Yaw and Sway	Steady State Curving	Spiral Negotiation	Dynamic Curving	Steady State Buff and Draft	Longitudinal Train Action	Longitudinal Impact
WHEEL												
Profile, Conicity		*1/40*										
Low	< 2%	☐	0				20	10	10			
Medium	2 – 10%	✓	20				10	5	5			
High	> 10%	☐	30				0	0	0			
TRUCK												
Total Shear Stiffness		*HIGH*										
Low	(See Note 2)	☐	20				20	5	5			
Medium		☐	10				10	5	5			
High		✓	0				0	0	0			
Tot. Axle Yaw Bending Stiff.		*HIGH*										
Low	(See Note 3)	☐	20				0	0	0			
Medium		☐	10				10	5	5			
High		✓	0				30	10	10			
Wheel Base		*13 FT.*										
Short	≤ 7.0 ft	☐	5				0	0	0			
Long	> 7.0 ft	✓	0				10	10	10			
Yaw Friction		*MEDIUM*										
Low	< 1.5 in-lb/lb	☐	10					0	0			
Medium	1.5 – 3.0 in-lb/lb	✓	5					5	5			
High	> 3.0 in-lb/lb	☐	0					10	10			
Number of Axles/Truck		*3*										
Low	1 or 2	☐	5				0	0	0			
High	3 or more	✓	0				10	15	15			
Yaw Moment of Inertia		*HIGH*										
Low	< 30,000 lbsec²in	☐	5					0	0			
Medium	30,000 – 45,000 lbsec²in	☐	5					1	3			
High	> 45,000 lbsec²in	✓	0					2	5			
Wheelset Weight		*HEAVY*										
Light	≤ 5,000 lb	☐	0					0	0			
Heavy	> 5,000 lb	✓	5					2	5			
Net Braking Ratio		*STANDARD*										
Standard/Unit Train	(See Note 4)	✓								10	0	
High/Low (Interchange)		☐								30	20	
COUPLER/DRAFT GEAR												
Long. Compressive Energy		*LOW*										
Low	≤ 61,000 ft. pounds	✓										20
High	> 61,000 ft. pounds	☐										10
Long. Energy Absorption		*LOW*										
Low	≤ 40,000 ft. pounds	✓									10	
High	> 40,000 ft. pounds	☐									30	
SUMMARY BY ISSUE (ADD QUANTITIES ✓)												
SUBTOTAL (Page 1)			*50*	*0*	*0*	*0*	*60*	*49*	*55*	*10*	*10*	*20*

TABLE N-8: EXAMPLE OF PERFORMANCE ISSUE EVALUATION OF A 6-AXLE LOCOMOTIVE (continued)

PARAMETER	RANGE	TEST VEHICLE CONDITION (✓)	Hunting	Twist and Roll	Pitch and Bounce	Yaw and Sway	Steady State Curving	Spiral Negotiation	Dynamic Curving	Steady State Buff and Draft	Longitudinal Train Action	Longitudinal Impact
BODY												
Truck Center Spacing 37 feet 58 feet Other	 36 - 42 ft. 55 - 61 ft. Other	40 FT. ✓ ☐ ☐		30 10 5	40 40 10	40 40 10			10 10 5	0 10 10		
Bounce Natural Frequency Low High	 ≤ 6 Hz > 6 Hz	LOW ✓ ☐			10 5				[illegible] 1			
Bounce Damping Low High	 ≤ 0.20 > 0.20	LOW ✓ ☐			20 5				5 1		0 0	
Pitch Natural Frequency Low High	 ≤ 6 Hz > 6 Hz	LOW ✓ ☐			10 5				3 1			
Pitch Damping Low High	 ≤ 0.20 > 0.20	LOW ✓ ☐			20 5				5 1		20 5	30 10
Roll Natural Frequency Low High	 ≤ 3 Hz > 3 Hz	LOW ✓ ☐		20 10					2 1			
Roll Damping Low High	 ≤ 0.20 > 0.20	LOW ✓ ☐		20 10					5 1			
Yaw Natural Frequency Low High	 ≤ 3 Hz > 3 Hz	LOW ✓ ☐				10 [illegible]			3 1			
Yaw Damping Low High	 ≤ 0.20 > 0.20	LOW ✓ ☐				20 5			5 1		20 5	
Sway Natural Frequency Low High	 ≤ 3 Hz > 3 Hz	LOW ✓ ☐				10 5			3 1			
Sway Damping Low High	 ≤ 0.20 > 0.20	LOW ✓ ☐				20 5			5 1		20 5	
Torsional Stiffness Low High	 ≤ 10^9 in-lb/rad > 10^9 in-lb/rad	HIGH ☐ ✓						10 30				
Overall Length Short Long	 ≤ 75 ft. > 75 ft.	65 FT. ✓ ☐						10 20		20 60		
Center of Gravity Height Low High	 ≤ 90.0 in > 90.0 in	80 IN. ✓ ☐		15 30			10 20	0 3	2 5			10 40
SUMMARY BY ISSUE (ADD QUANTITIES ✓) SUBTOTAL (Page 2)			0	85	100	100	10	20	50	20	60	40
TOTAL (Page 1 & Page 2)			30	85	100	100	70	69	105	30	80	50

REFERENCES -- SECTION N and APPENDIX N-A

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3. J. K. Hedrick, "Truck Parameters: Intercity/Transit/Freight," Massachusetts Institute of Technology, memo to Arthur D. Little, Inc., February, 1982.

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13. Ellsworth, K. G., ed., "The Car and Locomotive Cyclopedia of American Practices," 4th edition, Simmons-Boardman Publishing Corporation, 1980.

APPENDIX N-A

POTENTIAL TECHNIQUES FOR VEHICLE CHARACTERIZATION

PARAMETER:

Wheel Profile

STATISTIC:

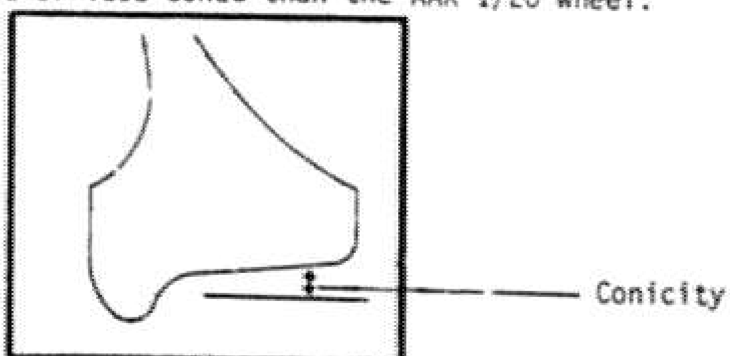
Conicity, mean

CONDITIONS:

Low Conicity	< 2%
Medium Conicity	2 → 10%
High Conicity	> 10%

MEASUREMENT DEFINITIONS AND TECHNIQUES:

Use tracing profilometer to get cross-sectional profile of test wheel. Do same for AAR 1/20 new wheel. Overlay traces. Compare tread slopes and determine if test wheel is substantially more or less coned than the AAR 1/20 wheel.



This assumes that the vehicle will be exposed to a wide variety of rail profiles in service.

SAMPLE CASES:

Low Conicity	Medium Conicity	High Conicity
Cylindrical	AAR 1/20, 1/40 most "worn", Heumann, CNR, ORE	Severely worn, self-steering truck wheels

References [1, 3]

PARAMETER:

Total Truck Shear Stiffness

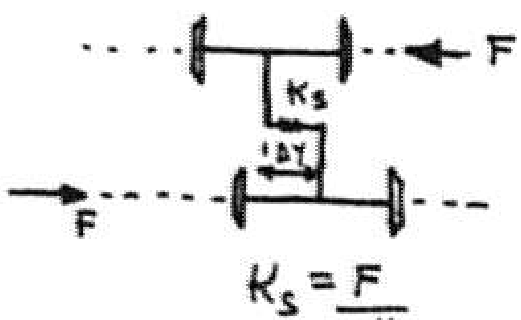
STATISTIC:

Stiffness, Mean, in operating range

CONDITIONS:

		Nonsteerable	Steerable
Freight	Low	$\leq 2.0 \times 10^7$ lb/ft	$< 6.0 \times 10^5$ lb/ft
	Medium	$> 2.0 \times 10^7$ lb/ft	$6.0 \times 10^5 \rightarrow 9.8 \times 10^5$ lb/ft
	High	N/A	$> 9.8 \times 10^5$ lb/ft
Passenger	Low	$< 8.0 \times 10^4$ lb/ft	N/A
	Medium	$8.0 \times 10^4 \rightarrow 1.3 \times 10^5$ lb/ft	$< 3.0 \times 10^6$ lb/ft
	High	$> 1.3 \times 10^5$ lb/ft	$\geq 3.0 \times 10^6$ lb/ft

MEASUREMENT DEFINITIONS AND TECHNIQUES:



$$K_s = \frac{F}{\Delta Y}$$

Laboratory measurement using test truck under full vertical load, on a low friction surface. A similar test involving an appropriate selection from the samnle cases should be performed also for comparison.

SAMPLE CASES:

FREIGHT TRUCK

Nonsteerable: Conventional 3 piece 70 ton freight truck (1.9 x 107 lb/ft) (cannot become much softer due to "pinned joints" and cannot become much stiffer without becoming a radial design)

Steerable: Radial design 70 ton freight truck (7.5×10^5 lb/ft) (significant changes to shear stiffnesses are unlikely)

References [1, 2, 3]

(Total Truck Shear Stiffness - continued)

PASSENGER TRUCK

Nonsteerable:	Budd-Pioneer 3 truck (1.0×10^5 lb/ft) (some design variations are possible)
Steerable:	GSI-Scheffel (3.7×10^6 lb/ft) (significant design variations are unlikely)

PARAMETER:

Total Truck Axle Yaw Bending Stiffness

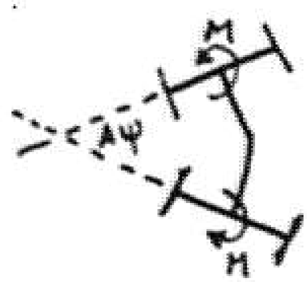
STATISTIC:

Stiffness, Mean, in operating range

CONDITIONS:

		Nonsteerable	Steerable
Freight	Low	N/A	$< 10^6$ ftlb/rad
	Medium	$\leq 10^8$ ftlb/rad	$10^6 \rightarrow 2.0 \times 10^6$ ftlb/rad
	High	$> 10^8$ ftlb/rad	$> 2.0 \times 10^6$ ftlb/rad
Passenger	Low	$< 2.0 \times 10^6$ ftlb/rad	$< 8.5 \times 10^5$ ftlb/rad
	Medium	$2.0 \times 10^6 \rightarrow 4.0 \times 10^6$ ftlb/rad	$> 8.5 \times 10^5$ ftlb/rad
	High	$> 4.0 \times 10^6$ ftlb/rad	N/A

MEASUREMENT DEFINITIONS AND TECHNIQUES:



$$K_b = \frac{M}{\Delta\psi}$$

Laboratory measurement using standard truck and test truck, under full vertical load, on low friction surface. Use outermost axles on 3-axle trucks.

SAMPLE CASES:

FREIGHT TRUCK

Nonsteerable: Conventional 70 ton 3 piece (4.0×10^8 ft-lb/rad) (stiffness is fixed by design)

Steerable: Radial design 70 ton ft. (1.3×10^8 ft-lb/rad (some design modifications are feasible)

PASSENGER TRUCK

Nonsteerable: Pioneer 3 (Budd) (2.4×10^6 ft-lb/rad)

Steerable: Radial GSI-Scheffel (6.0×10^5 ft-lb/rad) (some bending stiffness changes may be significant)

References [1, 2, 3]

PARAMETER:

Wheel Base

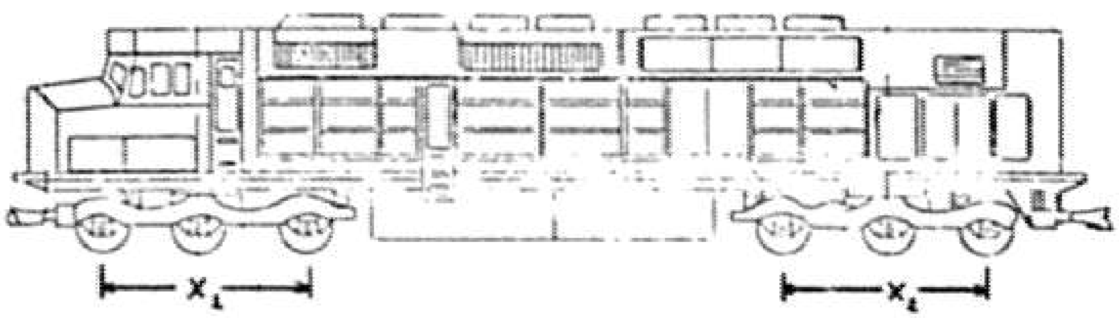
STATISTIC:

Measurement, feet

CONDITIONS:

	Range
Short	≤ 7.0 feet
Long	> 7.0 feet

MEASUREMENT DEFINITIONS AND TECHNIQUES:



Measure "X_i" with tape measure.

SAMPLE CASES:

Short Wheel Base	Long Wheel Base
70 ton Frt Truck (5.67')	GSI (Passenger) Swing hanger (8.75')
125 ton Frt Truck (6.00')	EMD 6 Wheel HTC (13.7')

References [4, 5]

PARAMETER:

Truck Yaw Friction

STATISTIC:

Break-away torque/vertical load, in-lb/lb

CONDITIONS:

Low Friction	< 1.5 in-lb/lb - vertical
Medium Friction	1.5 → 3.0 in-lb/lb - vertical
High Friction	> 3.0 in-lb/lb - vertical

MEASUREMENT DEFINITIONS AND TECHNIQUES:

Break-away torque is the peak torque needed, under quasi-static conditions, to initiate truck motion.

