REPORT NO. FRA-OR&D-76-70

A REVIEW OF MEASUREMENT TECHNIQUES, REQUIREMENTS, AND AVAILABLE DATA ON THE DYNAMIC COMPLIANCE OF RAILROAD TRACK

Willard D. Kaiser
Gerald L. Nessler
Howard C. Meachem
Robert H. Prause

MAY 1975

INTERIM REPORT

Document is available to
the public through the
National Technical Information Service,
Springfield, Virginia, 22161

Prepared for

U.S. DEPARTMENT OF TRANSPORTATION
FEDERAL RAILROAD ADMINISTRATION
OFFICE OF RESEARCH AND DEVELOPMENT
Washington,D.C., 20590

NOTICE

The contents of this report reflect the views of Battelle's Columbus Laboratories, which is responsible for the facts and the accuracy of the data presented herein. The contents do not necsarily reflect the official views of the Department of Transportation. This report does not constitute a standard, specification, or regulation.

NOTICE

The United States Government does not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

Technical Report Documentation Page

1. Report No. FRA-OR&D-76-70	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle A REVIEW OF MEASUREMENT TECHNIQUES, REQUIREMENTS, AND AVAILABLE DATA ON THE DYNAMIC COMPLIANCE OF RAILROAD TRACK		5. Report Date May, 1975
		6. Performing Organization Code
7. Author(s) W. D. Kaiser, G. L. Nessler, H. C. Meacham, R. H. Prause		8. Performing Organization Report No.
9. Performing Organization Name and Address Battelle-Columbus Laboratories 505 King Avenue Columbus, Ohio 43201		10. Work Unit No. (TRAIS)
		11. Contract or Grant No. DOT-FR-30051
		13. Type of Report and Period Covered Interim Report June 1973 - December 1973
12. Sponsoring Agency Name and Address U. S. Department of Transportation Federal Railroad Administration 400 Seventh Street, S. W. Washington, D. C. 20591		14. Sponsoring Agency Code
15. Supplementary Notes None		

16. Abstract

SUMMARY

The need for increasing train speeds and operating safety while reducing track maintenance is responsible for much of the current research on track structures, vehicle dynamics, and vehicle/track interaction. This report covers Phase I of a 3-phase program to design and fabricate equipment for measuring track dynamic characteristics. It is generally recognized that the available data and measurement techniques for obtaining this type of data for U. S. track are inadequate. This Phase I report includes a review of previous measurement techniques, a compilation of available data on track dynamic characteristics, an evaluation of data requirements, and the development of concepts for measuring track dynamic compliance.

MANAGEMENT REVIEW STATEMENT

The information in this report is intended for use by research personnel who have an interest in railroad track performance as related to vehicle/track interaction and track maintenance and in the measurement of track deflections and dynamic characteristics for developing track analysis models and evaluating track structure condition.

17. Key Words Track, track modulus, track dynamic compliance, track impedance, track dynamics, track stiffness	18. Distribution Statement Document is available to the public through The National Technical Information Service, Springfield, Virginia 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
UNCLASSIFIED	UNCLASSIFIED		

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

PREFACE

This report presents the Phase I results from a 3-phase program having the objective of designing and building equipment to measure the dynamic compliance of railroad track. The report was prepared by Battelle's Columbus Laboratories (BCL) under Contract DOT-FR-30051 from the Office of Research, Development and Demonstrations of the Federal Railroad Administration (FRA).

Mr. Thomas P. Woll, RA-42, was the technical monitor for this contract. The cooperation and suggestions provided by Mr. Woll and Mr. William B. O'Sullivan from the Rail Systems Division of FRA are gratefully acknowledged. Dr. Leonard Kurzweil from the Transportation Systems Center (TSC) and Dr. Ta-Lun Yang and Mr. John Corbin from ENSCO, Inc. also deserve recognition for their suggestions. The authors are also grateful for the cooperation of many persons in the railroad community and to the several authors and publishers who granted permission for the use of copyrighted material in this report.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF FIGURES (Continued)

INTRODUCTION

In recent years the need for increased train speeds, train loads, and reduced track maintenance costs has resulted in the initiation of several research programs to study track structures, vehicle dynamic performance, and how the track and vehicles interact. One result obtained from many of these programs is the recognition that the available data--and means for obtaining data--on the dynamic properties of track structures are inadequate. Without adequate data on the dynamic properties of the track structure, analyses of vehicle dynamic performance may result in vehicle designs which are unstable or overdesigned; analyses of track structures cannot be verified with experimental data, and rail vehicle test and simulation equipment cannot be used with confidence to accurately simulate realistic railroad operating conditions.

In order to develop the information needed for vehicle, track structure, and simulation equipment studies, the Federal Railroad Administration (FRA) initiated a program at Battelle to develop a track dynamic compliance measuring system. This program has been divided into three phases. This report covers the Phase I work which included a review of measurement techniques which have been used previously, a compilation of data on typical track dynamic characteristics, a determination of track compliance measurement requirements, and an identification of concepts for measuring track compliance.

Following the Phase I work, which was basically a review and evaluation of available literature, a supplementary track measurement task was initiated to obtain preliminary experimental compliance data which can be used as input data for Phase II. The data to be obtained from this measurement program will include track damping properties, track compliance, natural frequencies and how these parameters vary as a function of position along the track and track conditions. These experimental data are needed because very little information applicable to the Phase II feasibility and design study was found in the literature.

The Phase II work will consist of conceptual design studies and detailed evaluation of system concepts which can be developed to meet the identified measurement objectives. The Phase II work will then be followed by a Phase III detailed design, construction, and testing phase in which a complete measurement system is constructed and evaluated, assuming the design concept recommended at the conclusion of Phase II is approved by the Federal Railroad Administration.

SUMMARY

A review of dynamic compliance measurement techniques indicated that the technology, as applied to highways and airports, has advanced to the point where dynamic measurements can be used to predict the life of concrete pavement as a function of the load it carries; however, no references to this technology being applied to railroad track structures were found in the literature. In addition, no reference was found which indicated that dynamic compliance measurements have been successfully made on any type of structure from a moving vehicle. Many references were found giving data on track vertical and lateral static stiffness and natural frequencies measured from stationary equipment. Some data on track damping properties and typical track geometry errors were also obtained.

Three objectives for a track dynamic compliance measuring system are to provide data for:

(1) An evaluation of track structure condition
(2) Vehicle/track dynamics research
(3) Wheel/rail dynamics laboratory.

For track structure condition evaluation, the functions which might be performed using dynamic compliance measurement techniques are:

(1) detect defective ties or fasteners
(2) Measure vehicle dynamic excitation properties
(3) Detect potential track buckling problems
(4) Determine load carrying capacity of existing track
(5) Detect rail fractures.

If possible, track evaluation measurements should be performed at normal operating speeds.

For vehicle and track dynamic studies, and also for use in programming the wheel-rail simulator being built at Pueblo, the measurements considered to be of primary interest are the driving point dynamic compliance at wheel loading points, and the transfer dynamic compliance betwen wheel loading points. It is desirable to be able to measure these dynamic compliances in both the vertical and lateral directions in the speed range from zero up to the highest train speeds which might be encountered in practice.

It is desirable to measure from a fast moving train to minimize interference with normal rail traffic and to determine if track compliance is a function of train speed. The importance of minimizing interference with normal rail traffic depends on the ultimate use for the system. If the system is used frequently and/or for long time periods, this would be an important factor. The importance of being able to determine if compliance is affected significantly by train speed would depend on the types of analytical and developmental work that are expected in the future.

The frequency ranges of primary interest are 0 Hz and the range of 10 to 100 Hz. There is a secondary interest in the range of 100 to 500 Hz, and a slight interest in higher frequencies up to about 1000 Hz. The compliance (or stiffness) at the 0 Hz frequency defines the static load-deflection characteristics of the track structure. This is important because it is the parameter most often used by both track structure and vehicle suspension designers, and it provides the most information about the condition of the track structure. Other track structure parameters will almost always be related to track compliance. Also, measurement of the 0 Hz, or static, compliance will usually provide a guide to the values of compliance that might be expected at other frequencies.

Measurements in the frequency range of 10 to 100 Hz are important because data in the literature indicate that with conventional track structures, the track structure's natural frequency with a typical vehicle unsprung mass is about 30 Hz. With new track structures and/or vehicle suspension systems, the natural frequencies will probably be increased, possibly to the 50 to 60 Hz range. The dynamic track compliance usually changes significantly at the track natural frequency, and the rapid changes in compliance can have a significant effect on measurements of track structure and vehicle stresses and motions.

There will be higher order resonant frequencies above 100 Hz where specific elements of the track and vehicle system may interact, but because the frequency is much higher than the fundamental natural frequency, the complete ballast, tie, and subgrade system will not respond. It is, of course, desirable to know how all parts of the system interact; however, because of the limited number of elements that interact at higher natural frequencies, these modes can usually be adequately studied in the laboratory.

In addition to measurement of vertical and lateral track compliance characteristics, it may also be desirable to measure the track longitudinal compliance. This measurement has been requested by Wyle Laboratories as one of the parameters needed for the wheel/rail dynamics laboratory. This measurement would be very difficult to make from a moving vehicle because it would require a complete set of compliance measuring equipment specifically designed for this purpose. However, it can be obtained with a moderate amount of effort with portable equipment that could be clamped to the track.

In order to satisfy some or all of these objectives, several different measurement systems were considered. Table 1 summarizes the principal capabilities of the different excitation systems with regard to measuring track stiffness or track dynamic compliance from a moving or stationary vehicle. The numerical ranking shown is only intended to indicate a general variation in capability. A more detailed feasibility study will be completed as Phase II of this program.

One system that meets most of the measurement objectives consists of two similar loading and measurement cars. One car would measure forces and motions caused by track profile errors. The second car would measure the same parameters, but with an added force excitation. The motion measurements would be made relative to a chord supported by wheels located outside the load affected zone. The resulting signals could be processed to yield accurate dynamic compliance measurements even in the presence of large profile error "noise" signals. By measuring from a chord reference system, static stiffness could be measured while moving at high speeds.

A simpler system which might also be used is similar to the one described previously except that the provision for cancellation of rail profile errors would be eliminated. This would significantly reduce the speeds at which accurate measurements could be made. However, the cost of providing the second measurement system would also be eliminated. The system could also be built using an inertial reference measuring system in place of the chord reference measuring system. This substitution would eliminate the capability for making static stiffness measurements. Other alternatives to simplify the system are the elimination of components for processing or for making some driving point or cross tranfer dynamic compliance measurements. If a chord measurement

TABLE 1. SUMMARY OF MEASUREMENT SYSTEM CAPABILITIES

Excitation System	Stationary Measurements: Track Static Stiffness	Stationary Measurements: Track Dynamic Compliance, Discrete Frequency	Stationary Measurements: Track Dynamic Compliance, Continuous Frequency	Moving Measurements: Track Static Stiffness	Moving Measurements: Track Dynamic Compliance, Discrete Frequency	Moving Measurements: Track Dynamic Compliance, Continuous Frequency
Variable Static Loads	1	NA	NA	1	NA	NA
Rotating Weight	NA	2	2	NA	1	NA
Nonround Wheels	NA	NA	NA	2	1	NA
Sinusoidal Excitation (variable frequency)	1	1	1	NA	1	2
Pulse Excitation	2	NA	1	2	2	1
Random Excitation	2	NA	1	2	2	1

NA - Not applicable

1 - Best Choice

2 - Second Choice

system were used, all the capabilities are included for dynamic compliance measurements and static measurements. If an inertial reference system is used, the capability for making static measurements is eliminated. Otherwise, the systems yield the same data.

CONCLUSIONS AND RECOMMENDATIONS

A basic conclusion reached during this study is that the relationship between track defects and dynamic compliance are not well enough understood at this time to select measurement techniques for detecting specific defects. Therefore, the first system to be built should probably be versatile enough to evaluate different track evaluation techniques. The preliminary measurement program is intended to evaluate the effect of some diffent track structure abnormalities on the dynamic compliance functions. This information will then be used to aid in the design of more complete measurement equipment.

At this early stage of the project, it appears that a measurement system consisting of two measurement cars will be needed to provide the required versatility. Each of these cars would be equipped with independently, or semi-independently suspended wheels which can be loaded to produce static track forces. One of the cars would be equipped with hydraulically powered dynamic exciters and force transducers. A digital data processing system, either on-board or at a stationary location, would be used to store and process data to enhance the signal-to-noise ratio and calculate dynamic compliance in the many modes of interest. It is recommended that one of the tasks to be performed with this general purpose instrumentation system would be to evaluate and demonstrate the correlation between the dynamic compliance function and track condition anomalies. Following completion of that work, a simple, special-purpose dynamic compliance measuring system might then be constructed.

TECHNICAL DISCUSSION

The nomenclature and definitions of terms used to describe the static and dynamic characteristics of railroad track can be quite confusing to persons having a varied background. Therefore, only a few descriptive terms have been selected for this report, and they have been used according to the definitions which follow.

Track modulus is a term commonly used in railroad engineering to describe the average elastic support of the foundation under the rail that is provided by the combination of discretely spaced ties supported by a roadbed composed of ballast on top of a subgrade. This is strictly a static parameter, with units of lbs/in. per inch of rail length. It is not intended to include any dynamic effects such as frequency dependent damping or mass. Since the measurements considered in this report are all related to the rail head and include the rail as a part of the track assembly, track modulus is not of direct interest.

Track stiffness is also used to describe the static, rather than dynamic, characteristics of track. Track stiffness as used in this report refers to the track load-deflection ratio (lb/in.), for a point load applied to the rail head, and this includes the stiffness contributed by both the rail and the foundation.

Track dynamic compliance is based on the definition that is commonly used in vibration analysis--the complex ratio of displacement to force (includes amplitude and phase) representing the frequency dependent transfer function for steady-state sinusoidal excitation. A measurement of dynamic compliance over a selected frequency range describes the dynamic characteristics of structural behavior such as resonant frequencies, anti-resonant frequencies, and energy dissipation (damping). Unless otherwise indicated, the term compliance, or track compliance, will refer to forces and displacements measured at the rail head. Therefore, as the frequency of interest approaches zero, the track compliance is directly related to the inverse of the track stiffness. Also the inverse of the dynamic track compliance at low frequencies is sometimes identified as the dynamic track stiffness to differentiate the results from a static and dynamic measurement.

It is important to realize that there are several other dynamic quantities found by the ratios of applied force and response variables (displacement, velocity or acceleration) that differ only by being inverse ratios or are proportional to the exciting frequency. These include mobility, velocity/force; apparent mass, force/acceleration; apparent stiffness or dynamic stiffness, force/displacement; and impedance, force/velocity. Since all of these give equally adequate information about track dynamics for sinusoidal excitation, it is sufficient to be able to measure any one in detail in order to determine track dynamic compliance. Therefore, a discussion of techniques for measuring dynamic displacements and force will appear in this report along with the term dynamic compliance, thereby employing an understanding of this relationship.

Literature Review

Literature Sources

The first step in the program was to search through several literature sources to locate information pertinent to this project. The specific sources searched were:

(1) Railroad Research Information Service (RRIS) data base which includes railroad literature from France, England, Japan, and Canada
(2) BCL track structure search file
(3) Track-train dynamics bibliography
(4) ORE reports catalog
(5) A bibliography of 1300 Russian references on railroads
(6) Track Impedance Seminar proceedings.

In searching the above library references, several key words such as ballast rigidity, track stability, track inspection equipment, vibration, etc. were used. Somewhat different key words were used in the different library searches. From these key words, several hundred abstracts were located and reviewed, and about 75 articles were selected for detailed evaluation. About one half of these articles had some information which was pertinent to this project. The articles of most direct interest are listed in the references and bibliography at the end of this report.

The objective of the literature review was to obtain information in the following areas:

(1) Techniques and equipment used to measure track parameters.

(2) Data for typical track and the expected variations as a function of track deterioration, season of the year, etc.

(3) Data requirements for both the development of scientific data and for the evaluation of track structure conditions.

Some other data on general purpose dynamic compliance measurement equipment, track inspection equipment, fasteners, track structure testing techniques, etc., were also collected.

In addition to the above literature search, several people from organizations which have been performing work in the track and compliance measurement fields were contacted. These contacts included visits to the Canadian National Railways and to the U. S. Army Waterways Experiment Station at Vicksburg, Mississippi, letters to Wyle Laboratories and British Railways Research Center, and telephone calls to several major U. S. railroads. A list of trip reports and telephone conversations is included as Appendix B.

Literature on Techniques and Equipment for Compliance Measurements

Almost all the literature in this category is in the area of highway or airport runway design and maintenance. The common techniques and equipment which have been used for evaluating absolute or relative values of strength, stiffness, and/or dynamic compliance of highway and runway type structures are:

(1) Standard Seismic Technique. The structure is impulsed by a falling weight or with a hydraulic cylinder, and the velocity of a transverse wave is measured by vibration transducers located a known distance from the impact point. Analysis of propagation velocity and the material density yields modulus of elasticity (E) data. Measurement of the vibration decay can yield damping information. To use this technique with any degree of accuracy, the density of the material must be known accurately.

This technique is used to determine changes of strength or condition of highway pavement, which can be considered to be a relatively continuous system. For a track structure system consisting of a rail, tie, ballast, and subgrade, this technique would be very difficult to use, and the results might still be questionable.

(2) Sinusoidal Excitation. A sinusoidal load is applied with a hydraulic or rotating weight exciter, and vibration transducers are used to measure phase shift of the transmitted wave as a function of distance from the exciter. The phase shift information is used to determine modulus of elasticity from the propagation velocity, which is dependent upon the density.

(3) Seismic Technique. An impulse load is applied by a falling weight, and the deflection of the surface near the point of impact is measured. By knowing a standard deflection for "good" pavement, comparisons can be made between surfaces under test and standard reference surfaces.

(4) Benkelman Beam Deflection Tests. A vehicle with a heavy wheel load is driven slowly past a beam supported at its end points, and the deflection of the highway pavement surface relative to the beam is measured near the beam center. The deflection and the known load are used to calculate the static stiffness.

