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Anthology of Rail
Dynamics Research

Steven E. Shladover

Systems Control Technology, Inc.
1801 Page Mill Road
Palo Alto, CA 94306

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16. Abstract

This report is intended to provide the railroad industry and other interested parties with an anthology of recent technical information of long term value which has resulted from FRA-sponsored studies of rail system dynamics. This anthology includes brief descriptions of FRA contract reports and professional papers based on FRA contract work in the areas of wheel-rail interface phenomena, track characteristics, vehicle dynamics, vehicle-track interactions, longitudinal train dynamics, train resistance and lading response. A comprehensive bibliography of these documents is included to aid the user of this report in finding the documents of greatest interest to him. In addition, a representative sampling of the referenced papers is reprinted as part of the report to illustrate the breadth of the technical accomplishments in rail system dynamics which have been achieved under FRA sponsorship between 1971 and 1981.

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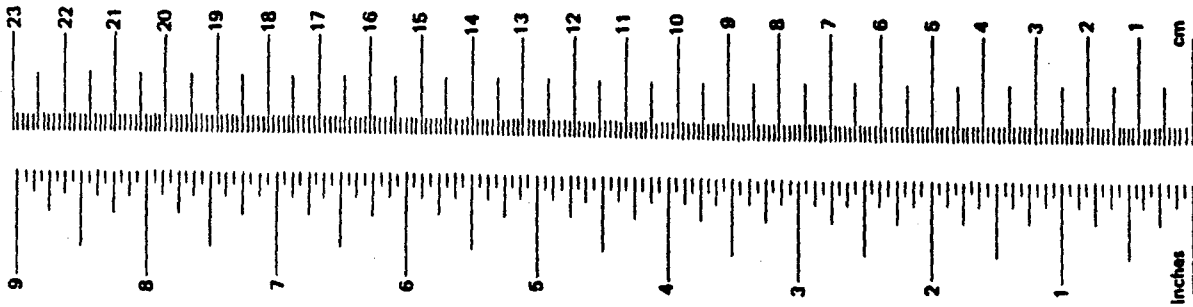| 19. Security Classif. (of this report) UNCLASSIFIED	20. Security Classif. (of this page) UNCLASSIFIED	21. No. of Pages 29	22. Price

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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		
in²	square inches	6.5	square centimeters	cm²
ft²	square feet	0.09	square meters	m²
yd²	square yards	0.8	square meters	m²
mi²	square miles	2.6	square kilometers	km²
	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	16	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
ft³	cubic feet	0.03	cubic meters	m³
yd³	cubic yards	0.76	cubic meters	m³
		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 Weight 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		
cm²	square centimeters	0.16	square inches	in²
m²	square meters	1.2	square yards	yd²
km²	square kilometers	0.4	square miles	mi²
ha	hectares (10,000 m²)	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
m³	cubic meters	36	cubic feet	ft³
m³	cubic meters	1.3	cubic yards	yd³
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F

Temperature scale:

°F   -40   0   32   40   80   98.6   120   160   200   212
°C   -40   -20   0   20   37   40   60   80   100

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I. INTRODUCTION

This report provides an overview of the publications on rail system dynamics which have appeared as the products of FRA-sponsored research in the decade from 1971 to 1981. These include FRA contract reports and technical papers presented through the professional societies. In general, reports published since 1971 and papers published since 1975 have been included. The end of 1981 has been chosen as the cut-off date for more recent work.

The technical subject matter which falls under the category of rail system dynamics does not fit entirely into well-defined classifications. The decisions about what subject areas to include (and exclude) have of necessity been judgemental. A good summary of the subject matter which is covered here can be gained by reviewing the outline of the remaining chapters of this report:

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The text of the report includes a brief discussion of each of the documents which has been obtained in the search through FRA-sponsored projects, with citations to a complete bibliography. In addition, twenty representative papers were selected for incorporation into Volume 2 of this report to display some of the results which have been achieved during this decade of FRA sponsorship. These papers have been chosen for inclusion because taken together they give the reader an effective picture of the breadth of the accomplishments in rail system dynamics which the FRA has promoted. This selection was based on the author's judgment, and should not be interpreted as an official endorsement of these papers to the exclusion of others.

It is the author's hope that this anthology is as complete as possible within the defined categories of subject matter, years of publication and sponsorship. Work which was not sponsored by the FRA is not included here. Some university projects are particularly affected by this restriction, in that only the documents which resulted from FRA sponsorship are covered here, while others produced exclusively under the sponsorship of the DOT Office of University Research are not covered. Some work sponsored jointly by FRA and AAR in the Track-Train Dynamics (TTD) program is included, but the majority of the TTD reports and papers, particularly those produced by the AAR staff, are not included.

The citations for the documents which are covered in this report were assembled from several sources. The search was initiated using the bibliographies and contract descriptions in the FRA's 1980 directory, "Improving Railroad Technology" and the Railroad Research Information Service (RRIS) File Search of August 22, 1979 prepared for the FRA Office of Research and Development. Using the names of authors of FRA reports found in both of these sources, new computerized literature searches were performed on the Engineering Index and RRIS data bases to identify additional documents. Some of the authors whose works appeared most frequently were provided with listings of the citations to their works and were asked to indicate which were performed under FRA sponsorship. They also supplied citations to additional documents which were not found in the computerized searches. The documents were then obtained from a variety of sources, including SCT's collection of rail dynamics literature, the DOT and FRA/RRD libraries in Washington, D.C., the Engineering Societies Library in New York and the libraries of the Massachusetts Institute of Technology, Princeton and Stanford Universities, and the University of California.

II. SOURCES FOR OVERVIEW INFORMATION

FRA sponsorship of work in railroad system dynamics has taken two different forms:

(1) support of individual research projects

(2) support of conferences and symposia which disseminate information about projects conducted under both public and private sponsorship.

This section includes examples which fit in both of these categories. Several FRA-sponsored projects have been designed in whole or in part to review the status of some aspects of existing rail dynamics work, rather than performing new analyses and tests. These projects have led to the development of some useful reference reports, which can help lead readers to the original sources for more detailed information, as well as serving as good introductions to their subject matter in their own right. The conferences and symposia which FRA has sponsored have been valuable forums for the exchange of ideas on the state of the art of railroad technology among the participants, while the proceedings reports which have resulted have provided effective overviews for those who were not able to participate in person.

The first interim report of the "Freight Car Truck Design Optimization" project by the Southern Pacific Transportation Company was a three-volume literature review [1]. This review was an annotated bibliography, including abstracts and some copies of technical papers or sections of reports, providing a comprehensive overview of the (largely domestic) literature on railroad trucks prior to 1975. The reports were organized into five separate sections:

- the history of the freight car truck
- truck design
- truck components
- track-train dynamics as related to truck performance
- truck performance

The Battelle-Columbus Laboratories have prepared an extensive bibliography on rail technology for TSC, under FRA sponsorship [2]. Most of the material in Reference 2 was oriented towards issues which are specific to the rails themselves, but some was related to the influence of the rails on vehicle performance.

The University of Virginia, with the assistance of some outside authorities, has completed a review of the computer programs which have been developed to represent railroad vehicle dynamics [3]. The existing programs were found to have been developed for very specific uses in most cases, and were infrequently found to be used by organizations other than their developers'. Most of the programs were not sufficiently well documented or validated for general use, and the input data requirements were often found to be deterrents to their use. The work reported in

Reference 3 should save significant effort for other rail dynamics researchers who are interested in finding existing computer programs which they can use.

The FRA's sponsorship of conferences on railroad system dynamics has been most visible in the annual Railroad Engineering Conferences between 1975 and 1979, the proceedings of which were published as FRA reports [4-7]. Prior to 1975, these conferences were conducted under private sponsorship and there was no conference in 1978 to avoid conflicts with that year's International Wheelset Congress, which was held in Colorado Springs.

Some of the work reported in References 4-7 was sponsored by FRA, but much of it was conducted overseas or under private sponsorship. The FRA-sponsored papers are discussed by subject area in the appropriate later sections of this report. The conference proceedings in their entirety serve as useful surveys of the significant railroad research work accomplished during the four years of their coverage.

The FRA also served as co-sponsor of the Symposium on Railroad Track Mechanics and Technology at Princeton in 1975 [8] and the Conference on Advanced Techniques in Track Train Dynamics at Chicago in 1977 [9]. The track symposium proceedings contains significant papers on a wide range of track issues, serving as an excellent overview of the international state of the art in track mechanics as of 1975. The papers found in References 8 and 9 which are related to rail vehicle dynamics and were prepard under FRA sponsorship are covered in later sections of this report. Reference 9 is a broader overview of the entire field of track-train dynamics as of 1977, focused on work conducted in the joint FRA-AAR-RPI Track Train Dynamics Program.

Three more recent conferences co-sponsored by the FRA also deserve mention here. These have been reported in the following proceedings volumes:

"Accomplishments in the 70's, Goals for the 80's: A Track Train Dynamics Conference," AAR Report R-400, November 27-29, 1979, Chicago, IL

"FAST Engineering Conference - 1981 Proceedings," November 1981, Denver, CO, Report FRA/ TTC-82/01.

"Proceedings: International Conference on Wheel/Rail

Load and Displacement Measurement Techniques,"

January, 1981, Cambridge, MA, Report DOT-TSC-UMTA-82-3.

The first of these three reports was concerned with the accomplishments of the Track-Train Dynamics Program in many aspects of

railroad technology, not only dynamics. The
dynamics issues addressed in that conference were
principally train action and wheel/rail loads.
The second report was largely concerned with the
wear-related issues addressed at the FAST track
in Pueblo, rather than with dynamics as such.
The third report contains a collection of papers
which provide detailed descriptions of state of
the art techniques for measuring wheel/rail for-
ces and displacements, some of which were devel-
oped under FRA sponsorship and some of which were
not. The proceedings as a whole is a valuable
reference on international developments in wheel/
rail instrumentation systems, which can help
provide important information about rail vehicle
dynamic performance.

III. WHEEL-RAIL INTERFACE PHENOMENA

Among the most challenging problems to confront researchers in rail vehicle dynamics is the difficulty of determining precisely what happens at the interface between the steel wheel and steel rail. Extremely high stresses are generated within a small contact patch in order to transmit the large forces needed to support, guide, and propel rail vehicles. A thorough understanding of the wheel-rail interface is needed in order to be able to predict the dynamic response of rail vehicles. Unfortunately, the interface phenomena are very difficult to observe and measure empirically, impeding the development of fully satisfactory theories to explain these phenomena. The physics at work in the wheel-rail interface are extraordinarily complex for a variety of reasons, including:

- mixture of elastic and plastic deformation of materials

- extremely high stresses, which change rapidly in time and space

- nonlinear wheel-rail contact geometry

- creep force saturation

- abrupt changes in contact angles and force vectors for small changes in wheelset position.

Much research effort has been devoted to these wheel-rail interface phenomena within the past decade, under a variety of different sources of sponsorship. This concentration of effort has been based on the fact that the wheel-rail interface must be modeled correctly before the responses of railroad vehicles to diverse conditions can be predicted with confidence.

FRA support of wheel-rail interface research dates back to the work of Nayak at Bolt, Beranek, and Newman, reported in 1972 [10]. This work dealt with some of the fundamental properties of rolling contact between bodies which are not ideally smooth, relaxing some of the simplifying assumptions of earlier work. Reference 10 was concerned with two-dimensional rolling contact, and did not extend to consideration of the problems specific to railroad wheels on rails.

The high-speed testing of the Linear Induction Motor Research Vehicle (LIMRV) provided an opportunity to measure the available adhesion of a rail vehicle as a function of speed over a very wide speed range. These empirical results were compared with published data for moderate speed tests in Reference 11, indicating that the attainable adhesion on unpowered steel wheels was more dependent on the running rail surface than on the vehicle speed.

In conjunction with the DOT Office of University Research, FRA has supported a long-term research investigation into wheel-rail contact phenomena at the University of Pennsylvania. This work, under the direction of Professor Burton Paul, has been reported in a series of papers and reports since 1975 [12-23]. The series began with a comprehensive review, including an extensive bibliography, of the literature which was available prior to 1975 [12-13]. This review serves as an excellent reference on the physical processes at work in the contact patch, and points to the need for development of methods of analyzing the non-Hertzian contact phenomena which are present at the wheel-rail interface.

Reference 14 presented numerical solution methods for three-dimensional, frictionless, conformal elastic contact, with examples for a sphere indenting a spherical seat and a cylinder indenting a cylindrical seat. A method for defining the three-dimensional contact patch was also presented in this report. The work continued with numerical solutions of the counterformal contact stress problem [15-17], including a user's manual for the computer program which was developed [16] and an example for non-Hertzian contact of a railroad wheel and rail [15, 17]. Extensions to the analysis method and computer program for conformal contact were documented in References 18-20a, and improved solution methods were then covered in References 21-23. Reference 17 is reprinted in Volume 2 as documentation of some of the accomplishments of this program.

Although the work documented in References 12-23 has not been presented in the form of a vehicle dynamic model, its results will be useful in helping to develop more accurate models of the forces and moments transmitted across the wheel-rail interface. In contrast to that work, the second major FRA program on wheel/rail contact characterization took a more macroscopic approach to the problem, focused on developing relationships which could be applied directly in vehicle dynamic models. This program, led by Professor Neil K. Cooperrider at Arizona State University and Professor E. Harry Law at Clemson University, has also produced an extensive set of documentation [24-31]. It has had two principal foci, the development of analytical descriptions of nonlinear (rigid) wheel-rail geometric constraint relationships [24-28] and the development of transferable FORTRAN computer programs to implement the creep theories originally formulated by Professor J.J. Kalker at the Delft University of Technology [29-31].

