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Review and Summary of Computer Programs for Railway Vehicle Dynamics

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Final Report

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03 - Rail Vehicles &
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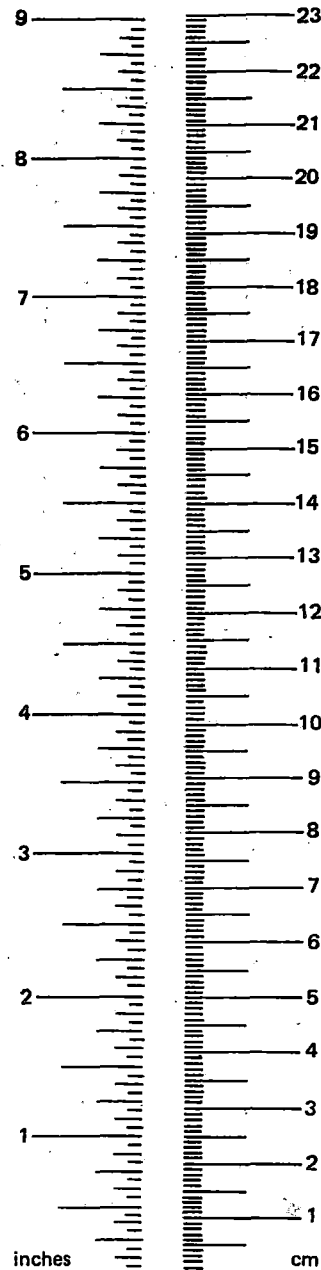
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16. Abstract <p>To assess the state of development of computer programs which apply to the dynamics of rail vehicles, reviews were prepared of programs in six different categories: lateral stability, curving dynamics, wheel/rail contact, freight vehicle dynamics, analog hybrid simulation, and train dynamics. In addition, a number of European programs were summarized. A survey of users of the programs was also undertaken.</p> <p>The great majority of available programs are not widely used; some were developed for specific purposes and are not suitable for general use. The three programs which are most frequently applied are Train Operations Simulator (TOS), Quasi-Static Lateral Stability Model (QSLTS), and Nonlinear Flexible Car Body Vehicle Model (FVEH). These codes appear to be the best choices for further improvement and verification. Other areas in which users believe computer programs could be profitably employed are wear, fatigue, fracture, inelastic behavior, and impact.</p> <p>The principal drawback in applying existing codes seems to be the difficulty in obtaining accurate input data, such as damping constants, moments of inertia, stiffnesses, and locations of mass centers.</p>					
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METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

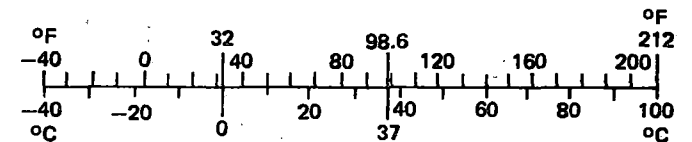
Symbol	When You Know	Multiply by	To Find	Symbol
LENGTH				
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
AREA				
in ²	square inches	6.5	square centimeters	cm ²
ft ²	square feet	0.09	square meters	m ²
yd ²	square yards	0.8	square meters	m ²
mi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

*1 in. = 2.54 cm (exactly). For other exact conversions and more detail tables see NBS Misc. Publ. 286. Units of 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				
cm ²	square centimeters	0.16	square inches	in ²
m ²	square meters	1.2	square yards	yd ²
km ²	square kilometers	0.4	square miles	mi ²
ha	hectares (10,000 m ²)	2.5	acres	
MASS (weight)				
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
VOLUME				
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m ³	cubic meters	36	cubic feet	ft ³
m ³	cubic meters	1.3	cubic yards	yd ³
TEMPERATURE (exact)				
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



Executive Summary

The purpose of this survey was to assess the state of development of computer codes which apply to the dynamics of rail vehicles. A list of these codes was compiled, and the codes were divided by function into six groups. An authority was then selected to prepare a summary of the program in each group. In addition, users of the programs were queried to obtain information on the effectiveness of the codes and to identify areas in which improvements were needed. Some information on German and British rail dynamics programs was also gathered.

Jeffrey L. Hadden of Battelle-Columbus Laboratories reviewed the programs which deal with lateral stability of rail vehicles. He summarized and compared ten codes which are based on linear models and one code which uses a quasilinear model. He concluded that a program for validation of computed results is needed before computer codes can be relied on for more than predicting qualitative trends in vehicle behavior.

The programs dealing with curving dynamics of rail vehicles were reviewed by Robert S. Jeffcoat of Foster-Miller Associates Inc. Sixteen programs and two analytical models were summarized in this group. The review includes discussions of such topics as solution methods, models, and features which programs should possess.

The wheel/rail contact review included descriptions of five codes: CONFORM and COUNTACT by B. Paul, Kalker's Simplified Theory and Kalker's Exact Theory by James Goree, and DUVOROL by J. Kalker.

N. Sussman, formerly of the Mitre Corporation, has summarized and compared two programs in the Freight Vehicles Dynamics Section; these programs were FRATE and the IIT Freight Model. The similarities and differences of these two codes are described in detail in this section.

In the Analog/Hybrid Simulation section, Carl Malstrom discusses analog/digital systems in general and describes recent activity in using hybrid systems in rail vehicle simulation.

The final group review by S. Shum deals with train dynamics models. Six models which apply to either longitudinal, lateral, or vertical train dynamics are described.

A translation of a German summary of a number of European programs used to study rail vehicle dynamics is also included, and a brief description of three British programs is presented. Some of these programs could be useful to American analysts.

The response to the users questionnaires indicated that the most widely applied programs are Train Operations Simulator (TOS), Quasi-Static Lateral Train Stability Model (QSLTS), and Nonlinear Flexible Car Body Vehicle Model (FVEH). The majority of the available codes are not in use; only eleven of a list of seventy codes were reported as being applied by at least one of the thirty-three responding users. Some programs which were not developed specifically for railroad applications are being used to analyze trains and rail cars, e.g., STRUDL, NASTRAN, and STARDYNE.

A limited amount of experimental and analytical verification of computed results has been done; most users felt that the programs gave reasonable results and that they executed efficiently. The complaint was frequently voiced that input data was difficult to obtain and organize. Many programs lack complete documentation; they were developed for specific tasks and are not suitable for general use.

Wear, fatigue, fracture, inelastic behavior, and impact were mentioned as areas in which computer programs might advantageously be applied. There appears to be a pressing need to apply existing codes more widely and effectively. Because of relatively wide application, programs TOS, QSLTS, and FVEH seem the best choices to be objects of improvement and validation programs.

Acknowledgments

The editors of the report wish to thank the FRA Office of Research and Development and the Association of American Railroads for their assistance in identifying programs, reviewers, and users. Special thanks are due to Dr. N. Tsai, the Contract Office Technical Representative, who contributed much valuable assistance in completing this survey.

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1.0 INTRODUCTION

Many computer programs which pertain to the dynamics of rail vehicles have been developed under the sponsorship of the Federal Railroad Administration (FRA) and the Association of American Railroads (AAR). To provide a preliminary assessment of the state-of-the-art of these and other dynamics programs, a survey of program authorities and users was undertaken. The computer codes were summarized, compared, and evaluated. Recommendations were made for further improvement in computer technology as applied to the dynamics of rail vehicles. A list of the programs was prepared, and the programs were grouped according to area of application. For each group of programs authorities were solicited to prepare summaries and reviews of the programs. In addition, persons who were likely to have used the codes were identified and queried to gain information for guiding further developments in computer programs.

The study consists of six reviews which were prepared by American authorities and one section on European programs. The responses of the users have also been summarized. The group reviews differ widely in the extent and detail of the coverage of the programs. A concluding section attempts to summarize the results of the study.

2.0 PROGRAM REVIEWS

2.1 INTRODUCTION

The list of computer programs which apply to the dynamics of rail vehicles was first broken down into seven groups according to functions (see Appendix C). An authority on the programs in each particular group was then selected to prepare a review of that group of programs. The classifications and the names of the reviewers are listed in Table 1 (on the following page).

In addition to the American programs, some information on German and British rail-vehicle codes is included in a section at the end of the group reviews. The group reviews vary in the extent of program coverage; some reviews are fairly complete, unified treatments; others are merely a collection of summaries of several programs. For this reason, introductory explanatory material has been added to some of the reviews.

Table 1. The six classifications used for rail-vehicle dynamics computer programs and the reviewers of each group of programs.