(5) Deflection Test. A dynamic load is generated with rotating weights or a hydraulically oscillated weight to vibrate the pavement surface. Dynamic deflections are measured at the load point and/or at other points near the load point. Typically, these measurement points are selected so that the magnitude of the deflection at the load point can be determined and also either the slope of the deflection curve or the complete shape of the deflection curve can be determined in the vicinity of the load application device.

(6) Bearing Plate Tests. A static load is applied to a surface with a hydraulic jack attached to a heavy vehicle, and the deflection of the surface at the load application point is measured relative to a beam which is supported at points outside the load affected zone. Both (5) and (6) are based on comparing data on the static or dynamic stiffnesses and the slope of the deflection curve with reference values to evaluate the relative condition of the pavement. In considering this method, it was determined that the slope is dependent upon numerous track parameters, so this method wouldn't identify a particular problem with sufficient accuracy.

The previous types of devices have been used almost wholly for evaluation of highways and airport runways. An evaluation has been made of these systems to determine their effectiveness for determining the load carrying capabilities of existing flexible pavements in areas subjected to frost action. The conclusion reached in this study by Schrivner et al[1] was that a system which applied dynamic loads and measures dynamic deflection (Trade name Dynaflect in their study) proved to be more sensitive than other instruments to changes in strength of flexible pavements. They also determined that the results obtained with the "Dynaflect" could be used with reasonable accuracy to predict the results of plate bearing tests (described previously in Item 6) and Benkelman Beam Deflection tests (described in Item 4). Similar conclusions have been reached based on work performed at The Ohio State University[2]. In a report on this type of equipment with the trade name of "The Pavement Profiler", Mr. L. Berger[3] states that this equipment can evaluate 10 to 20 miles of highway per day when 15 tests per mile are made.

Considering techniques that have actually been used on railway track structures, the general type of dynamic excitation and measurement equipment described in Item 5 has been used by the Waterways Experiment Station (WES) to measure impedance on the FRA Kansas Test Track structures. Unfortunately, WES has not analyzed the data from these measurements to the point where conclusions can be drawn or they can be included in this study. Similar equipment has also been used by the Japanese National Railways and by the German Federal

Railways, primarily for ballast settling and compaction studies. However, one report by Y. Satoh et al[4] shows data from tests which actually were a form of compliance measurement. Figure 1 shows two plots from this report, one for wooden tie track and one for concrete tie track. To obtain the data in Figure 1, a 2-axle freight car was equipped with two rotating eccentric weights connected to one of the axles. The eccentric weights were driven by two rotating shafts connected with a gear box and motor on a trolley. The unbalanced weights were 5.3, 8.5, 11.4, and 14.6 lb, and the eccentricity was 23.3 in. With a maximum rotating speed of 2000 rpm, this system generated a maximum force of 38,679 lb peak to peak. The data presented in this report were not extensive enough to obtain good quantitative information on the track's dynamic characteristics. However, inspection of Figure 1 does indicate that the system damping was high and that the track exciter system resonant frequency may have been as low as 900 CPM for the wooden tie track and about 1500 CPM for the concrete tie track. However, the 900 CPM peak is unusually low for a track structure resonance, so it may be a resonance of the test equipment.

Other equipment which has been used for track measurements consists of special (Japanese) cars with flat spots ground into the wheels[5]. A special (French) "derailment car"[6] equipped with a third axle installed near the center of the car was used to apply vertical and lateral loads to a rail in order to measure lateral track deflections. Also, an attempt to measure track dynamic compliance using impact loading was made by British Railways. Unfortunately, the results of this work have not been published.

Literature Concerning Track Parameters

The collected literature was reviewed to determine typical track parameters, and also to determine how these parameters would be expected to change as a function of track deterioration. These data were collected to provide a basis for determining the measurement requirements for the track dynamic compliance system, and for evaluating different track condition evaluation systems. Typical data of these types are listed in Table 2.

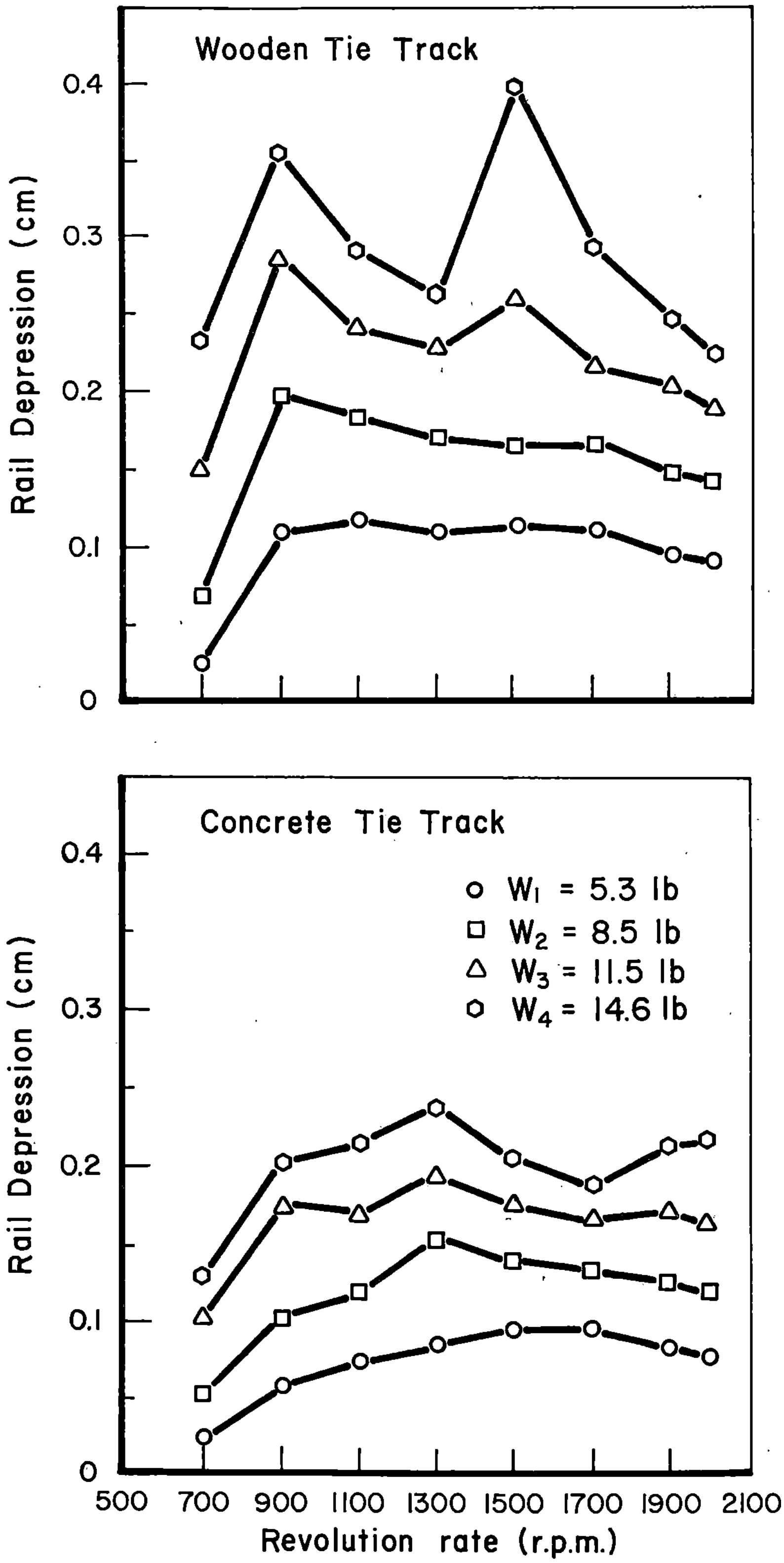


FIGURE 1. RAIL DEPRESSION (DEFLECTION) VERSUS REVOLUTION RATE FOR A ROTATING WEIGHT EXCITOR

TABLE 2. SUMMARY OF TRACK PARAMETER DATA (References shown in [ ])

A. Track Vertical Natural Frequency	**Frequency, Hz**
Vibrator Tests on GFR [8, p 433]	20 - 27
Track Measurements [9, p 59]	25 - 30
	100 - 170
BART Aerial Structure [10, p 18]	30
	500 - 1000
Wood ties - JNR [4, p 43]	15, 25
Concrete ties - JNR [4, p 43]	20
Concrete slab track - JNR [11, p 182]	> 25
Wood tie analysis - no vehicle [12, p 25]	32 - 166
Concrete tie analysis - no vehicle [12, p 25]	26 - 105
Wood tie analysis - no vehicle [13, p 9]	36 - 110
Wood tie analysis - with vehicle [13, p 9]	16 - 38
B. Track Lateral Natural Frequency	**Frequency, Hz**
Wood tie analysis - no vehicle [12, p 25]	32 - 180
Concrete tie analysis - no vehicle [12, p 25]	25 - 109
C. Vertical Track Stiffness	**Stiffness, Kips/in.**
Typical analysis [9, p 17]	170
Mid-rail measurement [9, p 54]	350 - 490
Joint measurement [9, p 54]	116 - 164
Track on swampy ground [8, p 444]	28 - 140
Track on argillaceous ground [8, p 444]	84 - 112
Track on gravel [8, p 444]	112 - 336
Track on rock [8, p 444]	168 - 224
Track on Frozen ballast [8, p 444]	447 - 895
Original source was BR [14, p 432]	490
Variable ballast depth [15, p 6]	45 - 280
D. Lateral Track Stiffness	**Stiffness, Kips/in.**
Wood tie analysis [12, p 25]	52 - 640
Concrete tie analysis [12, p 25]	63 - 720
Increase due to ballast compaction [8, p 442]	75 - 87
Washington Metro spec. [20]	64
Measured data - no vertical load [19]	95 - 150
E. Track Damping Factor	**Damping Ratio**
Estimate for analysis [14, p 432]	0.20
Estimated from Figure 2 [4, p 43]	0.25
Estimated from WES data [unpublished]	0.25
Embankment Tests - no rail [25, p 13]	0.086 - 0.136
Range for Several Tracks [ORE D87/RP6]	0.12 - 0.21

Some of the graphical data which cannot be easily reduced to tabular form are shown in Figures 2 and 3. For example, Figures 2 and 3 show how the subgrade modulus as defined by secant modulus or tangent modulus* might be expected to vary as a function of time of year and moisture content. Data in Reference 15 show that the settlement of the tie due to ballast flow decreases with increasing modulus (more rigid track). Other data on highways (Reference 24) show that most of the damage to highways occurs during the spring thaw period. Apparently, 20 percent of the total damage developed under 0.7 percent of the total test load applications during one spring, and in the second spring 40 percent of the total damage occurred under 13 percent of the load applications. The previous data imply that one potential use of track measurements is to determine the load carrying capability of track by deflection measurements, and to establish load limits which might vary with the time of the year.

The shape of the track static load-deflection curve and the distance the deflection extends from the load point are of interest in determining the type and location of measurements which might be made to determine track conditions. Figure 4 shows a comparison of the load-deflection curves in the vertical direction for cases of (1) a "standard" uniform track, (2) standard track with one tie missing, and (3) standard track with reduced subgrade modulus. The data used to plot these curves are from computer runs made during a study of the effect of missing ties (Reference 16). Somewhat similar load-deflection curves from Reference 26 are shown in Figure 5 for the lateral direction.

---

* For nonlinear materials, the tangent modulus is the slope of the stress-strain curve at a particular stress value. The initial tangent modulus is the slope at the origin (zero stress). The secant modulus is the slope of a straight line from the origin to a particular stress value on the curve, so this gives the average modulus for stresses below the selected value.