A laboratory test is required to quantify the break-away torque under typical full load weight conditions. The weight on the truck is also required.

SAMPLE CASES:

Low Friction	Medium Friction	High Friction
Teflon Surface (0.41 in-lb/lb)	70 ton Frt, dry (2.1 in-lb/lb) 50 ton Frt, dry (2.4 in-lb/lb) 125 ton Frt, dry (2.8 in-lb/lb)	

Reference [4]

PARAMETER:

Number of Axles/Truck

STATISTIC:

Number

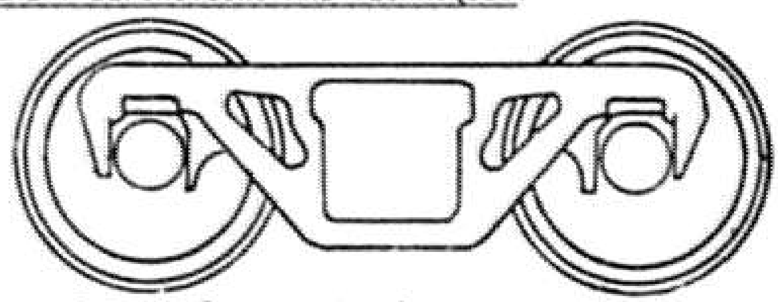
CONDITIONS:

Range

1 or 2

3 or more

MEASUREMENT DEFINITIONS AND TECHNIQUES:



Count axles per truck.

SAMPLE CASES:

1 or 2	3 or more
Conv. 3-piece Frt.	6 axle locomotives
Passenger	Special purpose frt. cars
4 axle locomotives	

References [4, 5]

PARAMETER:

Truck Yaw Moment of Inertia

STATISTIC:

Mass-distribution Moment of Inertia about centerplate

CONDITIONS:

	Range
Low	< 30,000 lb sec^2 in
Medium	30,000 - 45,000 lb sec^2 in
High	> 45,000 lb sec^2 in

MEASUREMENT DEFINITIONS AND TECHNIQUES:

Support truck on low-friction bearings, apply torque, T, and measure angular acceleration, Ω;

$$\text{M. of I.} = \frac{\text{Torque}}{\Omega}$$

SAMPLE CASES:

Low	Medium	High
Pioneer 3 Passenger (24,000 lb sec^2 in)	50 Ton Frt (30,400 lb sec^2 in) 100 Ton Frt (43,820 lb sec^2 in) 70 ton Frt (35,950 lb sec^2 in)	Locomotive 4-WH G.E. (80,000 lb sec^2 in)

Reference [4]

PARAMETER:

Wheelset Weight (Effective Lateral Weight*)

STATISTIC:

Weight, pounds

CONDITIONS:

	Range
Light	≤ 5,000 pounds
Heavy	> 5,000 pounds

MEASUREMENT DEFINITIONS AND TECHNIQUES:

*Under dynamic loading conditions (e.g., Dynamic Curving), the "effective lateral" wheelset weight is affected by the weight of the axle and any components which are "tightly" coupled to it, such as traction motors. Each design in question must be reviewed and some portion of the weight of all attached components based on geometry and clearances, will be added to the wheelset weights.

SAMPLE CASES:

Light	Heavy
50 ton Frt trucks (1932 pounds)	Locomotive (4 axle EMD) (5136 pounds)
70 ton Frt trucks (2164 pounds)	
100 ton Frt trucks (2588 pounds)	
125 ton Frt trucks (3130 pounds)	
Passenger (Pioneer 3) (3437 pounds)	

Reference [4]

PARAMETER:

Net Braking Ratio (NBR)

STATISTIC:

$\frac{\text{Braking Force}}{\text{Wheel Load}}$ x 100% at 20 psi brake pipe reduction

CONDITIONS:

RANGE

AAR Standard or Dedicated Consist 6.5% $\leq NBR_g \leq$ 10% (of gross wheel load) and $NBR_e \leq$ 30% (of empty wheel load)

High/Low Ratio (Interchange) NBR_g < 6.5% (gross) or NBR_g > 10 (empty) or NBR_e > 30% (empty)

MEASUREMENT DEFINITIONS AND TECHNIQUES:

$$\text{Braking Force} = \left(\begin{matrix}\text{Net Braking Force at}\\ \text{20 psi Br. Pipe Reduc}\end{matrix}\right) \times \left(\frac{\text{Test Shoe Friction}}{\text{Std. Composition Shoe Friction}}\right) \times \left(\frac{\text{Radius of Applicator}}{\text{Radius of Tread}}\right)$$

Net Braking Force: Measure with "calibrated brake shoe" instrument

Shoe Friction: Use manufacturer's spec's. or laboratory research

Radius: Measure with metal tape measure

$$NBR_{gross} = \left(\frac{\text{Braking Force}}{\text{Gross single wheel load}}\right) \qquad NBR_{empty} = \left(\frac{\text{Braking Force}}{\text{Empty weight single wheel load}}\right)$$

SAMPLE CASES:

All AAR-accepted brake systems fall within the "standard" range. Determined as: brake rigging with leverage ratio = 7.5 and 50 psi brake cylinder pressures at 20 psi brake pipe reduction.

Reference [6]

PARAMETER:

Coupler Draft Gear Longitudinal Energy Absorption

STATISTIC:

Energy absorbed per loading cycle, ft-lbs/cycle

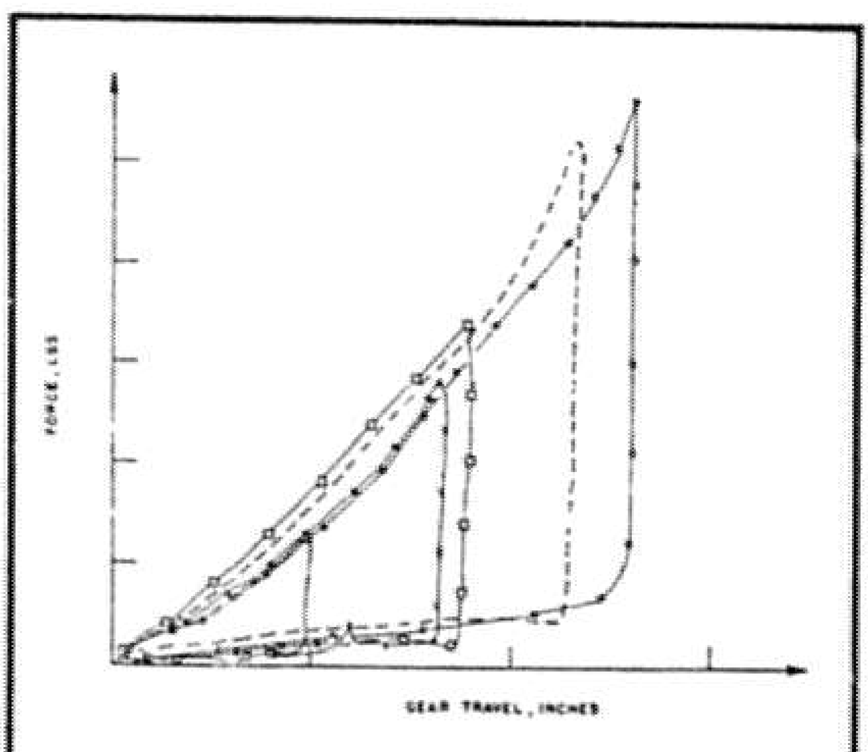
CONDITIONS:

	Range
Low Energy Absorption	≤ 40,000 ft. lbs.
High Energy Absorption	> 40,000 ft. lbs.

MEASUREMENT DEFINITIONS AND TECHNIQUES:

The energy absorbed during one loading cycle of the draft gear is equal to the work required to compress the gear minus the work returned during the release of the gear.

If the condition is unknown, a laboratory experiment can be performed to achieve a Force/Displacement plot for one complete loading cycle for a draft gear with low damping and the test draft gear. A quasi-static test may be used to be conservative.



The difference in the work is the energy absorbed and can be measured graphically as the area between the load and release curves.

SAMPLE CASES:

Low Energy Absorption — High Energy Absorption

Reference [7]

PARAMETER:

Coupler Draft Gear Compressive Energy

STATISTIC:

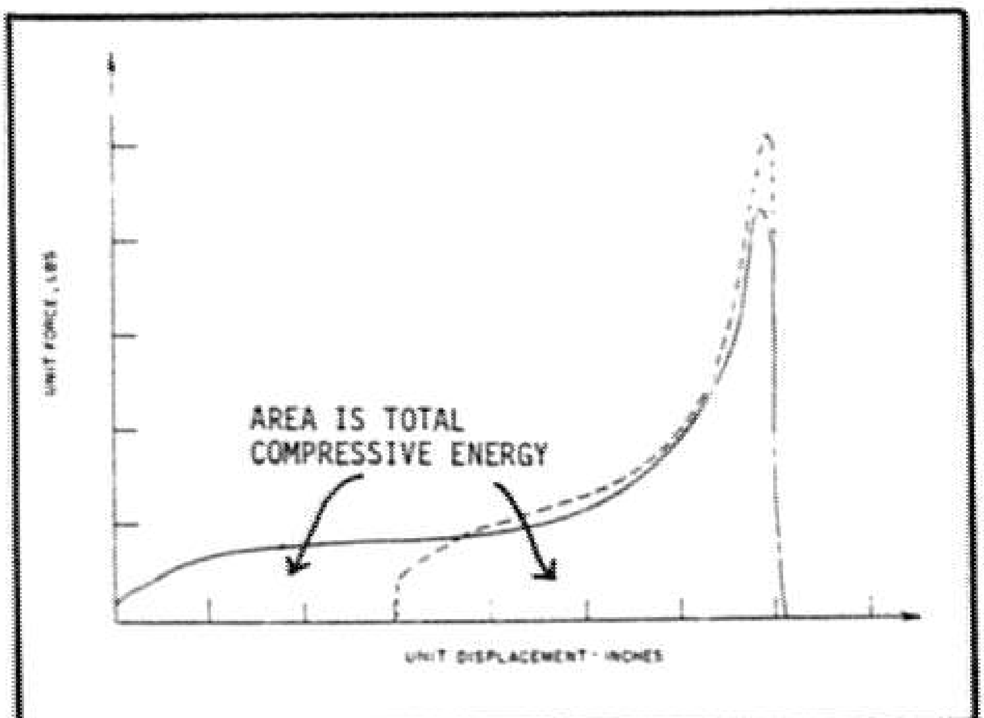
Total Energy

CONDITIONS:

Low	≤ 61,000 ft. lbs.
High	> 61,000 ft. lbs.

MEASUREMENT DEFINITIONS AND TECHNIQUES:

In a laboratory or field test, compress the draft gear to its full excursion. Instrument the coupler to continuously measure longitudinal force during the impact. Integrate the force-displacement measurements to estimate the total energy which can be absorbed during compression. This is then compared to the energy required to decelerate a 100-ton vehicle from 3 to 0 miles per hour.



SAMPLE CASES:

Low	High
Miner SL-76 (47,820 ft. lbs)	Miner RF-75 (84,280 ft. lbs.)

Reference [13]

PARAMETER:

Truck Center Spacing

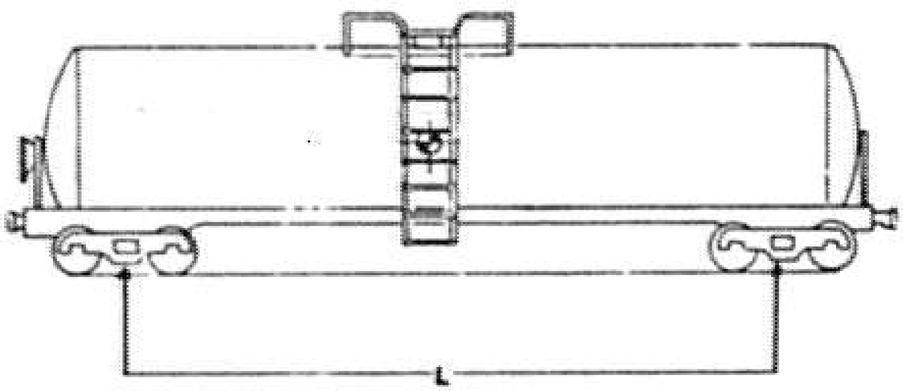
STATISTIC:

Measurement, feet

CONDITIONS:

	Range
39 ft	36 - 42 ft.
58 ft	55 - 61 ft.
Other	< 36 ft., or > 42 ft. and < 55 ft., or > 61 ft.

MEASUREMENT DEFINITIONS AND TECHNIQUES:



Use tape measure to measure "L".

SAMPLE CASES:

39 FT.	58 FT.	Other
70 Ton Box (40 ft.)	Passenger cars (60 ft.)	F 7/9 loco (30 ft.)
100 Ton Coal Gond (40.5 ft.)	70 Ton Flat car (58 ft.)	GP 7/9 loco (30 ft.)
Six axle loco (40 ft.)		100T Covered Hopper (46 ft.)
		70 Ton Tank Car (29 ft.)
		70 Ton Vehicular Flat (65 ft.)

Reference [4, 5]

PARAMETER:

Vehicle Resonant Frequencies; in Bounce, Pitch, Roll, Yaw, Sway

STATISTIC:

Frequency, Hz

CONDITIONS:

Bounce	Low	≤ 6
	High	> 6
Pitch	Low	≤ 6
	High	> 6
Roll	Low	≤ 6
	High	> 6
Yaw	Low	≤ 6
	High	> 6
Sway	Low	≤ 6
	High	> 6

MEASUREMENT DEFINITIONS AND TECHNIQUES:

Under conditions of "free response" to an initial displacement, the carbody will oscillate at its natural (resonant) frequency. The vehicle lading and maintenance condition is selected through accident history investigations or analytical considerations, as determined during the Assessment Procedures.

FIELD TEST with perturbation input; record response during free response immediately after leaving perturbation, count oscillations per second.

LABORATORY TEST with static displacement, then release and record free response. Count oscillations per second.