The analytical and experimental determinations of the macroscopic wheel-rail geometric constraints (including users' manuals for computer programs) were described in detail in Reference 24 for symmetrical wheels and rails, while the extension to asymmetrical cases was reported in Reference 28. In this work, scale models of wheel and rail cross-sectional profiles were used to experimentally validate the analytical method (a computer program) which calculates the effective conicity and gravitational stiffness of a wheelset for arbitrary wheel and rail head pro-

files (assuming negligible deflections due to contact stresses). These relationships were based on a numerical evaluation of the geometric constraint functions for rolling radii, angle of wheel/rail contact and wheelset roll angle [27]. Those three nonlinear geometric constraints were expressed as describing functions for application to a quasi-linear analysis of the hunting stability of rail freight vehicles [25, 26]. This analysis, which included a describing function representation of suspension dry friction, illustrated the dependence of hunting behavior (critical speed) on wheel profile and the amplitude of vehicle response (limit cycles). Reference 26 is included in Volume 2 to provide a more detailed overview of this work.

References 29 and 30 are documentation of the conversions of Professor Kalker's original Algol programs for calculation of a nonlinear creep force-creepage relationship into FORTRAN. These reports were designed as detailed users' manuals to enable other analysts to generate the creep force-creepage relationships needed for many rail vehicle dynamics models. Reference 31 is the users' manual for an additional FORTRAN program which uses Kalker's linearized creep theory and the Hertz theory of rolling contact to determine contact patch geometry and linearized creep forces.

A parallel effort to that described in References 24-28 was conducted under FRA sponsorship at TSC at about the same time. References 32 and 33 described the work of D.P. Garg in augmenting the realism of frequency domain modeling of wheelset dynamics using describing functions. He showed the dependence of wheelset critical speed on a variety of parameters, such as primary suspension yaw and lateral stiffness and axle load. As part of the same general effort, a preliminary analysis of truck performance in curves (with nonlinear creep and flange contact forces) was also developed [34].

A third major FRA-sponsored program of university research on wheel-rail interface phenomena has been led by Professor Sudhir Kumar at the Illinois Institute of Technology (IIT). Much of the work in this program has been oriented toward wear, rather than dynamics, but many of the results are still applicable to rail vehicle dynamics problems [35-40].

Reference 35 described the scale model friction-creep test facility at IIT, which was used to measure coefficients of friction and creep (longitudinal) in braking. Results were produced for clean rail and rail contaminated by water and oil.

Reference 36 covered continuations of this work, including investigations of the size and shape of the contact patch, which was shown to change rather quickly from an ellipse to a rectangle. One key result of this work was the empirical demonstration that the product of the contact area and creep is a constant for a given normal load and coefficient of friction, with the contact area increasing and creep decreasing as wear progresses [38]. A second result, which proceeded from that, was the development of a single nondimensionalized curve for adhesion as a function of creep [37]. This curve, which demonstrates the saturation of creep force for increasing creepages, was shown to fit Kalker's theory for very smooth wheels. Reference 37 is included in Volume 2 to provide a more complete description of these findings.

Reference 39 provided a broad overview of the work presented in [35-38] and then added a new treatment of the lateral friction-creep relationship, which was found to have a higher peak value than the longitudinal relationship, followed by a fast drop (not merely a monotonic saturation). Reference 40 continued this work into the realm of wear, demonstrating the effects of worn wheels on the contact patch (using FAST data) and suggesting the need for a special wheel profile (as yet undefined) to minimize the severity of the effects of wear on hunting stability.

IV. VEHICLE-TRACK DYNAMICS

The majority of the attention which has been devoted to rail system dynamics comes under the category of vehicle-track dynamics. For better understanding of this review, this category has been subdivided further. Track characteristics are covered first, in Section 4.1. These are followed by vehicle dynamics for essentially fixed track geometry, in 4.2, and finally vehicle-track interactions in 4.3.

4.1 TRACK CHARACTERISTICS

The most significant inputs (forces) which act on rail vehicles are those imposed by the track. This makes it futile to try to understand the vehicle's dynamic behavior without understanding the characteristics of the track which supports and guides it. The geometry of the track can be measured in either a loaded or unloaded condition, giving different results. The differences are attributable to the compliance of the track. Both geometry and compliance should be known in order to be able to predict the responses of a vehicle traversing the track. These responses can in turn be used to help direct maintenance-of-way planning so that the track is always maintained in a condition which is both safe and economical for vehicle operations.

Based on the above discussion, Section 4.1 has been subdivided further into three categories:

    4.1.1 Track Geometry Measurement and Characteristics
    4.1.2 Track Mechanics (Compliance)
    4.1.3 Maintenance of Way

4.1.1 Track Geometry Measurement and Characterization

FRA has invested considerable research effort in the measurement and analytical characterization of track geometry, in support of the development and updating of its Track Safety Standards. Much of this effort has been devoted to the design and installation of special instrumentation in test cars, known as the Track Geometry Cars and then the Track Geometry Measurement System (TGMS). This instrumentation has been described in a number of technical papers [41-45], starting in 1973.

The inertial profilometer [41] measures track profile (vertical) deviations by detecting the displacement and acceleration of a mass which is free to slide vertically relative to the truck journal on which it is mounted. Appropriate signal processing produces a vertical space curve description of each rail, suitable for use in vehicle simulation studies. Track curvature is measured by using a gyroscope to measure the car's yaw rate, an axle tachometer to measure speed and velocity transducers for the relative

motions between the car and trucks [42]. Reference 43 described an analysis of a gyroscopically compensated vertical pendulum system for measuring track superelevation from a moving vehicle, although it did not refer to its implementation on any of the FRA test cars. References 44 and 45 described gauge measuring techniques, again without reference to their implementation.

Two generations of integrated track geometry measurement systems were described in considerable detail in the FRA reports on the extensive validation test programs to which they were subjected [46, 47]. More compact and accessible descriptions of these systems may be found in two technical papers, one on the T-6 car [48], and the other on the T-10 car [49]. The latter of these two papers is included in Volume 2 of this anthology to provide good documentation of the type of track geometry data which can be made available for analytical investigations.

The pseudo space-curve track geometry data produced by the FRA test cars are voluminous and although they are usable for time-domain simulation studies, they cannot be readily used for frequency domain modeling and analysis or for general evaluations of track quality. Appropriate methods for reducing these track data into a manageable form were the subject of a series of reports and technical papers by John C. Corbin and others at ENSCO [50-54]. The concept of using the power spectral density (PSD) was introduced in Reference 50 and then expanded in Reference 51, which is particularly valuable for its discussion of signal processing requirements, its highlighting of the inherent limitations of the approach and the results it presents, characterizing several segments of track data. Reference 51 is included in Volume 2 of this anthology to illustrate how meaningful information can be extracted from the track geometry measurements.

The track geometry characterization work continued with a report [52] which relates the statistical measures (such as PSD) to more traditional visual measures of track condition, such as photographs and space curves. The entire effort culminated in a large two-volume report [53, 54] which described the use of a stationary random process model for homogenous track structures and a more complicated model for anomalies such as welds and joints. This report described the data processing which must be done in great detail and demonstrated the great pains the author took to ensure the mathematical correctness of each step of the analysis.

4.1.2 Track Mechanics (Compliance)

Significant efforts have also been devoted to the determination of the compliance (or its inverse, the stiffness) of railroad track. These characteristics are important to the study of vehicle dynamics because they permit the geometry of the track to change when a vehicle passes over it, producing dynamic interactions between the vehicle and track. These interactions (cov-

ered in greater depth in Section 4.3) can be more easily understood if the track compliance is evaluated independently of interactions with vehicles.

Although the large majority of the FRA supported work on track mechanics has been experimental, one of the earlier papers on the subject was concerned with the development of analytical models [55]. Although the track is in fact a complex distributed-parameter system, it is much easier to work with lumped-parameter models such as those which were developed and compared with test data in Reference 55, which is included in Volume 2. These models include the effects of the rails, ties and foundation (ballast and subgrade), the discontinuities introduced by joints and the further levels of detail needed to represent wheel-rail impact response, to separate vertical and lateral effects and to incorporate track geometry variations. Experimental results for tie plate vertical loads plotted against rail vertical deflection were used to validate the models (showing significant systematic differences by season, with winter's frozen foundations producing higher stiffnesses).

Most of the literature on track mechanics which has been produced under FRA sponsorship has focused on the experimental techniques needed to measure track stiffness (or compliance) [56-60]. Reference 56 explained how mid-chord offset and profilometer measurements can be combined to produce stiffness estimates, including a proof test at the Kansas Test Track. References 57-59 described techniques for measuring the static and dynamic compliance of railroad track, using both constant and time-varying preloads.

Results of track mechanics measurement projects were reported in References 61 and 62. The first of these two reports described the use of data from static and dynamic tests of the Kansas Test Track to validate a dynamic track structure model suitable for evaluation of non-conventional track structure designs. The other report described tests con- ducted on mainline track of the Chessie System to determine how lateral track stiffness varies with changes in the condition of ties and ballast.

4.1.3 Maintenance of Way

Track characteristics are continually changing under the influence of the loads imposed by moving vehicles. These characteristics must be maintained within appropriate tolerances in order to avoid unsafe vehicle dynamic behavior. Because of the very substantial costs which the railroad industry incurs for maintaining its track, this area has been an important extension of FRA work on track characteristics.

The existing systems available for track maintenance (track renewal) in Europe and North America were surveyed in Reference 63, which also included reviews of three studies of the economics of track renewal systems for U.S. rail-

roads. References 64-66 considered the use of detailed track geometry data, such as that acquired by the FRA Track Geometry Cars, as a maintenance management planning tool. The track geometry measurements were distilled into a set of "track quality indices" by appropriate data processing, and these indices were then used by railroad personnel to allocate maintenance resources to the track sections most in need of work. The most useful indices were found to include alignment, gauge (both roughness and wide gauge), surface warp and superelevation.

This work was extended [67] to consider what track geometry deviations would be acceptable to keep vehicle dynamic responses from exceeding thresholds which would be undesirable for reasons of safety or wear and lading damage. These standards were referred to as performance-based track geometry descriptors. Reference 67 is included in Volume 2 to provide a more complete description of this innovative use of track geometry data.

4.2 VEHICLE DYNAMICS FOR GIVEN TRACK GEOMETRY

The largest category of work which has been performed on rail system dynamics is that devoted to the dynamics of the rail vehicles themselves. Because of the size of this category, it has been further subdivided into programs which are primarily analytical, those which are primarily experimental, and those which combine both analysis and experiment.

4.2.1 Analytical Rail Vehicle Dynamics

There are only a few programs which FRA has sponsored in the purely analytical category. These can be summarized chronologically as:

(1) Linear frequency domain modeling techniques (DYNALIST II) - TRW/J.H. Wiggins Co./TSC

(2) Mathematical modeling for comparison of freight and passenger vehicles - Battelle Columbus Laboratories

(3) Mathematical modeling of freight car lateral stability and forced response - Arizona State and Clemson Universities

(4) Application of quasi-linearization techniques to rail vehicle dynamics - Massachusetts Institute of Technology, Arizona State and Clemson Universities

(5) Analysis of the design trade-offs between stability and tracking ability for rail passenger trucks - Massachusetts Institute of Technology.

The earliest of these analytical projects, the development of DYNALIST II, was reported in a four-volume set of reports [68-71] and two technical papers [72, 73]. DYNALIST II uses the

method of component mode synthesis to compute the response of rail vehicle systems to sinusoidal or stationary random rail irregularities. This work has been extended to include the capability to represent periodic and transient time-history responses, but is still restricted to use on linear or linearized systems. The linear frequency domain vehicle modeling approach was continued in reports from TSC [74, 75], which reviewed several computer programs developed and/or used at TSC for the analysis of rail vehicle dynamics, including DYNALIST II. The TSC work has also involved a review [76] of the analytical methods which have been used to predict the lateral responses (including forces) of rail vehicles in curves (both steady state and transient).

The Battelle Columbus Laboratories have developed computer models to be used to compare the dynamic performance of railroad freight and passenger vehicles. This comparative analysis was undertaken to try to evaluate the differences in track geometry errors and speed limits which should be permitted for operations by freight and passenger vehicles. The evaluation criteria used to rank the different class of vehicles were ride quality, track damage potential (forces) and stability (a basic set of derailment quotients). The concept of this project, with its reliance on analysis rather than experimentation and its use of sophisticated performance measures, was innovative for its time (early 1970's) in the rail dynamics field. However, its results were limited by the linearity of the 14 degree-of-freedom vehicle model, and some of the track descriptions and performance measures have been superseded by more recent work. Descriptions of this study can be found in two FRA reports [77, 78] and two technical papers [79, 80].

Extensions of this analytical work at Battelle led to applications on other FRA-sponsored projects. This included a study of the relationships among track geometry, vehicle suspension characteristics and passenger comfort for operations in curves and transitions [81]. This study, conducted for application to the Northeast Corridor Project, showed that for a Metroliner-like vehicle with high roll stiffness, the AREA standard for minimum spiral length was conservative. Battelle also reported a parametric study, using a similar linear vehicle model, showing that reducing the torsional stiffness of a wheelset can significantly reduce the critical speed for hunting [82].

The Freight Car Dynamics research program conducted by Arizona State and Clemson Universities has had a strong analytical orientation throughout, as well as including a major test program (discussed in Section 4.2.3). The two main thrusts of the analytical results reported from this research have been the digital computer modeling and analysis of hunting behavior and the analog/hybrid computer simulation of vehicle lateral dynamics.

The analytical models used to explore freight car hunting were derived in Reference 83, beginning with the model of a single wheelset. Two such wheelset models were incorporated in a general 9-degree-of-freedom truck model which can be used to represent a wide range of truck designs. Then, two such truck models were combined with a car body model which has three rigid body degrees of freedom plus the first lateral bending and torsional modes to produce a 23-degree-of-freedom full vehicle model. These models are among the most thoroughly documented of any which have been developed for rail vehicles, thanks to a detailed user's manual [84].

Extensive parametric studies were conducted to determine how the critical speed for hunting is affected by different truck design parameters. The analyses were all linear, and the outputs were the eigenvalues and eigenvectors for the respective degrees of freedom. The results of the parametric studies were discussed in Reference 85, which is reprinted in Volume 2 as an effective representation of this work. The same work was later extended to cases with different wheel profiles on the same axles and asymmetric loadings [86], revealing some important differences from the results obtained with symmetric models (such as a strong sensitivity to the direction of motion). This extension required the introduction of describing functions for quasi-linearization of the wheel-rail geometric constraint functions (rolling radius difference and contact angle difference), although the remainder of the vehicle model remained linear. A general review paper [87], describing the hunting phenomenon in terms of limit cycles, was also produced under the general aegis of this project.