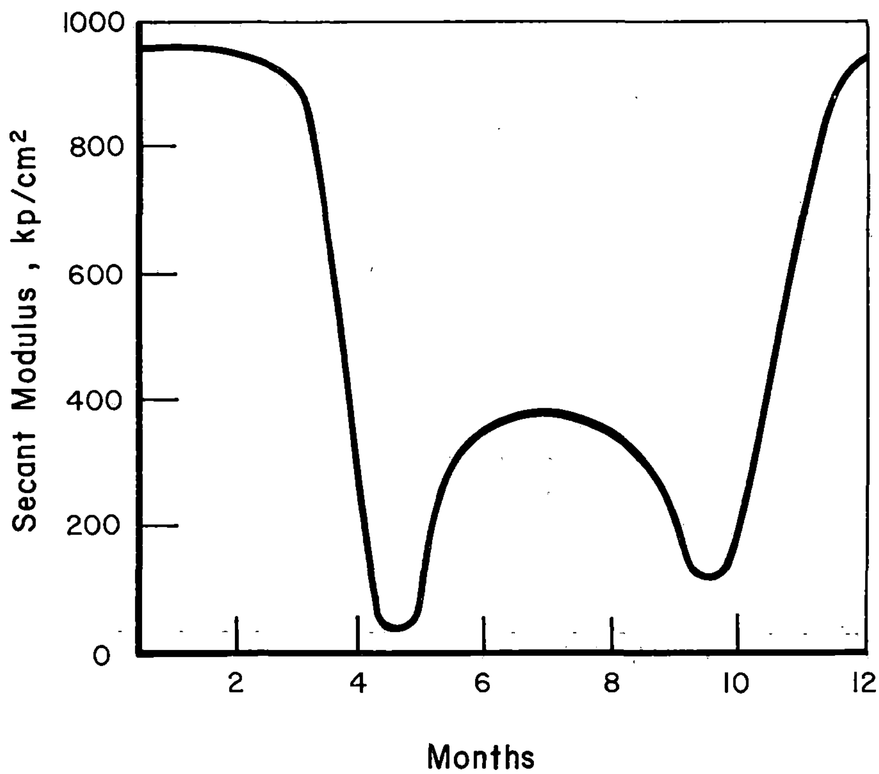


FIGURE 2. TYPICAL VARIATION OF SUBGRADE SECANT MODULUS DURING A YEAR

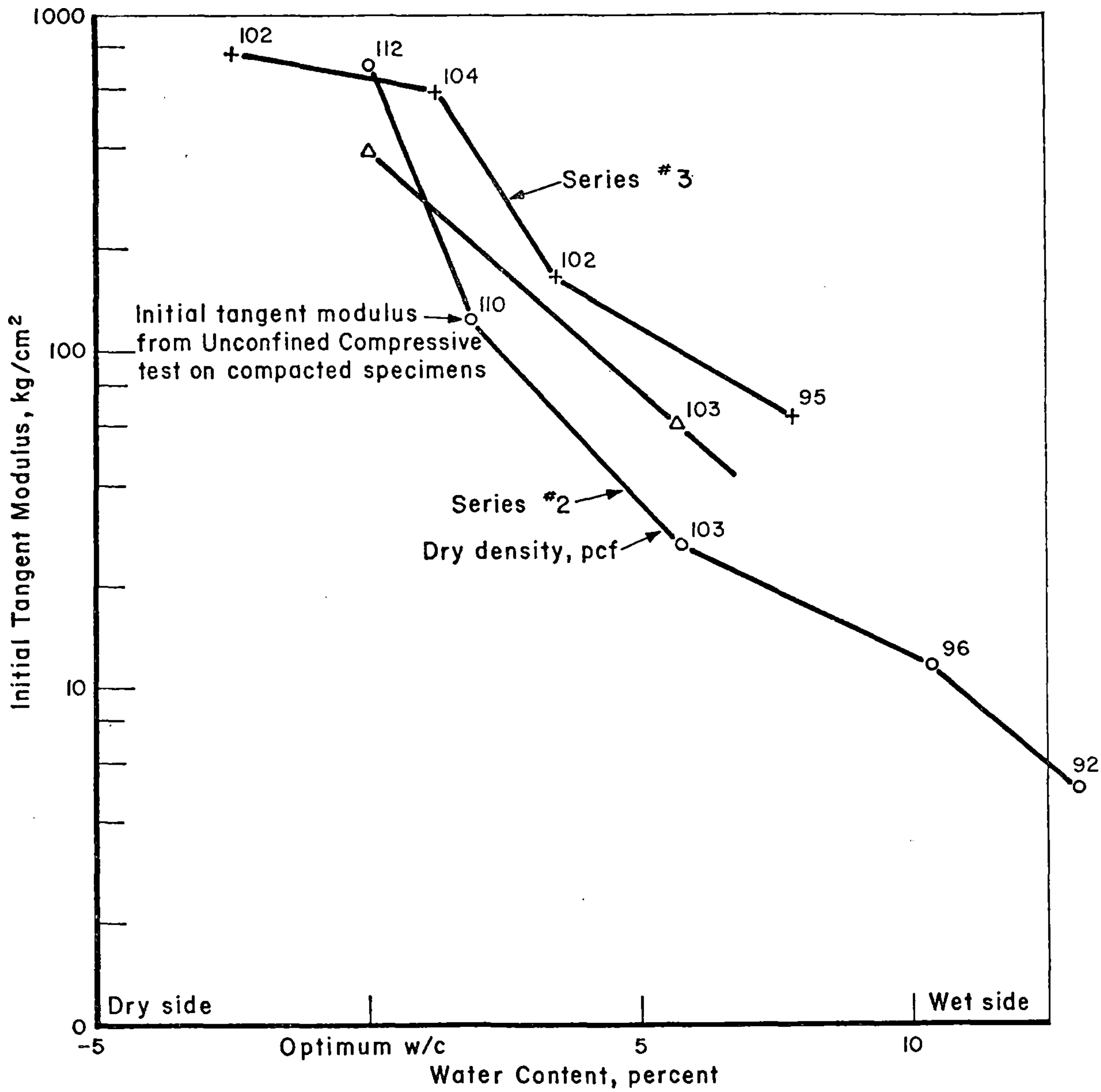


FIGURE 3. ELASTIC MODULI FROM UNCONFINED COMPRESSIVE TESTS ON COMPACTED CLAY SAMPLES

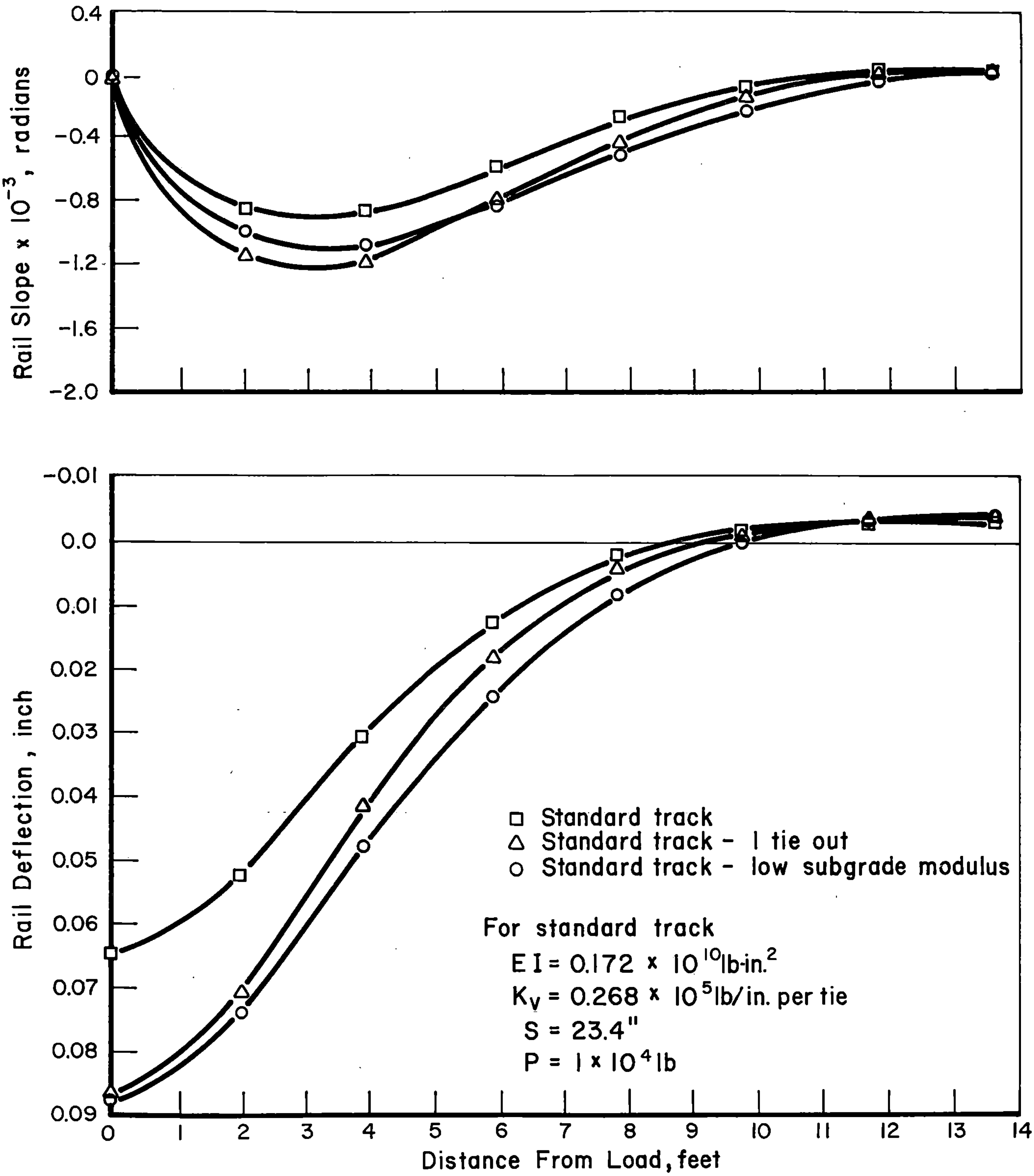


FIGURE 4. VERTICAL RAIL DEFLECTION AND SLOPE FOR THREE DIFFERENT TRACK CONDITIONS

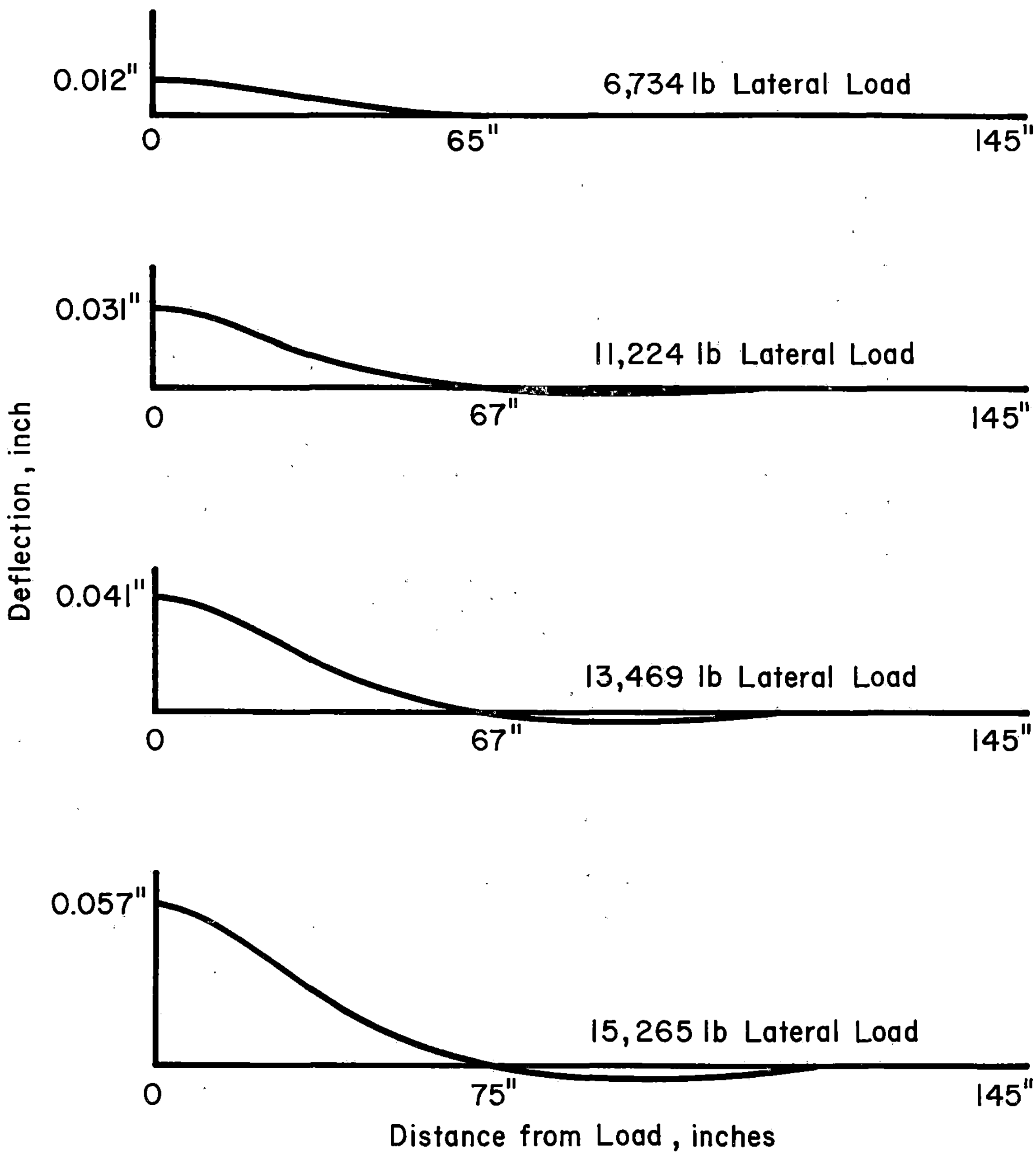


FIGURE 5. LATERAL TRACK DEFLECTION WITH 27,000-LB AXLE LOAD AND THE INDICATED LATERAL LOAD

When evaluating track structure conditions from a moving vehicle, a major source of signal noise will be the roughness profile of the track geometry. Therefore, to design a measurement system, the typical track roughness must be known. Figures 6 and 7 from Reference 27 show idealized track geometries for the vertical and lateral directions with Class 6 track. For lower grade jointed track, much of the noise will result from low joints and, in some cases, corrugations. Corrugations typically have a wavelength of 6 to 10 inches and a depth between 0.005 in. and 0.050 in., although corrugation depths up to 1/4 in. have been measured.(13) A typical shape for track with low joints is similar to a full-wave rectified sine wave. For this assumed shape, Table 3 gives the harmonic content that would be expected.

Figure 8 from Reference 28 shows some suggested guidelines for the amplitude of vertical track profile errors as a function of their wavelength for three speed ranges. These data can be interpreted in terms of amplitude and frequency, using the relations for frequency, wavelength, and train speed shown in Figure 9. From these data, knowing a profile wavelength and train speed, one can easily determine typical amplitude and frequency relations for track geometry excitation.

TABLE 3. HARMONIC CONTENT OF RECTIFIED SINE WAVE SHAPE RAIL PROFILE

Harmonic Number	Amplitude, percent of maximum	Wavelength for 39-foot rail length, ft
Fundamental Frequency	63.6	39.0
2d Harmonic	42.3	19.5
4th "	8.5	9.75
6th "	3.6	6.50
8th "	2.0	4.87
10th "	1.3	3.90
12th "	0.89	3.25
14th "	0.65	2.78
16th "	0.50	2.44
18th "	0.39	2.17
20th "	0.32	1.95