Estimate natural frequency, knowing suspension stiffnesses and masses or moments of inertia, as

$$w_n^2 = \frac{K}{M}$$

: w_n = natural frequency, rad/sec
K = stiffness
M = mass

SAMPLE CASES:

70 Ton Box Car is "Low" for all modes

Reference [8, 9, 10]

PARAMETER:

Vehicle Damping; in Bounce, Pitch, Roll, Yaw, Sway

STATISTIC:

Damping ratio

CONDITIONS:

Bounce	Low	≤ 0.20
	High	> 0.20
Pitch	Low	≤ 0.20
	High	> 0.20
Roll	Low	≤ 0.20
	High	> 0.20
Yaw	Low	≤ 0.20
	High	> 0.20
Sway	Low	≤ 0.20
	High	> 0.20

MEASUREMENT DEFINITIONS AND TECHNIQUES:

- Select vehicle lading configuration through Assessment Procedures.

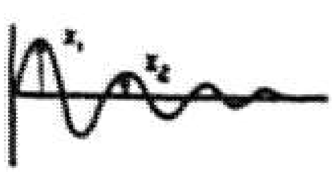
FIELD TEST or LABORATORY TEST; Displace carbody and release; record carbody displacements during free response, measure oscillation amplitudes, for each consecutive pair of oscillations; calculate δ (logarithmic decrement) as

$$\delta = \ln (x1/x2)$$

where x_1 and x_2 are consecutive amplitudes; calculate ζ (damping ratio as

$$\zeta = \left(\frac{\delta^2}{\delta^2 + 4\pi^2}\right)^{1/2}.$$

The following table is a sample:



ζ	x_1/x_2
.03	1.21
0.10	1.88
0.20	3.61
0.30	7.21

SAMPLE CASES:

70 Ton Box Car is "Low" for all modes.

References [8, 9, 10]

PARAMETER:

Carbody Torsional Stiffness

STATISTIC:

Torque twist (in-lb/rad)

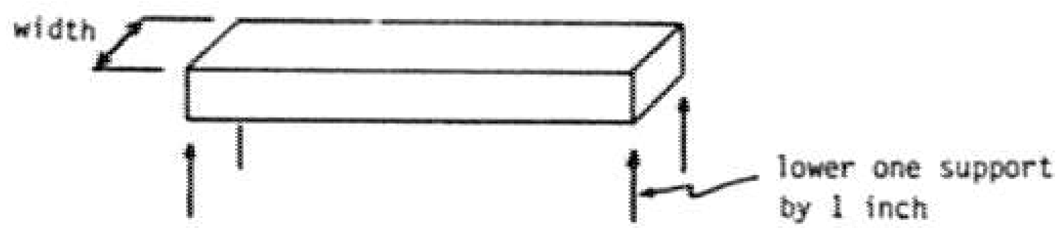
CONDITIONS:

Low Stiffness $\leq 10^9$ in-lb/rad

High Stiffness $> 10^9$ in-lb/rad

MEASUREMENT DEFINITIONS AND TECHNIQUES:

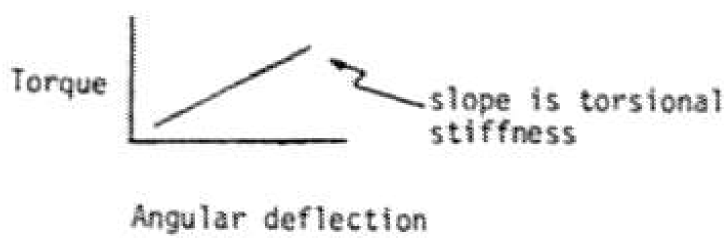
In laboratory, support carbody level on load cells at each of 4 corners



lower support at one of the corners by 1 inch and measure resulting forces (F), repeat until force at low corner is <10% of force on high corner

Plot Torque $\left[= \left(F_{high} - F_{low}\right)(\text{width})\right]$ vs. Angular Deflection

$$\left[= \tan^{-1}\left(\frac{\text{displacement of support}}{\text{width}}\right)\right]$$



SAMPLE CASES:

Low	High
50' 70 ton box (41×10^7 in-lb/rad)	10,000 gal 50 ton tank car (2105×10^7 in-lb/rad)
40' 50 ton box (171×10^7 in-lb/rad)	locomotives

PARAMETER:

Overall Length between Coupler Pulling Faces

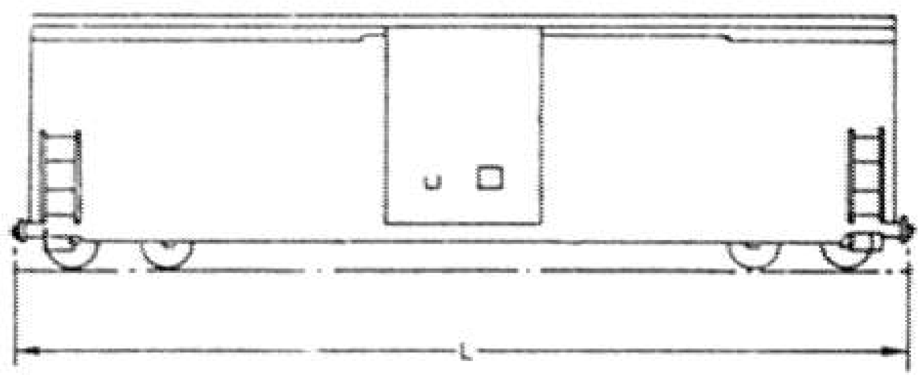
STATISTIC:

Measurement, feet

CONDITIONS:

	Range
Short	≤ 75 feet
Long	> 75 feet

MEASUREMENT DEFINITIONS AND TECHNIQUES:



Measure "L" with tape measure.

SAMPLE CASES:

Short

100 ton box (68 ft.)
70 ton refrigerated box car (58 ft.)
100 ton covered hopper (54 ft.)
6 axle locomotive (65 ft.)

Long

High cube box cars (90 ft.)
TOFC/COFC flats (90 ft.)
70 ton Auto Rack (94 ft.)

References [4, 5]

PARAMETER:

Center of Gravity Height

STATISTIC:

Center of gravity, height above railhead, loaded

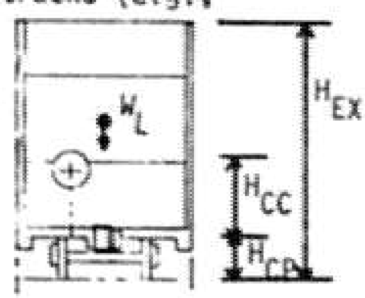
CONDITIONS:

Low < 90.0 inches

High ≥ 90.0 inches

MEASUREMENT DEFINITIONS AND TECHNIQUES:

- Estimate by calculations; knowing weight of truck assemblies, weight of empty carbody, design strength of trucks (e.g., 100 ton).



- Measure: (empty car)
  Weight on all wheels, $\Sigma 1 \rightarrow 8 = W_W$
  Weight of carbody alone $= W_C$
  Calculate:
  Lading weight, W_L = Design Strength - W_W
  Measure:
  Height of centerplate above railhead, H_{CP}
  Extreme height of car above railhead when loaded, H_{EX}
  Calculate approximate height of carbody center of gravity above centerplate, H_{CC} (default is to geometric center; $\frac{1}{2}(H_{EX} - H_{CP})$).
  Assume W_L will be located at the geometric center of the loaded carbody

$$H_{cg} \times W_w = (W_w - W_c)\frac{H_{CP}}{2} + W_c\,(H_{CC} + H_{CP}) + W_L\,\left(\frac{H_{EX} - H_{CP}}{2} + H_{CP}\right)$$

solve for Height of Center of Gravity, H_{cg}

SAMPLE CASES:

Low Center of Gravity	High Center of Gravity
70 ton covered hopper (80 in)	100 ton tank car (92 in)
70 ton box car (70 in)	100 ton coal hopper (98 in)
6 axle locomotive (80 in)	

References [4, 5]

SECTION O
USE AND CHOICE OF REFERENCE VEHICLES

O-1. INTRODUCTION

This report is concerned with the use of Reference Vehicles in rail vehicle testing and relates their use to the Performance Issues described in Appendix O-A. Only those in which a reference vehicle concept is appropriate are included in this study. The concept of the use of a vehicle, regarded and perhaps maintained as a standard, against which other test vehicles and/or measured results can be compared, is an attractive extension of many more fundamental measurement techniques. However, the complexity of the dynamic process causes difficulties in the interpretation.

Several potential uses for Reference Vehicles are examined. Each has a different objective. In each, certain of the measurable system variables may be controlled, perhaps by special measurement and correction or simply by maintenance into a choice of standard under which the test is to be run. The uses identified were broken down into

- Track Calibration
- Test Calibration
- Baseline Comparison
- Extrapolation to Normal Track Service

- Model Validation
- Component Environment Assessment (to ascertain the service environment of a rail vehicle component by measurement on the reference vehicle).

In the last two uses above, the vehicle becomes the sole test vehicle, useful for its known characteristics, and no separate consideration of a reference vehicle is carried out in the study reported. The other uses are examined in detail. Each has its own features leading to different subsets of controlled vehicle/track system variables. A reasonably complete fundamental set of measurable system variables, defining or contributing to the dynamic response of a vehicle on track was undertaken in this study.

From the complete set, a subset was identified important to each of the Performance Issues in Appendix A. This is a judgemental step requiring knowledge of the results of analyses and tests for each issue. The identification of each subset is described in the report. The reason for the inclusion of each system variable has been discussed with other experienced persons and use made of published material. Each system variable is also identified by cause for the standard freight car in Table O-1. The freight car of present design is considered as the basic vehicle type in this study.

Since the objective of a reference vehicle is to provide the least expensive means of satisfying the defined use, the most desirable use will be that in which the least number of variables can be measured by the simplest observation, perhaps even by visual inspection, during the use. To that end, the immediate objective of the task reported here is to report on the optimum choice and means of using reference vehicles leading to the least complex observation. The study however, also identifies the cost of complexity where needed to do the test conclusively and makes comparison with alternatives using vehicle simulations and additional measurements.

0-1.1 <u>SUMMARY</u>

From the discussions of reference vehicle validity and the cost of alternative means of measurement it is concluded that good use can be made of freight reference vehicles in tests for hunting, twist and roll, pitch and bounce and steady-state curving. Extrapolation of the results to service conditions is difficult unless the test and reference vehicles are similar or an analytic model is available.

Three basic freight reference vehicles are sufficient to cover all uses. They are an 89 ft. flat-car (70 ton, 69 ft TCD), a 60 ft. box-car (100 ton, 39½ ft. TCD), and a coal gondola or long covered hopper (100 ton, 48 ft. TCD. Vehicle maintenance is required for consistant vehicle dynamic performance, and wheel profiles must be selected for the specific test.

For passenger and locomotives the variety of designs requiring testing suggests that the reference vehicle be chosen to suit the particular test. The choice should be made to effect similarity with the test vehicle and if possible a previous history of performance and test records.

TABLE O-1
CHARACTERISTICS FOR FREIGHT VEHICLE

CODE	PHYSICAL DESCRIPTION	VARIABLE SYSTEM CHARACTERISTIC	PERFORMANCE ISSUES AFFECTED (APPENDIX A) 1	2	3	4	5	6	7	LOCATION OF VARIABLE: VEHICLE	TRACK	CAUSE OF VARIATION: DESIGN	WEAR HISTORY	CLIMATE HISTORY	CLIMATE TEST
1.1	TRACK GEOMETRY	ALIGNMENT	✓			✓	✓	✓	✓		✓	✓	✓	✓	
1.2		GAUGE	✓			✓	✓	✓	✓		✓	✓	✓		
1.3		SURFACE PROFILE		✓	✓			✓	✓		✓	✓	✓	✓	
1.4		CROSS LEVEL		✓	✓			✓	✓		✓	✓	✓	✓	
1.5		CURVATURE					✓	✓	✓		✓	✓	✓	✓	
1.6		SUPERELEVATION					✓	✓	✓		✓	✓	✓	✓	
2.1	TRACK COMPLIANCE	VERTICAL TRACK STIFFNESS		✓	✓			✓	✓		✓	✓	✓	✓	✓
2.2		VERTICAL DAMPING		✓	✓				✓		✓			✓	✓
2.3		LATERAL RAIL STIFFNESS	✓			✓		✓	✓	(✓)	✓	✓	✓	✓	✓
2.4		LATERAL DAMPING	N/A												
3.1	WHEEL-RAIL CONTACT	WHEEL PROFILE	✓	✓		✓	✓	✓	✓	✓		✓	✓		
3.2		RAIL PROFILE	✓	✓		✓	✓	✓	✓		✓	✓	✓		
3.3		SURFACE CREEP + SPIN	✓	✓		✓	✓	✓	✓	✓	✓		✓	✓	✓
4.1	BODY GEOMETRY	TRUCK CENTERS		✓	✓	✓		✓	✓	✓		✓			
5.1	BODY TO BOLSTER SUSPENSION	ROLL STIFFNESS		✓		✓		✓	✓	✓		✓	✓		
5.2		YAW DAMPING	✓			✓		✓	✓	✓		(✓)	✓		
6.1	BODY COMPLIANCE	TORSIONAL STIFFNESS	✓	✓				✓	✓	✓		✓			
6.2		VERTICAL BENDING STIFFNESS			✓					✓		✓			
7.1	LADING/BODY INERTIA	MASS	✓	✓		✓	✓	✓	✓	✓		✓			
7.2		ROLL RAD OF GYR		✓		✓		✓	✓	✓		✓			
7.3		PITCH RAD OF GYR			✓					✓		✓			
7.4		YAW RAD OF GYR	✓			✓		✓	✓	✓		✓			
7.5		C.G. POSITION	✓	✓	✓	✓	✓	✓	✓	✓		✓	✓		
8.1	TRUCK GEOMETRY	WHEEL RADIUS	✓			✓	✓	✓	✓	✓		✓			
8.2		WHEEL BASE	N/A												
9.1	TRUCK COMPLIANCE	LATERAL BEARING STIFFNESS	✓	✓		✓		✓	✓	✓		✓			
9.2		LATERAL BEARING DAMPING	N/A												
9.3		TRAM STIFFNESS	✓			✓	✓	✓	✓	✓		✓			
9.4		TRAM DAMPING	N/A												
10.1	TRUCK (BOLSTER) SUSPENSION	VERTICAL STIFFNESS		✓	✓	✓		✓	✓	✓		✓			
10.2		VERTICAL DAMPING		✓	✓	✓		✓	✓	✓		✓	✓	(✓)	(✓)
10.3		LATERAL STIFFNESS	✓	✓		✓	✓	✓	✓	✓		✓			
10.4		LATERAL DAMPING	N/A												

*N/A – NOT APPLICABLE
(✓) – POSSIBLY BUT NOT NORMALLY A SOURCE OF VARIATION

O-2. REFERENCE VEHICLE USES

The following paragraphs describe more completely the uses identified for the reference vehicles.