<u>Classification</u>	<u>Reviewer</u>
Lateral Stability	Jeffrey A. Hadden Research Scientist Battelle-Columbus Laboratories Applied Dynamics and Acoustics Section 505 King Avenue Columbus, Ohio 43201
Curving Dynamics	Robert Jeffcoat Manager Applied Dynamics Division Foster-Miller Associates, Inc. 350 Second Avenue Waltham, Mass. 02154
Wheel/Rail Contact	J. Goree Department of Mechanical Engineering Clemson University Clemson, South Carolina 29631 and Burton Paul 111 Towne Building D3 University of Pennsylvania Philadelphia, PA 19104
Freight Dynamics	Nathan E. Sussman formerly of The Mitre Corporation 1820 Dolly Madison Boulevard McLean, VA 22101
Analog Hybrid Simulation	Carl Malstrom Department of Mechanical Engineering Clemson University Clemson, South Carolina 29631
Train Dynamics	Sam K. Shum Manager - Analytical Support Mechanical Engineering - Conrail 233 30th Street Station Philadelphia, PA 19104

2.2 LATERAL STABILITY

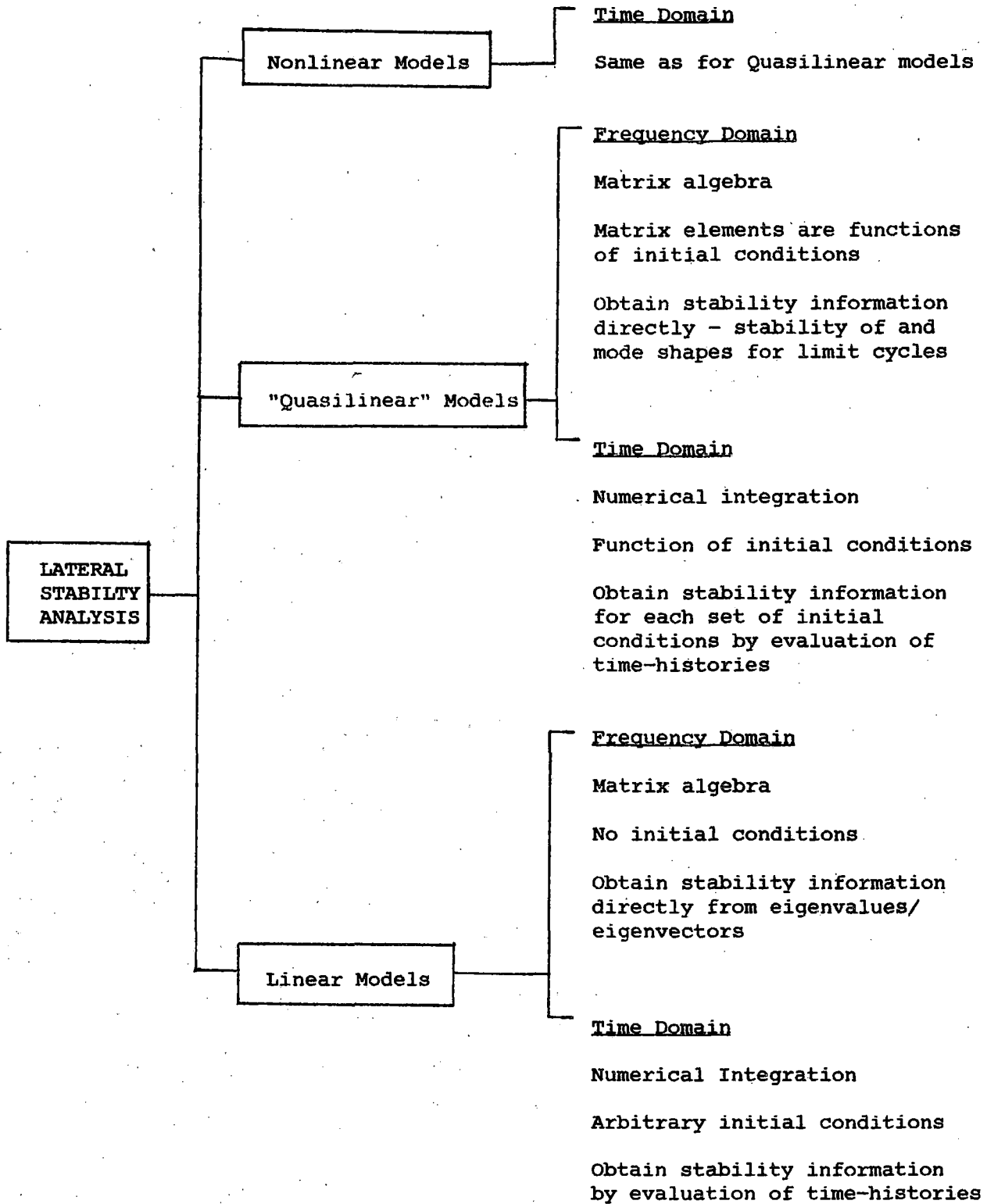
INTRODUCTION

In recent years there has been a dramatic upsurge in research in North America in the rail vehicle area. This has spawned the application of sophisticated analytical methods to the study of rail vehicle dynamics. As a result, a substantial number of digital computer programs has been developed to study rail vehicle lateral stability. In this section several of these programs are compared and evaluated with respect to their capabilities, availability, and documentation.

A major obstacle in preparing this review was the lack of formal documentation of many existing computer programs. This may be attributed partly to the fact that rail vehicle dynamics is a relatively new field of research in North America. Many computer programs that have been developed remain specifically for a given task and given group of users, and have not yet been "tailored" for general use by others.

Another problem that may be attributed partly to the newness of this field is the lack of sufficient experimental data to validate fully the computer programs. Consequently, the best validation for some programs is to show similar model behavior with other previously developed models and with qualitative observations of vehicle behavior. In spite of this shortcoming, these computer programs generally have proved valuable in at least predicting trends in vehicle behavior. With more complete, quantitative validation, these programs should become powerful design tools for the railroad industry. A breakdown of the analysis methods used presently to evaluate rail vehicle lateral stability is shown in Table 1. The elements of this chart are discussed in detail in the next section.

Table 1 Breakdown of Analytical Methods Used In Digital Computer Programs To Examine Rail Vehicle Lateral Stability



BACKGROUND

General Vehicle Dynamic Behavior

The lateral stability of a rail vehicle represents one aspect of the overall dynamic behavior. Other aspects of dynamic behavior include curve entry and curve negotiation characteristics, and the response to stochastic and deterministic excitation from the track, wind, and other vehicles.

A lateral, or "hunting," instability problem in conventional rail vehicles is caused by the nature of the wheel/rail interaction. Hunting is characterized by coupled yaw and lateral oscillations of the wheelsets which increase in amplitude until repeated flanging of the wheels on the rail occurs. There exists a "critical speed" above which the response to an arbitrary small perturbation is manifested in hunting oscillations. These oscillations, which are coupled with motions of the rest of the vehicle, are sustained in a "limit cycle" condition at wheelset lateral amplitudes equal to the flange clearance. Above the critical speed, the wheels will climb the rail and derailment may occur. Below the critical speed, the oscillatory response will either die out or decrease to a relatively safe, small amplitude limit cycle condition.

It is possible that for certain worn or unconventional wheel profiles sustained limit cycle oscillations will occur without flanging. For new wheels, however, the limit cycle condition exists only for the flanging condition.

Nonlinear Modeling

The hunting behavior described previously is inherently nonlinear due primarily to the nonlinear wheel/rail geometry (including flanging) and wheel/rail contact forces. Suspension nonlinearities, friction, stops, and clearances throughout the rail vehicle also contribute to the nonlinear performance. Therefore, the most accurate model of rail vehicle lateral dynamics would include realistic representations of these nonlinearities. For this approach, the only analytical method that can be used is that of numerical integration of the nonlinear equations of motion. The response of a nonlinear system is generally a function of the initial conditions. Thus, a reasonable range of initial conditions must be prescribed to obtain a set of time-domain solutions that represents the range of behavior expected in practice.

Depending on the purpose of the study, the time and costs involved to exercise a large, nonlinear, time-domain model several times may not be justified. These are motivating factors for the use of approximate methods in lateral stability analyses. By making reasonable approximations, computer time and costs can be cut substantially while the program provides sufficiently accurate results. Linear and quasilinear modeling are two classes of approximate methods which are discussed in the following sections.

Linear Modeling

A linear rail vehicle stability model consists of a set of second order, constant-coefficient, homogeneous differential equations. To obtain this type of model, several simplifying assumptions are made. These include:

All displacements are small enough so that second and higher order quantities in the variables may be neglected.

Friction elements may be approximated by linear elements, such as by calculating an equivalent viscous damping coefficient.

Equivalent linear springs may be used to approximate small displacement behavior of nonlinear spring elements.

Nonlinear wheel/rail geometry terms may be represented by neglecting terms higher than first order in the Taylor series expansion for the particular terms. Flanging cannot occur.

The possibility for sliding of the wheels on the rails is neglected--pure creepage occurs between the wheels and rails.

All stops and clearances are either neglected or accounted for in linear suspension terms.

The vehicle is traveling at a constant forward speed (this assumption is used for both linear, quasilinear, and nonlinear stability models).