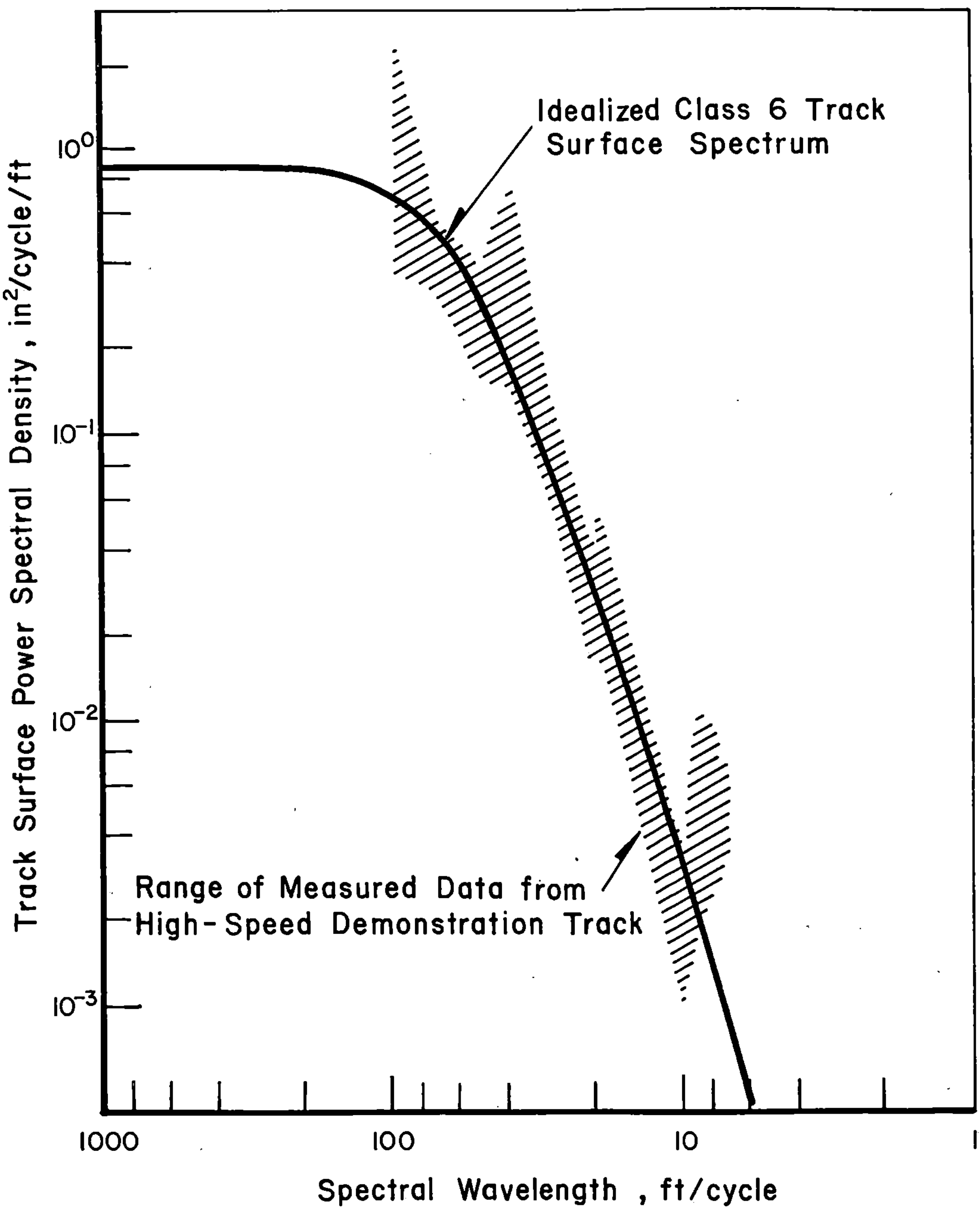


FIGURE 6. TRACK SURFACE GEOMETRY POWER SPECTRAL DENSITY FOR IDEALIZED CLASS 6 TRACK

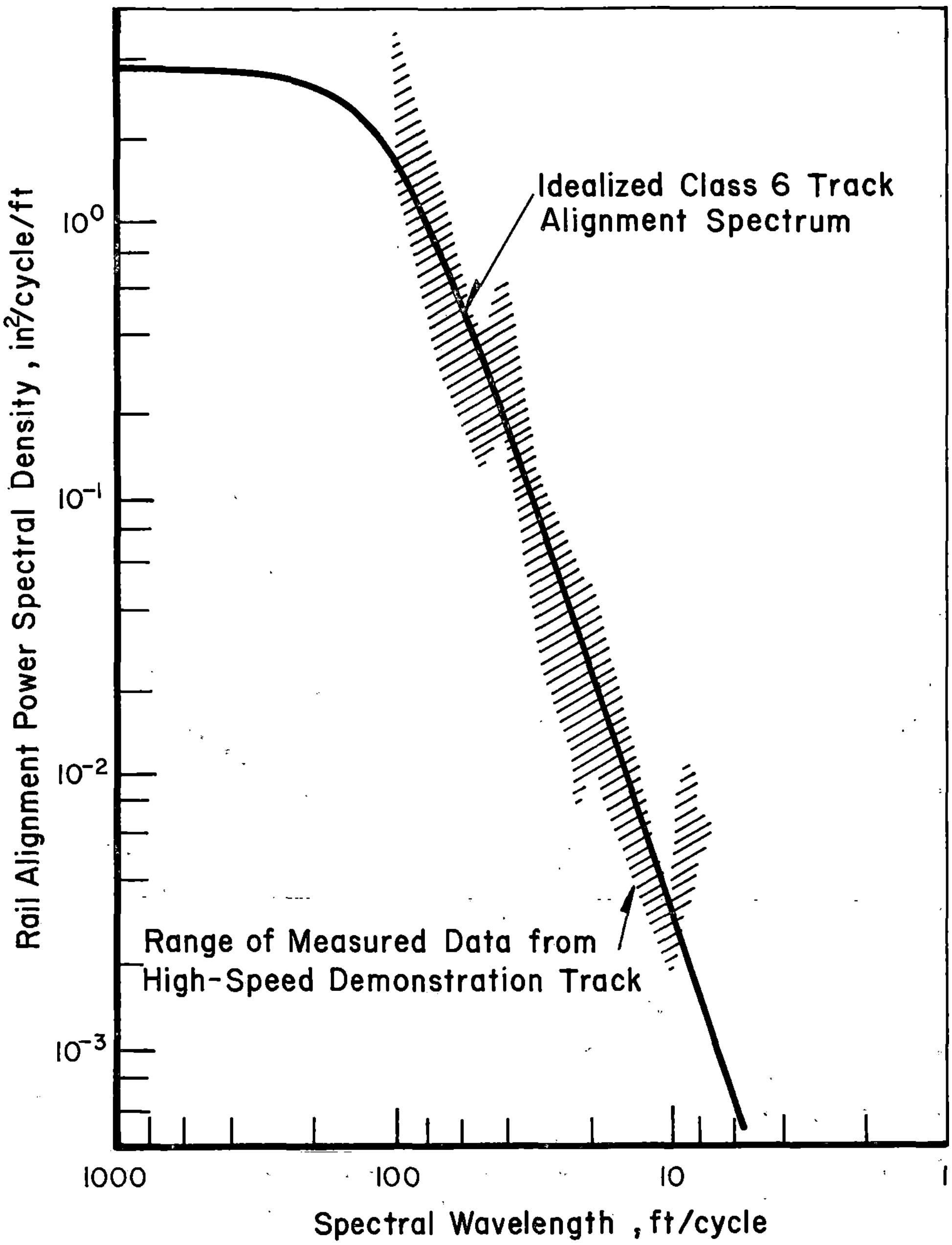


FIGURE 7. TRACK ALIGNMENT GEOMETRY POWER SPECTRAL DENSITY FOR IDEALIZED CLASS 6 TRACK

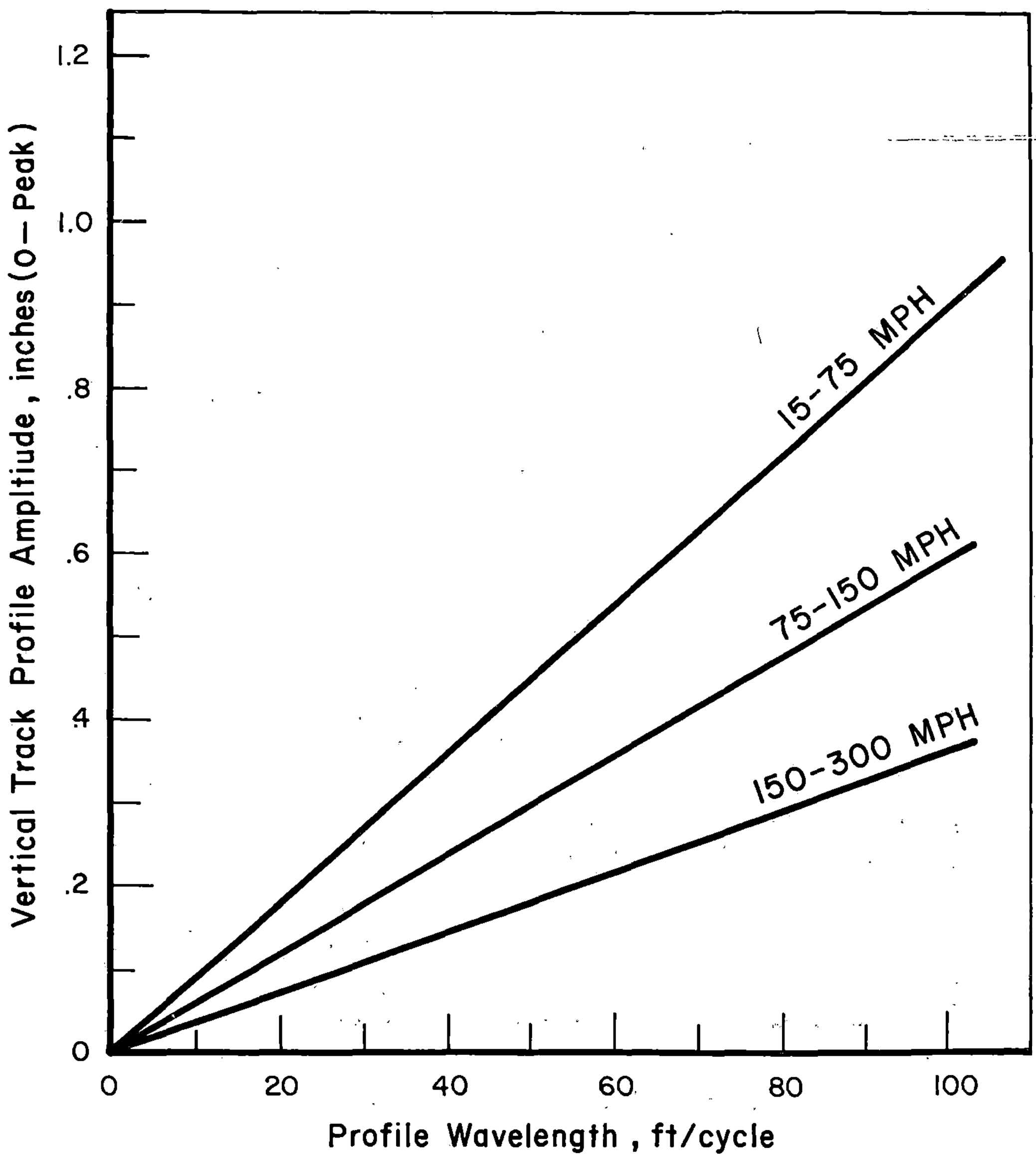


FIGURE 8. TYPICAL DESIGN REQUIREMENTS FOR SIMULATING VERTICAL TRACK IRREGULARITIES

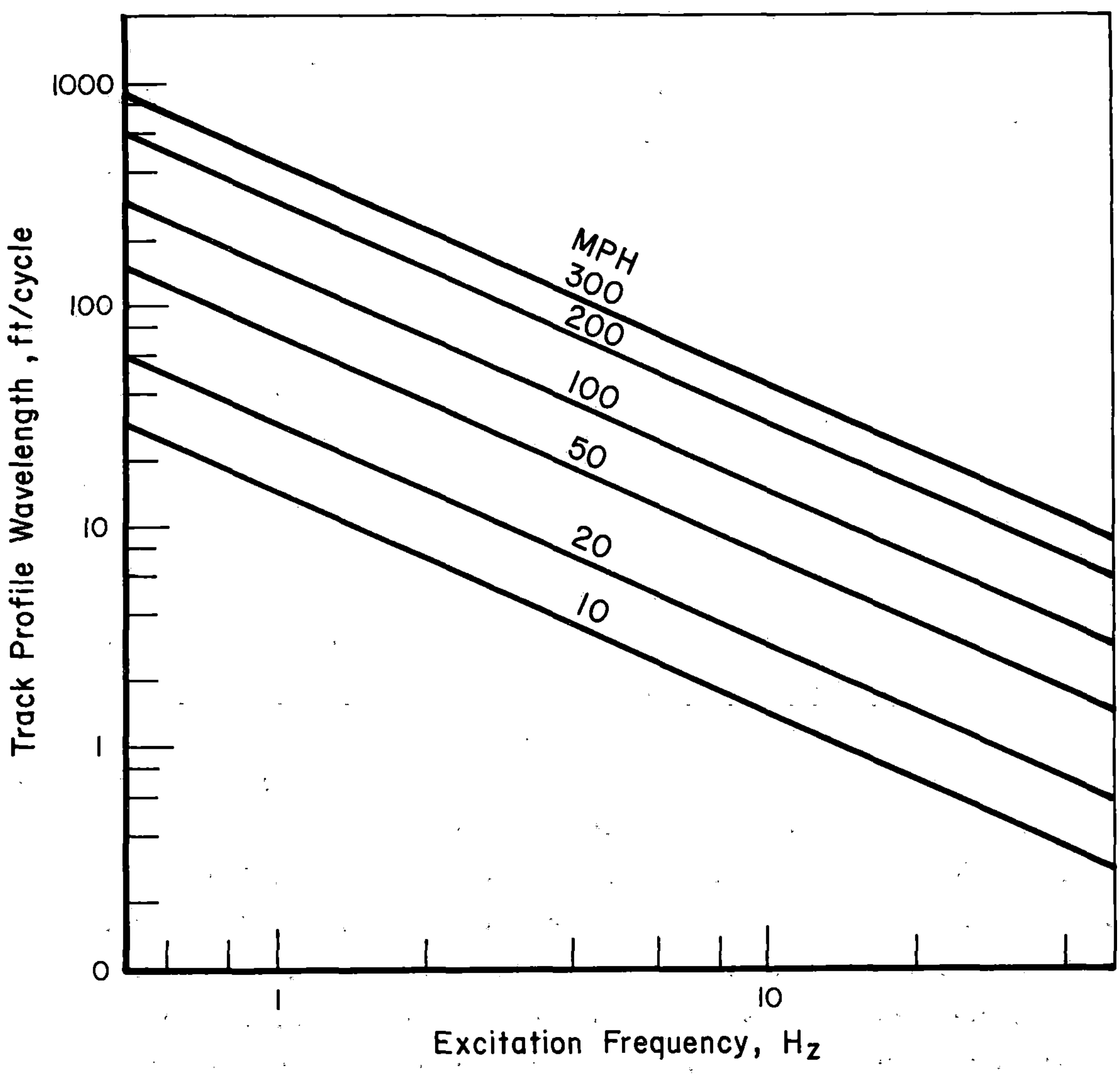


FIGURE 9. EFFECT OF TRAIN SPEED ON THE EXCITATION FREQUENCY FOR TRACK GEOMETRY IRREGULARITIES

Measurement Requirements

An effort was made, primarily through contacts with persons associated with the railroad industry, to identify track parameters which should be identified and/or measured by a track measuring system. Three general areas of interest are (1) for track structure condition evaluation, (2) to develop data for analytical studies of track and vehicle dynamics, and (3) to develop data to be used in programming the wheel-rail simulation facility now under construction at Pueblo, Colorado.

Track Condition. For track condition evaluation, the following areas of potential interest have been identified:

(1) Detect loose or missing spikes or fasteners
(2) Detect missing, loose, or deteriorated ties
(3) Measure the vehicle dynamic excitation characteristics of the track
(4) Detect potential track buckling, wide gage, or rail rollover problems (i.e., lateral weakness)
(5) Measure the load-carrying capacity of existing track structure
(6) Detect rail fractures.

In addition to the above, a related use for track measurements might be to determine the properties of the subgrade and/or ballast in order to obtain data for use in designing improved track structures.

In the literature search, and in the discussions with railroad industry personnel, a very minimal amount of data were obtained which related track deflection or stiffness measurements to track conditions, and which could be used to specify the forces and excitation frequencies which would be required in measuring track with the objective of identifying the features listed above. Even though data relating defects to dynamic compliance measurements are not available, conclusions were reached on some of the criteria required for a track condition evaluation system. One conclusion is that it will be impractical to detect missing spikes or fasteners using only vertical force and motion measurements. Additional data are needed to determine if defective rail fasteners can be detected using lateral loading. The fact that rail spikes are usually installed with about 1/8-in. clearance between the head of the spike and the rail may make the detection of missing spikes in individual ties difficult or impossible; however, some finite number of missing or excessively loose spikes in adjacent ties may result in a low lateral stiffness or measurable excessive gage spread resulting from lateral loading.

There are two potential measurement techniques which might be used to identify most types of track structure anomalies. One is to apply a constant load in the vertical and lateral direction as the measurement car moves along the track and measure the resulting deflection. The second technique is to apply a periodic load and measure the resulting dynamic deflection. The use of a constant load will produce a measurement which is essentially a measure of the static stiffness of the system. The use of a periodically applied load will produce a dynamic compliance measurement. If the periodic loading technique is used, the load must be repeated at a rate that will produce a minimum of one complete cycle of excitation, whether it's an impulse, sine wave, or periodic random excitation, for every tie spacing traversed if the effects of individual ties are to be detected. This implies a minimum application rate of 30 Hz at a train speed of 30 mph, or 60 Hz at a train speed of 60 mph.

The dynamic excitation characteristics of the track can be measured by a combination of track profile measurements and stiffness or dynamic compliance measurements. A measurement of rail profile under two or more different wheel loads would be a direct measure of vehicle dynamic excitation characteristics.

Data from highway research indicates that either static stiffness (constant loading) or dynamic compliance measurements may be used for determining load-carrying capacities of track. Measurements for these type of data can, and probably should, be averaged over several feet along the track to average out the variable effects of individual ties.

Detection of rail fracture would probably require either a continuous static stiffness measurement or periodic excitation applied at very close spacing along the track. Distances as close as one cycle for each 6 inches of track might be required to detect rail fracture. However, the detection of rail flaws has a very low priority for this program.

Track and Vehicle Dynamics. In making vehicle dynamic studies, the parameters which influence the vehicle system response are (1) the compliance as seen by each wheel in both vertical and horizontal directions, (2) the motions and forces produced at each wheel on a car that result from forces and motions being transmitted through the track structure from adjacent wheels. There are theories that these compliances may vary substantially as a function of vehicle speed.

The information identified as desirable for use in vehicle dynamic studies and track structure studies is measurement of the vertical, lateral, and longitudinal driving-point compliances at the wheel-rail interface. The system should also have the capability of measuring the transfer impedances from the wheel-rail contact point on one rail to adjacent points on the same rail and the opposite rail. The distance over which transfer compliance data are needed would not be greater than the load-affected zone. For most track structures (see Figures 4 and 5) this distance would be about 10 feet or less. It should be possible to obtain these measurements as a function of wheel load over the range of about 1000 pounds to 25,000 pounds per wheel.

In order to evaluate the effect of train speed on track dynamic characteristics and to be able to make measurements at normal revenue traffic operating speeds, an operating speed range of 0 to 80 mph is desirable. For studies of track structure conditions, it would be desirable to determine the transfer function from the rail head to the tie-ballast interface and also from the tie-ballast interface into the subgrade in order to separate the effects of track and subgrade on the track dynamic characteristics. Ideally, the system would have a bandwidth of 0 to 1000 Hz in order to evaluate static stiffness, track resonant frequencies, and reaction forces at joints. However, a system with a bandwidth as low as about 10 to 100 Hz would be considered satisfactory as a primary system. This range would approximate static stiffness data and also include track fundamental frequency data. Alternate measurement systems, having d-c to 10 Hz response and having a bandwidth of about 100 to 500 Hz might also be provided to extend the range of useful date to include true static stiffness data and data on the higher frequency modes of track vibration.

<u>Wheel-Rail Simulator</u>. A letter was sent to Wyle Laboratories requesting information on the data requirements for the wheel-rail simulator at Pueblo, Colorado. In response to this request, Wyle prepared the list of requirements which is included as Appendix A. In general, the data required

for the wheel-rail simulator are similar to that required for analytical studies of track and vehicle dynamics. The major difference is that the desired bandwidth for the wheel-rail simulator is d-c to 100 Hz ; therefore, it is expected that any system which will meet all or most of the general requirements will produce adequate data for the wheel-rail test facility.

Basic Data Acquisition Techniques

There are three basic dynamic excitation techniques available to obtain track dynamic compliance data. The first is a steady-state sinusoidal technique where the excitation frequency is swept through the frequency range of interest. The second method uses a transient input (impulse) to produce a transient response from which the transfer function can be calculated. The third method is to apply a random signal to the system and measure its response.

In addition, there are also three techniques for obtaining data on track structure condition. The first is to use a nonround wheel with some special function machined into the wheel to excite the track. The second method is to use track geometry errors as excitation. These would probably have a random spatial variation and would yield averaged values of track condition. The third technique is to use a constant wheel load and measure track stiffness. The stiffness data would then be used as an indication of track condition.

Sinusoidal Excitation

The simplest, lowest cost method for determining dynamic characteristics is to use a sinusoidal force at varying frequencies and measure the resulting response. In the simplest form, force and motion measurements are manually recorded from meters or oscilloscopes and the data is plotted. The plots of dynamic compliance would be in the form of curves of peak-to-peak displacement divided by the peak-to-peak force versus frequency. In many cases a second plot would also be made of the phase shift between the force and displacement signals as a function of frequency. This system can be automated by using "transfer function analyzers" to automatically record and plot transfer functions of a system.

The major disadvantage of a swept sinusoidal excitation system is that it is relatively slow. The sweep speed is limited by the bandwidth of the filters, and for systems now on the market a rapid sweep is impossible. For track evaluation purposes it would be desirable to excite the system every 18 in. through a complete frequency span of 0 - 100 Hz or higher while moving. This is not possible with a sinusoidal swept system except at very low train speeds. However, this technique does have the advantage of requiring lower peak forces than other excitation systems, and it also has the potential of working with simpler and lower cost components than most other systems. The sinusoidal force input can be generated in various ways, and several of these are discussed in the following sections.

<u>Counter-Rotating Weight Systems.</u> One of the simplest and, in the past, most widely used dynamic excitation systems is a gear box with unbalanced counter rotating shafts. This system can, and has been (Reference 6), mounted directly to a railroad car axle to produce vertical or lateral track loads. It could also be mounted on a wheel and axle assembly with its rotation axes parallel to the axle to produce a longitudinal excitation while moving along the track. Or, for stationary longitudinal measurements the gear box could be clamped directly to a rail. Rotating weight systems can produce dynamic excitation in the frequency range of about 5 to 100 Hz.

The major disadvantage of the standard rotating weight excitation system is that the magnitude of the generated force is proportional to the square of the rotational speed times the amount of unbalance on the rotating shafts. Therefore, controlling the excitation force independently of the speed (frequency) requires stopping the exciter and manually changing the unbalance on the rotating shafts. This disadvantage can be eliminated by installing a small gear motor on the rotating shaft to adjust the unbalance weights while the system is running. However, this modification increases the cost and complexity of the system, thereby tending to negate the system's main advantages of simplicity and low cost.

When using a counter-rotating weight system for track condition evaluation purposes, the system might normally be operated at a constant rotational speed, and therefore the lack of flexibility in adjusting force levels would not be a disadvantage.

Hydraulic Exciters. A hydraulic excitation system can be constructed using a hydraulic cylinder, servo valve and inertial reactance mass as shown in Figure 10. This basic system can be operated in several different modes to produce different excitation characteristics. In its simplest form it can be operated as a sinusoidal force generator. When operated in this mode, the force generated at low frequencies is limited by the cylinder stroke and the weight of the reactance mass. Figure 11 shows the relationship between these variables.

At high frequencies, the response of the hydraulic exciter will be limited primarily by the servovalve natural frequency and/or the control system closed loop dynamic response characteristics. Typically, the type of valve required for a hydraulic exciter with a force capability in the 1,000 to 10,000 lb force range will have a response characteristic which is down about 6 dB with a 90 degree phase lag at frequencies in the range of 125 to 150 Hz. For smaller valves, this limiting frequency can extend up to about 200 Hz.

In addition to standard servovalves, special high-frequency valves which have apparent natural frequencies (the frequency at which 90 degree phase lag occurs) in the 400 to 500 Hz range have been built and are listed in catalogs. Hydraulic excitation systems can produce some dynamic excitation at frequencies significantly above the natural frequency of the valve. For example, one manufacturer of hydraulic excitation systems claims a force capability which is 20 dB (10:1) down from the system's maximum force capability at a frequency which is about five times higher than the natural frequency of the valve.

In addition to operating as sinusoidal force generators, hydraulic excitation systems have the advantage that they can also be operated as pulse generators or as random force generators. The hydraulic excitors can also be used to generate constant forces (i.e., they can generate d-c response data) if they are attached to a car structure so that their reaction forces can be transmitted through the car structure and suspension back into the track at a substantial distance from the point on the track where the compliance measurements are being made.