O-2.1 TRACK CALIBRATION

The use is intended to

- Identify levels of track change which change vehicle performance
- Provide guidelines on permissible tolerances to track geometry
- Identify when and where track maintenance is required.

The vehicle has the effect of filtering the track inputs including those which would not normally be part of any present track record, so that the total track input may be judged as consistent in a particular performance issue for which the reference vehicle is chosen.

The main feature of this use is that the reference vehicle activity is independent of any actual test. It may be periodic if the test site is to remain operational for an extended period. The environment in which the reference vehicle is used may be controlled by selection, e.g., rainy days may be avoided. In this sense, track calibration is most appropriately related to the repeated use of a particular track for testing. Since the same reference vehicle is used for each calibration, vehicle design is not variable. However, those features of the design requiring maintenance are variable and must be controlled. The remaining variables are those associated with track design and history (wear, track heave, usage, etc.). These are the variables which the reference vehicle is used to measure. Identifying them for each performance issue defines the nature and choice of reference vehicle and its effectiveness in calibrating the track.

O-2.2 TEST CALIBRATION

As with the track calibration use, only the reference vehicle results are compared in this use and hence, its design is not variable for any particular performance issue. However, it may vary historically due to wear or climate and is assumed to be maintained to minimize these variations. The objectives of test calibration are to:

- Identify changes in performance due to test conditions
- Develop factors for normalizing the test results.

The variations which this use is designed to measure are those due to climatic conditions on the system at the time of the test. One obvious example of this use is the running of the reference vehicle in the test consist, not for direct comparison with the test vehicle discussed under baseline comparison, but to identify changes in the climatic test conditions at test times and their effect on issue under test. In a more general approach it may be possible to provide normalizing factors for each climatic variable, from the reference vehicle test results, assuming the vehicle remains constant and the track is maintained to a standard using other means of measurement. Thus, for example, humidity may be correlated with a particular reference vehicle response quantity.

O-2.3 BASELINE COMPARISON

The objective of the baseline test is the comparison and assessment of vehicle designs and only vehicle design variation is considered, all other variables due to climate, wear or track design are eliminated from Table O-1 or specially maintained constant. This results from the assumed running of the test and reference vehicles under identical conditions on the same track. Direct comparison is attempted between the response of the reference vehicle and the test vehicle in the same consist or in tests carried out consecutively. These results are used to infer comparisons between different tests and different or modified test vehicles using the same reference vehicle used for test calibration. The assumption is made that the test conditions are the same for both the test and reference vehicles in each test and that differences between tests may be compensated through comparison with the reference vehicle results for the particular performance issue under study. Track compliance variation is still possible due to variation in vehicle weight. It's importance is dependent on the performance issue under test.

O-2.4 PERFORMANCE EXTRAPOLATION TO SERVICE CONDITIONS

The objective of this use is to develop means of predicting the performance of new, perhaps experimental, test vehicles in service using the performance of the reference vehicle in test and under service conditions. The major test work is undertaken on the reference vehicle to provide a standard basis for comparison. The method reduces the need for putting untried vehicles into service conditions. The approach may be described as

- Carry out a baseline test (as described in Section O-2.3) for the test vehicle under consideration together with the reference vehicle
- Record reference vehicle performance under service conditions
- Infer the test vehicle's performance in service conditions.

The process is identified in Fig. O-1. For validity, the reference vehicle must have identical characteristics in service and under test. The service reference vehicle test variables are the same as in test and track calibration but only those variables identified as due to vehicle history are controllable through maintenance in the field. Variations due to track history, design, and test climate are not controllable since they relate directly to real world conditions. (In terms of Table O-1, this means that the controllable variables comprise the union between the controllable variables in test and track calibration for the particular performance issue subset).

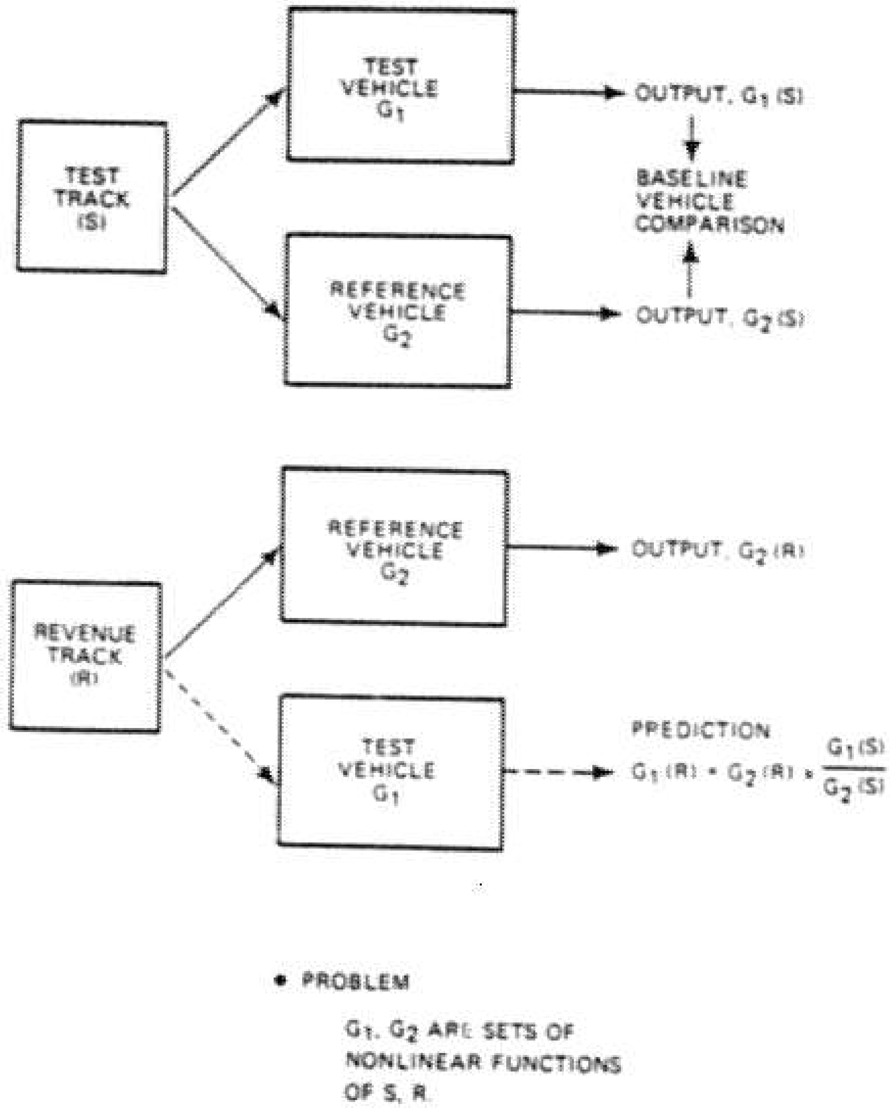


Figure O-1 The Process of Extrapolation to Service

O-2.5 CONSTRUCTION OF PERFORMANCE ISSUE TABLES

Using these concepts for the four reference vehicle uses, the sets of variables given in Table O-1, and knowledge of the dynamic processes during each performance issue, it is possible to discuss the validity of the reference vehicle concept for each issue. The process is summarized for the uses designated as follows.

0-2.5.1 Track Calibration

- Vehicle History - controlled (√)
- Track Design and History - to be measured √
- Test Climate - controlled (does not include vehicle design) (√)

0-2.5.2 Test Calibration

- Vehicle History - controlled (√)
- Track History - controlled (√)
- Test Climate - to be measured (does not include vehicle design) √

0-2.5.3 Baseline Use

- Vehicle design only - √
- Historical variations - (√)
- Lateral rail stiffness - (√)

0-2.5.4 Extrapolation to Service

- Union of Track and Test Calibration for extrapolation (only the test of the reference vehice in service is discussed under this heading. The complete process also involves a Baseline Test)

In the above √ indicate significant variability

◯ indicate control

hence (√) indicates a controlled variable

() special case of variability

O-3. REFERENCE VEHICLES AND PERFORMANCE ISSUES FOR FREIGHT CAR TESTING

As has been indicated in Table O-1, each performance issue in Appendix O-A has its own set of variable system characteristics. In this chapter the severity of their effect is discussed together with the subsets associated with each reference vehicle use. Mention is made of those which would normally vary if not controlled. This will be identified for track and reference vehicle maintenance requirements. Thus, for each performance issue a minimum set of system variables remains which must be deduced from the reference vehicle response or from some other special measurement. Each is discussed in turn following which conclusions are reached and summarized in Section O-3.8.

O-3.1 PI #1-HUNTING

Table O-2 summarizes the variable system characteristics for hunting tests and gives an indication of the severity of their effect on performance. The breakdown into each reference vehicle use and into those variables requiring control, (√), and those in which the reference vehicle response may be used as a measurement, √, is now discussed for each use.

O-3.1.1 Track Calibration

In this use, changes in the reference vehicle response indicate variations in track alignment, gauge, lateral

TABLE O-2
PERFORMANCE ISSUE NO. 1-HUNTING

CODE	PHYSICAL DESCRIPTION	VARIABLE SYSTEM CHARACTERISTIC	AFFECT ON PERFORMANCE ISSUES		SET OF CHARACTERISTICS* AFFECTING PERFORMANCE			
			MODERATE	SEVERE	TRACK CAL.	TEST CAL.	BASELINE USE	SERVICE
1.1	TRACK GEOMETRY	ALIGNMENT	✓		✓	⊘		✓
1.2		GAUGE		✓	✓	⊘		✓
2.3	TRACK COMPLIANCE	LATERAL RAIL STIFFNESS	✓		✓	✓	(✓)	✓
3.1	WHEEL-RAIL CONTACT	WHEEL PROFILE		✓	⊘	⊘	⊘	⊘
3.2		RAIL PROFILE		✓	✓	⊘		✓
3.3		SURFACE CREEP + SPIN		✓	⊘	✓	⊘	✓
5.2	BODY TO BOLSTER SUSPENSION	YAW DAMPING		✓	⊘	⊘	⊘	⊘
6.1	BODY COMPLIANCE	TORSIONAL STIFFNESS	✓				✓	
7.1	LADING/BODY INERTIA	MASS		✓			✓	
7.4		YAW RAD OF GYR		✓			✓	
7.5		C.G. POSITION	✓		⊘	⊘	⊘	⊘
8.1	TRUCK GEOMETRY	WHEEL RADIUS	✓				✓	
9.1	TRUCK COMPLIANCE	LATERAL BEARING STIFFNESS		✓			✓	
9.3		TRAM STIFFNESS		✓			✓	
10.3	TRUCK (BOLSTER) SUSPENSION	LATERAL STIFFNESS	✓				✓	

*⊘ – SUBSET THAT MUST BE CONTROLLED FOR THIS USE.
(✓) – CHARACTERISTICS POSSIBLY BUT NOT NORMALLY VARIABLE IN THIS USE.

rail stiffness and rail profile. Wheel profiles must be measured and controlled through regular turning to a standard. Wheel surface condition can greatly affect vehicle performance. Hunting is typified by the "critical" speed at which it commences and this is generally reduced with wheel/rail profiles of high "effective conicity" (change in the rolling radius difference between wheels on the same axle when displaced laterally). A profile giving a high enough effective conicity to promote hunting is desirable. The Canadian National Railway "worn wheel" profile is frequently used for this purpose and is suitable (Ref. 1). Rail profiles also contribute to effective conicity through the variation of position at which the wheel contacts the track. This is measurable from the vehicle response as a change in wavelength of the kinematic oscillation, i.e., the wandering from side to side during hunting. The amplitude may also be affected.

Like the effect of rail profile, the variation of gauge can give rise to variation in "effective conicity" with similar results. Together with alignment, gauge variation can also give rise to a lateral excitation thought to encourage hunting at lower critical speeds by forcing the wheelset into a limit cycle oscillation only stable above a certain amplitude (Ref. 2). The independent effect of alignment and lateral rail elasticity are moderate within the normal range of their values.

It is possible to conclude that a carefully maintained reference vehicle can be put to good effect in this use. Particular attention is required for maintenance of a consistently low level of friction at the centerplate (yaw damping). It will, however, remain difficult to establish which track variable is responsible for performance change, since some will effect the hunting in a superficially similar way. Since the techniques are available for measuring track parameters independently and are only moderately difficult to perform it is generally recommended that these be carried out. Of particular importance is the rail profile. Track compliance is presently a complex measurement which can be avoided using tolerances on reference vehicle response (Ref. 3 and 4).

The concept of controlling the rail/wheel surface condition by choosing the time of track testing may provide difficulties for some geographic locations and is important in the choice of a test site or season. This and rail profile may both benefit from independent measurement. However, measured wheelset response can also be used to identify track changes. More complete discussions of the effect on vehicle response due to variation in track profiles can be found in Ref. 5 and 6.