These assumptions may impose substantial limitations on the validity of the models, as determined by the degree of nonlinear characteristics inherent in the actual rail vehicle. However, by making intelligent choices for the linearized model's parameters, qualitative trends in behavior usually can be identified. Thus, a primary benefit of the linear stability model is to illustrate the basic dynamic behavior of rail vehicles.

An attractive feature of linear models is that the stability characteristics are independent of the initial conditions. Thus, arbitrary initial conditions may be prescribed for time-domain simulations of a linear model. Then, the stability characteristics can be extracted by evaluation of the displacement time-histories. It should be emphasized that the linear stability characteristics are amplitude independent, due to the general nature of linear systems.

A major benefit of stability analysis with linear models is that frequency domain techniques can be used conveniently. Specifically, stability information is provided directly by solution of the eigenproblem. The sign of the real part of the eigenvalues are the damped natural frequencies for the corresponding (eigenvectors or "modes" (a zero imaginary part implies a nonoscillatory mode)). The system damping ratio for each mode can be calculated from the real and imaginary parts. Finally, relative magnitude and phase relationships between the degrees of freedom of the system for each mode are provided by the eigenvectors. The frequency-domain solution usually is faster and cheaper to exercise on the computer than is the time-domain solution. These savings typically are more substantial for larger models.

"Quasilinear" Modeling

The application of quasilinearization (or describing function) techniques to rail vehicle stability analysis is an area of relatively recent interest. The essence of these techniques is that the fundamental form

linear characteristics of the system are included, while the mathematical form of the system allows the application of frequency-domain analysis, the benefits of which were explained in the previous section. Specifically, quasilinearization consists of approximating a nonlinear function by one or more gains that are a function of the input signal amplitudes. In contrast, linearization consists of approximating the nonlinear function by a single gain that is amplitude-independent. The stability of the quasilinear rail vehicle model is described typically in terms of stable and unstable limit cycle oscillations, which are a function of the amplitude and/or frequency of motion.

General Comments

It should be noted that almost all lateral dynamics time-domain simulations may be used to determine rail vehicle stability characteristics. However, the manipulations necessary to extract these characteristics are usually cumbersome and costly. The nature of rail vehicle lateral dynamics allows the use of convenient frequency-domain techniques to approximate stability characteristics. Thus, this review is restricted to the class of frequency-domain stability models.

It should also be noted that this review is by no means complete. Some existing computer programs have been omitted from consideration, mainly because of lack of sufficient information on the program details. However, the sample of programs presented is believed to be representative of the range of analytical capabilities that presently exists in the field of rail vehicle dynamics.

SURVEY OF COMPUTER PROGRAMS

CU/ASU Freight Car Lateral Stability Models

Categories: Hunting, lateral stability, freight car stability, wheel profile asymmetries, loading asymmetries, wheelset interconnection, torsionally flexible wheelsets

Authors: E. H. Law

Department of Mechanical Engineering
Clemson University
Clemson, South Carolina 29632

N. K. Cooperrider
Department of Mechanical Engineering
Arizona State University
Tempe, Arizona 85282

J. A. Hadden (23 degree-of-freedom model only)
Battelle
Columbus Laboratories
505 King Avenue
Columbus, Ohio 43201

Maintenance: Authors

Date: Development of 17 and 19 degree-of-freedom (DOF) models
comprised latest update (1976-7)

Capabilities: Series of four models, having 9, 17, 19, and 23 DOF.

Programs calculate eigenvalues (frequency and damping) and eigenvectors (mode shapes) for the system equations. 9 DOF model specialized to roller bearing freight trucks and rigid car body. Other programs include capability to simulate plain bearing,

passenger, "radial" (interconnected wheelsets) and unconventional trucks. Twenty-three DOF model also includes torsionally flexible wheelsets. Seventeen DOF model includes wheel profile and loading asymmetries. Nineteen and twenty-three DOF models include first torsional and lateral bending modes of car body. Models approximate nonconical wheel profiles at an assumed wheelset displacement amplitude.

Method: QR Algorithm, as described by Wilkinson [1]¹ and Marcotte [2]

Limitations and Restrictions: Linear systems only. Asymmetries in 17 DOF model are limited to fore and aft loading, and to identical wheel profiles on each axle. Relative roll between car body and bolsters does not exist. 9 DOF model truck representations are limited to roller bearing freight or rigid trucks.

Programming Language: FORTRAN

Documentation: User's manuals are in preparation. Equations of motion and/or model derivations are presented in Ref. [3, 4].

Input: Mass, damping, and stiffness parameters, physical dimensions and vehicle speeds.

Output: Real and imaginary parts of eigenvalues, damping ratios, and relative magnitudes and phase angles between displacements for each eigenvalue.

Software Operation: Batch

Hardware: Programmed for IBM 370/165-II and UNIVAC 1110.

Usage: Developed for the U.S. Department of Transportation (DOT) Federal Railroad Administration (FRA) under Contract DOT-OS-40018 in a joint effort by Clemson University and Arizona State University.

Typical Running Time: Unknown.

Availability: Dr. E. H. Law
Department of Mechanical Engineering
Clemson University
Clemson, SC 29632

Program TRKHNT II

Categories: Hunting, lateral stability, passenger truck stability, wheelset interconnection, torsionally flexible wheelsets.

Descriptive Program Title: Linear Passenger and Radial Truck Hunting Model.

Author: G. R. Doyle
Applied Dynamics and Acoustics Section
Battelle - Columbus Laboratories
Columbus, Ohio 43201

Maintenance: G. R. Doyle

Date: 1974; latest update in 1978 - revisions made to include radial truck model.

Capability: 9 DOF model of single passenger truck with torsionally flexible wheelsets and suspension interconnection between wheelsets. Can represent passenger, rigid and "radial" trucks.

Method: Solution of eigenproblem, based on Ref. [5].

¹ Numbers in brackets refer to References at the end of this article.

Limitations and Restrictions: Linear systems only. Rigid truck frame disallows modeling of conventional 3-piece freight truck. No car body flexural degrees of freedom. Conical wheels only. No asymmetries.

Programming Language: FORTRAN

Documentation: Not available. Model described and equations of motion (without wheelset interconnection capability) presented in Ref. [6].

Input: Mass, damping and stiffness parameters, physical dimensions, vehicle speeds.

Output: Real and imaginary parts of eigenvalues, relative magnitudes and phase angles between displacements for each eigenvalue.

Software Operation: Batch

Hardware: Program designed for CDC 6400

Usage: Used at Battelle for several sponsored research programs over past several years.

Typical Running Time: 10 sec.

Availability: Author

Program CARHNT II

Categories: Hunting, lateral stability, passenger car stability, torsionally flexible wheelsets.

Descriptive Program Title: Linear Passenger Car Hunting Program.

Authors: R. H. Prause and G. R. Doyle

Applied Dynamics and Acoustics Section

Battelle - Columbus Laboratories

Columbus, Ohio 43201

Maintenance: G. R. Doyle

Date: 1974

Capability: 21 DOF model of complete passenger rail vehicles with torsionally flexible wheelsets.

Method: Solution of eigenproblem, based on Ref. [5]

Limitations and Restrictions: Linear systems only. Rigid car body model disallows car body flexural motions. Conical wheels only. No asymmetries.

Programming Language: FORTRAN

Documentation: Not available. Model described and equations of motion presented in Ref. [6].

Input: Mass, damping and stiffness parameters, physical dimensions and vehicle speeds.

Output: Real and imaginary parts of eigenvalues, and relative magnitudes and phase angles of displacements for each eigenvalues.

Software Operation: Batch

Hardware: Programmed for CDC 6400.

Usage: Used at Battelle for several sponsored research programs over the past several years.

Typical Running Time: 30 sec.

Availability: Authors

Program DYNALYST II

Categories: Hunting, lateral stability, rail vehicle dynamic response, component mode synthesis.

Descriptive Program Title: Computer Program for Stability and Dynamic Response Analysis of Linear Rail Vehicle Systems.

Authors: T. K. Hasselman and A. Bronowicki
J. W. Wiggins Company

1650 South Pacific Coast Highway
Redondo Beach, California 90277

Date: 1974; several revisions made in 1975-6, including forced response capability, improved plotting capability, and a computer matrix generator.

Capability: Stability analysis, and forced response to deterministic and random excitation. Flexible car body modeling. Up to 25 DOF models. Capable of simulations of freight and passenger vehicles and locomotives. Plot routine for frequency and system damping vs speed. Two preprogrammed rail vehicle models, consisting of 8 DOF truck and 14 DOF complete vehicle. General program can accommodate asymmetries, nonconical wheel profiles.

Method: Component mode method (Ref. [7]). Component masses are defined independently. Constraint relations are defined to combine components into complete vehicle, with editing capability for deletion of characteristics associated with large eigenvalues.

Limitations and Restrictions: Linear systems only. Preprogrammed models limited to rigid truck frames and rigid car body, no asymmetries, and conical wheels only. No car body roll in 14 DOF model. General purpose program limited to 25 DOF.