A major advantage of hydraulic exciters is their small size and high force capacities. These features make it possible to provide a high force exciter which is easily portable, and which can be mounted on or between

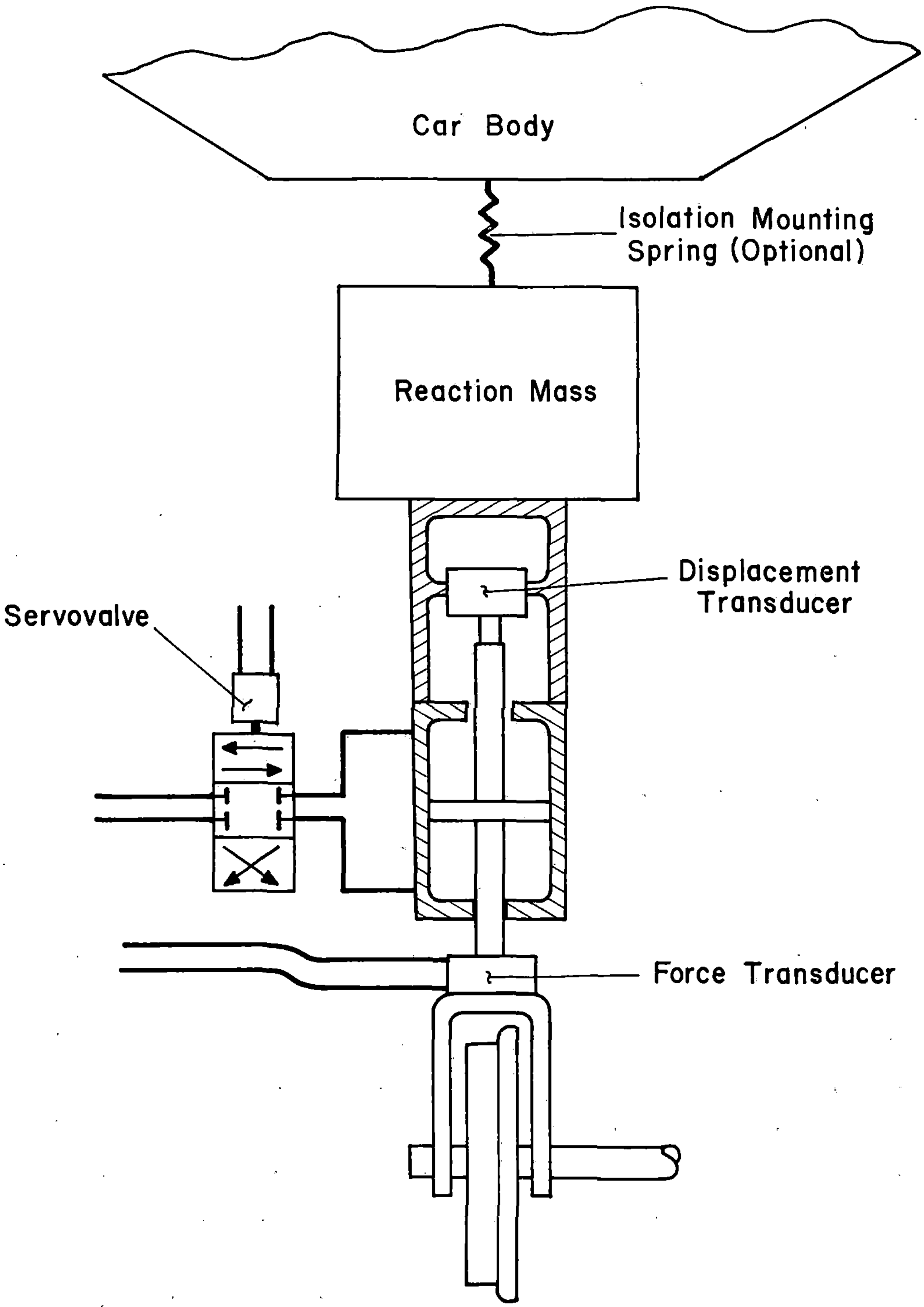


FIGURE 10. HYDRAULIC TRACK EXCITATION SYSTEM WITH SERVOVALVE CONTROL

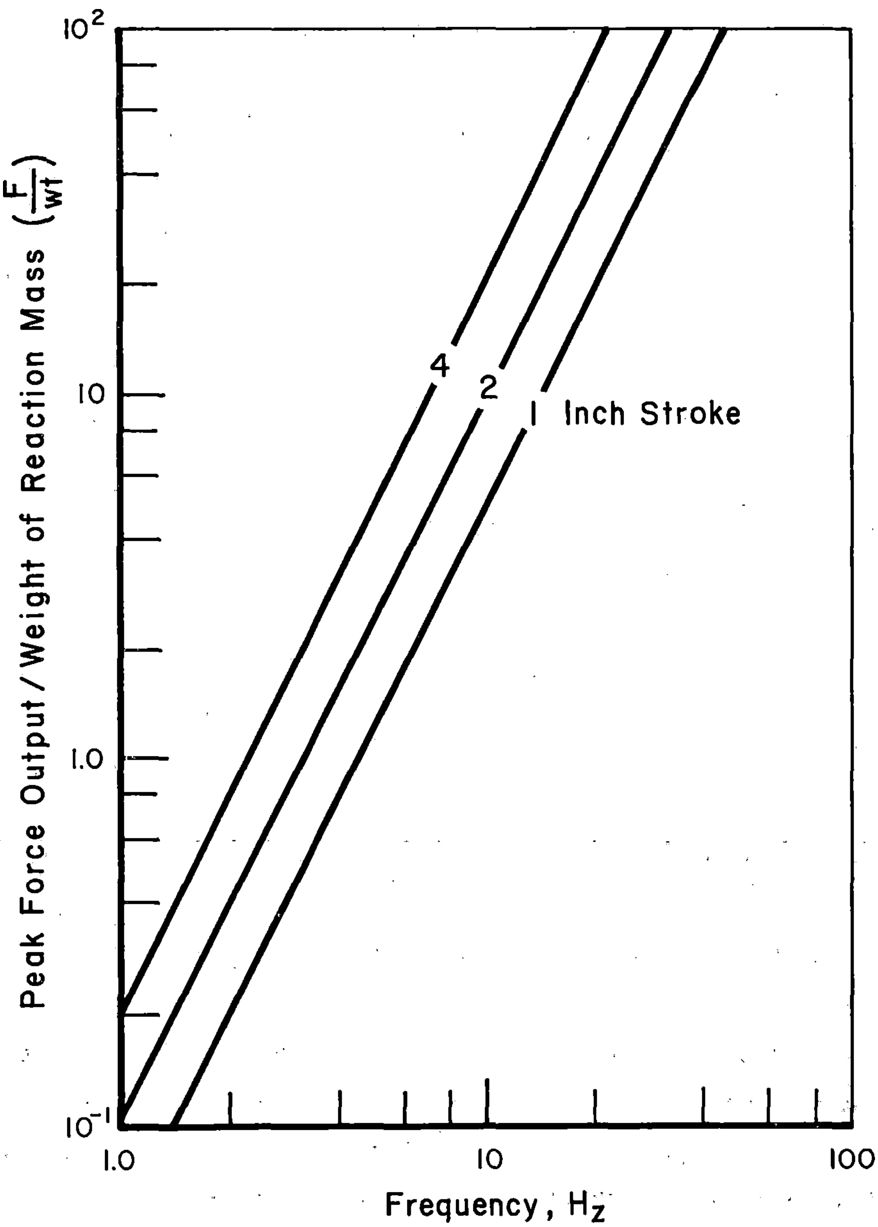


FIGURE 11. DYNAMIC SINUSOIDAL FORCE CAPABILITY FOR HYDRAULIC TRACK EXCITATION SYSTEM

suspension elements to produce vertical and/or lateral track excitation. Two exciters could be mounted on an axle to produce longitudinal track excitation from a moving vehicle, or the exciters could be clamped directly to the track for stationary measurements.

Electrodynamic. The operational and performance characteristics of an electrodynamic exciter are similar to those of the hydraulic exciter. Major exceptions are that, in general, electrodynamic exciters usually have a much higher frequency response than hydraulic exciters, and electrodynamic exciters are usually much larger than hydraulic exciters with similar force capacities.

Pulse Excitation

A system which is simple mechanically, but requires more complex data analysis, is one where a pulse is applied to the rail and the resulting forces and motions are analyzed. The basic concept is to determine the dynamic characteristics of the system using transient excitation, and the basic advantage is that a multiple frequency excitation is obtained without the time required for a frequency sweep at each location. Analysis is accomplished by using the Fourier Transform which converts data from the time domain to the frequency domain. The frequency response or transfer function of the system is defined as the Fourier Transform of the output divided by the Fourier Transform of the input. From the system transfer function, information such as static and dynamic stiffness, natural frequencies, effective mass, and damping can be obtained.

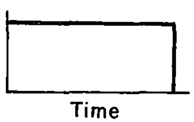
In practice, the analysis can be performed by recording the excitation forces and resulting motions on magnetic tape and then analyzing the tapes with a computer. Dynamic system analyzers specifically designed for this type of analysis are commercially available from at least four companies. The heart of these systems is a digital computer combined with special software for calculating system dynamic characteristics. Typically, software is provided so that dynamic compliance and many other system parameters can be calculated.

The advantages obtained by using this system are that a complete analysis can be obtained very rapidly, and for some systems, very simple low cost exciters can be used. The choice of an exciter depends on the force levels required, pulse lengths required, repetition rate required, and the range of frequencies which are to be excited.

The range of frequencies which must be excited is a very important parameter because the frequency content of the pulse is inversely related to the pulse width. The narrower the pulse, the broader the frequency range, and the broader the pulse, the narrower the frequency range of excitation. Table 4 shows a comparison of pulses of varying area and shape as to their effect on a single-degree-of-freedom system without damping. The data in this table are calculated for a pulse amplitude of 5,000 lb, a stiffness of 200,000 lb/in., and an effective mass of 2,200 lb. This table shows the small displacements yielded by a relatively large force of 5,000 lb for short duration pulses. As the pulse is broadened, the frequency bandwidth of the pulse decreases and the energy is concentrated at low frequencies. Thus, the displacement of the system at its natural frequency of 30 Hz increases. The problem then, is to excite a broad frequency band and obtain significant displacements above the signal noise level while still keeping the force level reasonable.

Wheels with flats or a machined contour, hydraulic exciters, and electrodynamic exciters can all be used as impulse excitation systems. Impulse excitation can also be produced by combustion (free piston engine, for example) or by impact between moving bodies. Impact could be produced on a repetitive basis by slider crank mechanisms. Control of the force, pulse shape, and width for an impact system would require adjustment of speed, stroke and substitution of impact materials. Pulse characteristics cannot easily be modified over a significant range for the combustion excitation or impact systems. Pulse excitation systems could be provided to produce lateral, vertical, and--with some devices--longitudinal excitation.

TABLE 4. PULSE METHOD

Pulse Shape	Duration Milliseconds	Pulse Area, lb-sec.	Force, lb	Displacement, in.	Effective Mass, lbm.	System Natural Frequency, Hz
	2.2	5.5	5000	0.005	2200	30
	5	12.5	5000	0.012	2200	30
	10	25	5000	0.023	2200	30
	10	50	5000	0.047	2200	30

Random Excitation

Another technique similar to the pulse excitation technique is one where a random force is used to excite the track structure and the Fourier Transform is applied to the resulting signals in order to calculate the system's dynamic properties. This method also has the advantage of high data acquisition rate and analysis speed. But it has the disadvantage that usually a more complex excitation system is required than is needed for sine or pulse excitation systems. Also, random excitation requires an exciter with higher peak force capabilities under similar operating conditions.

Displacement Excitation Systems

Two potential sources of dynamic displacement excitation are (1) the use of nonround wheels, and (2) the use of track geometry errors which are normally in the track. Wheels can be machined to produce a sinusoidal displacement excitation at a frequency which is an integral multiple of the wheel rotational speed. More complex functions could also be machined into a wheel so that a fundamental and several harmonic frequencies would be produced. A simple example of this is a wheel with a flat spot; however, more complex shapes could be produced which would not have the impact problems associated with a wheel flat. If the wheel is attached to a heavy mass, or any other load with known dynamic response, and the motion of the load and/or the wheel is measured, the force developed at the wheel-rail interface can be determined. For the case where the load is a rigid heavy mass, the force generated is equal to the mass times its acceleration. By measuring the acceleration, a voltage proportional to force is easily obtained. However, there are some practical difficulties in measuring the low frequency content of the acceleration from impact excitation.

With a nonround wheel, the motion of the track structure can be determined by measuring the motion of the load and adding the nonround wheel profile. It will probably be necessary to subtract track profile errors, depending on the allowable signal-to-noise ratios and instrumentation averaging times. The geometry errors which are normally associated with track structures can also be considered as a system excitation input similar to that produced by a nonround wheel. These might be used as the sole system excitation.

The disadvantage of the displacement input systems as devices for producing data for analytical purposes are their lack of flexibility, the fact that they cannot operate at zero speed, and they cannot produce longitudinal excitation. However, these concepts, and especially the nonround wheel concept, still have potential as an effective, low cost track condition evaluation system.

Constant Wheel Load Excitation Systems

If a loaded round wheel rolls on a straight uniform track it will cause the track to deform to a shape similar to the curves shown in Figure 4. A measurement of the magnitude of the deflection at the point under the wheel load, relative to a point not affected by the wheel load, can show that track deterioration in some form has occurred. For example, Figure 4 shows that the effect of removing one tie has the same effect as reducing the track modulus by 34 percent. Figure 4 also shows that for this track, the slope measured 5.5 feet from the load point would also increase by about 34 percent with either one tie missing or with the track modulus decreased by 34 percent. The basic problem involved in using measurements of the type described above to measure track stiffness is that track profile errors are normally of about the same amplitude as the displacements caused by wheel loads. Therefore, a change in track stiffness cannot be distinguished from a profile error using measurements from a single loaded wheel.

To eliminate or minimize this problem, a system of the type shown schematically in Figure 12 can be used. In this system the track profile errors are measured under a lightly loaded wheel. These measurements are stored in a digital storage system, tape recorder, or other data storage device for the time required for the train to travel the distance between the lightly loaded and heavily loaded wheels. The stored signal is then subtracted from the signal being measured by the heavily loaded wheel, and the resulting signal is then displayed or recorded.

This technique of measuring track stiffness has the advantage that, because the excitation is continuous, measurements can be obtained at very high vehicle speeds while maintaining the ability to resolve changes in track

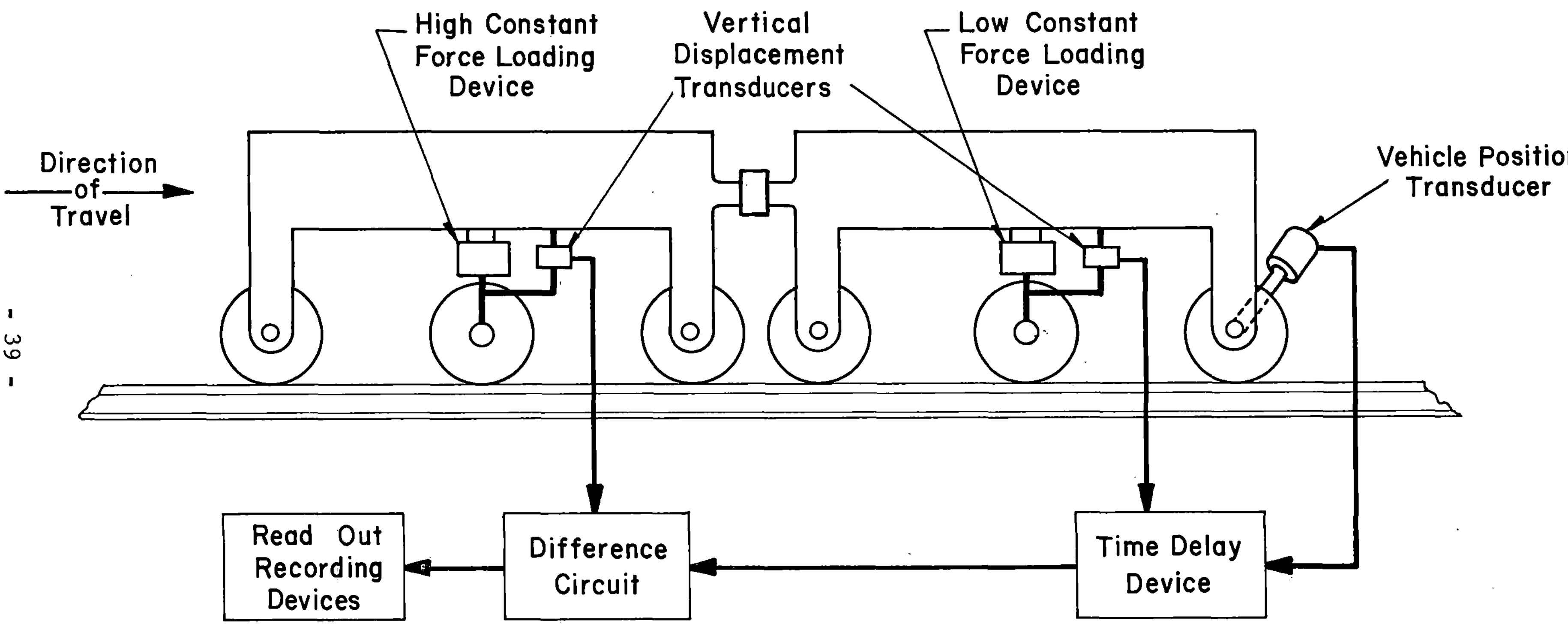


FIGURE 12. LIGHT-WHEEL, HEAVY-WHEEL TRACK STIFFNESS MEASUREMENT SYSTEM

stiffness related to variations caused by individual ties. The concept can be used for both lateral and vertical measurements; however, for lateral measurements transmission of the force with a conventional flanged wheel might produce high flange wear rates and wheel squeal, while transmission of the force with a wheel having a vertical axis would make it necessary to provide automatic track obstruction detection and wheel lifting systems. The system could not be used for longitudinal measurements or for true dynamic compliance measurements. The constant wheel load excitation methods are considered primarily as track condition evaluation systems to be used for high speed measurements.

Design Concepts for Track Dynamic Compliance Measurement Devices

If the track is not excited by normal track profile errors or a shaped wheel, the system required to excite the track and measure its response will probably have some or all of the elements shown schematically in Figure 13. In this figure, the measuring equipment is assumed to be moving forward with a velocity V over a rail which has an initial profile error X_p with a wavelength λ. A loading fixture produced a force, F_r, between the rail head and the fixture. This load in turn produces a deflection in the track structure X_f. In order to determine the dynamic track compliance, it is necessary to measure and determine the relationship between the transmitted force F_r and the rail motion X_f resulting from that force, or to determine the deflection which results only due to the exciter force F_g. With the system shown in Figure 13, the deflected rail position X_L can be determined if the loading fixture impedance Z_L is known, but the original rail profile X_p and the load-generated deflection X_f cannot be separated with only the components shown in Figure 13. One solution is to make the excitation forces large enough so that the force-produced deflection X_f is sufficiently large relative to the "noise" produced motion X_p that the noise is negligible. Another solution is to measure the track profile X_p separately and subtract it from the total displacement X_L. This will require two measurement systems of the type shown in Figure 13.