Analytic techniques now exist using vehicle and track models to differentiate between causes of track variation such as used in (Ref. 7). However, they have yet to be used specifically for such a purpose. With the advancing technology they will become increasingly important.

0-3.1.2 Test Calibration

In this use, lateral rail stiffness and its surface condition remain to be determined following careful maintenance of both track and vehicle to pre-determined standard. Of particular importance to the maintenance of the track, are gauge and rail profile and in the vehicle, truck yaw damping at the centerplate. The uncontrollable variable is the rail/wheel surface interface which may vary considerably and which is predominant in its effect on hunting. The reference vehicle may be used with confidence to identify whether a change has taken place, since this is the only significant variable unaccounted for. Freight vehicles of present design have similar suspension geometry and those which hunt tend to have similar characteristics. They are generally light weight vehicles and may have worn wheels. A reference vehicle should also have these characteristics. In its most complete use, the reference vehicle response can be measured to identify the surface condition directly, if the measurements made contain the necessary wheelset forces and displacements, using an analytical vehicle model. This use of the reference vehicle would be experimental.

0-3.1.3 Baseline Use

Variables identified for this use are all due to vehicle differences. Those having a severe effect, such as wheel profile, surface conditions and yaw damping, may be maintained to give similarity between the reference vehicle and test vehicle. However, there remain other variables of severity which are a consequence of the design, such as lading/body mass, yaw inertia, lateral axle bearing stiffness and truck tram (out-of-square) stiffness. These are also important design variables and their optimization may be the reason for the test. The usefulness of direct comparison between the reference and test vehicles is therefore dependent upon the number of different design variables they have or the instrumentation applied to both test and reference vehicles. If the important ones mentioned are all significantly different, no design related conclusion can be reached directly from test results without further analysis involving a significant number of measured response parameters on both vehicles. However, if the reference vehicle is of a similar type and the test used to identify improvements in a particular area, such as a sidebearing change, then meaningful direct comparison is possible.

At the present date there are a large number of computer simulations of freight car hunting, e.g., Ref. 5, which are relatively inexpensive and can be used to identify the significance of hunting test results. To be used properly the models require knowledge of the vehicle variables as tested. For this performance issue, values of the significant variables periodically measured on the reference vehicle may remain constant for a significant time. Since the utility of the reference vehicle is related to its similarity with the vehicle being tested for hunting performance, it makes sense to choose a reference vehicle in common usage susceptible to hunting as in the previous use.

O-3.1.4 Extrapolation to Service

The process of extrapolation into service includes the baseline use for the reference vehicle. The preceding discussion therefore also applies to this process. The remaining test comparing the performance of the reference vehicle on test track and in service has characteristics similar to both test and track calibration. However, the number of uncontrollable variations is increased due to the nature of the climate and geography in service. The most important variations are related to the region of wheel/rail contact and in particular, to the profiles and friction and creep coefficients. Service conditions provide a variety of input conditions, occurring simultaneously, which can show similar effects in the response. Hunting response is generally characterized as body yaw with truck kinematic oscillation, the latter comprising lateral and yaw motion of the wheelsets. These amplitudes if measured on the reference vehicle in service and on test track will give an indicator of the test severity. The validity of the extrapolation is primarily limited by the baseline test and measurements and analyses associated with it.

O-3.2 PI #2-TWIST AND ROLL

Table O-3 shows the variable system characteristics affecting response in twist and roll. Once again those to be controlled for each use are indicated (√).

O-3.2.1 Track Calibration

The variations in the reference vehicle response in this use are track surface and crosslevel, vertical track stiffness and damping and rail profile. Of these only cross-level has a severe effect on the vehicle response. It may prove difficult to calibrate the track under consistent weather conditions in the north where freezing is possible. However, the reference vehicle, maintained to give consistency to wheel profile and surface, suspension roll stiffness (e.g., sidebearer clearance), and lading, will give a very effective measure of variations in track condition through measurement of roll angle response. Further insight has been found from use of analytic models as with Ref. 8.

O-3.2.2 Test Calibration

With the track maintained to the required standard, the most significant test variables will be associated with vertical snubbers due perhaps to changes in the friction co-efficient with humidity and to track compliance variations. Very little qualitative work has been documented identifying the effect of weather on the latter. Undoubtedly freezing of a wet ballast or subsoil will increase its rigidity. The reference vehicle use in this manner is experimental.

TABLE O-3

PERFORMANCE ISSUE NO. 2-TWIST AND ROLL

CODE	PHYSICAL DESCRIPTION	VARIABLE SYSTEM CHARACTERISTIC	AFFECT ON PERFORMANCE ISSUES		SET OF CHARACTERISTICS* AFFECTING PERFORMANCE			
			MODERATE	SEVERE	TRACK CAL	TEST CAL	BASELINE USE	SERVICE
1.3	TRACK GEOMETRY	SURFACE PROFILE	✓		✓	⊙		✓
1.4		CROSS LEVEL		✓	✓	⊙		✓
2.1	TRACK COMPLIANCE	VERTICAL TRACK STIFFNESS	✓		✓	✓		✓
2.2		VERTICAL DAMPING	✓		✓	✓		✓
3.1	WHEEL-RAIL CONTACT	WHEEL PROFILE	✓		⊙	⊙	⊙	⊙
3.2		RAIL PROFILE	✓		✓	⊙		✓
3.3		SURFACE C[illegible] + SPIN	✓		⊙	✓	⊙	✓
4.1	BODY GEOMETRY	TRUCK CENTERS		✓			✓	
5.1	BODY TO BOLSTER SUSPENSION	ROLL STIFFNESS		✓	⊙	⊙	✓	⊙
6.1	BODY COMPLIANCE	TORSIONAL STIFFNESS	✓				✓	
7.1	LADING/BODY INERTIA	MASS		✓			✓	
7.2		ROLL RAD OF GYR		✓			✓	
7.5		C.G. POSITION		✓	⊙	⊙	✓	⊙
9.1	TRUCK COMPLIANCE	LATERAL BEARING STIFFNESS	✓				✓	
10.1	TRUCK (BOLSTER) SUSPENSION	VERTICAL STIFFNESS		✓			✓	
10.2		VERTICAL DAMPING		✓	⊙	(✓)	(✓)	✓
10.3		LATERAL STIFFNESS	✓				✓	

* ⊙ – SUBSET THAT MUST BE CONTROLLED FOR THIS USE.
(✓) – CHARACTERISTICS POSSIBLY BUT NOT NORMALLY VARIABLE IN THIS USE.

0-3.2.3 Baseline Use

Many of the critical parameters in twist and roll are vehicle design dependent. Using a reference vehicle reasonably geometrically similar to the test vehicle, direct comparison is possible. Otherwise additional simulation analysis is required. The importance of this geometric relationship is discussed in Ref. 9 which identifies the "geometric transfer functions". It is necessary to select a reference vehicle in this performance issue which is known to behave badly and will have characteristics not unlike a poorly behaving test vehicle. Since twist is a structural mode which varies with body design, roll is the more important use for the reference vehicle which should have a truck center distance close to rail length (39 ft.), and a roll stiffness characteristic (including sidebearing clearance) giving a roll frequency close to 0.7 Hz for a laden car with a high body center of gravity.

The significance of roll in this performance issue is the large and potentially unsafe roll oscillation excited by track crosslevel variation over each successive rail length. However, the activity of the trucks during derailment may be significant. Tests have shown considerable truck activity (Ref. 10). Measurements of the wheelset lateral and yaw dynamics may be required to ensure compatibility between vehicles.

0-3.2.4 Extrapolation to Service

The variation in rail/wheel surface condition during the test of the reference vehicle and the climatic variation of vertical and roll snubbing in service will cause differences between the severity of the track test and service conditions which may be identified. However, the nature of the performance issue demands a high roll response in service as in the track and test calibration. Any subsequent extrapolation for the test vehicle, using the baseline test results, has the same limitation expressed in Section O-3.2.3.

O-3.3 PI #3-PITCH AND BOUNCE

The variable system characteristics described in Table O-4, tracks with staggered joints, and design of freight cars combine to make this performance issue relatively safe. All variable system characteristics have therefore been regarded as having only a moderate effect. The major difference between twist and roll and pitch and bounce are in the frequency and modal shape. Both exercise the vertical suspension. Use of the reference vehicle for this issue may provide a means of track and test calibration for other issues.

O-3.3.1 Track Calibration

The track variables which affect the response of the vehicle in this issue are surface, crosslevel, vertical track stiffness and damping. Vertical response of the maintained reference vehicle suspension can be measured to calibrate the track but not directly separate the causes and this may vary with vehicle weight. Test runs with more than one reference vehicle may provide more insight. Recommendations on the nature of the required track maintenance will not be possible from reference vehicle response without additional measurements. An improved assessment of the cause may be possible using spectral analysis of the measured suspension movement (Ref. 11).

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TABLE O-4
PERFORMANCE ISSUE NO. 3-PITCH AND BOUNCE

CODE	PHYSICAL DESCRIPTION	VARIABLE SYSTEM CHARACTERISTIC	AFFECT ON PERFORMANCE ISSUES		SET OF CHARACTERISTICS* AFFECTING PERFORMANCE			
			MODERATE	SEVERE	TRACK CAL.	TEST CAL.	BASELINE USE	SERVICE
1.3	TRACK GEOMETRY	SURFACE PROFILE	✓		✓	⊙		✓
1.4		CROSS LEVEL	✓		✓	⊙		✓
3.1	TRACK COMPLIANCE	VERTICAL TRACK STIFFNESS	✓		✓	✓		✓
3.2		VERTICAL DAMPING	✓		✓	✓		✓
4.1	BODY GEOMETRY	TRUCK CENTERS	✓				✓	
6.2	BODY COMPLIANCE	VERTICAL BENDING STIFFNESS	✓				✓	
7.3	LADING/BODY INERTIA	PITCH RAD OF GYR	✓				✓	
7.5		C.G. POSITION	✓		⊙	⊙	⊙	⊙
10.1	TRUCK (BOLSTER) SUSPENSION	VERTICAL STIFFNESS	✓				✓	
10.2		VERTICAL DAMPING	✓		⊙	(✓)	(✓)	✓

*⊙ – SUBSET THAT MUST BE CONTROLLED FOR THIS USE.
(✓) – CHARACTERISTICS POSSIBLY BUT NOT NORMALLY VARIABLE IN THIS USE.

0-3.3.2 Test Calibration

Since vertical track compliance is the most significant variable following recommended track maintenance, use of the reference vehicle may provide a method of studying its effect with variation in climate. An investigation of this type with a suitable analytic model can provide factors relating test results to test climate for use in assessing other issues such as rock and roll.

0-3.3.3 Baseline Use

Tests for pitch and bounce response are similar to tests for twist and roll, but the dominant modes of activity are different. If the test and reference vehicles differ significantly, the response will differ and will require analysis to resolve the significant causes of the different response as measured. However similarity between vehicles may render an immediate interpretation directly from the results. A badly behaving reference vehicle is an unlikely choice for comparison, since freight vehicles generally behave well in this mode.

0-3.3.4 Extrapolation to Service

The test of the reference vehicle in service will give an indication of the severity of any special test undertaken for this performance issue, particularly since the climatic conditions have little effect at test time. The exception may be the indication of variations in track compliance. An assessment of test severity is still possible, especially for light vehicles.

0-3.4 PI #4-YAW AND SWAY

The variable system characteristics and the severity are shown in Table 0-5 for this performance issue. Derailments have occurred, particularly following track panel shift and rail rollover. Rail/wheel forces can become large and are dependent upon the contact conditions and vehicle modal response in yaw and sway. Since the issue is complex (Ref. 12) many system variables have a potentially severe effect and are so designated in Table 0-5. As the name implies, the mode of the oscillation has closely coupled yaw and sway content until flange contact of the wheel on rail.

0-3.4.1 Track Calibration

Maintenance of the reference vehicle in use in this issue is necessary to ensure consistent wheel profiles, roll stiffness, yaw damping, position of the center of gravity of the load and snubber action. In addition, control of the climate at the time of this test through choice of test time and weather is assumed. The remaining variables which the reference vehicle response indicates are track alignment and gauge, rail lateral compliance and rail cross sectional profile. These are all rated as having a severe effect on the response although the last two become severe only under rail climbing conditions.

The severity of these characteristics are amplitude/speed dependent and use may be made of this to separate their effects and to identify the condition of the track. A low speed run over perturbed track, sufficient to excite the vehicle response without severe flange contact, may be used as an indicator of track condition in alignment and gauge by measurement of the body response in yaw and roll and its variation from previous runs. Runs at worst response speed may

TABLE O-5

PERFORMANCE ISSUE NO. 4-YAW & SWAY

CODE	PHYSICAL DESCRIPTION	VARIABLE SYSTEM CHARACTERISTIC	AFFECT ON PERFORMANCE ISSUES		SET OF CHARACTERISTICS* AFFECTING PERFORMANCE			
			MODERATE	SEVERE	TRACK CAL	TEST CAL	BASELINE USE	SERVICE
1.1	TRACK GEOMETRY	ALIGNMENT		✓	✓	⊙		✓
1.2		GAUGE		✓	✓	⊙		✓
2.3	TRACK COMPLIANCE	LATERAL RAIL STIFFNESS		✓	✓	✓		✓
3.1	WHEEL-RAIL CONTACT	WHEEL PROFILE		✓	⊙	⊙	⊙	⊙
3.2		RAIL PROFILE		✓	✓	⊙		✓
3.3		SURFACE CREEP + SPIN		✓	⊙	✓		✓
4.1	BODY GEOMETRY	TRUCK CENTERS		✓			✓	
5.1	BODY TO BOLSTER SUSPENSION	ROLL STIFFNESS		✓	⊙	⊙	✓	⊙
5.2		YAW DAMPING	✓		⊙	⊙	⊙	⊙
7.1	LADING/BODY INERTIA	MASS		✓			✓	
7.2		ROLL RAD OF GYR		✓			✓	
7.4		YAW RAD OF GYR		✓			✓	
7.5		C.G. POSITION		✓	⊙	⊙	⊙	⊙
8.1	TRUCK GEOMETRY	WHEEL RADIUS	✓				✓	
9.1	TRUCK COMPLIANCE	LATERAL BEARING STIFFNESS		✓			✓	
9.3		TRAM STIFFNESS		✓			✓	
10.1	TRUCK (BOLSTER) SUSPENSION	VERTICAL STIFFNESS		✓			✓	
10.2		VERTICAL DAMPING		✓	⊙	(✓)	(✓)	✓
10.3		LATERAL STIFFNESS	✓				✓	

* ⊙ – SUBSET THAT MUST BE CONTROLLED FOR THIS USE.
(✓) – CHARACTERISTICS POSSIBLY BUT NOT NORMALLY VARIABLE IN THIS USE.

then be accompanied by rail/wheel force measurement to provide an assessment of rail lateral compliance. Further runs with reference vehicles of different weight may be necessary to establish the effect of compliance under varying static loads. A fundamental measure of rail profile is again desirable.