Analog and hybrid simulation techniques applied to rail vehicle dynamics were described in three technical papers [88-90] and one report [91]. These techniques, adapted from the aerospace industry, were introduced for use with a 5-degree-of-freedom half-car model of a freight car (including three degrees of freedom for the truck) in Reference 89. Nonlinear wheel/rail geometric constraints and coulomb suspension friction were included in the model. Results of stability analyses for individual wheelsets and the half-car model were shown in Reference 90 (phase plane trajectories and time histories of limit cycles, as well as limit cycle boundaries). Both references indicated the speed and running cost advantages of the hybrid simulation approach, while noting the need for substantial analog computer facilities to represent more realistic, larger scale vehicle models. One product of this work was a report [91] which evaluated the performance of three different methods (two digital, one analog) of simulating coulomb friction for use in general vehicle suspension models. Because of the prevalence of coulomb friction in rail vehicles, these results can be applied to many types of rail vehicle models.

A third analytical product of the Freight Car Dynamics project was a 9-degree-of-freedom linear frequency domain model of a freight car, which has been thoroughly documented in a user's manual [92]. This model can be used to calculate vehicle lateral transfer functions and forced response spectral densities.

The Arizona State/Clemson effort was later extended to include the participation of the Massachusetts Institute of Technology. This work involved evaluation of the use of quasi-linearization techniques (describing functions) to explore the limit cycle (hunting) behavior and forced response of rail vehicles [93-97]. The first paper on this subject [93] dealt with the modeling of a single wheelset, including three nonlinearities: (a) dry friction in parallel with a spring for lateral suspension, (b) flange clearance (deadband) and (c) dry friction in series with a spring for yaw suspension. The stable and unstable limit cycles for the wheelset were illustrated and the influences of the non- linearities on wheelset stability were discus- sed. This work was extended [94] to incorporate wheel-rail contact nonlinearities in a thorough set of parametric studies of the influences on hunting behavior. Reference 94 is included in Volume 2 as a representative description of the important products of this work, which are covered in more detail in the complete project report [95].

The describing function method of linearization was also applied to the analysis of freight car rock-and-roll response to track cross-level variations, in parallel with a nonlinear digital simulation of the same phenomenon [96]. It was shown to be an efficient method for conducting parametric studies requiring the evaluation of steady-state responses for many cases. The quasi-linearization approach of References 93-96 is applicable for approximately sinusoidal inputs (cross-level inputs from staggered rail joints) and for prediction of limit cycles (hunting). The extension for forced responses to track irregularities made use of statistical linearization methods with a 9-degree-of-freedom freight car model [97]. Reference 97 showed how these methods (incorporating an efficient iterative frequency domain numerical algorithm) can be used to show the effects on vehicle response and stability of wheel profile geometry, track gauge and roughness and nonlinear suspension variations.

The FRA-sponsored work on rail vehicle dynamics which followed at M.I.T. (evolving from a D.O.T. University Research and Training Grant) was directed toward the development of simplified analytical tools for designing rail passenger trucks [98-100]. This work was based in large part on the fundamental trade-offs between stability and curve tracking performance of rail vehicles (ensuring a critical speed comfortably above the maximum operating speed without producing excessive flange contact in curves). In addition, the trade-offs between vertical and lateral ride quality and suspension strokes were

considered in the design procedure [98]. The alternative truck designs were characterized by their shear and bending stiffnesses. As part of the evaluation of the truck designs, a detailed nonlinear analysis and simulation study was performed, incorporating the effects of normal force variations, wheel/rail geometry and creep force saturation [100]. This analysis showed the significance of nonlinear wheel/rail forces and the non-Gaussian distribution of wheelset excursions when the rms excursions exceed 40% of the flange clearance. Reference 100 is included in Volume 2 to provide a more thorough description of this study.

4.2.2 Experimental Rail Vehicle Dynamics

FRA's sponsorship of experimental rail vehicle dynamics projects has involved more and larger programs than were covered in the previous section. The major programs in this area have included:

- Development of the Rail Dynamics Laboratory at the Transportation Test Center in Pueblo, CO.

- Truck Design Optimization Project (TDOP), Phases I and II

- Passenger truck testing (Metroliner)

- Locomotive tests (SDP-40F and E-8) on Chessie System track and on perturbed track (PTT) at Pueblo

Several additional testing programs of smaller scope are also covered here, while those programs which have combined experimental and analytical work are found in Section 4.2.3.

The RDL development program was largely a hardware procurement, without extensive technical reporting. The earlier version of the RDL included a Vertical Shaker System (VSS), which was described in a technical report [101] and two conference papers [102, 103]. However, this unit was quickly upgraded to the Vibration Test Unit (VTU), which was described in a later conference paper [104]. The use of the VSS and VTU to validate dynamic models of railcars is covered later, in Section VI. A general overview of the RDL, its operation and capabilities can be found in Reference 105.

Much more extensive documentation was produced in the two phases of the Truck Design Optimization Project (TDOP). Although some efforts were devoted to analysis in this project, the bulk of the work was experimental and the entire project is therefore considered here (except for the three-volume literature search, Reference 1, which was already discussed).

The principal published products of Phase I of the TDOP program were ten technical reports [106-115] and four technical papers [116-119] (two of which are virtually identical). There

were also six supplementary reports covering details of individual tests which would only be of use to a reader who wishes to analyze large quantities of data himself.

The TDOP reports began with a general review of truck design considerations and planning for the tests to be done at a later time [106, 116] and continued with a description of the truck design modifications which were suggested for later evaluation by the Japan National Railways following a test program they conducted for the Southern Pacific Railroad, the TDOP Phase I contractor [107]. Detailed test plans were presented in Reference 108, including the selection of variations in spring groups and wheel profiles to be used in the TDOP I test matrix. A review of the seventeen different Type II trucks considered for inclusion in the test program [109] served as a useful compendium of the diversity of freight truck designs and applications, although these trucks do not correspond to those which were tested later in Phase II.

The results of TDOP Phase I were covered in a twelve-volume final report, of which the first six are considered here. The series began with a concise and probing Executive Summary [110], which contains the most significant content. This report summarized the goals of the program, the task breakdown, test series and data analysis. The conclusions and recommendations of Southern Pacific and of FRA were both incorporated here, along with an FRA evaluation of the project's difficulties. In addition, a comprehensive listing of the reports and data tapes generated by TDOP I was included for reference. The reports continued with very detailed documentation of the test program [111] (equipment, instrumentation, test track, vehicle and suspension characteristics) and of the frequency domain mathematical model which was also developed [112]. These were followed by evaluation reports from the Mitre Corporation diagnosing problems with the mathematical model [113], re-deriving the model's equations of motion as clearly as possible [114], and reviewing the entire TDOP Phase I effort [115], with recommendations about how to make use of its results.

The technical papers prepared under the TDOP Phase I program followed several of the project reports quite closely. The first paper [116] described the field test techniques and data processing procedures for the project while the second [117, 118] presented some of the results of the testing of Type I trucks, mostly in the time domain, and with no interpretation of their significance. The final paper [119] considered the use of the 13-degree-of freedom linearized mathematical model to predict hunting behavior, but without validation.

Phase II of the TDOP program involved analysis of some of the Phase I test data, as well as extensive additional testing. This phase was documented in ten technical reports [120-129] and four technical papers [130-133]. The earlier

reports were a direct extension from Phase I, beginning with the development of the data base system for handling the voluminous Phase I data, plus software enhancements and the data reduction and analysis approach [120]. This was followed by a summary and evaluation of the Phase I data [121], describing how it would be used in the Phase II analyses and how it would be supplemented with additional test cases (filling gaps in the matrix of test conditions) and additional measurements (lateral wheel/rail forces, improved ALD measurements and friction snubber forces).

The Phase II Introductory Report [122] included a very good general introduction to freight trucks, their design and evolution. It also provided a preview to the rest of Phase II, including future plans, a glossary, definitions of performance regimes and measures and consideration of the issues of truck testing, analysis, component wear and possible design changes. The one analytical report in this series [123] was a review of models available from prior sources, and an evaluation of the feasibility of validating them in TDOP Phase II. It is a useful compendium of these models, and also features an appendix which describes some of the simplest analytical models available in rail vehicle dynamics. This appendix is included in Volume 2 as one of the only known references for the simplest models.

Reference 124 provided a thorough description of the test program on the Friction Snubber Force Measurement System (FSFMS) developed in conjunction with TDOP. The report showed how these tests were used to estimate an effective coefficient of viscous (linear) friction for the friction snubber (based on equivalent energy dissipation) for a single test condition on two Type I trucks. This coefficient was intended for use in analytical models.

The remaining TDOP Phase II reports were directed toward characterizing the Type I and II freight trucks and developing performance specifications for them. The Analysis Plan [125] set forth the procedures to be followed, while the later reports [126-129] included the results. Reference 126 was notable for the discussion of the unsuccessful model validation attempts, including problems with the available test data, the model formulations (especially for friction) and validation criteria. The characterizations of Type I and II truck performance [127, 128] included many figures displaying the ranges of values experienced in the test program, covering four dynamic regimes. These displayed the general trends and the relative strengths of the different influences on truck performance (loading proving to be more important than wheel profile). Reference 127 also included a good general summary of the test conditions and equipment, to serve as a reference for the entire program. The Type II truck characterization showed the general trends of performance for radial versus rigid frame and primary versus secondary suspension trucks, while the specifications were de-

fined as performance bands, without explanation or justification [128]. The final report in the series [129] presented a suggested test specification to be used in evaluating Type II trucks.

The technical papers produced as part of TDOP Phase II began with a preliminary discussion of the technical approach and a review of the types of freight trucks being studied [130]. Evaluations of the lateral stability of the Type I truck, based on the Phase I data, appeared in the next paper [131]. This demonstrated the effects of wheel wear and car loading on the measured lateral acceleration of the car body (which was selected as the performance measure for hunting). A distinction was drawn between "nosing" and "fishtailing" transitions to hunting (respectively the initiation of hunting at the leading and trailing trucks). With the addition of some of the Phase II curving test data, performance characteristics of Type I trucks in the four chosen performance regimes were then shown in Reference 132, which is included in Volume 2 as an example documentation of the TDOP Phase II methods and results. A more limited set of TDOP results for Type I trucks can be found in Reference 133.

Another major FRA test program was conducted on the LTV/SIG passenger truck used on the Metroliner. These tests were designed to ensure that this new truck design would provide good ride comfort at the then-contemplated speeds of up to 160 mph. The tests are documented in a three-volume set of reports [134-136], while the results of comparing these test results with analytical predictions are discussed later, in Section 4.2.3.

The last of the major FRA-sponsored tests covered here was the series of tests on the SDP-40F and E-8 locomotives, which were conducted on mainline track of the Chessie System and on a special perturbed track at the Transportation Test Center in Pueblo. The Chessie tests were documented in three technical reports [137-139] and a technical paper [140], while the Perturbed Track Tests (PTT) were described in an additional technical report [141] and paper [142].

The principal discussion of the Chessie tests [138] has been summarized very effectively in its "Executive Brief" report [137] and the paper [140], while the details of the test procedures and instrumentation, plus a probabilistic analysis of locomotive derailment, appeared in Reference 139. These tests were very significant because of the great care with which they were conducted and the quality of their instrumentation (particularly the plate instrumented wheelsets for measuring vertical and lateral wheel/rail forces, supplemented by wayside track force measurements). This amount of care was needed to produce valid comparisons between the performance of the two types of locomotives, one of which had been involved in an unusual number of derailments. On the basis of the test results, some very specific and detailed sugges-

tions were presented to help avoid future locomotive derailments. Reference 140 is enclosed to illustrate the methodology and the results of this test program.

One of the recommendations of the Chessie test program was that the same locomotives be tested on a special track containing specified geometric perturbations, in order to avoid some of the problems associated with tests on revenue track. The PTT program resulted, described in great detail in [141]. Different combinations of vehicle suspension damping, coupler shimming, speed and track geometry were tested in an attempt to identify the factors which contribute to derailments. As in the Chessie tests, the data gathered here were of exceptionally high quality, and in this case the track geometry was also measured several times during the conduct of the tests. Although these tests were well documented in [141], a more concise description of their important results has not been published. Rather, the experience gained in the PTT program was used to develop design procedures for other perturbed track testing, as reported in a later technical paper [142].

Several other isolated reports and papers have resulted from FRA support in the area of rail dynamics testing. Some of the basic problems faced by rail vehicle instrumentation (especially shock and vibration), and some cautionary advice about rail vehicle test planning in general were reported in Reference 143. Another paper [144] demonstrated the similarities and differences among the forces measured in truck side frames and side bearings in four different tests conducted on revenue track. The paper illustrated the different ways of processing the data (different statistics) but could not draw any conclusions about vehicle dynamics because of the diversity of vehicle types and test conditions which were considered.

In support of the FRA's program to improve high-speed passenger train service, the Budd Company assembled a compendium [145] of the information available to it describing the design of a wide variety of high speed trucks from around the world. These data included schematics of the mass, spring and damping characteristics of the trucks as well as numerical values of the parameters needed to describe the trucks in mathematical models. A very different type of documentation was provided by an FRA-sponsored translation of a Russian report on the test procedures and instrumentation used to measure wheel/rail forces on freight car trucks in the USSR. [146]. This report was specifically concerned with the use of spoked instrumented (strain-gauged) wheelsets for truck force measurements aimed at defining L/V force ratios. The final report in this section [147] described a test designed to investigate the effects of vehicle component wear and track degradation on the ride quality of railcars (high-and-low-mileage hoppers instrumented for lateral and vertical wheel/rail forces and truck and carbody modal vibrations).

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4.2.3 Combined Analytical and Experimental Rail Vehicle Dynamics

The documents described in the preceding sections were respectively focused on the mathematical analysis and the testing of rail vehicle dynamics, with relatively little interaction between the two. Those considered here have combined the analytical and empirical approaches in an attempt to learn more about the dynamics of rail vehicles, in some cases including attempts to validate models for further use. A significant fraction of this work has been motivated by efforts to develop rail vehicles capable of operating at higher speeds, especially for providing passenger service.