If the measuring system is used to detect defective ties or fasteners, it should be capable of detecting changes in stiffness that occur over a distance of 1.5 feet or less. If one cycle of excitation is generated for each 1.5

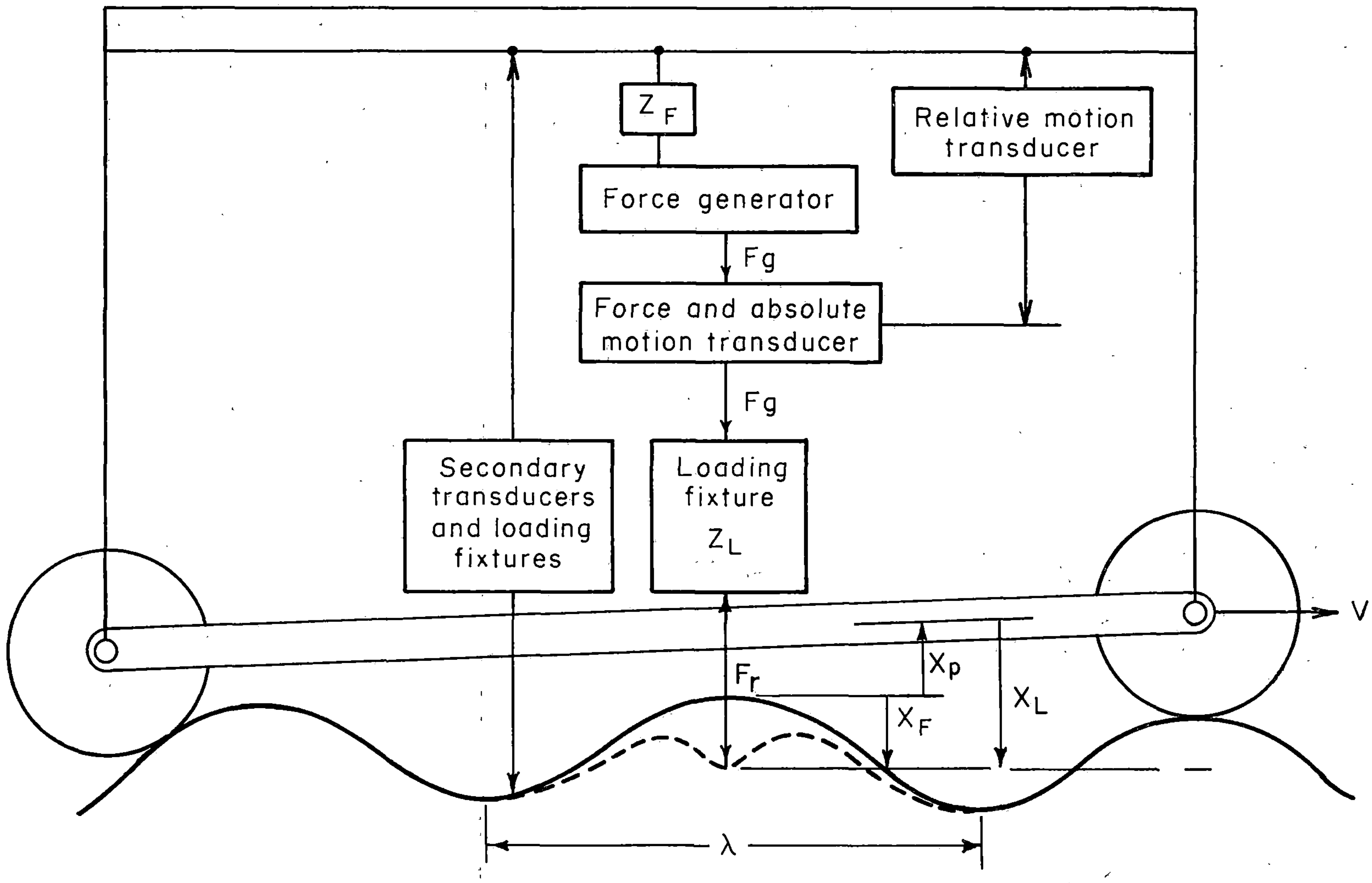


FIGURE 13. SCHEMATIC OF MOVING VEHICLE TRACK MEASUREMENT SYSTEM

feet traversed at 30 mph, the required excitation and processing rate is 30 Hz. One cycle in each 0.75 feet would require excitation and processing at 60 Hz, and a cycle each 0.5 feet would require working at a 90 Hz rate. With wavelengths in the 0.5 to 1.5 ft range, profile errors in the range of 0.0005 to 0.005-in. peak-to-peak would be expected for normal track. Near joints, or with corrugated rail, profile errors of about 0.025 in. peak-to-peak might be expected in this same wavelength range.

To obtain good data without using special control techniques to attenuate the unwanted track geometry signal, the motion resulting from the excitation force should produce deflections which are at least 10 dB higher than the profile errors. Therefore, rail motions produced by the exciter should be at least 0.0015 in. peak-to-peak, and for many track conditions they might have to be close to 0.1 in. peak-to-peak to obtain good data. To obtain these amplitudes at frequencies between 30 and 90 Hz will require excitation forces in the range of 20,000 to 30,000 lb peak-to-peak.

For long wave lengths, profile errors can be in the 1/4 to 1-in. peak-to-peak range. These long wave length errors would be expected to cause substantial noise problems when making low frequency response measurements at high train speeds. For example, with a 10 Hz excitation frequency and a train speed of 60 mph, the resulting wave length would be about 9 ft. To obtain a signal which is 10 dB greater than the profile noise with 9-ft wave lengths may require an excitation force greater than 100,000 lb peak-to-peak under some severe operating conditions.

Special noise control techniques which would reduce the magnitude of required excitation forces are to (1) average the data over a long section of track, or (2) measure the motions that are a function of the rail profile errors only and subtract these motion signals from the total response signal as discussed previously.

When a vibration exciter is used to force the system dynamically, the exact time that a cycle of excitation starts can be known accurately. Using this known starting time as a reference, the response signal can then be averaged many times. Each time the signal is averaged, the signals which are a function of the exciter force, having a consistent phase relationship to the exciting force, will add linearily with each successive accumulation. The noise components, being random, will tend to cancel each other. On the average, the signal-to-noise ratio will improve by about 3 dB each time the number of averages is doubled. For example, averaging two signals will improve the signal-to-noise by about 3 dB, averaging 16 signals will improve the ratio by about 12 dB, and averaging 256 signals will improve the ratio by about 24 dB. By averaging over many periods, signal levels which are much lower than noise levels can be measured accurately. The disadvantage of using the averaging process is that, by its very nature, the results calculated are average impedances or stiffnesses for long lengths of track. Consequently, changes in track condition which occur over short distances cannot be detected. Therefore, this noise control technique would not be suitable for track condition evaluation purposes where it is necessary to measure changes caused by individual ties and fasteners.

The use of narrow band filtering to enhance signal-to-noise ratios can improve the signal-to-noise ratio for sinusoidal excitation, but it is essential that the signal be applied to the filter for a period of time which is long compared to the filter transient-response time. To a first approximation, the transient-response time of a bandpass filter is inversely proportional to its bandwidth; therefore, the narrower the filter the longer the response time. Thus, when sweeping with a filter, the sweep scanning rate should be slow enough so that the filter remains near each point on the spectrum for a period of time which is long compared to the filter transient response.

Concept Development

To use a track dynamic compliance measuring system for evaluating track condition presents several significant problems that were discussed in previous sections of the report. At this time, it is not known how accurately specific track defects can be identified with any of the proposed loading techniques. Therefore, it is recommended that a very versatile measurement system be used initially to better determine the relationship between track defects and the data which can be obtained by different measurement techniques. This work is required before a final configuration and technique for evaluating track condition is chosen. Following a successful experimental evaluation and demonstration, a special purpose track evaluation device might then be built which is much simpler and less expensive than the general purpose equipment required for the basic studies.

For analytical studies, the system should be versatile enough to obtain vertical and lateral transfer compliance data on the same rail and between rails, both stationary and while moving. Providing the capability of measuring dynamic compliance and especially transfer compliance, while moving at high speeds is believed necessary because the cross coupling between wheels running on the same rail would be expected to vary significantly as a function of speed due to the change in the load effected zone.

To obtain the desired measurement capability and flexibility, a hydraulic exciter with the general configuration shown in Figure 10 is recommended. The exciter should be capable of producing a peak force of between 1000 and 5000 lb over the frequency range of about 10 to 100 Hz while moving over the track. Higher frequency capability should also be available with a peak force capability of about 100 lb. Compliance measurements at frequencies greater than 100 Hz would probably not have to be made while moving.

To obtain versatility in obtaining transfer compliance data under normal wheel loads with different truck configurations, a system of the type shown schematically in Figure 13 should be used. Physically, this system might be installed on a modified car as shown in Figures 14 and 15. There are several wheel suspension and excitation systems which might be used. Figures 16 and 17 show two different types of suspension utilizing independent wheel suspension, and Figure 18 shows a rigid axle type of suspension system which has been modified so that independent lateral excitation can be produced. Features common to all of the systems shown and recommended for this application are:

(1) Complete system moves laterally relative to the car body without producing force or measurement alignment problems on curved track.

(2) Controlled vertical and lateral preload forces can be applied.

(3) System natural frequencies in the desired loading directions can probably be made greater than 100 Hz.

(4) Lateral and vertical excitation can be produced at one wheel/rail interface almost independently of forces produced at the opposite wheel/rail interface.