Programming Language: FORTRAN

Documentation: Complete (Ref. [7]).

Input: Required inputs into preprogrammed vehicle models include vehicle mass, stiffness and damping characteristics, physical dimensions and vehicle speed. General purpose program requires programming of user's specific equations of motion.

Output: Stability information is presented in the form of a listing of the complex eigenvalues, and associated normalized (real and imaginary parts), for each vehicle component and the assembled vehicle. Plot options include frequency and damping ratio vs speed plotted on a Calcomp plotter for each conjugate pair of eigenvalues.

Software Operation: Batch. Uses three working files, which may be tapes or disks.

Hardware: Programmed for CDC 6600, requiring maximum 163 K of core.

Usage: Program was developed by the J. W. Wiggins Company for DOT.

Typical Running Time: Unknown

Availability: Through Transportation Systems Center, Cambridge, MA.

Freight Car Hunting Model

Categories: Hunting, lateral stability, freight car stability.

Descriptive Program Title: Freight Car Hunting Model.

Authors: T. W. Cheung, V. K. Garg and G. C. Martin

Association of American Railroads (AAR)

3140 South Federal Street

Chicago, IL 60616

Maintenance: AAR

Date: 1974

Capability: 25 degree-of-freedom. Primary suspension elements between wheelsets and truck. Truck models can represent freight, rigid

and passenger, and unconventional trucks.
Method: QR double step method and inverse iteration (Ref. [8]).
Limitations and Restrictions: Linear systems only. Conical wheels only. Rigid car body model. No asymmetries.
Programming Language: FORTRAN
Documentation: Complete (Ref. [9]).
Input: Mass, damping and stiffness characteristics, physical dimensions, and vehicle speeds. Also must specify stiffness matrix inversion option (yes or no), depending on accuracy desired for high frequency response.
Output: Eigenvalues, damping ratios and eigenvectors (in terms of normalized magnitudes and phase angles) for system equations.
Software Operation: Batch
Hardware: Programmed for IBM 370/158
Usage: Program was developed for AAR.
Typical Running Times: 171-184 seconds per run (one vehicle speed) for compilation (126 sec), link edit (4 sec), and execution (45-53 sec).
Availability: Director, Technical Center
Association of American Railroads
3140 South Federal Street
Chicago, IL 60616

Locomotive Truck Hunting Model

Categories: Hunting, lateral stability, locomotive stability, three-axle trucks.
Descriptive Program Title: Locomotive Truck Hunting Model
Authors: V. K. Garg, P. W. Hartmann, and G. C. Martin
Association of American Railroads (AAR)
3140 South Federal Street
Chicago, IL 60616
Date: Unknown
Capability: Linear stability program, accomodating models of 2, 7, 9, 17, and 21 DOF. These consist of a wheelset, two-axle truck, three-axle truck, four-axle locomotive and six-axle locomotive, respectively.
Method: QR double step method and inverse iteration (Ref. [8]).
Limitations and Restrictions: Linear systems only. Conical wheels only. Rigid truck frame and rigid car body only. Symmetrical wheel profiles only.
Programming Language: FORTRAN
Documentation: Complete (Ref. [10]).
Input: Mass, damping and stiffness characteristics, physical dimensions, vehicle speeds, choice of model, option for English or metric units, matrix inversion option, diagnostics printout options.
Output: Eigenvalues (real and imaginary parts), frequency (Hz), damping ratios, and normalized eigenvectors (magnitude and phase angle).
Software Operation: Batch
Hardware: Programmed for IBM 370/158
Usage: Programmed developed for use at General Motors Electro-Motive Division and AAR.

Typical Running Times: Compilation = 66.0 sec
Link Edit = 4.0 sec
Execution (per train speed) = 0.3 sec (2 DOF)
2.0 sec (7 DOF)
3.0 sec (9 DOF)
20.0 sec (17 DOF)
30.0 sec (21 DOF)

Availability: Association of American Railroads (AAR)
3140 South Federal Street
Chicago, IL 60616

Program FDM

Categories: Frequency Response, Freight Car Stability, Nyquist Stability.

Descriptive Program Title: Frequency Domain Model

Author: Southern Pacific Transportation Company
Technical Research and Development Group
One Market Plaza
San Francisco, CA 94105

Maintenance: Author

Date: 1976

Capability: 13 degree-of-freedom linear freight car model. Frequency response to deterministic or random forcing from track. Nyquist stability plots. Conical and concave wheel profiles. Suspension loading and wheel/rail geometry asymmetries. Car body fundamental torsional mode is included.

Method: Solution of 13 simultaneous equations of motion as function of frequency (Ref. [11]).

Limitations and Restrictions: Linear systems only. Rigid truck or roller bearing freight truck only. Requires track deflection data in format of TDOP test track data measured by DOT track geometry cars (available through National Technical Information Service (NTIS) on NTIS Tape PB 249 794/9WT). Tapes must be converted to proper form using a peripheral program.

Programming Language: FORTRAN

Documentation: Complete (Ref. [11]).

Input: Mass, damping and stiffness characteristics, vehicle speeds track geometry characteristics, physical dimensions, wheel profile type, friction forces (automatically converted to equivalent viscous damping).

Output: 21 response variables, as a function of frequency, option of Calcomp (or equivalent) plots of Nyquist diagram, Power Spectral Density plots, and time-domain plots.

Software Operation: Batch

Hardware: Programmed for IBM 370/168. Requires 194 bytes of memory.

Usage: Developed by and for use in Truck Design Optimization Program (TDOP).

Typical Running Time: 6 to 9 minutes of CPU time for execution for each simulation.

Availability: Author.

Quasilinear 9 DOF Freight Car Model

Categories: Hunting, lateral stability, limit cycles, quasilinearization, freight car dynamics.

Descriptive Program Title: Quasilinear 9 DOF Freight Car Model

Authors: N. K. Cooperrider

Department of Mechanical Engineering

Arizona State University

Tempe, AZ 85292

J. K. Hedrick

Department of Mechanical Engineering

Massachusetts Institute of Technology

Cambridge, MA

Maintenance: Authors

Date: 1977

Capability: Describing function approximations to system geometries and suspension nonlinearities. Computes existence and stability characteristics of limit cycle oscillations. Can examine dry friction, flanging, nonlinear creep and nonconical wheel geometry effects.

Method: Iterations on vehicle speed and limit cycle frequency for a specified amplitude of wheelset motion to arrive at eigenvalues/eigenvectors for limit cycle condition (Ref. [12, 13]).

Programming Language: FORTRAN

Documentation: Instructions presented in Ref. [12].

Input: Mass, damping and stiffness characteristics, physical dimensions, describing functions for nonlinearities, range of vehicle speeds and amplitudes of motion.

Output: Tabularized describing function data, amplitudes, speed and frequency of limit cycles.

Software Operation: Batch

Hardware: Programmed for UNIVAC 1110.

Usage: Program was developed under Contracts DOT-OS-40018 and DOT-TSC-902 to the Federal Railroad Administration and the Transportation Systems Center, respectively.

Typical Running Time: Unknown

Availability: Authors

COMPARATIVE EVALUATION OF PROGRAMS

A summary and comparison of the characteristics of the computer programs described in the previous section is presented in Table 2. Several of these characteristics are described in detail below.

Model Validation

Very few attempts have been made to validate rail vehicle stability models by matching model analytical with experimental results. For the most part, model validation has consisted of comparing model behavior to either qualitative rail vehicle behavior or to the behavior of other existing models. Because of the wide range of parameter values that may represent an actual rail vehicle, (due to the large variations that exist in wheel/rail contact force characteristics, wheel profile shapes, track conditions, effective stiffnesses and damping coefficients throughout the vehicle, etc.) combinations of parameters usually can be chosen to match the critical speed and the shape of the "hunting" mode. However, to more fully validate a rail vehicle stability model, it is necessary to match frequency and system damping characteristics, and shape of the "hunting" mode, as a function of the vehicle speed range (rather than at the critical speed only).

From the available documentation of the programs reviewed here, it appears that experimental data was used in a formula validation effort only for the CU/ASU models and the FDM model. For the FDM model [11], time-histories and output PSD's were used from test data on a refrigerator car to check the model performance. An experimental program was performed with an instrumented hopper car and parameter identification techniques were used with some success in an attempt to validate the CU/ASU model [14]. The results of these latter tests give a good indication of the problems which are encountered when attempting to validate rail vehicle models.

Time and Costs

Detailed time and cost data on several of the programs was not obtained. However, based on the nature of the computer methods, it appears that almost all of the eigenproblem-type programs should solve the system equations in under about 3 CPU minutes per simulation (one vehicle speed). The required computer time increases with the number of model degrees of freedom. Thus, there exists a trade-off between model detail and time/cost. The 25-DOF AAR/TTD Freight Car Model is the largest of models examined, and thus is expected to require the most computer time of the eigenproblem-type programs that were considered here. Of course, computer times are based on the specific computer characteristics, computer language characteristics, etc., and times would be expected to vary for a given program on different computers.