The earliest of these projects was the study of the dynamics of the Linear Induction Motor Test Vehicle (LIMTV) conducted by the British Railways Research Department under contract to FRA [148, 149]. This work was necessary to enable the vehicle to operate safely at speeds up to 250 mph on its test track. The report [148] contains detailed parametric analyses, both linear and nonlinear, of hunting, curving and random-input response of the vehicle to track inputs, leading to design recommendations for truck and suspension stiffness, wheel profiles, and track construction tolerance. This work appears to have been the first U.S. application of state-of-the-art rail vehicle modeling techniques, incorporating Kalker's creep model. The empirical aspect of this work, in addition to the analysis, was covered in the later technical paper [149]. Comparisons between theory and experiment were discussed there, along with comparisons of measured vehicle characteristics to those which were recommended in the original analytical study. Reference 149 is included in Volume 2 as documentation of this pioneering work.

The next major project of interest was the Metroliner Ride Improvement Program [150-155], intended to lead to better ride quality on the high-speed trains in the Northeast Corridor. Mathematical models [151] and laboratory and road tests [150] were used to determine the effects of changes in truck configurations. This work was described very effectively in a pair of technical papers [152, 153], which are unfortunately too lengthy to include in this anthology. The road tests, with track geometry measurements, and laboratory shaker tests were used to try to validate the vehicle simulation model (linear, frequency domain, lumped parameter). The model was then used to develop recommendations for modifying the Metroliner trucks and suspension to reduce ride vibrations which caused passenger discomfort near the 1 Hz peak [152]. The new truck design by LTV and SIG provided for the adjustability of most suspension parameters in order to permit ride quality "optimization" in tests. Both frequency domain and time domain analyses were used to select design characteristics for the new trucks [153].

The road test program and data analysis for the new truck design were discussed in a later paper [154], with the emphasis on load (force) measurements rather than ride quality. The data reduction reported here [154] was aimed at prediction of fatigue life of components, and therefore dealt with peak load counts under various conditions rather than with spectral densities. The end product was a description of the load environment which the Metroliner truck would be expected to experience in revenue service, for use as a truck design tool.

A wide-ranging study of freight car dynamics was conducted by Arizona State and Clemson Universities, in cooperation with the AAR, under FRA sponsorship. This work, which has been described in two reports [156, 157] and three technical papers [158-160], represents the most ambitious effort yet reported to develop a quantitative comparison between lateral dynamic theory and experimental results. The theoretical results used for these comparisons were discussed in Section 4.2.1 (References 83-82), while the field test procedures and results were presented in considerable detail in Reference 156. This report also included thorough comparisons of the theoretical and experimental results, with valuable in-depth explanations of the reasons for the disagreements which were found. The authors' conclusions included the very significant observation,

> "conclusive validation of the existing theory for rail car lateral dynamics was not obtained in this project. This should not suggest that the existing theory is inadequate, but rather that the comparison process is exceedingly difficult. Uncertainties in vehicle and roadbed parameters, experimental uncertainty in the data, the strongly nonlinear behavior of the test car, as well as uncertain and variable quantities in the wheel-rail force laws prevented definitive conclusions concerning the validity of the theory."

The three technical papers which described the experimental side of the Clemson/Arizona State Freight Car Dynamics Project [158-160] differ somewhat in their emphasis and their timing. The earliest of the three [158] attempted to provide an overview of both the analytical and experimental aspects of the project, prior to its completion, while the latter two [159, 160] were more directly focused on the experimental work and its comparison with theory. Reference 160 is included in Volume 2 as the best concise description available to date of this important work, its accomplishments and limitations.

Closely related to the project just described was an additional report [161] which described an attempt to validate a linear frequency domain model of the vertical dynamics of a railcar using the TDOP Phase I test data. This validation was found to be feasible for a middle frequency range, in which the track input spectra

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were well defined and the simple linear model included all the significant response modes. Truck suspension nonlinearities (especially dry friction) made it more difficult to validate a model of the suspension. The limitations of the direct spectral analysis approach and the data collection requirements for model validation were pointed out for application to the larger "Freight Car Dynamics" program.

The FRA "Improved Passenger Equipment Evaluation Program" (IPEEP) produced some combined analytical/experimental vehicle dynamics work [162-165] even though this was not its principal emphasis. This program was intended to review the advanced passenger trains and equipment available outside the U.S. for possible use in the U.S. One part of the program was an evaluation of ride quality and curving performance, using the models described in Appendices C and D of Reference 162. These analyses were applied using the parameter values which describe several of the candidate vehicles to estimate their ride quality and L/V force ratios in curves [163].

Some of the analytical work which was not published in the IPEEP reports appeared in two technical papers [164, 165]. The first of these was an analysis to compare the performance of conventional and self-steering radial trucks for high-speed passenger trucks. This modeling exercise showed that the radial trucks could improve curving performance (reducing wear) by a factor of two, while an improvement in the steering characteristics of conventional trucks (low primary longitudinal stiffness and high secondary yaw stiffness) could reduce wear by a factor greater than four [164]. The second paper used simple quasistatic curving analyses to define conservative criteria for the speed limits of rail vehicles in curves, in order to avoid derailments, track deformation, excessive wear and ride quality degradation [165].

A variety of smaller-scale FRA projects have also been conducted in this area. In conjunction with AAR's Track-Train Dynamics project, FRA sponsored several analytical/experimental characterizations of freight cars and trucks by Martin-Marietta [166-168]. Reference 166 is included in Volume 2 as a good example of the use of laboratory testing methods to define the dynamic characteristics of a freight car for use in a mathematical model (although the model had not yet been validated in a field test of hunting response). Two technical reports included a comparison of the nonlinear characteristics of two standard freight trucks [167] and a later study which compared model and test responses of an 80 ton open hopper car [168].

Some additional analytical/experimental rail vehicle dynamics projects included the evaluations of a lightweight intermodal flatcar [169] and a high-capacity, high-center-of-gravity DODX railcar [170]. The former included both modal analyses and test results for one conventional and one new design flatcar [169], while the

latter compared a nonlinear 22-degree-of-freedom model and full-scale field tests for determining the roll stability characteristics of four vehicles [170].

The final three documents discussed here [171-173] were focused more on the methodology for validating vehicle models using test data than on the results of the validations. Reference 171 discussed the use of non-traditional spectral analysis techniques for linear systems (applied to an FRA T-2 research car). In contrast, Reference 172 concentrated on the definition of the terms the authors preferred to use to describe the validation process, and then proceeded to apply Bayesian statistical parameter estimation to the validation of a nonlinear model of freight car "rock and roll." In both this paper and Reference 173, there was a strong emphasis on establishing the adequacy of the basic test data available for the validation process. Reference 173 defined the general structure of a model validation procedure, based on system identification techniques, and applied it to a sample case for locomotive test data from the Perturbed Track Tests.

4.3 VEHICLE-TRACK INTERACTIONS

The most challenging class of vehicle dynamics problems are those for which the track geometry cannot be assumed to remain fixed, but in which the compliance of the track produces an interaction with the dynamics of the vehicle. The track compliance must be considered whenever the forces between wheels and rails are to be measured or modeled and when derailment phenomena are to be predicted. The documents described in this section cover the FRA-sponsored efforts to investigate wheel/rail forces and potential causes of derailments.

The largest single body of work in this category is that conducted by the Battelle Columbus Laboratories under FRA sponsorship at TSC since 1975. Although a large portion of the Battelle work has been involved with track mechanics, the documents discussed here are concerned with the interactions between vehicles and tracks. The first interim report in this program [174] explained the objective of developing a statistical characterizaton of wheel/rail loads on U.S. railroads with the eventual aim of developing methods to reduce these loads in order to prolong track life. Reference 174 included comprehensive reviews of the available test data on wheel/rail loads as well as the analytical methods, instrumentation (wayside and on-board) and data processing procedures which could be used to obtain further information about these loads. It can thus serve as a valuable review of the state-of-the-art of track technology as of 1976.

Later work on the Battelle project produced additional technical papers and reports on vehicle-track interaction [175-181]. The first of these [175, 176] described how vehicle dynamic responses can produce gage-widening deformations

of tangent track. Field tests were conducted on revenue track, using a special track-mounted system for measuring rail displacements as well as the vertical load and transverse moment on the tie plates. The levels of load and displacement were correlated with the types of vehicles passing over the instrumented tie plate, demonstrating that the most severe gage widening inputs were associated with hunting as speeds increased and vehicle loading decreased. The loads were substantially higher during the winter, when the frozen ballast was unable to shift in response to the vehicle's passage. Another paper produced as part of this project [177] described the track instrumentation (strain gage circuit in rail web) and data reduction methods used to determine the wheel/rail forces.

A further report [178] and technical papers [179, 180] provided more complete descriptions of the wheel/rail load environment, including joint impact loads measured by instrumented wheelsets and wheel-flat loads measured by special wayside instrumentation. Both tangent and curved track and bolted-joint and continuous welded rail were included in these studies. Statistical characterizations of the lateral and vertical wheel/rail loads (amplitude distributions, frequencies of exceedance) experienced under mixed freight traffic were shown for different train speeds, and techniques for extrapolating these results to other track, traffic and operating conditions were described [179]. The vertical impact loads produced by anomalous rail joints or flat spots on wheels were also measured and compared to the predictions of a mathematical model [180]. The transient characteristics of the loads (time histories) were displayed, as well as the trends in the maximum and minimum loads with changes in train speed and length of wheel flat. This work was extended with the development of a very large data base on wheel/rail loading at the FAST Track in Pueblo [181]. That comprehensive set of data permitted the derivation of some powerful statistical descriptions of the wheel/rail force environment at FAST, including load amplitude (joint vertical and lateral distribution), and both load and L/V force ratio exceedance distributions. Reference 181 is included in Volume 2 as one of the more comprehensive available descriptions of the wheel/rail load environment.

Descriptions of the instrumented wheelsets which are used to measure wheel/rail forces are found in two different FRA-sponsored reports [182, 183]. Because of the expense of these direct measurement techniques, there has been considerable interest in developing more indirect ways of estimating wheel/ rail forces from other measurements. A description of a technique for estimating lateral forces from measurements of acceleration and displacement on the carbody and truck components is found in Reference 184. During the Perturbed Track Tests described previously, this technique was tested by comparing its estimates of locomotive truck lateral forces with the direct measurements made by costly plate instrumented wheelsets. By using careful esti-

mates of the locomotive physical parameters in a 12-degree-of-freedom model of lateral dynamics, it was shown that the acceleration measurements could be used to calculate the truck force time histories to within a very close agreement with the direct measurements (including peak forces to within 10%). Although this method permits identification of the contributions to total truck forces from the major vehicle masses, it cannot be used to estimate the lateral forces on individual wheelsets because of unknown longitudinal creep forces [184].

The remaining references covered in this section deal with the prediction of derailments based on wheel/rail contact phenomena. The first two of these [185, 186] were reports by the Naval Surface Weapons Center describing instrumentation which can be used to predict derailments caused by a variety of different mechanisms. The others were more directly concerned with the distinct mechanisms of derailment as studied by TSC [187, 188] and Princeton University [189-192]. The TSC work has been based entirely on analysis, while the Princeton work has combined analysis with scale-model experimentation.

The earlier TSC paper [187] used a quasi-linear frequency domain simulation of a passenger car operating over tangent track described by spectral density representations of geometric deviations. The L/V force ratio was used to define safety for wheel-climb derailments, and the analysis showed how different combinations of speed and track deviations would produce equivalent "safety." Two-and three-dimensional contours of permissible operating conditions were shown in this paper for the baseline passenger car [187]. A later extension to this work [188] considered the probability of derailments across a diverse fleet of rail vehicles, divided into generic car families defined on the basis of dynamic similarity. This study suggested the use of statistical descriptions of the vehicle and track characteristics, which could then be applied in a quasi-linear covariance propagation analysis to estimate the probabilities of five different modes of derailment (wheel lift, car-truck separation, wheel climb, rail deflection and sudden component failure). Reference 188 is included in Volume 2 to illustrate this unusual statistical approach to the analysis of rail vehicle dynamics, although it unfortunately includes only hypothetical results, and not results based on actual data.

The FRA-sponsored Princeton work on development of improved criteria for predicting wheel-climb derailments [189-192] is an extension of work begun under a DOT University Research and Training Grant. The first of these papers [189] proposed wheel-climb derailment criteria for a single wheelset on the basis of nonlinear simulation results, and included experimental verification of these criteria for quasisteady rolling conditions. The quasi-steady derailment analysis considered the L/V force ratio for an individual

wheel or for the entire axle (which required in-
clusion of the axle roll moment). The analysis
and scale model experiments were found to be in
reasonable agreement, producing derailments under
comparable conditions, and the L/V derailment
limits were found to be very consistent.

The extension to dynamic wheelclimb of a
wheelset [190, 191] and to a complete truck [192]
represented later stages of this work. Refer-
ence 191 is included in Volume 2 as the most com-
prehensive presentation of these wheelclimb cri-
teria, complete with the validation using experi-
mental data and an evaluation relative to the
widely used JNR Criterion. Reference 191 in-
cluded discussions of several different types of
derailment criteria based on time histories of
wheel loads, and showed the results of 112 de-
railment experiments plotted against the JNR cri-
terion and a rescaled modification to that cri-
terion. It was concluded that additional meas-
urements, beyond the L/V ratio time histories,
would be needed to discriminate derailment events.

V. LONGITUDINAL TRAIN DYNAMICS

The FRA has not sponsored as much work on longitudinal train dynamics as it has on the dynamics of individual rail vehicles. Much of the work in this area was performed by the AAR with FRA support. This section reviews some assorted longitudinal dynamics projects which were sponsored at least in part by the FRA. Two separate university efforts [193, 194] in longitudinal dynamics are included here, the first of which was funded in cooperation with the AAR Track-Train Dynamics Program, the second with the DOT Office of University Research.