O-3.4.2 Test Calibration

With the track and reference vehicle maintained to the required standards, there remain only lateral rail stiffness, snubbing friction if affected by weather, and rail surface condition as variables for which this calibration test is carried out. The effect of the rail stiffness and surface condition under severe flanging conditions are complex. It is unlikely that a simple, reliable and universally applicable set of factors are possible without the support of analytic models. One method of separating the effects would be to measure lateral track stiffness directly and use an analytic model to identify its effect in vehicle response. As with the hunting issue, complex fundamental measurement of wheel/rail forces, moments and dynamics may be used to provide the most direct comparison between tests accounting for test conditions without further analysis.

O-3.4.3 Baseline Use

The vehicle design parametric variables, identified in Table O-5 as not maintainable for consistent performance, are important to the yaw and sway response of the vehicle. Each different vehicle design will provide a different response with its own modal response ratios and worst frequency. If the vehicles are substantially similar, direct baseline test comparison is useful in identifying critical differences in vehicle response.

The conditions of derailment and the proximity to derailment in this issue are complex, yet they frequently comprise the sole test objective in this use. They involve wheelset lateral position and velocity, yaw angle and angular velocity, rotational speed and acceleration, wheel load, profile shapes of both wheel and rail and surface conditions. Analytic models of the process are just being perfected (Ref. 13) which can predict derailment behavior. There remains considerable difficulty in assessing derailment proximity without testing to derailment. Simple indicators such as the L/V ratio, monitored during tests of vehicles in this performance issue in Japan (Ref. 14) have been shown to be incomplete (Ref. 15). Difficulties have also arisen in the measuring methods for this issue and for subsequent issues (Ref. 16).

The most complete use for the reference vehicle in this baseline comparison is to provide analytical model validation and parameter identification under identical test conditions so that the model of the test vehicle can be used to assess its proximity to derailment. This is particularly true if the reference vehicle analytic model has been validated up to and including derailment under previous testing. The process of changing vehicle design parameters in an analytic model does not lead to inaccurate conclusions so long as the critical wheelset and rail parameters are known or do not change between models. If the reference and test vehicles are geometrically similar in most respects direct comparison is a meaningful way in which to identify the effect of the variation without recourse to analytic modeling.

O-3.4.4 Extrapolation to Service

In order to provide a baseline for subsequent extrapolation of the test vehicle results to indicate its performance in service, the reference vehicle must be of a type which responds with large amplitude itself in this issue in service. Evidence of this may be sought from accident statistics (Ref. 17). The limitations of direct extrapolation and the need for analytic models for all but the simplest comparisons are similar to those expressed in the discussion of the baseline test use. Extrapolation to service use adds the difficulty that the track conditions in service, identified in Table O-5, can not be measured from the reference vehicle beahvior. Some estimate of the conditions leading to service derailments have been attempted through model testing using the reference vehicle parameters following model validation.

O-3.5 PI #5-STEADY-STATE CURVING

Under normal operation, steady-state curving does not lead to derailment. It more often results, with the traditional freight car truck design, in bad wear on both wheels and rails which may subsequently promote a derailment condition. The steady-state curving process, although not simple, is now well understood (Ref. 18). The measurements required relate to rail/wheel forces and positions.

By its very nature this performance issue requires that the track provide no dynamically varying input to the vehicle response. The constant curve must be long enough for all transients to decay to a small value. In Table O-6, alignment implies variation in curvature, and crosslevel variation in superelevation. Since the motion of interest is in the plane of the track, crosslevel variation does not generally have a severe effect on vehicle performance. In the steady condition gauge and alignment variation combine to represent variation in alignment on each rail, the outer rail alignment

TABLE O-6

PERFORMANCE ISSUE NO. 5-STEADY-STATE CURVING

CODE	PHYSICAL DESCRIPTION	VARIABLE SYSTEM CHARACTERISTIC	AFFECT ON PERFORMANCE ISSUES		SET OF CHARACTERISTICS* AFFECTING PERFORMANCE			
			MODERATE	SEVERE	TRACK CAL.	TEST CAL.	BASELINE USE	SERVICE
1.1	TRACK GEOMETRY	ALIGNMENT		✓	✓	⊙		✓
1.2		GAUGE		✓	✓	⊙		✓
1.4		CROSS LEVEL	✓		✓	⊙		✓
1.5		CURVATURE	✓		✓	⊙		✓
1.6		SUPERELEVATION	✓		✓	⊙		✓
3.1	WHEEL-RAIL CONTACT	WHEEL PROFILE		✓	⊙	⊙	⊙	⊙
3.2		RAIL PROFILE		✓	✓	⊙		✓
3.3		SURFACE CREEP - SPIN		✓	⊙	✓		✓
7.1	LADING/BODY INERTIA	MASS		✓			✓	
7.5		C.G. POSITION	✓		⊙	⊙	⊙	⊙
8.1	TRUCK GEOMETRY	WHEEL RADIUS	✓				✓	
9.3	TRUCK COMPLIANCE	TRAM STIFFNESS		✓			✓	
10.3	TRUCK (BOLSTER) SUSPENSION	LATERAL STIFFNESS	✓				✓	

* ⊙ - SUBSET THAT MUST BE CONTROLLED FOR THIS USE.
(✓) - CHARACTERISTICS POSSIBLY BUT NOT NORMALLY VARIABLE IN THIS USE.

being essential to the steady-state path of the wheelset. All track variables have been identified as having a potentially severe effect in Table O-6 although the severity is dependent on the way in which they combine dynamically.

Rail and wheel profiles and surface conditions have an important effect on the forces generated during curving.

O-3.5.1 Track Calibration

Lateral leading wheelset activity of the maintained reference vehicle during flanging is a direct measure of outer rail alignment and gauge. Its dynamic content can be used in assessing track maintenance requirements. Rail profile effects may be apparent in the same response but are more likely to be seen as a variation in force. Direct measurement of this profile is desirable.

O-3.5.2 Test Calibration

Table O-6 shows that the controlled subset, indicating maintenance of vehicle and track, leaves only surface creepage and spin characteristics as a variable at test time. The low wheel/rail performance is particularly important here in that it provides a means of establishing the required characteristic which includes the value of the limiting coefficient of friction. This requires a knowledge of wheelset position relative to the track, the wheel and rail profiles and the forces and moments acting. These measurements are not simple. In particular, longitudinal forces are not presently measured using instrumented wheelsets in North America tests. However, approximations can be made using results from inexpensive analytic models (Ref. 18). Because there is no requirement for a dynamic model, the analysis can be performed at minimum cost. Apart from the calculation of fundamental characteristics, the reference vehicle is a good general measurement of test condition consistency in this performance issue.

O-3.5.3 Baseline Use

The vehicle design parameters having severe influence on steady-state vehicle curving are wheelset load ("mass" in Table O-6) and truck stiffnesses in the plane of the rail. Direct comparison of vehicle performance is therefore possible and is greatly enhanced by the inexpensive analyses previously mentioned, particulary if wear is to be studied. Basic measurements such as angle-of-attack of the wheelsets to the rail and lateral wheel/rail forces also provide a fundamental comparison of vehicle performance. Since the response is not dynamic the measured duration is irrelevant, greatly simplifying the assessment of proximity to derailment. This use for the reference vehicle provides a sound assessment of the relative merits of vehicles during curving.

O-3.5.4 Extrapolation to Service

The nature of this performance issue limits the extrapolation that can be made since it excludes the possibility of dynamic effects. It is therefore not a possible use for the reference vehicle. The reference vehicle can be used to ascertain what importance steady-state conditions play in identifying service use. This is perhaps better carried out using the records of track geometry available (Ref. 19).

O-3.6 PI #6-SPIRAL NEGOTIATION

Derailments during spiral negotiations are not infrequent, especially with torsionally stiff vehicles and constant contact side bearings. Rapid changes in superelevation (or crosslevel) cause wheel unloading which, together with high lateral forces, produce rail climbing potential, especially where the terrain leads to short spiral lengths. Uneven variation in curvature or alignment increases the potential for derailment Table O-7 gives an assessment of the severity of these track characteristics on the vehicle response in spirals. Lateral rail stiffness is judged as having only a moderate effect since the offending vehicles are often light. All vehicle characteristic associated with static body roll, especially differential roll between trucks are rated as having a severe effect. In addition, truck stiffnesses in the track plane have an important effect in the development of guiding forces.

O-3.6.1 Track Calibration

Track geometry records are the most direct measurement of the track variables listed in Table O-7. However, they may not exhibit similar track loading and in their absence similar information can be inferred from reference vehicle response. Short term transients during spiral negotiation are frequently seen in test records, especially if the test vehicle has a natural frequency and mode excited by the input. These can be noted and their location identified for track maintenance. Static measurements or slow speed runs may be used, for example roll response may be measured as an indicator of superelevation and lateral position during flange contact an indicator of high rail alignment. Rail profile is

TABLE O-7

PERFORMANCE ISSUE NO. 6-SPIRAL NEGOTIATION

CODE	PHYSICAL DESCRIPTION	VARIABLE SYSTEM CHARACTERISTIC	AFFECT ON PERFORMANCE ISSUES		SET OF CHARACTERISTICS* AFFECTING PERFORMANCE			
			MODERATE	SEVERE	TRACK CAL	TEST CAL	BASELINE USE	SERVICE
1.1	TRACK GEOMETRY	ALIGNMENT		✓	✓	⊙		✓
1.2		GAUGE	✓		✓	⊙		✓
1.3		SURFACE PROFILE	✓		✓	⊙		✓
1.4		CROSS LEVEL		✓	✓	⊙		✓
1.5		CURVATURE		✓	✓	⊙		✓
1.6		SUPERELEVATION		✓	✓	⊙		✓
2.1	TRACK COMPLIANCE	VERTICAL TRACK STIFFNESS		✓	✓	✓		✓
2.3		LATERAL RAIL STIFFNESS	✓		✓	✓	(✓)	✓
3.1	WHEEL-RAIL CONTACT	WHEEL PROFILE		✓	⊙	⊙	⊙	⊙
3.2		RAIL PROFILE		✓	✓	⊙		✓
3.3		SURFACE CREEP - SPIN		✓	⊙	✓	⊙	✓
4.1	BODY GEOMETRY	TRUCK CENTERS		✓			✓	
5.1	BODY TO BOLSTER SUSPENSION	ROLL STIFFNESS		✓	⊙	⊙	✓	⊙
5.2		YAW DAMPING	✓		⊙	⊙	✓	⊙
6.1	BODY COMPLIANCE	TORSIONAL STIFFNESS		✓			✓	
7.1	LADING/BODY INERTIA	MASS		✓			✓	
7.2	ROLL RAD OF GYR	ROLL RAD OF GYR	✓				✓	
7.4		YAW RAD OF GYR		✓			✓	
7.5		C.G. POSITION	✓		⊙	⊙	⊙	⊙
8.1	TRUCK GEOMETRY	WHEEL RADIUS	✓				✓	
9.1	TRUCK COMPLIANCE	LATERAL BEARING STIFFNESS	✓				✓	
9.3		TRAM STIFFNESS		✓			✓	
10.1	TRUCK (BOLSTER) SUSPENSION	VERTICAL STIFFNESS		✓			✓	
10.2		VERTICAL DAMPING	✓		⊙	(✓)	(✓)	✓
10.3		LATERAL STIFFNESS		✓			✓	

* ⊙ - SUBSET THAT MUST BE CONTROLLED FOR THIS USE
(✓) - CHARACTERISTICS POSSIBLY BUT NOT NORMALLY VARIABLE IN THIS USE

important and difficult to assess from reference vehicle response. It is readily measured directly using a rail profilometer. Wheel profile and surface condition must be controlled by maintenance and/or running-in to clean the wheel surface. In this use it is important to maintain the body to bolster roll characteristic by checking sidebearings and gaps and the bolster roll characteristic by checking snubber action.

3.6.2 Test Calibration

Maintenance and control of the reference vehicle, as in track calibration, together with track geometric maintenance, give lateral and vertical rail stiffnesses and surface condition as the remaining variables in Table O-7. This is rather similar to PI #4 Yaw and Sway, and not greatly different from PI #5, Steady-State curving. The difference is in the perceived importance of rail elastic response which is directly affected by the dynamic activity of the wheelsets and the degree of vertical unloading. The complexity of the measurement or requirement for analytic modeling lies between a full description and measurement as in yaw and sway and the direct steady wheel on rail measurements discussed in steady-state curving, although a more complex vertical track model is desirable in this issue. Spiral negotiation track input commences as in yaw and sway but finishes in a linear varying curved path in which flange contact persists as with steady-state curving but with the addition of wheel unloading. In flange contact the forces and wheelset position will vary with curvature as well as with surface conditions. It is again unlikely, therefore, that a simple, reliable set of factors can be generated without supporting analytical modeling and fundamental wheelset motion measurement sufficiently to identify the effect of test variables on vehicle response. However, records may be available in conjunction with less complex performance issues if tested concurrently.