The FDM program requires the most time of the programs examined (based on available information). This is because the primary purpose of the program is to compute frequency response characteristics due to forced excitation. These computations generally require a longer computer execution time than the eigenproblem solution does for the same model.

Computer cost may be considered proportional to computer time.

Versatility

Of the "special features" listed in Table 2, the ability to model asymmetries is more important than the flexible car body feature, from a stability standpoint. This is supported by analyses conducted with the CU/ASU 17 DOF [15] and 23 DOF [4] models. The analyses indicated that the critical speed of hopper and flat car models was negligibly affected by the car body lateral and torsional bending stiffness, while the existence of wheel/rail profile asymmetries can have a dramatic effect on stability.

Thus, from the standpoint of the range of asymmetries that can be modeled, the FDM program appears to be the most versatile, followed closely by the CU/ASU 17 DOF program. In terms of the range of truck types that can be modeled, the CU/ASU 17, 19, and 23 DOF models, and the AAR/TTD freight and locomotive models are most versatile. It should be noted that the DYNALYST II program offers the most overall versatility in terms of general programming capability. That is, the program can accept the user's equations of motion for a variety of vehicle models. However, the preprogrammed models provided by DYNALYST II are not as versatile as the models mentioned above.

The 9 DOF Quasilinear Program provides the most versatility for roller bearing freight car models, since it provides the most accurate depictions of nonlinear effects such as wheel/rail geometry and dry friction, of the models listed in Table 2.

Plot options in various forms are provided for the DYNALYST II, AAR/TTD and FDM models.

Documentation

The most complete and usable documentation is provided for the DYNALYST II, AAR/TTD and FDM models. The documentation for most of the other models consists of (1) presentation and/or derivation of the equations of motion, (2) detailed schematics of the models, and/or (3) program listings and general discussions of the program capabilities and usage. User's manuals for some of the programs are forthcoming.

CONCLUSIONS

Due to the wide range of rail vehicle types and operating conditions which exist, and the specialized needs of the program users, it is inappropriate to rank the computer programs in terms of performance. Each program offers features that may make it a suitable choice of a given user.

There is a definite need for the development of test programs and analytical methods for the accurate validation of rail vehicle models in general. Until then, many existing computer programs may be suitable only for predicting qualitative trends in vehicle behavior. These efforts will help to clearly establish the range of validity of linear and quasilinear models for evaluating rail vehicle lateral stability.

Table 2 Summary and Comparison of Digital Programs for Rail Wheel Lateral Stability Analysis

Program Name	Model Class				Domain		Vehicle Class		
	Linear	Quasilinear	Nonlinear	Time	Frequency	Freight	Passenger	6 Axle Locomotive	Unconventional
DYNALYST II	X					X	(4)	X	(4)
TRKHNT II	X				X	---	X	---	X
CARHNT II	X				X	---	X	---	---
CU/ASU 9-DOF	X				X	X	---	---	---
CU/ASU 17-DOF	X				X	X	X	---	X
CU/ASU 15-DOF	X				X	X	X	---	X
CU/ASU 23-DOF	X				X	X	X	---	X
AAR/TTD Freight Car Model	X				X	X	X	---	X
AAR/TTD Locomotive Model	X				X	---	X	X ⁽²⁾	---
FDM	X				X	X	---	---	---
9-DOF Quasilinear Model		X			X	X	---	---	---

Table 2 (Cont.)

Program Name	Special Features		DOF	Stability Data		Plot Option	Time, per Simulation, sec.	User's Manual	Other Documentation
	Flexible Car Body	Asymmetric		Eigen Problem Solution (Direct)	Manual Reduction				
DYNALYST II	(4)	(4)	8, 14	X		X	60	X	X
TRKHNT II	---	---	9	X		---	10	---	X
CARHNT II	---	---	21	X		---	30	---	X
CU/ASU 9-DOF	---	---	9	X		---	---		X
CU/ASU 17-DOF	X	X	17	X		---	---		X
CU/ASU 15-DOF	X	---	19	X		---	---		X
CU/ASU 23-DOF	X	---	23	X		---	---		X
AAR/TTD Freight Car Model	---	---	25	X		X	171- 184	X	X
AAR/TTD Locomotive Model	---	---	2, 7, 9 17, 21	X		X	90- 100	X	X
FDM	X	X	13		(3)	X	360- 540	X	X
9-DOF Quasilinear Model	---	---	9	X	---	---	---	---	X

- (1) Most passenger car truck models can also depict 4-axle locomotive/trucks.
- (2) Also depicts 4-axle locomotive.
- (3) Output is Nyquist diagram.
- (4) General program can depict rail vehicles other than passenger and 4-axle locomotive types, with up to 25-DOF flexible car bodies and asymmetries.

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2.3 CURVING DYNAMICS MODELS

INTRODUCTION

When a train negotiates a curve, significant lateral forces against the inner or outer rail may result. These are due in part to the buff and draft forces set up by operation over an irregular path; such "train action" forces are discussed elsewhere in this volume. Modifying these are other forces developed by the individual cars, which are attributable to kinematic accommodation of profiled wheelsets and to imbalance between gravitational and centrifugal forces. This latter group of curving forces is the subject of the analyses considered in this chapter.

It is evident after a little reflection that the net force and moment applied by the track to a car under steady conditions can be easily determined given the magnitude and direction of coupler and other external forces. A more microscopic view, however, is needed to calculate the distribution and dynamic variation of these forces. A car may derail due to a high total lateral load, but a high load on one wheel -- possibly of short duration -- can have the same effect. Curving models are thus central to studies of safety. They are also used to predict wear, which correlates with slip and which is a significant economic problem in curving territory.

MODELS

Degrees of Freedom

The choice of degrees of freedom for use in a curving analysis depends on the vehicle in question and the range of conditions being studied. A rigid carbody is sufficient for virtually all applications. Lateral and yaw carbody freedom are usually required, plus roll if significantly imbalanced operation is to be treated; a half carbody with fixed (generally nonzero) yaw has been used successfully.

Passenger and locomotive trucks may be reasonably treated as rigid in plan, with yaw and lateral freedom only. North American three-piece freight trucks, on the other hand, require at least three degrees of freedom (lateral, yaw, and warp) for adequate treatment. Additional wheelset degrees of freedom (i.e., primary suspensions to truck frame) are included only if high-frequency vibration and impact are to be modeled.

Nonlinearities

Nonlinearities of three main types appear in curving models: suspension elements (friction, slack, hardening springs, etc.); creep force relationships (formulations such as Kalker's [1] and Johnson's [2]); and wheel-rail contact geometry (from simple dead-band-spring flange representations through detailed constraint analysis). All, none, or some of these effects may be present in a given model.

Track Representation

At a minimum, the track must be represented by a radius of curvature and a super-elevation (which may be set implicitly to zero if desired). Quasi-steady and dynamic analyses allow these to be specified as functions of position in the curve. Track roughness, expressed as variations in gage, crosslevel, alignment, and superelevation which are superimposed on the curve, are sometimes allowed. One important use of track irregularities is to investigate vehicle response to high rail misalignment during negotiation of a curve above balance speed.

Most models assume that this geometry applies to a pair of rigid rails. Track compliance is introduced when it is important to reproduce the details of wheel-rail transients and impacts, since the rigid rail assumption predicts unrealistically high forces. In all cases known to the author, track compliance is modeled (if at all) as a set of springs acting at each wheel; crosscoupling through the track among the several wheelsets is not considered. Since the effect of lateral track compliance is insignificant while the wheel is running on its tread, a common practice is to model the rail as a rigid geometric curve, and to add a stiff lateral spring with a deadband to represent the stiffness after flange contact.

SOLUTION METHODS

Domain

It is useful to refer to three "domains" in which curving problems can be posed:

1. Steady -- Curving is assumed to continue indefinitely at a constant radius and speed; all vehicle components move in strictly circular paths. If curvature or imbalance varies through a curve, the vehicle adapts instantaneously to each condition.
2. Quasi-Steady -- A general curve is traversed, starting from arbitrary initial conditions, but acceleration of the vehicle is ignored. This is equivalent to neglecting the vehicle inertia -- the resulting response is kinematically determined.
3. Dynamic or Time Domain -- The full dynamic equations of vehicle motion are used to analyze response to arbitrary track input. The analysis is typically by simulation (time domain), but other methods are possible.

The choice of domain has a clear effect on the cost of solution. For an equivalent system model, going from dynamic to quasi-steady solution reduces the number of dynamic equations to be solved (e.g., integrated) by half; they are replaced by algebraic constraint equations. Similarly, the steady-state assumption allows one to replace the remaining dynamic equations with the same number of static algebraic equations, which need be solved at only one instant of time. It should be noted, however, that the complexity involved in solving a set of

nonlinear algebraic equations is typically greater than in integrating the corresponding dynamic equations.