The draft gear is the most critical element in determining longitudinal dynamic response, and because of its highly nonlinear spring-damper characteristics (coulomb friction, deadband, etc.) [193] it has not been easy to model. An improved model of draft gear dynamic response would greatly facilitate the analysis of the dynamic interactions among cars in a train, leading to a better understanding of the causes (and possible prevention) of many derailments. Reference 193 was an application of an equation error technique of system identification to define the parameters of a nonlinear draft gear model. The draft gear was subjected to a series of impact tests and the force-displacement trajectories (cross-plots) were compared with simulations of the draft gear model under the same input condition. The identified model predicted peak force and energy dissipation to within close agreement with the test results. Reference 194 described a simulation model for predicting the longitudinal-vertical motion of railroad cars in impact situations, as part of a study of the coupler bypass (override) phenomenon in collisions. Each car was represented as an idealized system with up to six degrees of freedom (including lading and truck motions), and including a variety of friction effects.

An isolated report with significant implications for longitudinal train dynamics was the design study for the Research Locomotive and Train Handling Evaluator [195]. Although this three-volume report did not in itself contribute to the understanding of train dynamics, it defined the requirements and specifications for a major new FRA test facility which will be useful for evaluating the effects of train operator performance on train dynamics.

The single most concentrated FRA-sponsored effort on longitudinal dynamics has been at TSC. The reports on this work began with a description of a generalized computer program [196] used to evaluate the buckling of trains in buff conditions. A later report [197] described the development of a "Draft-Buff Indicator" system to sense, display and record slack action in trains. This system was designed to provide a real-time display as a train-handling aid, as well as a recording for later analysis, of the distribution of draft and buff within a moving train. The TSC work also led to a patent application [198] for a derailment warning system which uses multiple sensors and a real-time on-board microprocessor analysis to give a train engineer advance warning of a potential derailment. The sensors measure train speed, imbalance in curves, track curvature and locomotive drawbar force, which serve as inputs to the train stability analysis which was compiled when the train was assembled in the yard. The train stability analysis, which is also used to help guide the yardmaster in configuring the train, is described in Reference 199. This paper is included in Volume 2 to illustrate the simple quasi static analysis which can quickly determine the ability of a consist to withstand the buckling and stringlining forces which could produce derailments in curves. The potential applications of the analysis method by the yardmaster and the train engineer are demonstrated in Reference 199.

VI. OTHER APPLICATIONS OF RAIL SYSTEM DYNAMICS

This section covers some FRA-sponsored work in rail system dynamics which did not fit neatly into the previous categories. The two main subject areas covered here are fuel consumption (or train resistance) and lading response, which could also be regarded as a subset of vehicle dynamics.

6.1 FUEL CONSUMPTION/RESISTANCE

Because fuel was a relatively insignificant expense for railroads prior to 1974, fuel consumption and resistance of trains received very little attention at that time. The first FRA-sponsored study of railroad fuel consumption appears to have been a two-volume TSC study conducted between 1973 and 1977 [200, 201]. The analytical part of this study demonstrated the contributions to fuel consumption (i.e. energy dissipation) from rolling and aerodynamic resistance, braking, idling and locomotive power generation and conversion losses [200]. Graphs were used to illustrate parametrically the effects of speed, grade, power/weight, load factor, etc. The results derived from 80 separate tests on line-haul freight movements, performed in cooperation with six different railroads, were used to demonstrate the consistency of the analytical estimates with operating experience [201].

A more intensive study by the Mitre Corporation produced a four-volume report [202-205] on freight train resistance aimed at determining how fuel could be conserved. This work showed the dependence of fuel savings on train operating procedures, which could make it difficult to achieve savings comparable to the theoretical reductions in train resistance. It also evaluated the savings effected by use of light-weight hopper cars in unit coal train service. Both computer predictions and field measurements were discussed in these reports.

With the increased use of intermodal unit trains and their higher than average operating speeds as important motivations, an intensive experimental study of the aerodynamic resistance of these trains was sponsored by the FRA [206-210]. Carefully controlled tests of models in wind tunnels were compared against full-scale field tests for various TOFC and COFC configurations, and the effects of rolling and aerodynamic drag were separated out. The effects of different gap spacings, new intermodal car designs, car loading orientation, changes in trailer frontal areas and specific aerodynamic treatments (fairings) were investigated in this study.

6.2 LADING RESPONSE

Most analyses of rail vehicle dynamics have ignored the dynamic effects associated with lading response by assuming the lading to be a simple mass rigidly connected to the car body. Several FRA-sponsored studies have taken a closer look at lading response in an attempt to gain a better understanding of how lading is damaged and how the lading can interact with the rail vehicle to modify its rigid-body dynamic response.

The first study in this category was a university project under the joint sponsorship of FRA, AAR, General Motors and the DOT Office of University Research [211, 212]. This involved the development of a nonlinear 27-degree-of-freedom model of the freight car, truck and freight element, which was used for time domain simulation and frequency domain analysis. The freight element was assumed to have three translational degrees of freedom, each of which was connected to the carbody center of mass by a parallel linear spring and damper. Time history outputs of the simulation were compared with the outputs of a similar model by the A. Stucki Company, but field test data were not available for model validation. The same model was used to evaluate a "six point suspension system" [212], which introduces additional spring/damper sets between the bolsters and carbody of a freight car.

The most concentrated FRA support of lading dynamics work has been in the development and validation of a model known as FRATE (Freight Car Response Analysis and Test Evaluation). This model began with the work of Battelle [77], which was then adapted by M.J. Healy of Wyle [213] and extended by MITRE [214-217]. The basic 11-and 17-degree of freedom vehicle models, upon which flexible body modes can be superimposed, were presented in Reference 213. A preliminary attempt to validate the model with test data was also described there [213], but the model did not yet incorporate an explicit treatment of lading. The extended model [214] included 31 degrees of freedom, to allow representation of two trailers mounted on a flatcar, with up to four flexible carbody normal modes. Although the user's manual [214] was restricted mainly to the mechanics of using the FRATE program, the separate technical paper on this work [215] provided a good description of the model and the attempt to validate it using tests of a TOFC configuration on the Vertical Shaker System in the Rail Dynamics Laboratory at Pueblo. That paper is included in Volume 2 to illustrate the FRATE program and the attempt to validate it. The model predictions and test results (resonant frequencies, deflection shapes and amplitudes at resonances) were not found to be in complete agreement, even with some manual adjustments of parameter values, and the authors therefore suggested including nonlinear spring representations and additional degrees of freedom for trailer flexibility.

The later extensions to FRATE included the addition of compliant lading (two spring-mounted masses in each trailer, leading to a total of 43 degrees of freedom) [216] and a conversion to a rigid boxcar with compliant lading [217]. These reports included simulation studies of rock and roll, hunting and vertical forced response (track irregularities). These studies indicated the

relative seriousness of the different operating
conditions for lading accelerations and wheel-
rail forces (combinations of speeds, track geo-
metry, trailer mounting and vehicle suspension
characteristics). Recommendations were offered
for vehicle operation and suspension changes
which could reduce the undesirable responses.

A final example of a lading response project
was Reference 218, which described an experimen-
tal program to characterize the shock and vibra-
tion environment of TOFC trailers carrying sensi-
tive equipment. The lading, trailers and flat-
cars were instrumented for test runs during typi-
cal revenue operations. Accelerations were
found to be most severe near the kingpin, and
least severe near the middle of the trailer
floor. Relatively minor differences were found
between the vibration environments on leaf-spring
and air-suspension trailers, and in both cases
the accelerations were considered mild enough to
be acceptable for vibration-sensitive equip-
ment. Vibration spectra and amplitude distribu-
tions were included as descriptions of the vibra-
tion environment experienced in a typical over-
the-road test.

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VII. REFERENCE LIST

Sources for Overview Information

1. "Freight Car Truck Design Optimization, Volumes I-III, Literature Search" Southern Pacific Transportation Company U.S. Department of Transportation Interim Reports No. FRA-OR&D-75-81A to 81C, June 1975

2. "A Bibliography on Rail Technology" Chapin, Walter E.; King, Rolland D.; Pestel, Helen C.; and Breslin, Ruth H. U.S. Department of Transportation Final Report No. FRA-OR&D-77/15, May 1977

3. "Review and Summary of Computer Programs for Railway Vehicle Dynamics" Pilkey, Walter D. U.S. Department of Transportation Final Report No. UVA-529162-MAE80-101, March 1980

4. 12th Annual Railroad Conference Proceedings, "Effect of Heavy Axle Loads on Track" U.S. Department of Transportation Report No. FRA OR&D 76-243, October 1975

5. 13th Annual Railroad Engineering Conference Proceedings, "Railroading Challenges in America's Third Century-Improved Reliability and Safety" U.S. Department of Transportation Report No. FRA/ORD-77/13, July 1977

6. 14th Annual Railroad Engineering Conference Proceedings, "R&D and Railroading: 1977" U.S. Department of Transportation Report No. FRA/ORD, March 1978

7. "15th Railroad Engineering Conference Proceedings, Railroad R&D Challenges of the 80's: Opportunities & Obstacles" U.S. Department of Transportation Report No. FRA/ORD-80/35, June 1980

8. Railroad Track Mechanics and Technology Kerr, Arnold D. (Editor) Proceedings of a Symposium held at Princeton University, April 21-23, 1975 New York: Pergamon Press, 1978

9. Track/Train Dynamics and Design: Advanced Techniques G.J. Moyer, W.D. Pilkey and B.F. Pilkey (Editors) Conference on Advanced Techniques in Track Train Dynamics, Chicago, 1977 New York: Pergamon Press, 1978

Wheel-Rail Interface Phenomena

10. "Surface-Roughness Effects in Rolling Contact" Nayak, P. Ranganath ASME Paper No. 72-APM-FF, Journal of Applied Mechanics, 1972

11. "Linear Induction Motor Research Vehicle Wheel/Rail Adhesion Test" Chen, R.P and D'Sena, G.O. U.S. Department of Transportation Final Report No. FRA-OR&D-76-261, April 1976

12. "A Review of Rail-Wheel Contact Stress Problems" Paul, B. (Pennsylvania University) Report No. FRA/ORD-76/141 (PB 251238), April 1975

13. "A Review of Rail-Wheel Contact Stress Problems" in Reference 8, pp 323-351.

14. "Contact Stresses for Closely Conforming Bodies--Application to Cylinders and Spheres" Woodward W. and Paul B. Report No. DOT-TST-77-48 (PB 271033), December 1976

14a. "Contact Stresses for Multiply-Connected Regions - The Case of Pitted Spheres" Paul, B., Singh, K.P. and Woodward, W.S. Proceedings of the Symposium on the Mechanics of the Contact Between Deformable Bodies, Delft University Press, Delft, Netherlands, 1975, pp 264-281

15. "An Improved Numerical Method for Counterformal Contact Stress Problems," Technical Report No. 3 Paul, B. and Hashemi, J. Report No. FRA/ORD-78/26 (PB 286228), July 1977

16. "User's Manual for Program Countact," (Counterformal Contact Stress Problems) Paul, B. and Hashemi, J. Report No. FRA/ORD-78/27, (PB 286097), September 1977

17. "Improved Numerical Method and Computer Program for Counterformal Contact Stress Problems" Paul, B. and Hashemi, J. ASME Special Publication AMD-30, "Computational Techniques for Interface Problems," December 1978, pp 165-180

18. "User's Manual for Program Conform" (Conformal Contact Stress Problems) Paul, B. and Hashemi, J. Report No. FRA/ORD-78-40 (PB 288927), June 1978

19. "Rail-Wheel Geometry Associated with Contact Stress Analysis," Technical Report No. 6 Paul, B. and Hashemi, J. Report No. FRA/ORD-78/41 (PB 80-142656), September 1979

20. "Numerical Determination of Contact Pressures Between Closely Conforming Wheels and Rails"
Paul, B. and Hashemi, J.
Report No. FRA/ORD-79/41 (PB 80-120462), July 1979

20a. "Contact Pressures on Closely Conforming Elastic Bodies"
Paul, B. and Hashemi, J.
Solid Contact and Lubrication, ASME Special Publication AMD-39, pp 67-78, 1980

21. "Contact Stresses on Bodies with Arbitrary Geometry, Applications to Wheels and Rails," Technical Report No. 7
Hashemi, J. and Paul, B.
Report No. FRA/ORD-79/23 (PB 299409), April 1979

22. "Contact Geometry Associated with Arbitrary Rail and Wheel Profiles"
Paul, B. and Hashemi, J.
The General Problem of Rolling Contact, ASME Special Publication AMD-40, 1980, pp 93-105

23. "Fundamental Studies Related to Wheel-Rail Contact Stress"
Paul, B.
Report No. FRA/ORD-81/05 (PB 81-194300), January 1981

24. "Analytical and Experimental Determination of Wheel-Rail Constraint Relationships"
Cooperrider, N.K.; Law, E.H.; Hull, R.; Kadala, P.S.; and Tuten, J.M.
U.S. Department of Transportation Final Report No. FRA-OR&D-76-244, December 1975

25. "Influence of Nonlinear Wheel/Rail Contact Geometry on Stability of Rail Vehicles"
Hull, R. and Cooperrider, N.K.
ASME Paper No. 76-WA/RT-2, December 1976

26. "Influence of Nonlinear Wheel/Rail Contact Geometry on Stability of Rail Vehicles"
Hull, R. and Cooperrider, N.K.
ASME Transactions, Journal of Engineering for Industry, Vol. 99 No. 1, February 1977, pp 172-185

27. "Analytical and Experimental Determination of Nonlinear Wheel/Rail Geometric Constraints"
Cooperrider, N.K.; Law, E.H.; Hull, R.; Kadala, P.S.; and Tuten, J.M.
Symposium on Railroad Equipment Dynamics (1976 Joint ASME-IEEE Railroad Conference, Chicago, IL), pp 41-69

28. "User's Manual for Asymmetric Wheel/Rail Contact Characterization Program"
Heller, R. and Cooperrider, N.K.
Report No. FRA/ORD-78/05 (PB 279707), December 1977

29. "Users' Manual for Kalker's Simplified Nonlinear Creep Theory"
Goree, J.G. and Law, E.H.
Report No. FRA/ORD-78/06 (PB 279503), December 1977