0-3.6.3 Baseline Use

Spiral negotiation exercises many of the vehicle design parameters. Wheel unloading is a predominantly steady condition due to rate of change of superelevation with distance along the track. Roll and yaw resonance are therefore discounted in this performance issue and regarded as having only a moderate effect. Steering forces are important. Direct baseline comparison may be misleading due to the complex combination of high lateral force response and vertical unloading. In some vehicles simple static wheel unloading is sufficient to cause derailment.

Since wheel unloading may be measured statically at the worst point in the curve a direct measure of this can be made on both test and reference vehicle for comparison. The reference vehicle is not necessary in this test since an absolute measure of wheel unloading and a limit to its value may be set directly. However, tests on a reference vehicle may help in establishing the initial safe-critical value for impending derailment.

If the judgment of unloading is made separately, comparison between test and reference vehicle in the spiral is reduced to the comparison of guiding forces and lateral wheelset response. Some measure of direct comparison is possible but can not be directly extrapolated to performance in other spirals because of the differences in the effect of wheel unloading and steering forces on different vehicles.

0-3.6.4 Extrapolation to Service

The testing of the reference vehicle in service for this performance issue requires continuous recording of guidance and vertical wheel forces in order to provide the necessary comparison between test and service conditions. For reasons mentioned under Baseline Testing above, variation between test and reference vehicle design will produce effects on derailment potential requiring a study of both lateral and vertical force response. The complexity of this consideration suggests a supporting analytic model. No such model currently exists in this country although a change to TASC's SIMCAR program (Ref. 20) is being considered to allow full freight vehicle simulation in spirals.

O-3.7 PI #7-DYNAMIC CURVING

This performance issue exercises nearly all the variable system characteristics identified in Table O-1 and listed in Table O-8 for this scenario. Vehicle performance is seldom discussed in such complex terms and analytic models are only just reaching the complexity necessary to simulate the full vehicle dynamics required (Ref. 20). However, the principal concern is with curving performance and as such the primary activity is in the plane of the rails. Roll activity of the body is important and vertical vehicle and track stiffness is therefore important. The response includes transient effects.

O-3.7.1 Track Calibration

As with all other performance issues discussed here, the test track geometry may be established by direct measurement on site or with a track geometry car. The problem with such methods lies in the fact that they are not measured under the load conditions seen during testing. If used, track recording cars are light compared to a fully laden 100 ton freight car and apart from hunting and static wheel unloading

TABLE O-8

PERFORMANCE ISSUE NO. 7-DYNAMIC CURVING

CODE	PHYSICAL DESCRIPTION	VARIABLE SYSTEM CHARACTERISTIC	AFFECT ON PERFORMANCE ISSUES		SET OF CHARACTERISTICS* AFFECTING PERFORMANCE			
			MODERATE	SEVERE	TRACK CAL	TEST CAL	BASELINE USE	SERVICE
1.1	TRACK GEOMETRY	ALIGNMENT		✓	✓	⊙		✓
1.2		GAUGE		✓	✓	⊙		✓
1.3		SURFACE PROFILE	✓		✓	⊙		✓
1.4		CROSS LEVEL		✓	✓	⊙		✓
1.5		CURVATURE		✓	✓	⊙		✓
1.6		SUPERELEVATION		✓	✓	⊙		✓
2.1	TRACK COMPLIANCE	VERTICAL TRACK STIFFNESS	✓		✓	✓		✓
2.2		VERTICAL DAMPING	✓		✓	✓		✓
2.3		LATERAL RAIL STIFFNESS		✓	✓	✓		✓
3.1	WHEEL RAIL CONTACT	WHEEL PROFILE		✓	⊙	⊙	⊙	⊙
3.2		RAIL PROFILE		✓	✓	⊙		✓
3.3		SURFACE CREEP + SPIN		✓	⊙	✓		✓
4.1	BODY GEOMETRY	TRUCK CENTERS		✓			✓	
5.1	BODY TO BOLSTER SUSPENSION	ROLL STIFFNESS		✓	⊙	⊙	✓	⊙
5.2		YAW DAMPING	✓		⊙	⊙	✓	⊙
6.1	BODY COMPLIANCE	TORSIONAL STIFFNESS	✓				✓	
7.1	LADING/BODY INERTIA	MASS		✓			✓	
7.2		ROLL RAD OF GYR		✓			✓	
7.4		YAW RAD OF GYR	✓				✓	
7.5		C.G. POSITION		✓	⊙	⊙	⊙	⊙
8.1	TRUCK GEOMETRY	WHEEL RADIUS	✓				✓	
9.1	TRUCK COMPLIANCE	LATERAL BEARING STIFFNESS		✓			✓	
9.2		TRAM STIFFNESS		✓			✓	
10.1	TRUCK (BOLSTER) SUSPENSION	VERTICAL STIFFNESS	✓				✓	
10.2		VERTICAL DAMPING	✓		⊙	(✓)	(✓)	✓
10.3		LATERAL STIFFNESS		✓			✓	

*⊙ - SUBSET THAT MUST BE CONTROLLED FOR THIS USE
(✓) - CHARACTERISTICS POSSIBLY BUT NOT NORMALLY VARIABLE IN THIS USE

it is the laden cars which are most susceptible to derailment under dynamic conditions. The concept of using a reference vehicle to identify changes to track under laden conditions is therefore attractive, particularly for Twist and Roll, Yaw and Sway and this performance issue.

The particular difficulty for this issue is that the track input varies in all six track geometric values generally recorded as well as track compliance. Consequently, it becomes difficult to identify with any precision, the nature of the track maintenance required due to differences in the reference vehicle behavior during testing. Fundamental measurement of vertical and lateral motion at each wheel is possible. The lateral position is an indicator of outside rail alignment, while the wheel is in flange contact with the rail. However, the position of the rail is that as dynamically laden and includes rail movement due to compliant track. This requires knowledge of the wheel/rail forces and separate measurement of track compliance under laden conditions in order to separate any changes in track by cause. No method of maintaining track for compliance has been tested sufficiently to ensure reliability. If the test track is on good "hard" foundations, track compliance may be neglected as a variable. Under these circumstances the reference vehicle performance may be used to calibrate the track and indicate the severity of changes in its geometry.

O-3.7.2 Test Calibration

The severity of the test reduces, as indicated in Table O-8, to consideration of track compliance, surface condition and snubbing effects. If track compliance is regarded as consistent or measured and maintained separately, the remaining variables can be assessed, since they have substantially different effects. Low rail performance can be used to measure creepage coefficients up to and including full slippage if the measurement system on the reference vehicle is appropriate. A more complete discussion of this possibility was given in preceding Test Calibration discussion, particularly Section O-3.5.2. In this issue varying wheel loads is an additional difficulty. This could be mitigated somewhat through analytic models of the wheel rail process if and when they are available.

O-3.7.3 Baseline Use

Unless the potential design variables in Table O-8 are reduced to a particular changed characteristic such as a damping device, direct comparison is only possible between the reference vehicle and test vehicle with considerable measurement and analytic model capability to identify overall performance. The selection of a limited measurement to compare the derailment safety of the test and reference vehicle is of uncertain validity at best and at worst could lead to a misleading assessment of the vehicle performance. It is recommended that efforts be made towards a full explanation of derailment potential through validation of vehicle models and subsequent use of these models for performance assessment. If the test and reference vehicles are of the same basic design direct comparison of results is possible.

3.7.4 Extrapolation to Service

Following the discussion under Baseline Use, no extrapolation is recommended without validated analytic model support in this complex performance issue unless the vehicles used are similar in design.

0-4. CONCLUSIONS: REFERENCE VEHICLE UTILITY AND CHOICE

The preceding Section O-3 discussed and identified the advisability of the uses of freight reference vehicles on technical grounds, making suggestions in general terms on how the vehicles should be used, the importance of maintenance where needed to ensure consistency in vehicle response, and the necessity for analytical support. Each performance issue was considered separately although some comments were made linking the issues for optimum reference vehicle use. It was assumed throughout that instrumentation packages discussed elsewhere (Ref. 21) were available but that a minimum level of complexity represented the best use for the reference vehicle.

In this section the costs of alternative measurements are discussed, conclusions are made on the utility of reference vehicles and their choice is discussed.

0-4.1 ALTERNATIVE MEASUREMENT METHODS

The present state of the art in measurement of the variable system characteristics is summarized in Table O-9 with a statement on the present alternative method to the reference vehicle use. These alternative methods do not imply any selectivity for the performance issues discussed. They range from easy, such as the measurement of wheel radius or truck center distance, to extremely hard, such as the measurement of creep and spin characteristics which cannot presently be carried out in the field. The cost is related to the difficulty.

TABLE 0-9

ALTERNATIVE MEASUREMENTS

CODE	PHYSICAL DESCRIPTION	VARIABLE SYSTEM CHARACTERISTIC	STATUS OF PRESENT MEASUREMENT METHOD: NEW	NEEDS MOD.	WILL DO	GOOD	MEASUREMENT DIFFICULTY: EASY	MOD-ERATE	HARD	POSSIBLE METHOD
1.1	TRACK GEOMETRY	ALIGNMENT			✓			✓		
1.2		GAUGE			✓			✓		
1.3		SURFACE PROFILE			✓			✓		TRACK GEOMETRY CAR OR WAYSIDE
1.4		CROSS LEVEL			✓			✓		
1.5		CURVATURE			✓			✓		
1.6		SUPERELEVATION			✓			✓		
2.1	TRACK COMPLIANCE	VERTICAL TRACK STIFFNESS		✓					✓	
2.2		VERTICAL DAMPING		✓					✓	SPECIAL CAR OR RIG
2.3		LATERAL RAIL STIFFNESS		✓					✓	
3.1	WHEEL-RAIL CONTACT	WHEEL PROFILE			✓			✓		PROFILOMETER AND COMPUTER
3.2		RAIL PROFILE			✓			✓		
3.3		SURFACE CREEP + SPIN	✓						✓	NEEDS DESIGN
4.1	BODY GEOMETRY	TRUCK CENTERS				✓	✓			TAPE MEASURE
5.1	BODY TO BOLSTER SUSPENSION	ROLL STIFFNESS			✓			✓		FIELD TEST
5.2		YAW DAMPING			✓			✓		SPECIAL RIG
6.1	BODY COMPLIANCE	TORSIONAL STIFFNESS			✓				✓	
6.2		VERTICAL BENDING STIFFNESS			✓			✓		LOADING AT SCALE
7.1	LADING/BODY INERTIA	MASS				✓	✓			
7.2		ROLL RAD OF GYR			✓		✓			
7.3		PITCH RAD OF GYR			✓		✓			ESTIMATION
7.4		YAW RAD OF GYR			✓		✓			
7.5		C.G. POSITION			✓		✓			
8.1	TRUCK GEOMETRY	WHEEL RADIUS				✓	✓			TAPE MEASURE
9.1	TRUCK COMPLIANCE	LATERAL BEARING STIFFNESS		✓					✓	
9.2		TRAM STIFFNESS		✓					✓	
10.1	TRUCK (BOLSTER) SUSPENSION	VERTICAL STIFFNESS				✓		✓		LOAD FRAME OR FIELD TEST
10.2		VERTICAL DAMPING		✓				✓		
10.3		LATERAL STIFFNESS		✓				✓		

In general the least costly adequate method has been indicated. For example use of the full size Vibration Test Unit at the Transportation Test Center involves an expensive test but could be used as the special rig in 0-5.2, for the measurement of yaw damping. Simpler methods using load cells, hand actuators and an air bearing have been used very successfully at moderate cost and are indicated (Ref. 22). A number of methods have been used to measure track compliance (see, for example, Refs. 23 and 24). They are generally complex and require a significant number of people and apparatus. Use of the reference vehicle as a vertical load source is possible with measurement of track displacement. Lateral loading generally requires a special device or vehicle such as the "Decarotor" (Ref. 3).

Measurement of rail and wheel profile for dynamic assessment purposes is not the same as for wear since a common reference is required for both wheels or both rails and a high degree of accuracy is required. However, devices presently exist such as that used at the Transportation Test Center (Ref. 25). They are moderately easy to use but over a significant length of rail can be time consuming. No satisfactory device exists for measuring surface forces in the field. Such a development is long overdue. Measurement of friction coefficient is possible but not easy.

Characteristics for all stiffness and yaw damping require the application of a known load and the measurement of a resulting angle. Both can be effected in the field with suitable tackle, load cells and displacement measurement. They require rigid points of attachment for load application. Torsional body stiffness has similar requirements but the loads are higher and the need for a rigid measuring base suggests a more formal laboratory test. Vertical body stiffness is easier and can generally be undertaken during loading at a suitable weigh scale with accompanying deflection measurement. The total vehicle weight can also be measured at this time.

The value of the various radii of gyration would be expensive to measure using perhaps a form of pendular suspension. Estimates assuming uniformity of the loading have proven accurate enough for most purposes. Truck compliance and suspension stiffnesses can be measured in the field with varying degrees of difficulty. These could be made more readily with the design of a standard rig to be applied to the truck. The most difficult measurement is that of tram stiffness. Methods used in measuring truck variables may be found in Refs. 26 and 27.

In Table O-9, "Status of Present Method,"

New implies the design of special equipment for use in the field.

Need Mod(ification) implies that the apparatus exists but may need improvement or adaptation.

Will do indicates that present methods are marginally adequate in accuracy or reading speed.

Good is completely satisfactory.

Using Table O-9 it is possible to evaluate those measurements which the reference vehicle testing will replace or result in a reduced requirement when the use is for track or test calibration. Table O-10 permits a judgment as to the saving in cost and effort which can be made with the reference vehicle use.