Friction Center Method

The friction center method was developed [3,4] to analyze steady curving of stiff trucks on curvatures sufficiently high that guidance is by flange contact, with at least some wheels slipping. Under the steady-state assumption, all truck components are moving in uniform circular arcs. The rigidity of the truck then makes it easy to calculate the magnitude and direction of tread slip at each wheel. (These four slip velocities are tangent to circles about a common center, whence the name of the method.) Tread friction forces, which act opposite to slip velocities, are thus determined. Flange forces, acting parallel to the axles, can then be calculated from the requirement of lateral force and yaw moment balance. The remaining longitudinal force resultant is finally balanced by varying the assumed location of the friction center.

The advantage of the friction center method is that it reduces the problem to be solved to a single-dimensional search for the friction center location along the truck centerline. The concept has been extended to flexible trucks [5] and to transient analysis [6].

Desirable Features

This section touches briefly on several of the more desirable features to be sought in computer programs for curving analysis. It goes without saying that correctness, efficiency, readable source code and documentation, and user-oriented input and output are helpful.

Realistic Wheel-Rail Profile

A simple analysis of curve negotiation for 1:20 conical tapered wheels will indicate that flange contact will occur on quite modest curves (the order of 2 degrees) even in the absence of imbalance. For this reason, it is essential that curving models incorporate more than a simple cone representation for wheel-rail geometry. A conical tread plus some abrupt flange action beyond a specified clearance is appropriate. The most widely used representation of this kind treats the rail as a stiff lateral spring acting against the wheel. Although individual implementations vary, two main objections can be raised concerning the rail spring model: first, that it does not adequately represent the abrupt change in force due to spin creep and reorientation of the normal load vector; and second, that it does not give rise to a sudden longitudinal force as a result of flange slippage. Either effect may give rise to unrealistically low forces and sluggish response.

Some programs use very detailed representations of wheel-rail contact geometry, based either on polynomial approximations or on arbitrary measured data. An intermediate approach is to use simplified relationships for wheel-rail force which, being based on detailed theory, give generally correct relationships among displacement, angle of attack, and forces.

Realistic Creep Relations

Because of the high creep rates associated with flanging in curves (especially transient flanging), a simple linear relationship between creepage and creep force is undesirable. At a minimum, the creep force should be limited to the value given by the coefficient of sliding friction. Other approximations to the creep characteristic can be used (e.g., those of Johnson and Levi-Chartet, [7]) but more important than the exact shape of the curve is that combined lateral and longitudinal creepage be properly accounted for. Kalker's complete theory [1] does this, but is seldom incorporated directly in curving analyses. An alternative adopted by Law and Cooperrider involves adjusting the individually calculated creep forces according to the total vector creepage.

Suspension Nonlinearities

It is usual for a vehicle negotiating a curve to be in a region of its suspension characteristics which, if not locally nonlinear, is at least different from what would be predicted based on "centered" measurements: slack is taken up, multiple rate springs are compressed, and friction is significant. For this reason, nonlinear characteristics should be modeled or otherwise taken into account (for example, by re-linearizing about the new operating condition).

Coupler Forces

A vehicle rarely negotiates a curve in isolation, and the coupler forces arising from train action very strongly affect curving behavior. It should be possible at least to specify constant coupler forces and angles at each end of the car, and preferably to input these quantities as a function of time (obtained, for example, from a train action simulation).

Efficient Solution Methods

For high-order nonlinear dynamic problems, consideration should be given to efficient integration techniques. Rail vehicle models are mathematically "stiff" -- i.e., their characteristic frequencies are widely spaced -- and this property contributes to very expensive simulations. Techniques to reduce this cost, such as variable-step and multiple-step integration routines, should be explored. The same comment applies to methods for solution of sets of algebraic equations.

CURVING ANALYSES AND PROGRAMS

Table 1 lists the 20 methods for curving analysis which are summarized below. Two of these are reports of analytical results rather than computer programs, but are included for completeness.

TABLE 1

SUMMARY OF CURVING ANALYSES

Sequence Number	Program Name	Source
1	Flexible Truck Steering Anal.	Newl
2	Side Thrust in Curves	JNR
3	SSCUR2: 2 Axle Steady Curving	BCL
4	2 Axle Steady Curve Neg.	L&C
5	Nonlinear Steady Curving, 9-DOF	L&C
6	Full Car Steady Curving	BCL
7	Full Car Steady Curving	L&C
8	Steady Curving Model, 17-DOF	L&C
9	SSCUR3: 3 Axle Loco. Curving	BCL
10	Quasi-Static Curve Neg.	TSC
11	RTCN: 2,3,4 Axle Rigid Truck	TTD
12	Half Car Curve Entry	BCL
13	Half Car Curve Entry	L&C
14	Freight Car Curving	TTD
15	Dynamic Locomotive Curving	TTD
16	Locomotive and Car Curving	TTD
17	CURVLOCO: 6 Axle Loco. Curving	L&C
18	RVDCADET.2: Freight Car Covariance	TASC
19	SSCURVE15: Linear Steady Curving, 15 DOF	MIT
20	Nonlinear Steady Curving, 6-DOF	MIT

Components	Type Vehicle	Domain	Deg. of Freedom	Method	Linear/Nonlinear	Available?	Documentation?
Trk	Idlz	Stdy	4	Alg	Lin	No	Yes
Hveh	Idlz	Stdy	4	Alg	Non	No	Yes
Trk	Psgr	Stdy	7	Alg	Non	Yes	Soon
Veh	Idlz	Stdy	7	Alg	Non	Yes	No
Veh	Frt	Stdy	9	Alg	Non	Yes	No
Veh	Psgr	Stdy	11	Alg	Non	No	No
Veh	Psgr	Stdy	11	Alg	Non	?	No
Veh	Frt	Stdy	17	Alg	Non	Yes	No
Trk	Loco	Stdy	9	Alg	Non	No	No
Trk	Idlz	Q-st	4	Int	Non	Yes	Yes
Trk	Loco	Q-st	10	Fctr	Non	Yes	Yes
Hveh	Psgr	Dyn	9	Int	Non	No	No
Hveh	Psgr	Dyn	9	Int	Non	?	No
Veh	Frt	Dyn	43	Int	Non	Soon	Soon
Veh	Loco	Dyn	59	Int	Non	Soon	Soon
2Veh	Loco	Dyn	?	Int	Non	No	No
Veh	Loco	Dyn	21	Int	Non	Yes	Yes
Veh	Frt	Dyn	14	Int	Non	No	No
Veh	Psgr	Stdy	15	Alg	Lin	Yes	Yes
Veh	Psgr	Stdy	6	Alg	Non	Yes	No

TABLE 1 (continued)

List Of Abbreviations

Newl	-	Newland, Sheffield University
JNR	-	Japanese National Railways
BCL	-	Battelle Columbus Laboratories
L&C	-	Law and Cooperrider
TSC	-	Transportation Systems Center
TTD	-	Track-Train Dynamics Program
TASC	-	The Analytic Sciences Corporation
MIT	-	Massachusetts Institute of Technology
Trk	-	Truck
Hveh	-	Half Vehicle
Veh	-	Vehicle
2Veh	-	Two Coupled Vehicles
Idlz	-	Idealized
Psgr	-	Passenger
Frt	-	Freight
Loco	-	Locomotive
Stdy	-	Steady
Q-st	-	Quasi-Steady
Dyn	-	Dynamic
Alg	-	Algebraic
Int	-	Integration
Fctr	-	Friction Center (algebraic)
Lin	-	Linear
Non	-	Nonlinear

Sources

Computer programs are available from several organizations and individuals currently active in the field. With the exception of Track-Train Dynamics, these programs are not intended for formal distribution; the people named below can, however, assist potential users with their inquiries.