30. "Users' Manual for Kalker's 'Exact' Nonlinear Creep Theory"
Goree, J.G.
Report No. FRA/ORD-78/50 (PB-287472), August 1978

31. "Users' Manual for Program for Calculation of Kalker's Linear Creep Coefficients"
Haque, I; Law, E.H.; and Cooperrider, N.K.
Report No. FRA/ORD-78/71 (PB-297802), March 1979

32. "Describing Function Techniques for the Nonlinear Analysis of the Dynamics of a Rail Vehicle Wheelset"
Garg, D.P.
Report No. FRA-OR&D-75-83, July 1975

33. "Wheelset Lateral Dynamic Analysis Using the Describing Function Technique"
Garg, D.P.
ASME Paper No. 77-DET-149, 1977

34. "Preliminary Analysis of the Effects of Nonlinear Creep and Flange Contact Forces on Truck Performance in Curves"
Perlman, A.B. and Weinstock, H.
Report No. FRA/ORD-75/56 (PB-262177), May 1975

35. "Friction-Creep and Wear Studies for Steel Wheel and Rail"
Karamchandani, K.C.; Kumar, S.; Sciammarella, C.A.; Seth, B.; Nailescu, L.; and Kalpakjian S.
U.S. Department of Transportation Interim Report No. FRA-OR&D-76-272, May 1975

36. "Study of Friction and Creep Between Steel Wheels and Rail"
Sciammarella, C.; Press, M.; Kumar, S.; Seth, B.; Nailescu, S.; and Kalpakjian, S.
Federal Railroad Administration Report No. FRA-OR&D-76-271, July 1976

37. "Similitude Law for the Creep-Adhesion Function in Dry Contact"
Sciammarella, C.A.; Nailescu, L.; Kumar, S.; and Seth, B.B.
ASME Transactions, Journal of Engineering for Industry Vol. 101, No. 3, p 278-284, August 1979

38. "Generalized Relations for the Creep-Adhesion Function in Dry Contact"
Sciammarella, C.A.; Kumar, S.; Press, M.; and Seth, B.B.
The Sixth International Wheelset Congress, Vol. 1, Colorado Springs, October 1978

39. "Some Wheel-Rail Interaction Factors In-
fluencing Vehicle Dynamics"
Kumar, Sudhir
Rail International, Vol. 11, No. 10,
October 1980, pp 599-610

40. "Laboratory Investigation of Wheel Rail
Contact Stresses for U.S. Freight Cars"
Kumar, S. and Rajkumar, B.R.
ASME Paper No. 80-WA/RT-8, November 1980

Vehicle-Track Dynamics: Track Characteristics

41. "Inertial Profilometer as a Rail Surface
Measuring Instrument"
Rudd, T.J. and Brandenburg, E.L.
ASME Paper No. 73-ICT-102, September 1973

42. "Track Curvature Measuring System and its
Application"
Mac Intyre, S.A. and May, J.T.
ASME Paper No. 73-ICT-110, September 1973

43. "Gyroscopically Compensated Vertical Pen-
dulum for Measuring Guideway Cant from a
Moving Vehicle"
Yang, Ta-Lun
IEEE Industrial Applications Society 10th
Annual Meeting Conference Record, Sep-
tember-October 1975, pp 523-526

45. "Electro-Optical Sensor for Measuring Rail
Gage"
Cantor, Clarence
Electro-Optical System Design Conference,
Proceedings of the Technical Program,
November 1975, pp 777-782

46. "FRA Track Geometry Measurement System
Validation Report"
Yang, T-L.
Federal Railroad Administration Report No.
FRA-ORD&D-75-05 (PB 243677), June 1974

47. "Track Geometry Measurement System"
Howerter, E.D.
Report No. DOT-TSC-FRA-80-25, FRA/ORD-80/
80 (PB 81-114563), September 1980

48. "Significant Development in FRA Test Cars"
Yang, T.L.
in Reference 6, pp 146-155

49. "Inertial and Inductive Measurement Tech-
niques for Track Geometry"
Yang, T.L.; Howerter, E.D.; and Inman, R.L.
ASME Paper No. 81-WA/DSC-18

50. "Application of Guideway Roughness Power
Spectral Density as a Management Tool"
Corbin, J.C. and Yang T-L.
ASME Paper No. 73-ICT-114, September 1973

51. "Classifying Track by Power Spectral Den-
sity"
Corbin, J.C. and Kaufman, W.M.
Mechanics of Transportation Suspension
Systems, AMD Vol. 15, presented at the
Winter Annual Meeting of the American
Society of Mechanical Engineers, Houston,
Texas, November 30-December 3, 1975

52. "Correlation of Statistical Representa-
tions of Track Geometry with Physical
Appearance"
Corbin, J.C.
U.S. Department of Transportation Final
Report No. FRA/ORD-79/35, June 1979

53. "Statistical Representations of Track Geo-
metry, Volume I - Main Text"
Corbin, J.C.
U.S. Department of Transportation Final
Report No. DOT-TSC-FRA-79-16, Vol. 1

54. "Statistical Representations of Track Geo-
metry, Volume II, Appendixes"
Corbin, J.C.
U.S. Department of Transportation, Report
No. FRA/ORD-80/22.2, March 1980

55. "The Development of Analytical Models for
Railroad Track Dynamics"
Ahlbeck, D.R.; Meacham, H.C.; and Prause,
R.H.
Paper presented at Symposium on Railroad
Track Mechanics,
in Reference 8, pp 239-263

56. "A Feasibility Study of a Method for
Observing Track Stiffness from Mid-Chord
Offset and Profilometer Measurements"
Talapatra, D.C. and Corbin, J.C.
IEEE Industrial Applications Society 10th
Annual Meeting Conference Record,
September-October 1975, pp 512-517

57. "A Review of Measurement Techniques, Re-
quirements, and Available Data on the
Dynamic Compliance of Railroad Track"
Kaiser, W.D.; Nessler, G.L.; Meacham,
H.S.; and Prause, R.H.
Interim Report No. FRA-ORD&D-76-70 (PB
250547), May 1975

58. "An Experimental Evaluation of Techniques
for Measuring the Dynamic Compliance of
Railroad Track"
Nessler, G.L.; Prause, R.H.; and Kaiser,
W.D.
Final Report No. FRA/ORD-78/25 (PB
285559), July 1978

59. "Design and Analysis of a Track Compliance
Measurement System"
Kaiser, W.D.; Meacham, H.C.; and Tuten,
J.M.
Final Report No. FRA/ORD-78/57 (PB
297055), November 1978

60. "Track Stiffness Measurement System Evaluation Program"
Hayes, G.; Joshi, P.; and Sullivan, J.
Report No. FRA/ORD-79/30 (PB 80-165293),
December 1979

61. "Analysis of Kansas Test Track Beam Response"
Anderes, J.R.
Report No. FRA/ORD-77/31, June 1977

62. "Lateral Resistance of Railroad Track"
Reiner, I.A.
U.S. Federal Railroad Administration Report No. FRA/ORD-77/41, August 1977

63. "Track Renewal Systems: A Survey Report"
Cataldi, G.R.; Elkaim, D.N.; and Larsen, K.W.,
Report No. FRA/ORD-79/43, July 1979

64. "Use of Automatically Acquired Track Geometry Data for Maintenance-of-Way Planning"
Hayes, G.; Bradley, K.; Price, B.; Sawyer, D.; and Dominguez, A.,
Report No. FRA/ORD-80/44, June 1980

65. "Prototype Maintenance-of-Way Planning System"
Hamid, A.; Sawyer, D.; Kenworthy, M.A.; and Rasmussen, K.
Report No. FRA/ORD-80/47, November 1980

66. "Track Quality Indices and Track Degradation Models for Maintenance-of-Way Planning"
Hamid, A. and Gross, A.
Transportation Research Record 802, 1981

67. "The Development of Performance Based Track Quality Measures and Their Application to Maintenance-of-Way: Methodology and Framework"
Corbin, J.C. and Fazio, A.E.
Transportation Research Record 802, 1981.

Vehicle-Track Dynamics: Vehicle Dynamics for Given Track Geometry - Analytical

68. "DYNALIST II, A Computer Program for Stability and Dynamic Response Analysis of Rail Vehicle Systems" Volume 1., Technical Report
Hasselman, T.K.; Bronowicki, A.; and Hart, G.C.
Report No. DOT-TSC-FRA-74-14.I, FRA/ORD-75/22.I (PB 256046), February 1975

69. "DYNALIST II, A Computer Program for Stability and Dynamic Response Analysis of Rail Vehicle Systems"
Volume 2: User's Manual
Bronowicki, A. and Hasselman, T.K.
Report No. FRA-OR&D-75-22.II (PB-257733), February 1975

70. "DYNALIST II, A Computer Program for Stability and Dynamic Response Analysis of Rail Vehicle Systems"
Volume III. Technical Report Addendum
Bronowicki, A. and Hasselman, T.K.
Report No. DOT-TSC-FRA-74-14-3, FRA/OR&D-75-22.III (PB 258193), July 1976

71. "DYNALIST II. A Computer Program for Stability and Dynamic Response Analysis of Rail Vehicle Systems"
Volume IV. Revised User's Manual
Bronowicki, A. and Hasselman, T.K
Report No. DOT-TSC-FRA-74/14-4, FRA/OR&D-75-22.IV (PB 258194) July 1976

72. "Dynamic Analysis of Large Systems by Complex Mode Synthesis"
Hasselman, T.K. and Kaplan, A.
ASME Transactions, Journal of Dynamic Systems, Measurement and Control, Vol. 96, No. 3, September 1974, pp 327-333

73. "Dynamic Analysis of Rail-Vehicle Systems Using Dynalist II"
Hasselman, T.K. and Bronowicki, A.J.
SAE Paper No. 751059, 1975

74. "Introduction to the Application of the Dynalist Computer Program to the Analysis of Rail System Dynamics"
Perlman, A.B. and Lanza, J.J.
Report No. FRA-ORD&D-75-2 (PB-235 361), August 1974

75. "Frequency Domain Computer Programs for Prediction and Analysis of Rail Vehicle Dynamics" Volume I. Technical Report and Volume II. Appendices
Perlman, A.B. and DiMasi, F.P.
Reports No. DOT-TSC-FRA-75-16.I, and .II FRA/ORD-76/135.I and .II (PB 259287 and PB 259288), December 1975

76. "Computational Methods for the Prediction of Truck Performance in Curves"
Perlman, A.B.
ASME Paper No. 76-WA/RT-15 presented at ASME Winter Annual Meeting, December 1976

77. "Comparative Analysis of Dynamics of Freight and Passenger Rail Vehicles"
Ahlbeck, D.R.; Prause, R.H.; Day, J.B.; and Meacham, H.C.
Final Report, March 1974 (PB 240329)

78. "Comparative Analysis of Dynamics of Freight and Passenger Rail Vehicles"
Ahlbeck, D.R. and Doyle, G.R. Jr.
Report No. FRA/ORD-77/04 (PB 265050), November 1976

79. "Criteria for Evaluating Rail Vehicle Dynamics by Computer Modeling Techniques"
Ahlbeck, D.R.; Prause, R.H.; and Meacham, H.C.
International Conference on High Speed Ground Transportation Proceedings Addendum, 1975, Arizona State University

22

80. "Preliminary Evaluation of Rail Vehicles by Computer Simulation"
Ahlbeck, D.R.
High Speed Ground Transportation Journal, Vol. 11, No. 3, September 1977, pp 281-296

81. "Effect of Track Geometry and Rail Vehicle Suspension on Passenger Comfort in Curves and Transitions"
Doyle, G.R.Jr. and Thomet, M.A.
(ASME Paper No. 77-RT-2) ASME Transactions, Journal of Engineering for Industry, Vol. 99 No. 4, November 1977, pp 841-848

82. "Hunting Stability of Rail Vehicles with Torsionally Flexible Wheelsets"
Doyle, G.R.Jr. and Prause, R.H.
(ASME Paper No. 75-WA/RT-2) ASME Transactions, Journal of Engineering for Industry, Vol. 99 No. 1, February 1977, pp 10-17

83. "General Models for Lateral Stability Analyses of Railway Freight Vehicles"
Law, E.H.; Hadden, J.A.; and Cooperrider, N.K.
Report No. FRA/ORD-77/36 (PB-272371), June 1977

84. "Users' Manual for Lateral Stability Computer Programs for Railway Freight Car Models"
Hague, I.; Law, E.H.; and Cooperrider, N.K.
Report No. FRA/ORD-80/30 (PB80-176266), April 1980

85. "Effects of Truck Design on Hunting Stability of Railway Vehicles"
Hadden, J.A. and Law, E.H.
(ASME Paper No. 76-WA/RT-1) ASME Transactions, Journal of Engineering for Industry, Vol. 99 No. 1, February 1977, pp 162-171

86. "Lateral Stability of Freight Cars with Axles Having Different Wheel Profiles and Asymmetric Loading"
Tuten, J.M.; Law, E.H.; and Cooperrider, N.K.
ASME Paper No. 78-RT-3

87. "Limit Cycle Behavior of Rail Vehicles"
Cooperrider, Neil K.
Proceedings of 1980 Joint Automatic Control Conference, San Francisco, CA

88. "Hybrid Simulation of Rail Vehicle Lateral Dynamics"
Heller, R.; Malstrom, C.W.; and Law, E.H.
Summer Computer Simulation Conference, Washington, D.C., July 12-14, 1976

89. "Hybrid Computations - An Advanced Computational Tool for Simulating the Nonlinear Dynamic Response of Railroad Vehicles"
Malstrom, C.W.; Heller, R.; and Khan, M.S.
in Reference 9, pp 241-260

90. "Analog/Hybrid Simulation of Rail Vehicle Lateral Dynamics"
Heller, R.; Malstrom, C.W.; and Law E. H.
Simulation, Vol. 32, No. 4, April 1979, pp 105-122

91. "Analog and Digital Computer Simulation of Coulomb Friction"
Heller, R.; Tuten, J.M.; Kadala, P.S.; and Law, E.H.
Report No. FRA/ORD-78/07 (PB 279465), December 1977