TABLE O-10
COST OF ALTERNATIVE MEASUREMENTS

PI #	PERFORMANCE ISSUE	TRACK CAL.	TEST CAL.	BASELINE USE	SERVICE
1	Hunting	Moderate	High	High	High
2	Twist and Roll	Moderate	Moderate	Moderate	Moderate
3	Pitch and Bounce	Moderate	Moderate	Low	Moderate
4	Yaw and Sway	High	High	High	High
5	Steady State Curving	Moderate	High	High	High
6	Spiral Negotiation	High	High	High	High
7	Dynamic Curving	High	High	High	High

The interpretation of the results for Baseline Test Use and Service Testing for Extrapolation are different from those for Track and Test Calibration. The track maintenance resulting from the Track Calibration and the factors required from the Test Calibration would require the alternative measurement to be carried out. In Baseline Use the measurements represent a complete set of design variables sufficient to carry out an analysis on the test vehicle which together with the service test would enable a full service simulation to be carried out without the use of the reference vehicle. However, the same process can be carried out on the reference vehicle to permit validation of the analytic tools prior to use on the test vehicle.

Difficulty was experienced in accounting for the severity of the variable on each use and issue. For example, track compliance is difficult to measure and may have only a moderate effect on vehicle behavior. In this case its degree of difficulty was reduced to moderate to give an overall picture. Where it is recommended that a measure be taken to support reference vehicle use it is omitted from consideration. This is particularly true of profile measurement. The costs related to measurement difficulty of easy, moderate, hard in Table O-9 are given the categories low, moderate, high, respectively. Although the approximate nature of this preliminary analysis prevents detailed costing, these categories would not generally be inconsistent with total costs for each variable measured of 0-$200, $200-$2000 and above $2000 respectively. These figures are given here only as a guide.

The resulting Table O-10 shows the impact of the high cost of rail compliance measurement and its importance to derailment studies resulting from tests in the high flanging load, dynamic performance issues.

O-4.2 CONCLUSIONS ON UTILITY OF THE FREIGHT REFERENCE VEHICLES

The preceding discussions have described the technical considerations in the uses of reference vehicles and the cost saving for each of the performance issues, using the tables of variable system characteristics in each use identified. Some technical considerations are repetitive in performance issues having similarities. For example, performance issues involving motions in the track plane are dependent upon its surface properties and vary with weather conditions, particularly humidity. Vertical motions involve vertical track stiffness which may change in freezing conditions. In general neither will be known in service testing but they are likely to be similar in baseline use.

The most satisfactory uses for the reference vehicle are those in which each unknown can be determined from a simple response measurement.

Table O-11 has been drawn up from the preceding discussion to summarize the reference vehicle uses and complexities in their validity. It is suggested from this table that the more complex performance issues lead to difficulties in the interpretation of reference vehicle results. Many would benefit substantially from soundly validated analytic models which describe the vehicle performance in the issue considered. Such models already exist for issues 1, 2, 3 and 5 and are under development for the remaining issues. In general direct extrapolation to service conditions is only possible where the baseline test is carried out on a test vehicle geometrically similar to the reference vehicle.

O-4.3 CHOICE OF FREIGHT REFERENCE VEHICLES

The choice of reference vehicle must include availability not mentioned in the preceding discussion. However, since the Performance Issues themselves were chosen from concerns arising out of the performance of the present fleet of vehicles, there already exist significant numbers of vehicles suitable for the purpose.

The approach to choosing suitable freight reference vehicles has been to identify the requirements for each performance issue. Table O-12 summarizes the requirement perceived for the Performance Issues considered. In some instances a need for more than one has been identified from the discussion undertaken in Section O-2. In drawing up this

TABLE O-11

CONCLUSIONS ON REFERENCE VEHICLE UTILITY

PI #	PERFORMANCE ISSUE	USE # 1 TRACK CALIBRATION	USE #2 TEST CALIBRATION	USE #3 BASELINE USE	USE # 4 EXTRAPOLATION TO SERVICE CONDITIONS
1	Hunting	Good use Weather important Light car Worn wheels Simple measure	Good use Maintenance important Light car Worn wheels Simple measure	Good use for similar vehicles Analysis available if cars differ Measure vehicle characteristics	Possible Measures test severity On board measures required
2	Twist and Roll	Good use Maintenance important Heavy car High center of gravity Simple measures	Good use to identify weather Heavy car High center of gravity Experimental	Good use for similar vehicles Analysis available if cars differ Measures to fit differences	Good use for similar vehicles Maintenance important Analysis desirable Measures simple for test severity
3	Pitch and Bounce	Good use Vary car weight Experimental Simple measure with spectral analysis	Good use Vary car weight Experimental to determine track compliance	Good use for similar vehicles Low priority issue	Good use for similar vehicle Low priority issue
4	Yaw and Sway	Complex use Weather important Maintenance important Measurements complex Analysis complex	Complex use Maintenance important Additional track measurements Analysis complex	Best used with analytic model Measurements complex	Best used with analytic model Measurements complex
5	Steady State Curving	Good use Weather important Direct simple measurement	Good use Simple or complex Fundamental measurement possible	Good use for similar vehicles Analysis available to extend to new vehicles	Not appropriate see dynamic curving
6	Sp'ral negotiation	Complex use Special vehicle maintenance and test runs in good weather	Complex use Difficult to analyze Experimental Combine with other issues	Complex use Not required for x-level Direct measure valid for test spiral only	Possible only with analytic model Complex use
7	Dynamic Curving	Complex use Analysis difficult Complex measurement Experimental	Good use Simple or complex Fundamental measurement possible	Possible only with similar vehicles or new analytic support	Not recommended without full analytic model support

table it has been assumed that the reference vehicle will be of standard form with standard three-piece trucks. This limits the choice of variables to body basic design, body truck connection and wheel profile. The change out or turning of wheels is relatively straightforward and in the following discussion it has been assumed that either new or worn profiles may be accommodated.

Similarly the degree of roll restraint between the carbody and bolster may be changed by changing the sidebearing configuration or center plate extension. The design choices are greater here but it is certainly possible to effect free play before contact at the sidebearing or rigidity without play but with increased yaw restraint. This choice is also assumed to affect the choice of basic vehicle.

The ideal vehicles indicated in Table O-12 do not necessarily exist. Compromise may therefore be necessary to give characteristics closest to that required. Since payload is the governing feature of the design the requirements are broken down by vehicle weight.

The following Table O-13 gives the breakdown by weight allowing for compromise in vehicle body compliance where both rigid and flexible designs are ideally required. This is reduced to a design of "mid(dle) flex(ibility)".

In Ref. 28, Radford identified the following vehicles:

Type A — 89' Flat-Car (or Tri-level) 70 ton 64' TCD

Type B — 60' Box Car 100 ton or 70 ton 46'-49' TCD

Type C — Covered Hopper Car 100 ton 39½' TCD

Coal Gondola Car 100 ton 39'-46' TCD

TABLE O-12

FREIGHT REFERENCE VEHICLE CHOICE

PI #	PERFORMANCE	#	BODY				TRUCK		COMMENT
			WEIGHT	TCD	CG HEIGHT	COMPLIANCE	ROLL* CONTROL	WHEEL PROFILE	
1	Hunting	1.1	Light	Long	Low	Flex	Free play	Worn	
2	Twist and roll	2.1 2.2	Heavy Light	39 ft 59 ft	High NC	NC Flex	Free play No play	New NC	Roll response Twist response
3	Pitch and bounce	3.1 3.2	Medium Heavy	49 ft 30 ft	Medium High	NC NC	NC NC	NC NC	Pitch response Bounce response
4	Yaw and sway	4.1	Heavy	59 ft	Medium	Flex	Free play	New	
5	Steady state curving	5.1	Light	NC	Low	NC	No play	New	
6	Spiral negotiation	6.1 6.2	Light Heavy	Long Long	NC NC	Rigid Rigid	No play No play	New New	For track Stiffness
7	Dynamic curving	7.1 7.2	Heavy Medium	39 ft NC	High Medium	NC NC	Free play Free play	New New	For track and length variation

NC - Not critical to this issues.

*Body to bolster (S.B.; CPEP, etc.)

TABLE O-13

MINIMUM CHOICE OF FREIGHT REFERENCE VEHICLES

TYPE	WEIGHT	TCD	CG HEIGHT	COMPLIANCE	** PI #s
A	Light	59 ft	Low	Midflex	1,2,5,6
B	Medium	40 ft	Medium	Flex	3,7
C	Heavy	39 ft	High	NC*	2,3,7
D	Heavy	59 ft	Medium	Midfle	4,6

*NC - Not Critical, ** See Appendix O-A.

The Coal Gondola is also known to hunt (PI #1) when light although its suitability for PI #6 Spiral Negotiation is not ideal since it is rather flexible in torsion. It is also somewhat shorter than the desired length. An alternative to the Gondola for Type D might be sought such as a long covered hopper, 48' TCD. It is generally difficult to find a car found frequently in service which is long, heavy and torsionally rigid. The torsionally flexible car required for issues #1, hunting, is perhaps better satisfied by the 89 ft Flat car of Type A.

O-4.4 CHOICE OF OTHER (NOT FREIGHT) VEHICLES

Two other types of vehicles were considered appropriate to this study. They are Locomotives and Intercity passenger vehicles. Two factors identify the differences between the freight vehicle discussions and those for these other vehicles. They are truck design in which considerable variety exists and, where powered, the power source.

The truck design is important for several reasons;

- Variation of numbers of axles per truck in locomotives
- Prevalence of "rigid frame" designs for locomotives and passenger vehicles
- Different lateral suspensions including "swing hangers"
- Variation in primary suspension includes rubber chevrons bushings and helical springs with guideways
- Different forms of "equalization" in primary suspensions
- Variation in connection between the body and truck including center plates, shear pads, air springs, rubber springs, flexicoils.

The suspensions can generally be broken down into primary and secondary suspension issues. Table O-1 can be adjusted to suit the new requirement. However, the number of variables for designs in present use provides the necessity for a different form of Table O-1 for each design and this was not undertaken. The recommended approach for these vehicles is to identify a similar vehicle of known performance, perhaps even the same type for baseline comparison. Track and test calibration can then be examined for each vehicle using the philosophy outlined for the freight vehicle in each particular case where such testing is thought desirable.

Since the variation in design is considerable, analytic models are of considerable advantage to aid in resolving reasons for the apparent differences in response. The Perturbed Track Test on 6-axled locomotives (Ref. 12) is an excellent example both of the use of geometrically similar vehicles and of the need for good analytic models which were not readily available in validated form at the time of these tests

For passenger vehicles there exists a compendium of suspension types (Ref. 29) which may be used in identifying a vehicle similar to the test vehicle and available for use. A likely source of reference vehicle is the supplier of the test vehicle. In general the choice of reference vehicle must accompany the test planning. The location of the proposed test will also address the need for an appropriate source of power which will then be available to both test and reference locomotive.

It is suggested that the reference vehicle be chosen at test planning time, with appropriately similar truck design to the test vehicle satisfying the power source requirement and with known service performance. Issues such as the need for instrumentation, supporting analysis, and the method of track and test calibration to be used, must be addressed using an approach similar to that used in this report for the freight vehicle, drawing up the particular set of characteristics for the particular vehicle options and performance issues concerned.

APPENDIX O-A

PERFORMANCE ISSUES

The following is a numerical listing and description of the Performance Issues as used in this section.

1. Hunting -- A form of self-excited oscillation of wheelset, truck or carbody that is also termed an "instability". It can arise on perfect track and self-excites once it is started. It is one of the most complex dynamic phenomena observed in the railroad environment, and a complete understanding of all the parameters affecting it does not exist. It is known, however, that many aspects of the design and wear characteristics of the trucks and the carbody are important, including specifically the design of the suspension system and the wear profiles of the wheels and rails. Hunting occurs in certain speed ranges, demarcated by "critical speeds". Often, the objective of the vehicle designer is to achieve critical speeds which lie outside the speed range in which the vehicle is expected to operate.

2. Twist and Roll -- A form of low-speed, externally excited, resonance-type oscillation in which the vehicle ocsillates about an axis parallel to the train. Twist refers to the torsional bending of the carbody, whereas roll refers to the rotational motion of the carbody around a longitudinal axis. This oscillation has historically been associated with cars with a high center of gravity, whose truck spacing lies in a fairly narrow range of lengths, while operating on track with staggered-joint, bolted-rail construction having "dipped" joints, or on newly installed, continuously welded rail with joint memory in the track support, or car induced "dipped" or low locations caused by car roll dynamics.

3. Pitch and Bounce -- Externally excited vertical oscillations of the body of the vehicle, caused by track goemetry variation. Pitch refers to the rotational motion of the carbody around a lateral axis whereas bounce refers to the motion in the vertical direction. Usually of greater

concern for human comfort (as in locomotives) and lading damage (in freight cars), pitch and bounce occasionally contribute to derailments.

4. Yaw and Sway -- Externally excited transverse oscillations of the body of the vehicle, caused by track geometry variation. Yaw refers to the rotational motion of the carbody around a vertical axis, whereas sway refers to the motion in the lateral direction. These oscillations can be contributors to derailments by generating large lateral forces between wheels and rails, or when oscillations are coupled with light vertical wheel loads.

5. Steady-State Curving -- Large steady-state lateral forces may be generated between the rails and the wheels of the vehicle, even when track conditions are excellent. Contributing factors are trucks of large wheelbase on sharp curves, and inadequate maintenance of parts such as sidebearings and centerplates that may cause binding.

6. Spiral Negotiation -- Track warp, such as the spiral between tangent and curve, may cause loss of vertica contact between a wheel and rail, while large lateral wheel-rail forces are being generated. This phenomenon is typically associated with either improper track construction or maintenance such that the track is improperly superelevated, or with torsionally stiff and long carbodies, which are unable to accommodate the warp in the track, or contain insufficient sidebearing clearance or excessively stiff constant contact side bearings.

7. Dynamic Curving -- High lateral forces may be generated between wheel and rail as a result of geometric irregularities in a curve. Dynamic curving is still a relatively poorly understood phenomenon. High forces have been observed typically with vehicles that have high axle loads. Many other vehicle factors, not yet clearly identified, also play an important role.

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