Track-Train Dynamics (TTD)

Closely affiliated with the Association of American Railroads, TTD develops programs for general industry use. They are provided as complete, ready-to-run packages including source and object files, test data, and full documentation. The programs conform to good professional software standards. For availability and technical information, contact:

Mr. J. G. Britten
AAR Technical Center
3140 South Federal Street
Chicago, Illinois 60616

or

Dr. V. K. Garg
Track-Train Dynamics
3140 South Federal Street
Chicago, Illinois 60616
(312) 567-3596

Battelle Columbus Laboratories (BCL)

Battelle has developed a number of programs for internal use. Most are considered proprietary, but some were developed under contract to DOT and can be obtained with DOT release. Documentation is not generally available outside BCL. Contact:

Mr. George Doyle
Battelle Columbus Laboratories
505 King Avenue
Columbus, Ohio 43201
(614) 424-6424

Law and Cooperrider

Professors Neil Cooperrider and Harry Law, together with their students, have collaborated in the development of a large number of computer programs for DOT. These tend to include detailed wheel-rail geometry, a good approximate creep relationship, and careful kinematic analysis. Documentation of some programs is available as DOT reports, but does not exist for most curving programs. Contact:

Professor N. K. Cooperrider
Mechanical Engineering Faculty
Arizona State University
Tempe, Arizona 85281
(602) 965-3797

or

Professor E. H. Law
304 Riggs Hall
Department of Mechanical Engineering
Clemson University
Clemson, South Carolina 29631
(803) 656-3294

Transportation Systems Center (TSC)

TSC staff members have developed analysis programs in-house, and have also obtained and modified programs from other sources. Contact:

Dr. Herbert Weinstock
DTS-744
Transportation Systems Center
Kendall Square
Cambridge, Massachusetts 02142
(617) 494-2459

The Analytic Sciences Corporation (TASC)

TASC has developed a package of statistically-oriented routines which incorporates curving among its inputs. In addition, it maintains a diverse library of computer programs from other sources. This work is under contract to TSC. Documentation will be available in 1980. Contact:

Dr. Fred Blader
The Analytic Sciences Corporation
6 Jacob Way
Reading, Massachusetts 01867
(617) 944-6850

Massachusetts Institute of Technology (MIT)

Ongoing work in the Department of Mechanical Engineering at MIT has led to a number of useful computer programs, some of which are available with documentation. Contact:

Professor David N. Wormley
Room 3-346
Massachusetts Institute of Technology
Cambridge, Massachusetts 02139
(617) 253-2246

Program Summaries

This section gives more detailed information on the programs in Table 1. For an overview of methods for curving analysis, see the paper by Perlman [8]. An excellent survey of computer tools for all aspects of rail vehicle dynamics is given in Ref. [9].

FLEXIBLE TRUCK STEERING ANALYSIS

Category: Curving, analysis, linear
Sequence Number: 1
Program Title: Flexible Truck Steering Analysis
Author: Newland: Sheffield University, England
Maintenance: N.A.
Date: 1969
Components Modeled: Truck
Type of Vehicle: Idealized
Domain: Steady
Degrees of Freedom: 4
Method: Algebraic
Linear/Nonlinear: Linear
Creep/Friction Model: Linear
Wheel/Rail Profile: Conical + Flange
Coupler Forces: Yes (truck)
Limitations and Restrictions: Analytical method only.
Programming Language: N.A.
Documentation: ASME Paper No. 69-RR-5
Software Operation: N.A.
Hardware: N.A.
Usage: N.A.
Availability: Published Paper

SIDE THRUST OF WHEELS IN CURVES

Category: Curving, analysis, nonlinear, half-vehicle, steady
Sequence Number: 2
Program Title: Side Thrust of Wheels in Curves
Author: Kuneida: Japanese National Railways
Maintenance: N.A.
Date: 1970
Components Modeled: Half Car
Type of Vehicle: Idealized
Domain: Steady
Degrees of Freedom: 4
Method: Algebraic
Linear/Nonlinear: Nonlinear
Creep/Friction Model: Linear
Wheel/Rail Profile: Conical + Flange
Coupler Forces: No
Limitations and Restrictions: Analytical method only.
Programming Language: N.A.
Software Operation: N.A.
Hardware: N.A.
Usage: N.A.
Availability: Published Paper

TWO AXLE STEADY CURVING (SSCUR2)

Category: Curving, nonlinear, vehicle, steady
Sequence Number: 3
Program Title: SSCUR2: Two Axle Steady Curve Negotiation Model
Author: Battelle Columbus Laboratories
Maintenance: Same
Date: 1973
Components Modeled: Truck
Type of Vehicle: Passenger (Metroliner); Freight
Domain: Steady
Degrees of Freedom: 7
Method: Newland's (#1): Iterative Algebraic
Linear/Nonlinear: Nonlinear
Creep/Friction Model: Linear Kalker with Slip Limit
Wheel/Rail Profile: Conical + Flange
Coupler Forces: Yes (truck)
Other: Constant Centerplate Torque; Centrifugal Force
Limitations and Restrictions:
Programming Language: FORTRAN
Documentation: Not complete; forthcoming TSC report
Comments: Good
Input: Vehicle configuration, speed, truck loads
Output: Print: equations of motion, truck position, forces, L/V ratios
Software Operation: Batch
Hardware: CDC Cyber 73; 41,000 octal
Usage: BCL, TSC
Typical Running Time: 19 sec.
Availability: Available from TSC (H. Weinstock, 617-494-2459)
Remarks: Modified and documented under contract DOT-TSC-1051; Similar to #4.

TWO AXLE STEADY CURVING

Category: Curving, nonlinear, truck, steady
Sequence Number: 4
Program Title: Two Axle Vehicle Steady Curve Negotiation
Author: Law (Clemson University) & Cooperrider (Arizona State University)
Maintenance: Same
Date: ca. 1976
Components Modeled: Vehicle (or truck)
Type of Vehicle: Idealized, 2-axle
Domain: Steady
Degrees of Freedom: 7
Method: Iterative Algebraic
Linear/Nonlinear: Nonlinear
Creep/Friction Model: Linear Kalker with Slip Limit
Wheel/Rail Profile: Arbitrary
Coupler Forces: Yes
Other:
Limitations and Restrictions:
Programming Language: FORTRAN
Documentation: None
Comments:
Input:
Output:
Software Operation:

Hardware:
Usage:
Typical Running Time:
Availability: Clemson University (E. H. Law, 803-656-3294): Source Tape
Remarks: Similar to #3

NONLINEAR STEADY CURVING

Category: Curving, nonlinear, freight car, steady
Sequence Number: 5
Program Title: Nonlinear Steady Curving (9-DOF)
Author: Law (Clemson University) & Cooperrider (Arizona State University)
Maintenance: Same
Date:
Components Modeled: Vehicle
Type of Vehicle: Freight
Domain: Steady
Degrees of Freedom: 9
Method: Iterative Algebraic
Linear/Nonlinear: Nonlinear
Creep/Friction Model: Linear Kalker with Slip Limit
Wheel/Rail Profile: Arbitrary
Coupler Forces: Yes
Other: Three-piece trucks treated as parallelograms
Limitations and Restrictions: Geometry relations from preprocessor
Programming Language: FORTRAN
Documentation: None
Comments:
Input: Card Image: vehicle and track data
Output: Print, Plot: slip and flange forces, contact points, vehicle position
Software Operation: Batch
Hardware: IBM 370
Usage: About 4 users
Typical Running Time:
Availability: Clemson University (E. H. Law, 803-656-3294): Source Tape

NONLINEAR FULL-CAR CURVING

Category: Curving, nonlinear, passenger car, steady
Sequence Number: 6
Program Title: Nonlinear Full-Car Steady Curving (11-DOF)
Author: Battelle Columbus Laboratories
Maintenance: Same
Date:
Components Modeled: Vehicle
Type of Vehicle: Passenger (Metroliner)
Domain: Steady
Degrees of Freedom: 11
Method: Iterative Algebraic
Linear/Nonlinear: Nonlinear
Creep/Friction Model: Linear Kalker with Slip Limit
Wheel/Rail Profile: Arbitrary
Coupler Forces: Yes

Other:

Limitations and Restrictions:

Programming Language: FORTRAN

Documentation: None

Comments:

Input: Card Image: vehicle and track data

Data File: wheel-rail relationships

Print: vehicle position, forces

Software Operation: Batch

Hardware:

Usage: BCL only

Typical Running Time:

Availability: Restricted

Remarks: Similar to #7

NONLINEAR FULL-CAR CURVING

Category: Curving, nonlinear, passenger car, steady

Sequence Number: 7

Program Title: Nonlinear Full-Car Steady Curving

Author: Law (Clemson University) & Cooperrider (Arizona State University)

Maintenance: Same

Date:

Components Modeled: Vehicle

Type of Vehicle: Passenger (Metroliner)

Domain: Steady

Degrees of Freedom: 11

Method: Iterative Algebraic

Linear/Nonlinear: Nonlinear

Creep/Friction Model: Linear Kalker with Slip Limit (extension may exist)

Wheel/Rail Profile: Arbitrary

Coupler Forces: Yes

Other:

Limitations and Restrictions: Geometry relations from preprocessor

Programming Language: FORTRAN

Documentation: None

Comments:

Input: Card Image: vehicle and track data

Data File: wheel-rail relationships

Output: Print: vehicle location, forces

Software Operation: Batch

Hardware: IBM 370

Usage: About 4 users

Typical Running Time:

Availability: Clemson University: (E. H. Law, 803-656-3294): Source Tape

Remarks: Similar to #6. Said to have been used to model freight car also.