92. "User's Manual for Linear Freight Car Forced Lateral Response Analysis Computer Program"
Cooperrider, N.K. and Law, E.H.
Interim Report No. FRA/ORD-80/85, December 1980

93. "The Application of Quasi-Linearization to the Prediction of Nonlinear Railway Vehicle Response"
Cooperrider, N.K.; Hedrick, J.K.; Law, E.H.; and Malstrom, C.W.
Invited Paper Presented at the International Union of Theoretical and Applied Mechanics Symposium on the Dynamics of Vehicles on Roads and Railway Tracks, August 1975, Delft, The Netherlands

94. "Influence of Axle Load, Track Gage, and Wheel Profile on Rail-Vehicle Hunting"
Hannebrink, D.N.; Lee, H.S.H.; Weinstock, H.; and Hedrick, J.K.
(ASME Paper No. 76-WA/RT-3) ASME Transactions, Journal of Engineering for Industry, Vol. 99, No. 1, February 1977, pp 186-195

95. "The Application of Quasi-Linearization Techniques to Rail Vehicle Dynamic Analyses"
Hedrick, J.K.; Cooperrider, N.K.; and Law, E.H.
Report No. FRA/ORD-78/56, DOT-TSC-FRA-78-6 (PB 289849), November 1978

96. "Computational Methods to Predict Railcar Response to Track Cross-Level Variations"
Platin, B.E.; Beaman, J.J.; Hedrick, J.K.; and Wormley, D.N.
Report No. FRA-OR&D-76-293 (PB-272676), September 1976

97. "Nonlinear Analysis of Rail Vehicle Forced Lateral Response and Stability"
Hedrick, J. Karl and Arslan, A.V.
ASME Transactions, Journal of Dynamic Systems Measurement and Control, Vol. 101, No. 3, September 1979, pp 230-237

98. "Rail Passenger Vehicle Truck Design Methodology"
Wormley, D.N.; Hedrick J.K.; Horak, D.; and Bell, C.
Report No. DOT-TSC-FRA-81-1, FRA/ORD-81/11 (PB 81-165383), January 1981

99. "A Passenger Rail Truck Design Methodology"
Horak, D. and Wormley, D.N.
International Journal of Vehicle Design,
Vol. 2, No. 1, February 1981

100. "Nonlinear Stability and Tracking of Rail
Passenger Trucks"
Norak, D. and Wormley, D.N.
ASME Paper No. 81-WA/DSC-8

Vehicle Dynamics for Given Track Geometry -
Experimental

101. "VSS Demonstration Program, Part I: System
Performance Evaluation"
Wyle Laboratories
U.S. Department of Transportation Final
Report No. FRA-ORD-78/43, July 1978

102. "Laboratory Techniques for Quantifying the
Performance of Rail Vehicles Utilizing
Servo-Controlled Hydraulic Vertical Actua-
tors"
Bakken, G.B. and Fay, G.R.
ASME Paper No. 76-WA/RT-5, December 1976

103. "Flatcar Modeling Technique and Results"
Gibson, D.W.
in Reference 9, pp 125-148

104. "Vibration Test Unit Control and Computer
System"
Coupland, R.O. and Nintzel, A.J.
Proceedings of Annual Technical Meeting,
Institute of Environmental Science, May
1980, pp 207-211

105. "Rail Dynamics Laboratory Performance Re-
quirements and Hardware Configurations"
Gross, Arnold
in Reference 6, pp 323-332

106. "Freight Car Truck Design Optimization,
Introduction and Detailed Test Plans -
Series 1, 2, and 3, Tests - Phase I"
Southern Pacific Transportation Company,
Technical Research and Development Group
U.S. Department of Transportation, Report
No. FRA-OR&D 75-79, June 1975

107. "Freight Car Truck Design Optimization
Project - Detailed Test Plans for Series 4"
Southern Pacific Transportation Company
U.S. Department of Transportation Interim
Report No. FRA-OR&D-75-60, August 1975

108. "Freight Car Truck Design Optimization,
Detailed Test Plans for Series 5 Test,
Phase I"
Southern Pacific Transportation Company
U.S. Department of Transportation Interim
Report No. FRA-OR&D-75-82, November 1975

109. "Freight Car Truck Design Optimization,
Survey and Appraisal of Type II Trucks"
Southern Pacific Transportation Company
U.S. Department of Transportation Interim
Report No. FRA-OR&D-76-05, December 1975

110. "Freight Car Truck Design Optimization,
Vol. I, Executive Summary"
Fay, G.R. and Bang, A.J
Federal Railroad Administration Final
Report No. FRA/ORD 78/12.I, February 1978

111. "Freight Car Truck Design Optimization,
Vol. II - Phase I Final Report"
Southern Pacific Transportation Company
Federal Railroad Administration Final
Report No. FRA/ORD 78/12.II, February 1978

112. "Freight Car Truck Design Optimization,
Vol. III, Phase I Frequency Domain Model"
Southern Pacific Transportation Company
Federal Railroad Administration Final
Report No. FRA/ORD78/12.III, February 1978

113. "Freight Car Truck Design Optimization.
Volume IV. Critique of Frequency Domain
Model-Solution Techniques"
Sussman, N.E.
Report No. FRA/ORD-78/12.IV (PB 278701),
February 1978

114. "Freight Car Truck Design Optimization,
Vol. V, Critique of Frequency Domain Model
- Equations of Motion"
Muhlenberg, J.D.
Federal Railroad Administration Final
Report No. FRA/ORD 78/12.V, February 1978

115. "Critique of Phase I - Test Series Results
Reports"
Muhlenberg, J.D.
Federal Railroad Administration Final
Report No. FRA/ORD 78/12.VI, February 1978

116. "Computer Oriented Data Collection and Re-
duction System for Analysis of Railroad
Freight Car Truck Behavior"
Luttrell, N.W.; Andresen, J.A.; and Bard-
well, R.A.
ASME Paper No. 75-WA/RT-4

117. "Performance Characteristics of Freight-
Car Trucks Determined Through Road Testing"
Byrne, R. and Andresen, J.A.
ASME Paper No. 76-WA/RT-4, 1976

118. "Performance Characteristics of Freight-
Car Trucks Determined Through Road Testing"
Byrne, R. and Andresen, J.A.
ASME Transactions, Journal of Engineering
for Industry, February 1977, pp 196-205

119. "Graphical Output-Oriented Computer Model
of a Railroad Freight Car with Conven-
tional Trucks"
Luttrell, N.W.
ASME Paper No. 77-RT-11, 1977

120. "Truck Design Optimization Project (TDOP)
PHASE II-Phase I Data Evaluation and Anal-
ysis Plan"
Gibson, D.
Report No. FRA/ORD-78/34, September 1978

24

121. "Truck Design Optimization Project, Phase II. Phase I. Data Evaluation and Analysis Report"
Gibson, D.W. and Glaser, R.J.
Report No. FRA/ORD-78/52 (PB 300969), August 1979

122. "Truck Design Optimization Project, Phase II. Introductory Report"
Cappel, K.
Report No. FRA/ORD-78/53 (PB-288739), November 1978

123. "Truck Design Optimization Project, Phase II. Analytical Tool Assessment Report"
Johnson, L.; Gilchrist, A.; Healy, M.; Bush, C.; and Sheldon, G.
Report No. FRA/ORD-79/36, (PB80-104888), August 1979

124. "Truck Design Optimization Project, Phase II. Friction Snubber Force Measurement System (FSFMS) Field Test Report"
Gibson, D.
Report No. FRA/ORD-79/24, October 1979

125. "Truck Design Optimization Project (TDOP) Phase II Analysis Plan"
Johnson, L.L. and Gilchrist, A.J.
Federal Railroad Administration Report FRA-OR&D-80/31, March 1980

126. "Truck Design Optimization Project (TDOP) Phase II Interim Report"
Sheldon, G.; Bakken, G.; Cappel, K.; Gibson, D.; and Gilchrist A.
Report No. FRA/ORD-80/59, (PB81-104945), June 1980

127. "Truck Design Optimization Project (TDOP), Phase II.
Performance Characterization of Type I Freight Car Trucks"
RamaChandran, P.V. and El Madany, M.M.
Federal Railroad Administration Report FRA/ORD-81/10, January 1981

128. "Truck Design Optimization Project: Phase II Performance Specification for Type II Trucks"
RamaChandran, P.V. and El Madany, M.M.
Department of Transportation Technical Report FRA/ORD-81/36-I, August 1981

129. "Truck Design Optimization Project: Phase II Test Specification for Freight Car Trucks"
RamaChandran, P.V. and El Madany, M.M.
Department of Transportation Technical Report FRA/ORD-81/36-II, August 1981

130. "Truck Design Optimization Project — Assessment of Truck Design Characteristics"
Tsai, N.T; RamaChandran, P.V.; and Cappel, K.L.
ASME Paper 79-WA/RT-15

131. "Lateral Dynamics of 70-Ton Freight Car Trucks"
El Madany, M.M. and RamaChandran, P.V.
ASME Paper No. 81-WA/RT-2

132. "Performance Characteristics of Conventional Freight Vehicle Systems"
RamaChandran, P.V.; El Madany; M.M.; and Tsai, N.T.
ASME Paper No. 81-WA/RT-3

133. "Dynamic Response of Freight Vehicle Systems--A Performance Characterization"
El Madany, M.M.; Rama Chandran, P.V.; and Tsai, N.T.
ASME Paper No. 81-RT-4, 1981

134. "LTV/SIG Metroliner Truck. Final Design Report"
Bumgardner, H.M.; Dean, F.E.; and Hall, V.W.II
Report No. FRA/ORD-76/250 (PB 265136), August 1975

135. "LTV/SIG Metroliner Truck Test. Volume I"
Sandlin, N.H.; Bumgardner, H.M.; Dean, F.E.; and Johnston, A.W.
Report No. FRA/ORD-76/251 (PB 265134), August 1975

136. "LTV/SIG Metroliner Truck Test. Volume II. (Suspension Parameter Variation Test Report)"
Dean, F.E.; Johnston, A.W.; and Sandlin, N.H.
Report No. FRA/ORD-76/252 (PB-265135), August 1975

137. "Tests on the Amtrak SDP-40F Train Consist Conducted on Chessie System Track/Executive Brief"
Office of Rail Safety Research
U.S. Department of Transportation Final Report No. FRA-OR&D-79/18, May 1979

138. "Tests of the Amtrak SDP-40F Train Consist Conducted on Chessie System Track"
Tong, P.; Brantman, R.; Greif, R.; and Mirabella, J.
Report No. FRA/ORD-79/19, DOT-TSC-FRA-79-14 (PB 297711), May 1979

139. "SDP-40F/E-8 Locomotives Test Results Report Dynamic Performance Testing," Volumes I & II
Kesler, K. and Yang, T.L.
U.S. Department of Transportation Final Report No. FRA-ORD-79/11-1 and -2, September 1977

140. "Analysis and Measurement of Locomotive Dynamic Characteristics"
Tong, P.; Brantman, R; and Greif, R.
ASME Paper 79-WA/RT-10, August 1979

141. "A Description of the Tests Conducted and Data Obtained During the Perturbed Track Test"
Coltman, M.; Brantman, R.; and Tong, P.
U.S. Department of Transportation Final Report No. FRA/ORD-80/15, January 1980

142. "Designing Perturbed Test Tracks for Evaluating Rail Vehicle Dynamic Performance"
Brantman, R. and Boghani, A.B.
ASME Paper No. 81-RT-7, 1981

143. "Instrumentation for Data Collection on a Revenue Freight Train"
MacIntyre, S.A. and Kaufman, W.M.
IEEE Industrial Applications Society 10th Annual Meeting Conference Record, September-October 1975, pp 518-522

144. "Summarization and Comparison of Freight Car Truck Load Data"
Johnson, M.R.
ASME Paper No. 77-WA/RT-3

145. "Engineering Data on Selected High Speed Passenger Trucks"
Shapiro, S.M.
U.S. Department of Transportation Final Report No. FRA-OR&D-78/29, April 1979

146. "Dynamic Loads on the Undercarriage of Freight Cars"
Krudryautseu, N.N.
U.S. Department of Transportation Report No. FRA-OR&D-79/33, July 1979

147. "Dynamic Hopper Car Test"
Kenworthy, M. and Jones, C.T.
Report No. FRA/TTC-80/01 (PB80 187925), March 1980

Vehicle-Track Dynamics: Combined Analytical and Experimental Rail Vehicle Dynamics

148. "A Study of the Stability and Dynamic Response of the Linear Induction Motor Test Vehicle"
Pearce, T.G. and May, B.J.
Federal Railroad Administration Final Report No. FRA-RT-70-25, September 1969

149. "The Lateral Dynamics of the Linear Induction Motor Test Vehicle"
Hobbs, A.E.W. and Pearce, T.G.
ASME Paper No. 74-Aut-Q, June 1974

150. "Summary of Metroliner Test Results"
Herring, J.M. Jr. and Strong, P.M.
Report No. PB 208284, February 1972

151. "Metroliner Ride Improvement Program"
Herring, J.M.
Report No. FRA-RT-73-30 (PB 221272), February 1973

152. "Development of Advanced Suspension Systems for High Speed Railcars. The Metroliner, a Case Study. Part 1 Dynamic Performance Requirements"
Strong, P.M. and Herring, J.M.
ASME Special Publication No. AMD-Vol. 15, 1975, pp 67-82

153. "Development of Advanced Suspension Systems for High Speed Railcars. The Metroliner, a Case Study. Part 2, Prototype Development and Testing"
Dean, F.E.
ASME Special Publication No. AMD-Vol. 15, 1975, pp 83-108

154. "Development of Design Loads Criteria for High Speed Railcar Trucks"
Sandlin, N.H.
Proceedings of Fourth Annual Intersociety Conference on Transportation, Paper D&0-32, July 1976

155. "Metroliner Truck Improvement Program"
Seely, R.M.
U.S. Department of Transportation Final Report No. FRA-OR&D-80/74, September 1980

156. "Freight Car Dynamics: Field Test Results and Comparison with Theory"
Cooperrider; N.K., Law, E.H.; and Fries, R.H.
Report No. FRA/ORD-81/46, June 1981