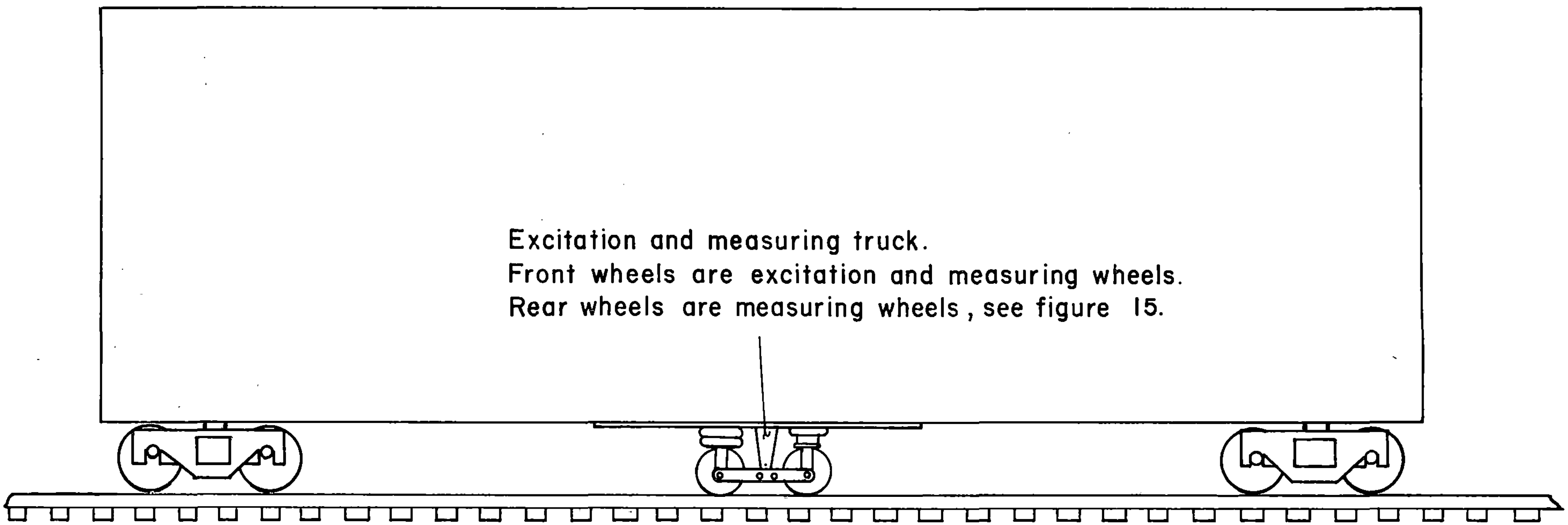


FIGURE 14. RELATIVE POSITION AND MOUNTING OF TRACK MEASUREMENT SYSTEM IN A MODIFIED BOX CAR

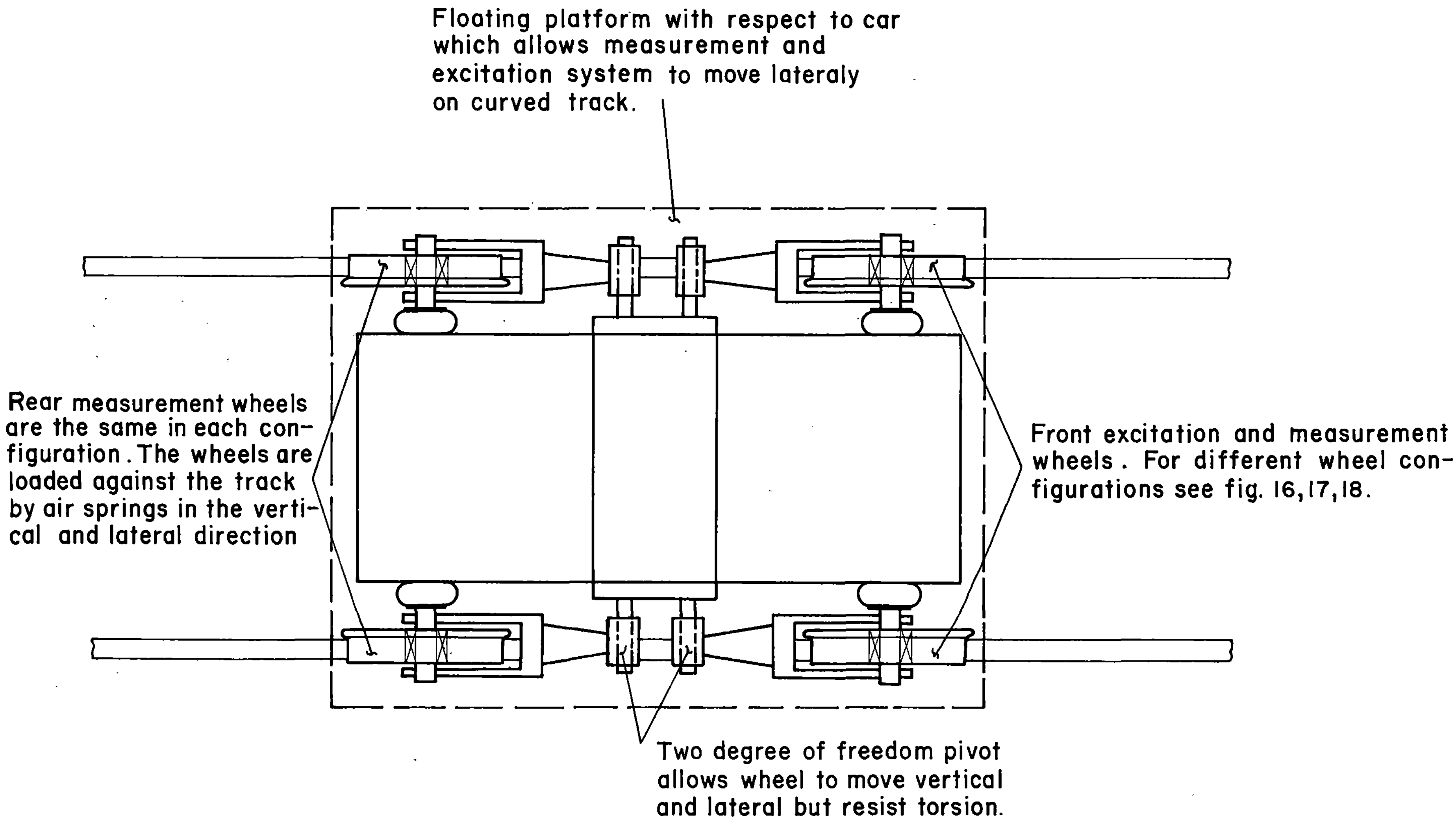


FIGURE 15. EXCITATION AND MEASUREMENT TRUCK

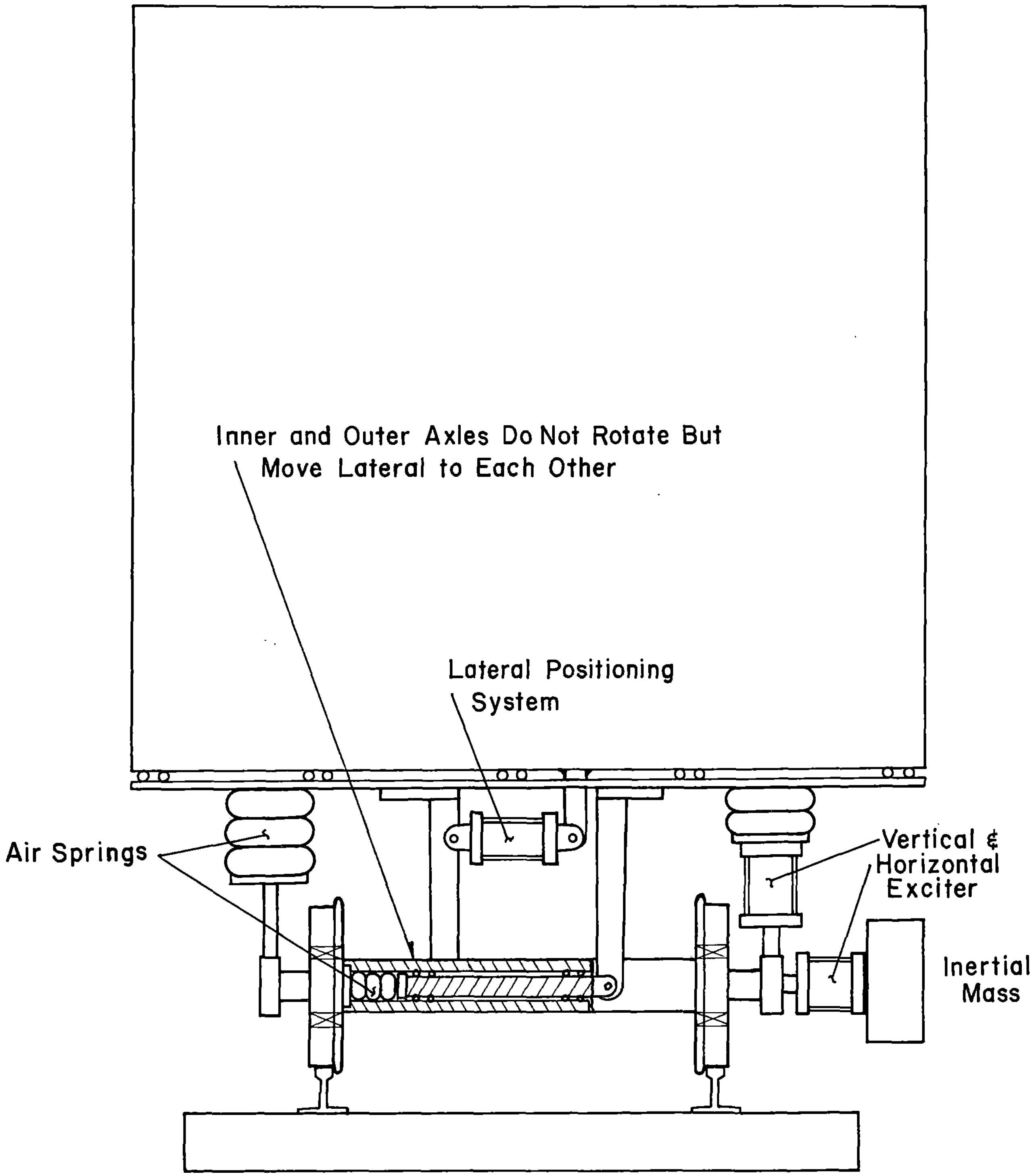


FIGURE 16. INDEPENDENT WHEEL SUSPENSION WITH PIVOTED ARM SUPPORT

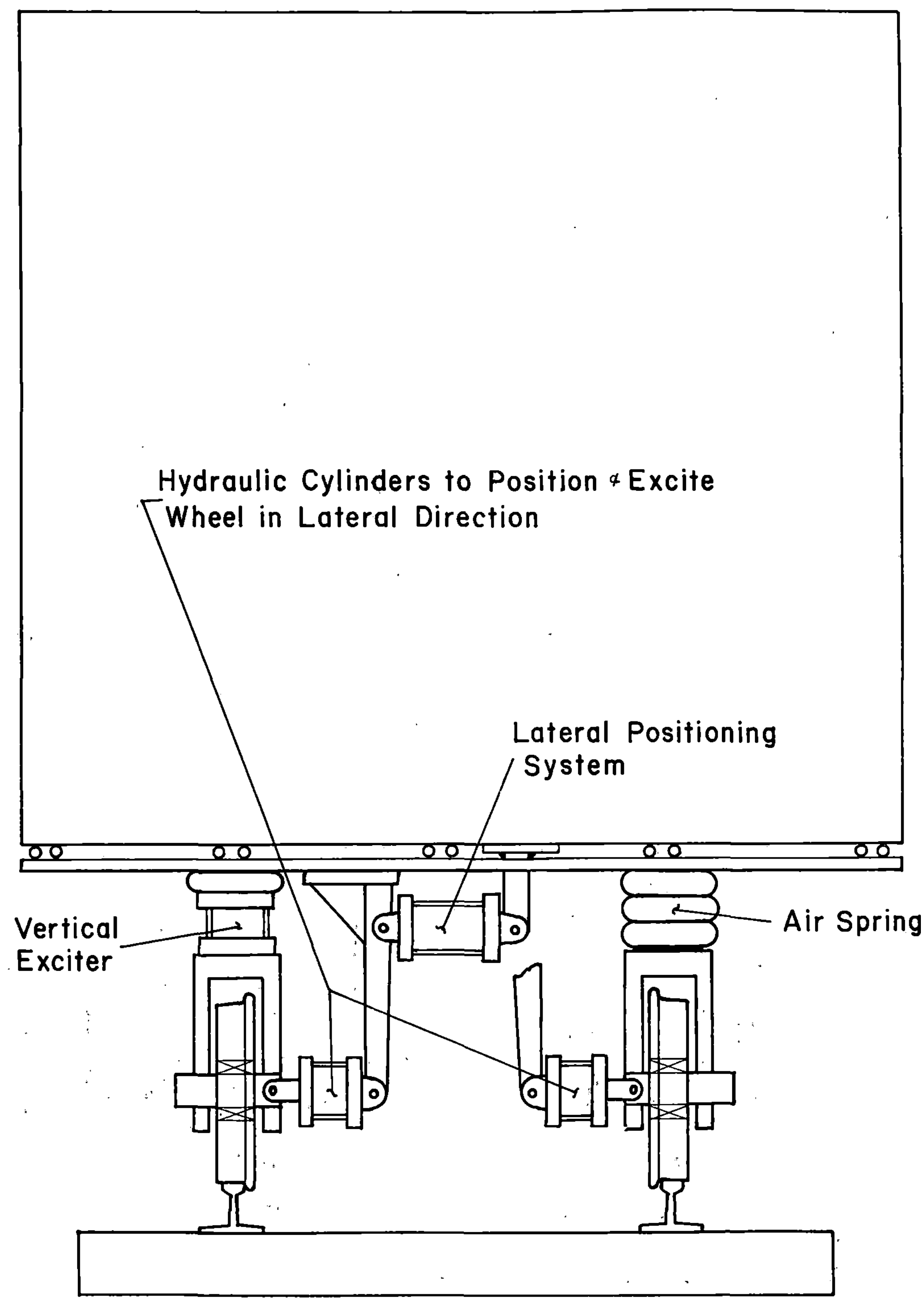


FIGURE 17. INDEPENDENT WHEEL SUSPENSION SYSTEM WITH PARALLEL ARM SUPPORT

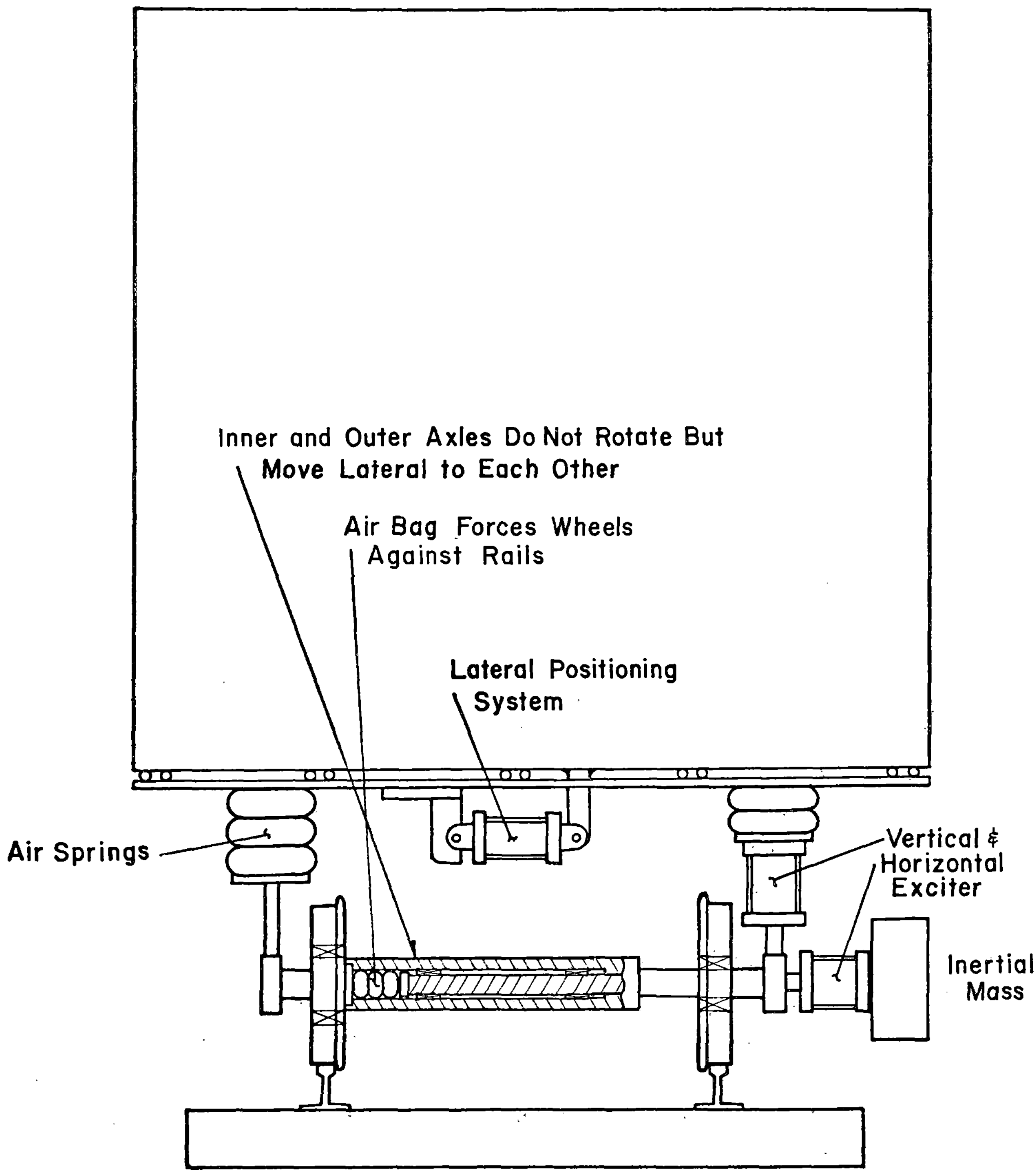


FIGURE 18. MODIFIED RIGID AXLE WHEEL SUSPENSION

The system shown in Figure 16 is an independent suspension similar to the "twin I beam" suspension used on Ford trucks. This has the desirable characteristics that very effective isolation can be obtained between the excited and unexcited wheels. Other advantages are that independent lateral loads can be applied to each wheel. Also, it could be built with either a rotating or nonrotating axle.

The concept shown in Figure 18 is similar to a conventional rigid axle system except the axle is made in two pieces. An air spring can be located between the two halves to provide a constant lateral rail loading and lateral isolation between the two wheels. This concept is probably lower in cost than the others, but it has the disadvantage that both lateral and vertical isolation is relatively poor. Ideally, the forces should be introduced so that a negligible amount of coupling occurs in the loading fixture. However, the fact that coupling between modes will occur with some systems will not make them impossible to use. If the coupling is negligible relative to the cross coupling being measured in the track, the system would still be satisfactory. Or, if the coupling is known, it can be--within limits determined by measurement accuracies--accounted for in the data processing.

With the excitation devices conceived as being practical for this application, it will not be possible to obtain adequate signal-to-noise ratios under all operating conditions unless signal averaging and/or noise cancellation techniques are used. Because of the track geometry noise problem, and also because it will be necessary to process large quantities of data, it will probably be desirable to use digital analysis, and the noise cancellation techniques discussed earlier. With digital analysis equipment, capabilities for averaging and noise cancellation are readily provided. Another reason for recommending the use of noise cancellation technique is that the equipment used for noise cancellation measurements can also be used to experimentally evaluate the heavy wheel, light wheel static compliance measuring concept.

The instrumentation required to measure dynamic track compliance will consist of some, or all, of the following components:

(1) Force transducers to measure the force generated by the dynamic exciters.

(2) Accelerometers on the wheel support fixtures to be used for mass cancellation and/or to measure wheel motion amplitudes or velocities.

(3) Displacement transducers to measure gage spread, track position at the exciters and measurement wheels, and to control the lateral position of the loading system.

(4) A pulse transducer and/or encoder to indicate position along the track.

For most types of measurements, the motion of the track that results from application of the excitation force can be measured either relative to an inertial reference using accelerometers, or relative to sections of track outside of the load affected zone using a chordal reference system. However, to make static stiffness measurements with d-c response using the heavy-wheel, light-wheel measurement concept, the chordal reference must be used. The heavy-wheel, light-wheel concept can be used with an inertial measuring system to measure changes in stiffness that occur over short distances, but not to measure absolute values of stiffness. Several possible methods of implementing a chordal measurement system with the general system shown in Figure 13 are to (1) use the car body as the reference chord, (2) install an independently suspended chord inside the car body, or (3) use a light of laser beam reference chord in the car body. Further analysis will be required to determine which of the above systems represents satisfactory accuracy at the lowest cost.

REFERENCES

1. Highway Research Board, Division of Engineering, National Research Council, National Academy of Sciences, National Academy of Engineering. "Detecting Seasonal Changes in Load-Carrying Capabilities of Flexible Pavements". National Cooperative Highway Research Program Report No. 76 (1969).

2. Personal telephone communication with Professor Kamran Majidzadeh of The Ohio State University.

3. Berger, L., "The Pavement Profiler, A New Technique for Evaluating Highways". VL World Highway Conference (1970).

4. Satoh, Y. and Hirata, G., "Repeated Shock Test of Railway Track - Dynamic Properties of Rail-Tie-Ballast Systems", Railway Technical Research Institute Quarterly Report, Vol. 4, No. 2, 1963, pp 42-45.

5. Satoh, Y., "Dynamic Effect of Flat Wheel on Track Deformation", Bulletin of the Int. Railway Congress Assoc., 42 (8-9), Sept., 1964, pp 547-553.

6. Prudhomme, A., "The Resistance of the Permanent Way to the Transversal Stresses Exerted by the Rolling Stock", Bulletin of the Int. Railway Congress Assoc., November, 1967, pp 731-766.

7. Tyc, P., "Protecting the Track Formation by Means of PVC Foils", C. Sc. Hochschule fur Verchrswesen, Prague, January, 1961.

8. Birmann, F. , "Theoretical and Experimental Solutions of Track Problems for High Speeds", IRCA-UIC High Speeds Symposium, 1968, Bulletin of the Int. Railway Congress Assoc., 45 (4), April, 1968, pp 391-460.

9. Meacham, H. C., Prause, R. H., Ahlbeck, D. R., and Kasuba, J. A., "Studies for Rail Vehicle Track Structures", Report No. FRA-RT-71-45 prepared for U. S. Dept. of Transportation, Federal Railroad Administration by Battelle Memorial Institute, April, 1970.

10. Wilson, G. P., "Diablo Test Track Noise and Vibration Measurements" Technical Report, June, 1967, prepared for Parsons Brinkerhoff-Tudor -Bechtel, San Francisco, California, by Wilson, Ihrig & Associates, Inc.

11. Muromachi, T., Komine, T., and Yasuda, Y., "Soft Subsoil Exploration at the Koise River Valley on the Joban Line-Comparison of Effect of Treatments for Soft Subsoils", Japanese National Railways, Quarterly Report of the Railway Tech. Res. Inst., Vol. 8, (1967), pp 153-156.

12. Kurzweil, L., "Dynamic Track Compliance", Report No. TSC-GSP-067, DOT/TSC, Cambridge, Mass., May, 1972.

13. Meacham, H. C., and Ahlbeck, D. R., "A Computer Study of Dynamic Loads Caused by Vehicle-Track Interaction", Transactions of the ASME, Journal of Engineering for Industry, 91 (3), August, 1969, pp 808-816.

14. Bjork, L. J., "Dynamic Loading at Rail Joints-Effect of Resilient Wheels", Railway Gazette, June 5, 1970.

15. Okabe, Z., "Laboratory Investigation of Railroad Ballast", Permanent Way, No. 13, Vol. 4, No. 4, Permanent Way Society of Japan, December, 1961.

16. Prause, R. H., Meacham, H. C., and Wright, J. J., "An Analysis of the Effect of Missing Ties on Track Safety", Report prepared by Battelle-Columbus Laboratories for DOT/FRA, October, 1971.

17. Butler, A. B., "An Analysis of Bending Stresses and Deflections in Railroad Rails, Thesis to U. of Illinois, Urbanna, Ill., 1967.

18. Sato, Y., "Lateral Ballast Resistance and Stability of Track in Earthquake", Railway Tech. Res. Inst. Quarterly Report, Vol. 11, No. 1, March, 1970, pp 3-6.

19. Ahlbeck, D., and Meacham, H., "Calculations of Vertical and Lateral Compliance of Rail-Tie Portions of Track Structure", Report prepared by Battelle-Columbus Laboratories for U. S. Department of Transportation, Federal Railroad Administration, March 26, 1971.

20. "Trackwork Study - Volume II - Recommended Trackwork Standards", prepared by De Leuw, Cather and Co., for the Washington Metropolitan Area Transit Authority, August, 1968.

21. Birmann, Op. Cit., p 80.

22. Birmann, F., "Lateral Strength or Resistance of the Track" Schnellfahrt & Oberbau, 1971, pp 45-49.

23. Dietrich, R. J., and Salley, J. R., "Embankment Support for a Railroad Test Track", Report No. FRA-RT-72-07 prepared by Shannon and Wilson, Inc., for DOT/FRA (PB 202-808), August, 1971.

24. Yoder, E. J., "Principles of Pavement Design", John Wiley & Sons, Inc., New York, 1959, pp 101-106.

25. U. S. Army Engineer Waterways Experiment Station, Soils and Pavements Laboratory, Vicksburg, Mississippi. "Vibroseismic Survey, Railroad Test Embankment, Aikman, Kansas", Miscellaneous Paper S-72-36, June, 1972.

26. Prud'homme, M. A., and Janin, M. G., "The Stability of Tracks Laid with Long Welded Rails", Bulletin of the Int. Railway Congress Association, October, 1969, pp 601-602.

27. Ahlbeck, D., Prause, R., and Meacham, H., "An Application of Computer Modeling Techniques to Predict the Effects of Railroad Track Geometry", The Intersociety Conference on Transportation, Denver, Colorado, September 24-27, 1973.

28. "Technical Review and Design Consolidation for the DOT Dynamic Simulator" Report prepared by Battelle-Columbus Laboratories for Office of High-Speed Ground Transportation, U. S. Department of Transportation, 1969.

BIBLIOGRAPHY

1. Kasuba, J. A., "Comments on Dynamic Track Modulus Measurements", (unpublished BCL memorandum), November 9, 1970.

2. "Stresses in Railroad Track", Progress Report of the Special Committee--Stresses in Track, Journal American Railway Engineers Association, Vol. 19, pp 878-893 (1918).

3. "Dynamic and Static Forces on the Track", Railway Research and Engineering News, Section C, Bibliography Series.

4. Kitaoka, H., "Track Irregularities-JNR Studies in Search of New Tolerances for Track Maintenance", Japanese Railway Engineering, Vol. 17, No. 3, September, 1966.

5. Lewis, F. M., "Vibration During Acceleration Through a Critical Speed", Trans. ASME, Vol. 54, 1932, pp 253-261.

6. Deenik, Ir.J.F., and Eisses, J. A., "Fastening Rails to a Concrete Deck", The Railway Gazette, March 18, 1966, pp 230-236.