157. "Freight Car Dynamics: Final Report"
Law, E.H. and Cooperrider, N.K.
U.S. Department of Transportation Final Report FRA/ORD-81/47, August 1981

158. "Theoretical and Experimental Research on Freight Car Lateral Dynamics"
Cooperrider, N.K.; Law, E.H.; Fries, R.H.; and Tsai, N.T.
Proceedings of Heavy Haul Railways Conference, Perth, Western Australia, September 1978

159. "Railway Freight Car Field Tests"
Fries, R.H.; Cooperrider, N.K.; and Law, E.H.
ASME Paper No. 80-WA/DSC-7, 1980

160. "Experimental Investigation of Freight Car Lateral Dynamics"
Fries, R.H.; Cooperrider, N.K.; and Law, E.H.
Journal of Dynamic Systems, Measurement, and Control, Vol. 103, September 1981, pp 201-210

161. "An Investigation of Techniques for Validation of Railcar Dynamic Analyses"
Fallon, W.J.; Cooperrider, N.K.; and Law, E.H.
Interim Report No. DOT-FRA-ORD&D-78/19 (PB 279996), March 1978

162. "Improved Passenger Equipment Evaluation Program—Methodology Used in the Train Reviews"
Bachman, J.A.; Meacham, H.C.Jr.; Uher, R.A.; and Watson, R.B.
Final Report No. FRA/ORD-80/13 (PB80-161763), March 1979

163. "Improved Passenger Equipment Evaluation Program--Train System Review Report. Volume 1-Baseline Data"
Bachman, J.A.; Marchetti, J.W.; Meacham, H.C.Jr.; Uher, R.A.; and Watson, R.B.
Final Report No. FRA/ORD-80/14.I (PB80-161789), March 1978

164. "Conventional Versus Self-Steering Radial Trucks for High-Speed Passenger Trains"
Doyle, G.R.Jr.
ASME Paper No. 79-RT-3, January 1979

165. "Criteria for High-Speed Curving of Rail Vehicles"
Dean, F.E. and Ahlbeck, D.R.
ASME Paper No. 79-WA/RT-12, August 1979

166. "Track-Train Dynamics"
Abbott, P.W.; Morosow, G.; and Macpherson, J.
Society of Automotive Engineers Paper No. 751058, November 1975

167. "Comparison of the Nonlinear Dynamic Characteristics of Barber S-2 and ASF Ride Control Freight Trucks"
Abbott, P.
Report No. NASA-CR-150113, (NTIS Accession Number N77-13655/4ST), September 1976

168. "Analytical Methods for Freight Car/Truck Dynamic Problems"
Martin-Marietta Corporation
U.S. Department of Transportation Final Report No. FRA/ORD-80/29, July 1980

169. "Lightweight Intermodal Flatcar Evaluation Program, Vol. II: Test Results Report (including Appendix A - Transducer Locations)"
Kenworthy, M.A. and Edelman, J.
U.S. Department of Transporation Final Report No. FRA-ORD-80/07.II, December 1979

170. "Mathematical Modeling of DODX Railcars"
Jones, C.T.
Final Report No. FRA/ORD-78/47, (PB80-156961), February 1980

171. "Analysis of the Dynamics of a Rail Car from Its Response to Random Inputs"
Hutchens, W.A.; Haight, E.C.; and Milner, J.L.
High Speed Ground Transportation Journal, Vol. 9, No. 1, 1975, p 449-457

172. "Validation and Verification of Rail-Vehicle Models"
Hasselman, T.K. and Johnson, L.
ASME Paper No. 79-WA/DSC-8, July 1979

173. "Rail Vehicle Dynamics Model Validation"
Shladover, S.E. and Hull, R.L.
Report No. FRA/ORD-81/52, August 1981

Vehicle-Track Dynamics: Vehicle-Track Interactions

174. "Evaluation of Analytical and Experimental Methodologies for the Characterization of Wheel/Rail Loads"
Ahlbeck, D.R.; Harrison, H.D.; Prause, R.H.; and Johnson, M.R.
Federal Railroad Administration Final Report No. FRA-OR&D-76-276, November 1976

175. "An Investigation of Factors Contibuting to Wide Gage on Tangent Railroad Track"
Ahlbeck, D.R.; Harrison, H.D.; and Noble, S.L.
ASME Paper No. 75-WA/RT-1

176. "An Investigation of Factors Contributing to Wide Gage on Tangent Railroad Track"
Ahlbeck, D.R.; Harrison, H.D.; and Noble, S.L.
ASME Transactions, Journal of Engineering for Industry, Vol. 99 No. 1, February 1977, pp 1-9

177. "Techniques for Measuring Wheel/Rail Forces with Trackside Instrumentation"
Ahlbeck, D.R. and Harrison, H.D.
ASME Paper No. 77-WA/RT-9, 1977

178. "Measurements of Wheel/Rail Loads on Class 5 Track"
Ahlbeck, D.R.; Johnson, M.R.; Harrison, H.D.; and Tuten, J.M.
Report No. FRA/ORD-80/19, DOT-TSC-FRA-80-6 (PB80-196868), February, 1980

179. "Predicting the Load Environment on Railroad Track"
Ahlbeck, D.A.
ASME Paper No. 80-RT-7, 1980

180. "An Investigation of Impact Loads Due to Wheel Flats and Rail Joints"
Ahlbeck, D.R.
ASME Report No. 80-WA/RT-1 November 1980

181. "Characterization and Analysis of the Wheel/Rail Load Environment at the Facility for Accelerated Service Testing (FAST)"
Tuten, J.M. and Ahlbeck, D.R.
ASME Paper No. 81-WA/RT-13

182. "Instrumentation for Measurement of Forces on Wheels of Rail Vehicles"
Association of American Railroads and ENSCO, Inc.
U.S. Department of Transportation Final Report No. FRA-OR&D-75-11, May 1974

183. "Plate Instrumented Wheelsets for Measurement of Wheel/Rail Forces"
Thompson, W.I.,III
Report No. FRA/ORD-80/58, (PB81-116113), October 1980

184. "A Technique to Estimate Lateral Rail Vehicle Forces from Acceleration Measurements"
Kesler, J.K. and Yang, T.L.
ASME Paper No. 81-WA/DSC-21

185. "Anti-Derailment Sensor System Phase I Feasibility Study"
Armstrong, J.H.; Kluge, F.C.; Swaim, F.H.; Terrell, J.D.; and Wassmann, W.W.
Report No. FRA-ORD&D-74-17, April 1973

186. "G-Sensing Derailment Detector"
Nance, P.
Report No. FRA/ORD-80/75 (PB81-127466), October 1980

187. "Parametric Study to Relate Railcar Speed to Permissible Combinations of Track Geometry Deviations"
DiMasi, F.P. and Weinstock, H.
ASME Journal of Dynamic Systems, Measurement, and Control, Vol. 100, No. 4, December 1978, pp 252-259

188. "A Methodology for Estimating the Derailment Probability of a Fleet of Railway Vehicles"
Brantman, R.; Griffin, J.W.; and Jeffcoat, R.L.
ASME Paper No. 79-WA/RT-6, August 1979

189. "Wheelclimb Derailment Criteria Under Steady Rolling and Dynamic Loading Conditions"
Sweet, L.M.; Karmel, A.; and Moy, P.K.
Proceedings of Sixth Vehicle System Dynamics - International Union of Theoretical and Applied Mechanics Symposium on the Dynamics of Vehicles on Roads and Tracks, Berlin, September 1979, pp 496-510

190. "Evaluation of Time-Duration Dependent Wheel Load Criteria for Wheelclimb Derailment"
Sweet, L.M. and Karmel, A.
ASME Paper No. 80-WA/DSC-21, 1980

191. "Evaluation of Time-Duration Dependent Wheel Load Criteria for Wheelclimb Derailment"
Sweet, L.M. and Karmel, A.
ASME Transactions, Journal of Dynamic Systems, Measurement and Control, Vol. 103 No. 3, September 1981, pp 219-227

192. "Derailment Mechanics and Safety Criteria for Complete Rail Vehicle Trucks"
Sweet, L.M.; Karmel, A.; and Fairley, S.
Proceedings of Seventh Vehicle System Dynamics - International Union of Theoretical and Applied Mechanics Symposium on the Dynamics of Vehicles on Roads and Tracks, Cambridge, England, September 1981

Longitudinal Train Dynamics

193. "Automatic Parameter Identification Applied to a Railroad Car Dynamic Draft Gear Model"
Ward, E.D. and Leonard, R.G.
ASME Transactions, Journal of Dynamic Systems, Measurement and Control, Vol. 96, No. 4, December 1974, pp 460-465 (ASME Paper No. 74-WA/Aut-1

194. "Theoretical Manual and User's Guide: Longitudinal-Vertical Train Action Model"
Yin, S.K.
Federal Railroad Administration Report No. FRA/ORD-76/278, April 1980

195. "Research Locomotive and Train Handling Evaluator Definition"
Hulbert, S.; Wheeler, J.; Dompe, R.; Witham, C.; and Csanky, L.
U.S. Department of Transportation Final Report No. FRA-OR&D77/47 (Three Volumes), September 1977

196. "Program Multi: A Multi-Purpose Program for Computing and Graphing Roots and Values for Any Real Function. Users/Programmers Manual"
Brantman, R.
Final Report No. FRA/OR&D-76-143 (PB 261121), May 1976

197. "Development of a System to Display and Record Slack Action in Freight Trains"
Vrabel, J.D; Sussman, E.D.; and Ofsevit, D.
U.S. Department of Transportation Final Report No. FRA-OR&D-77/53, August 1977

198. "Derailment Warning Indicator"
Brantman, R.; Vrabel, J.D.; and Sussman, E.D.
Department of Transportation Patent Report No. PAT-APPL-765-929 (PB 263732), 1977

199. "A Quasi-Static Model to Rapidly Assess Lateral Train Stability"
Brantman, R.
ASME Paper No. 81-WA/DSC-15

Other Applications

200. "Railroads and the Environment - Estimation of Fuel Consumption in Rail Transportation, Volume I - Analytical Model"
Hopkins, J.B.
U.S. Department of Transportation Final Report No. FRA-OR&D-75-74.I, Reprint October 1975

201. "Railroads and the Environment - Estimation of Fuel Consumption in Rail Transportation, Volume II - Freight Service Measurements"
Hopkins, J.B. and Newfell, A.T.
U.S. Department of Transportation Final Report No. FRA-OR&D75-74.II, September 1977

202. "Resistance of a Freight Train to Forward Motion, Vol. I, Methodology and Evaluation" Muhlenberg, J.D. U.S. Department of Transportation Interim Report No. FRA-OR&D78/04.I, April 1978

203. "Resistance of a Freight Train to Forward Motion, Vol. II, Implementation and Assessment" Muhlenberg, J.D. U.S. Department of Transportation Interim Report No. FRA-OR&D78/04.II, April 1979

204. "Freight Train Fuel Consumption: Economic Analysis and Correlation of Predictions with Field Data" Muhlenberg, J.D. U.S. Department of Transportation Final Report No. FRA-OR&D78/04.III, February 1981

205. "Resistance of a Freight Train to Forward Motion, Vol. IV, Users' Manual for Freight Train Fuel Consumption Program" Muhlenberg, J.D. U.S. Department of Transportaion Final Report No. FRA-OR&D78/04.IV, February 1981

206. "Aerodynamic Forces on Freight Trains. Volume 1: Wind Tunnel Tests of Containers and Trailers on Flatcars" Hammitt, A.G. Final Report No. FRA/OR&D-76-295.I (PB 264304), December 1976

207. "Aerodynamic Forces on Freight Trains. Volume II -- Full-Scale Aerodynamic Validation Tests of Trailer-on-a-Flat Car (Series II)" Joshi, P.B. Report No. FRA/ORD-76-295.II (PB 281823), March 1978

208. "Aerodynamic Forces on Freight Trains -- Volume III Correlation Report-Full Scale Tests of Trailers on Flatcars and Comparison with Wind Tunnel Results" Hammitt, A.G. Final Report No. FRA/ORD-76-295.III, (PB-288137), September 1978

209. "Aerodynamic Forces on Freight Trains - Volume IV Wind Tunnel Tests of Freight Cars and New Trailer and Container Car Designs" Hammitt, A.G. Final Report No. FRA/ORD-76/295.IV, June 1979

210. "Aerodynamic Forces on Various Configurations of Railroad Cars for Carrying Trailers and Containers. Wind Tunnel Tests of Six Scale Model Configurations" Hammitt, A.G. Final Report No. FRA/ORD-79/39, (PB80-174881), January 1979

211. "Mathematical-Computer Simulation of the Dynamics of a Freight Element in a Railroad Freight Car" Shum, K.L. and Willis, T. U.S. Federal Railroad Administration Report No. FRA/ORD-77/28, May 1975

212. "Six-Point Suspension System for a Railcar Body" Willis, T. and Shah, H.B. Proceedings of Fourth Annual Intersociety Conference on Transportation, Paper D60-33, July 1976

213. "A Computer Method for Calculating Dynamic Responses of Nonlinear Flexible Rail Vehicles" Healy, M.J. ASME Paper No. 76-RT-5, January 1976

214. "FRATE, Volume I: User's Manual" Kachadourian, G.; Sussman, N.E.; and Anderes, J.R. Technical Report No. FRA/ORD-78/59, (PB 291206), September 1978

215. "Freight Car Vibration Test and Analysis Comparison -- Validation of FRATE" Kachadourian, G. and Tsai, N.T. SAE Paper No. 781049, 1978

216. "TOFC (Trailer on Flatcar) Lading Response Analyses for Several Track Profile and Hunting Conditions" Kachadourian, G. Report No. FRA/ORD-80/3, (PB80-178171), April 1980

217. "Response Analyses of a Box Car with Compliant Lading for Several Track Profile and Hunting Conditions" Kachadourian, G. and Sussman, N.E. Technical Report No. FRA/ORD-80/4, (PB80-177637), April 1980

218. "Transportation of Vibration Sensitive Equipment by Highway Trailer on an Intermodal Railcar," Vol. 1 Kenworthy, M. U.S. Department of Transportation Final Report No. FRA-ORD-79/05.1, July 1979

29