7. Satoh, Y., and Toyoda, M., "Deformation of Railway Track Under High-Speed Train-Measurements on the Test Run Section of the New Tokaido Line", Quarterly Report RTRI, Vol. 7, No. 2, 1966.

8. "The Test on Buckling of Curved Track", Permanent Way - Japan, No. 1, pp 1-15.

9. Ikemori, M., "Relation Between Track Irregularities Under Train Loads and No Load, Railway Technical Research Institute, Quarterly Report. Vol. 4, No. 2, 1963, pp 48-50.

10. Satoh, Y., Onishi, A., and Takenaka, S., "Experiment on Grading of Crushed Stone for Railway Ballast", Railway Technical Research Institute, Quarterly Report, Vol. 3, No. 2, 1962, pp 26-29.

11. Nayak, P. R., and Tanner, R. B., "Frictional and Vibratory Behavior of Rolling and Sliding Contacts", Report FRA-RT-73-13, July 21, 1972, for DOT/FRA, Washington, D. C.

12. Birmann, F., "Track Parameters, Static and Dynamic", Paper 5, Proc. Inst. Mechanical Engineers, Vol. 180, Pt 3F, 1965-66.

13. Holmes, P. J., and White, R. G., "Data Analysis Criteria and Instrumentation Requirements for the Transient Measurement of Mechanical Impedance", J. of Sound and Vibration, 25 (2), 1972, pp 217-243.

APPENDIX A

REQUIREMENTS FOR WHEEL-RAIL SIMULATOR

WYLE LABORATORIES

August 10, 1973

BATTELLE
Columbus Laboratories
505 King Avenue
Columbus, Ohio 43201

ATTENTION: Mr. R. H. Prause

SUBJECT: Impedance Information for BATTELLE

Dear Mr. Prause:

In response to your telephone conversation of July 27, 1973 with R. Coupland and ~~I~~ me on the track impedance data requirements for the track simulation aspects grammar! of the Wheel/Rail Dynamics Laboratory, we feel that the following list summarizes the anticipated requirements.

a) Both phase and amplitude of the input impedance at the wheel/rail contact point in the vertical, lateral and longitudinal directions, to be obtained at 18-inch intervals for each rail.

b) Both phase and amplitude of the transfer impedance at the wheel/rail contact point, in the vertical, lateral and longitudinal directions, to cover the area encompassed by the largest truck envisioned (approximately ± 10 feet), to be obtained at 18-inch intervals for each rail. Both interrail and between rail transfer impedances are required.

c) Data is required over distances of the order of 5 miles, and should be obtained about every two hundred yards and over a frequency range of DC to 100 Hz.

d) While not of immediate concern, it would be useful to have ballast point transfer function in addition if these could be obtained with a minimum of difficulty and cost.

I also have attached two figures that should clarify items a) and b) above.

Sincerely,

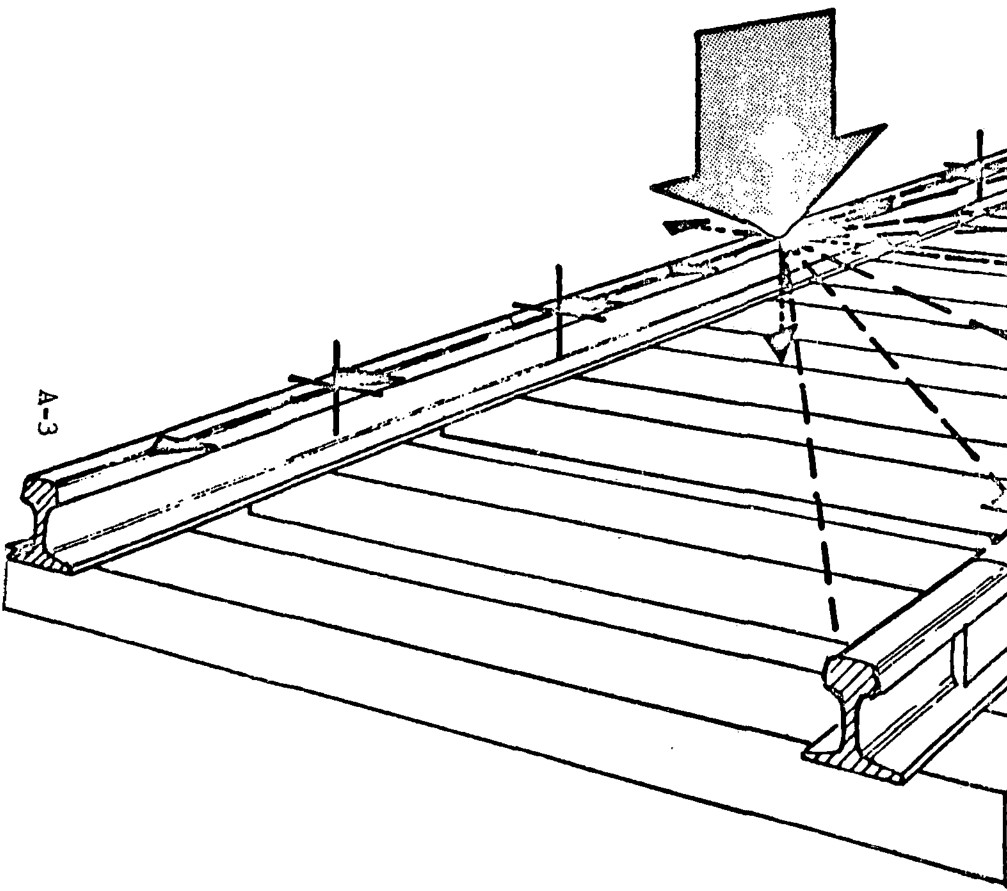
WYLE LABORATORIES
Eastern Operations

Daniel Bozich

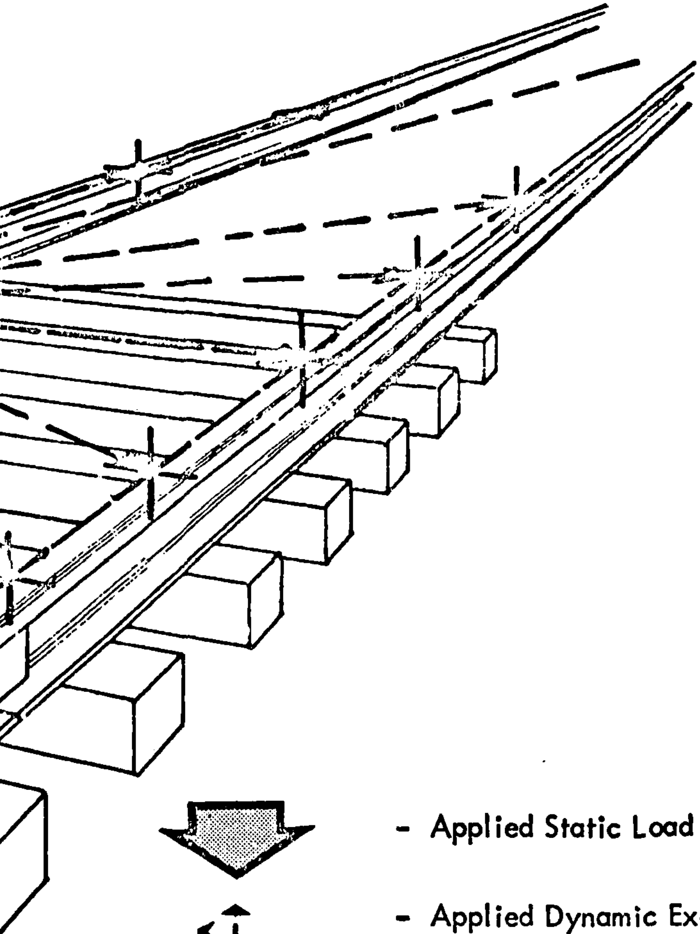
Daniel Bozich, Chief
Advanced Technology

DB:dc

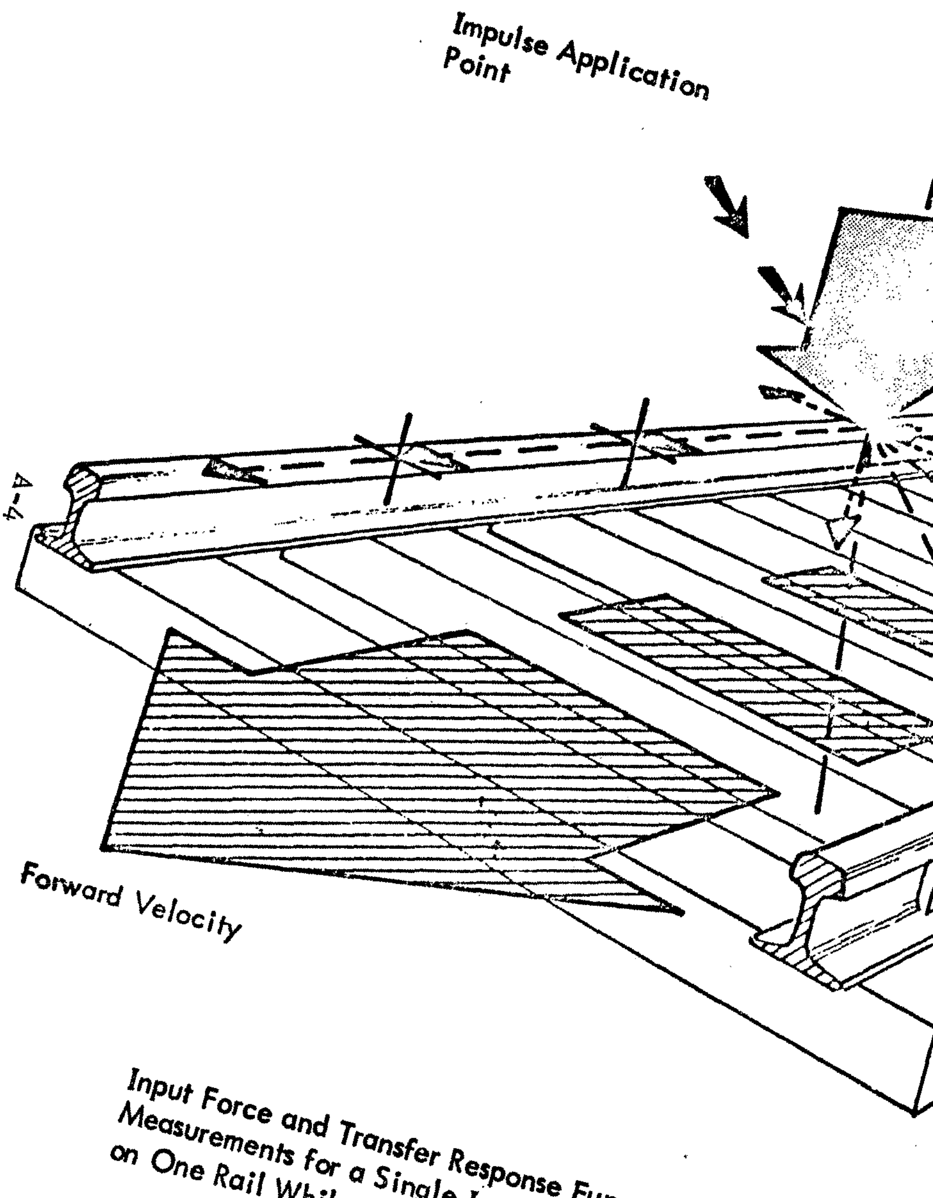
Attachments



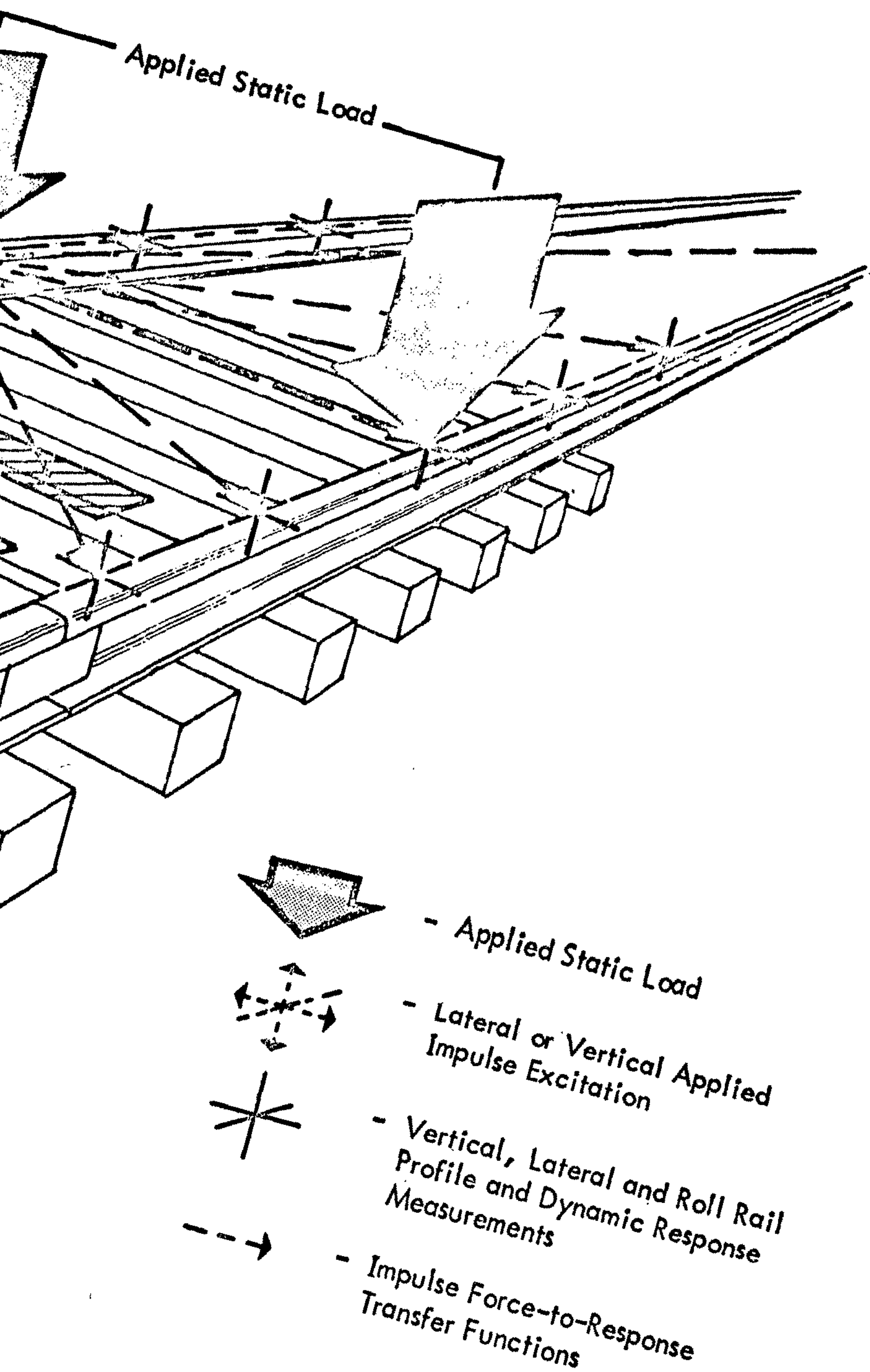
Input and Transfer Impedance Measurement (Calibration) with Each Dynamic Force Direction Applied Separately and with a Vertical Static Load Applied at Each of the Measurement Points while Stationary



- Applied Static Load
- Applied Dynamic Excitations (Triaxial Input Forces and Responses)
- Vertical, Lateral and Longitudinal Response Measurement Points
- Force-to-Response Transfer Functions



Input Force and Transfer Response Function Measurements for a Single Impulse Applied on One Rail While Moving at Some Velocity.


Applied Static Load
- Applied Static Load
- Lateral or Vertical Applied Impulse Excitation
- Vertical, Lateral and Roll Rail Profile and Dynamic Response Measurements
- Impulse Force-to-Response Transfer Functions

APPENDIX B

LIST OF TELEPHONE CONVERSATIONS AND TRIP REPORTS

1. Trip Report for Montreal, Canada, to visit Canadian National Railways on 8/6/73. Persons contacted were Nelson Caldw ell, Mr. Peirre Marcott, and Mr. Henry Girard.

2. Trip Report for a seminar on "Recommendations for Future Track Testing Procedures" by Dr. Arnold Kerr from New York University on 7/31/73. Persons contacted were R. C. Arnlund, FRA, I. A. Reiner, Chessie Systems, L. G. Kurzweil, DOT/TSC, G. C. Martin, AAR, D. P. McConnell, DOT/TSC, Ta Lun Yang, Ensco, and W. B. O'Sullivan, DOT/FRA.

3. Trip report for Vicksburg, Miss. to Waterways Experiment Station on 9/5/73. Persons contacted were Frank McLean, WES and Bob Bollanger, WES.

4. Trip report for Washington, D. C. to participate in DOT/FRA "Track Impedance Measurement Symposium" on 2/27/72. Persons contacted were Mr. W. B. O'Sullivan, DOT/FRA.

5. Telephone conversation on 7/27/73 with Dan Bozich and Roger Cooper, Wyle Laboratories, Huntsville, Alabama.

6. Telephone conversation on 6/29/73 with Dr. Frank McLean and Joe Curro, U. S. Army Engineer Waterways Experiment Station, Vicksburg, Miss.

7. Telephone conversation on 7/23/73 with Jerry Sullivan of Southern Pacific Railroad.

8. Telephone conversation on 8/9/73 with Mr. R. M. Brown, Chief Engineer, Union Pacific Railroad, Omaha, Nebraska.

9. Telephone conversation on 8/9/73 with Mr. W. M. Jaekle, Vice President, Engineering & Research, Southern Pacific Railroad, San Francisco, Calif.

10. Telephone conversation on 8/9/73 with Mr. Ray Kollen of Santa Fe Railroad at Topeka, Kansas.

A Review of Measurement Techniques, Requirements, and Available Data on the Dynamic Compliance of Railroad Track, 1975
US DOT, FRA, WD Kaiser, GL Nessler, HC Meachem, RH Prause