NONLINEAR STEADY CURVING

Category: Curving, nonlinear, freight car, steady

Sequence Number: 8

Program Title: Nonlinear Steady Curving Model (17-DOF)

Author: Law (Clemson University) & Cooperrider (Arizona State University)

Maintenance: Same

Date:

Components Modeled: Vehicle
Type of Vehicle: Freight
Domain: Steady
Degrees of Freedom: 17
Method: Iterative Algebraic
Linear/Nonlinear: Nonlinear
Creep/Friction Model: Linear Kalker with Slip Limit
Wheel/Rail Profile: Arbitrary
Coupler Forces: Yes
Other:
Limitations and Restrictions:
Programming Language: FORTRAN
Documentation: None
Comments:
Input: Card Image: vehicle and track data
Data File: wheel-rail relationships
Output: Print and Plot: vehicle position, creep and flange forces
Software Operation: Batch
Hardware: IBM 370
Usage: About 4 users
Typical Running Time:
Availability: Clemson Univeristy (E. H. Law, 803-656-3294): Source Tape

LOCOMOTIVE STEADY CURVING (SSCUR3)

Category: Curving, nonlinear, locomotive, steady
Sequence Number: 9
Program Title: SSCUR3: Three Axle Locomotive Truck Steady Curving Model
Author: Battelle Columbus Laboratories
Maintenance: Same
Date:
Components Modeled: Truck
Type of Vehicle: Locomotive
Domain: Steady
Degrees of Freedom: 9
Method: Newland's (#1): Iterative Algebraic
Linear/Nonlinear: Nonlinear
Creep/Friction Model: Linear Kalker with Slip Limit
Wheel/Rail Profile: Conical + Flange
Coupler Forces: Yes (truck)
Other: Constant Centerplate Torque; Centrifugal Force
Limitations and Restrictions:
Programming Language: FORTRAN
Documentation: Not Complete
Comments: Good
Input: Vehicle configuration, speed, truck loads
Output: Print: equations of motion, truck position, forces, L/V ratios
Software Operation: Batch
Hardware: CDC Cyber 73
Usage: BCL only
Typical Running Time:
Availability: Restricted
Remarks: Adapted from #3

QUASI-STATIC CURVING

Category: Curving, nonlinear, truck, quasi-steady
Sequence Number: 10
Program Title: Quasi-Static Curve Negotiation Model
Author: Perlman & Weinstock: TSC
Maintenance: Same
Date: 1975
Components Modeled: Truck
Type of Vehicle: Idealized
Domain: Quasi-Steady
Degrees of Freedom: 4
Method: Integration
Linear/Nonlinear: Nonlinear (linear suspension)
Creep/Friction Model: Cubic Approximation (Johnson, Ref. [2])
Wheel/Rail Profile: Polynomial
Coupler Forces: No
Other: Knife-Edge Rails
Limitations and Restrictions:
Programming Language: FORTRAN
Documentation: Interim Report No. FRA-ORPD-75-56
Comments:
Input:
Output:
Software Operation:
Hardware:
Usage:
Typical Running Time:
Availability: TSC (H. Weinstock, 617-494-2459)

RIGID TRUCK CURVE NEGOTIATION (RTCN)

Category: Curving, nonlinear, locomotive, quasi-steady
Sequence Number: 11
Program Title: RTCN: 2,3,4, Axle Rigid Truck Curve Negotiation Model
Author: Track-Train Dynamics
Maintenance: Same
Date:
Components Modeled: Truck
Type of Vehicle: Locomotive
Domain: Quasi-Steady
Degrees of Freedom: 10 (lateral and yaw, frame and wheelsets)
Method: Friction Center (iterative algebraic)
Linear/Nonlinear: Nonlinear
Creep/Friction Model: Linear + Slip Friction
Wheel/Rail Profile: Cylindrical + Flange
Coupler Forces: Yes (truck)
Other:
Limitations and Restrictions:
Programming Language: FORTRAN
Documentation: Tech. Rept. (R-206), Pgm. Rept. (R-205), User's (R-204)
Comments: Good
Input: Card: truck data, traction/braking, buff/draft, curvature
Output: Print: flange and tread forces, friction center location
Software Operation: Batch
Hardware: IBM 370; 600 K byte
Usage: Significant; about 10 users

Typical Running Time: 10 sec (3031), single case
Availability: Readily available from TTD: source, object, data tapes, and
documentation. J. G. Britten, AAR Technical Center, 3140 South Federal
Street. Chicago, Illinois 60616. \$50 tape, \$8 all documents.
Remarks: Outgrowth of GM-EMD model

NONLINEAR HALF CAR CURVE ENTRY

Category: Curving, nonlinear, passenger car
Sequence Number: 12
Program Title: Nonlinear Half Car Curve Entry Model
Author: Battelle Columbus Laboratories
Maintenance: Same
Date:
Components Modeled: Half Car
Type of Vehicle: Passenger (Metroliner)
Domain: Dynamic
Degrees of Freedom: 9
Method: Integration
Linear/Nonlinear: Nonlinear
Creep/Friction Model: Linear with Slip Limit
Wheel/Rail Profile:
Coupler Forces: Yes
Other:
Limitations and Restrictions:
Programming Language: FORTRAN
Documentation: None
Comments:
Input:
Output:
Software Operation: Batch
Hardware:
Usage: BCL ONLY
Typical Running Time:
Availability: Restricted
Remarks: Similar to #13

NONLINEAR HALF CAR CURVE ENTRY

Category: Curving, nonlinear, passenger car
Sequence Number: 13
Program Title: Nonlinear Half Car Curve Entry Model
Author: Law (Clemson University) & Cooperrider (Arizona State University)
Maintenance: Same
Date:
Components Modeled: Half Car
Type of Vehicle: Passenger
Domain: Dynamic
Degrees of Freedom: 9
Method: Integration
Linear/Nonlinear: Nonlinear
Creep/Friction Model: Extended Kalker (simplification with vector force limit)
Wheel/Rail Profile: Arbitrary
Coupler Forces: Yes
Other:

Limitations and Restrictions:

Programming Language: FORTRAN

Documentation: None

Comments:

Input: Card: vehicle and track data

Data file: wheel-rail relationships

Output: Print, plot: states and forces

Software Operation: Batch

Hardware: IBM 370

Usage: About 4 users

Typical Running Time:

Availability: Clemson University: (E. H. Law, 803-656-3294)

Remarks: Similar to #12

FREIGHT CAR CURVING

Category: Curving, freight car, nonlinear

Sequence Number: 14

Program Title: AAR Freight Car Curving Model

Author: Track-Train Dynamics

Maintenance: Same

Date: 1978

Components Modeled: Vehicle

Type of Vehicle: Freight

Domain: Dynamic

Degrees of Freedom: 43

Method: Integration

Linear/Nonlinear: Nonlinear

Creep/Friction Model: Nonlinear (Johnson)

Wheel/Rail Profile: Conical + Flange

Coupler Forces: Yes

Other: Track compliance in detail

Limitations and Restrictions: No carbody yaw. No super-elevation.

Programming Language: FORTRAN

Documentation: Not complete. See ASME Paper No. 76-WA/RT-14

Comments:

Input:

Output:

Software Operation:

Hardware:

Usage: Internal TTD and AAR plus about 2 others

Typical Running Time:

Availability: Restricted pending completion of documentation. Contact
J. G. Britten, AAR Technical Center, 3140 South Federal Street, Chicago,
Illinois 60626.

Remarks: Adapted from K. R. Smith's work at IIT.

LOCOMOTIVE CURVING

Category: Curving, locomotive, nonlinear

Sequence Number: 15

Program Title: AAR Dynamic Locomotive Curving Model

Author: Track-Train Dynamics

Maintenance: Same

Date: 1979

Components Modeled: Vehicle
Type of Vehicle: Locomotive (6 axle)
Domain: Dynamic
Degrees of Freedom: 59
Method: Integration
Linear/Nonlinear: Nonlinear
Creep/Friction Model: Linear
Wheel/Rail Profile: Conical + Flange
Coupler Forces:
Other:
Limitations and Restrictions:
Programming Language: FORTRAN
Documentation: Not complete
Comments:
Input:
Output: Print, plot: states, forces, L/V ratios
Software Operation: Batch
Hardware:
Usage: Internal TTD and AAR
Typical Running Time:
Availability: Restricted pending completion of documentation. Contact
J. G. Britten, AAR Technical Center, 3140 South Federal Street, Chicago,
Illinois 60616.

LOCOMOTIVE AND CAR CURVING

Category: Curving, nonlinear, locomotive
Sequence Number: 16
Program Title: AAR Dynamic Curving of a Locomotive and Car
Author: Track-Train Dynamics
Maintenance: Same
Date: 1979
Components Modeled: Locomotive + 1 car
Type of Vehicle: Locomotive, Passenger (baggage)
Domain: Dynamic
Degrees of Freedom:
Method: Integration
Linear/Nonlinear: Nonlinear
Creep/Friction Model: Linear
Wheel/Rail Profile: Conical + flange
Coupler Forces: Internal
Other:
Limitations and Restrictions:
Programming Language: FORTRAN
Documentation: None
Comments:
Input:
Output: Print, plot: states, forces, L/V ratios
Software Operation: Batch
Hardware:
Usage: Internal TTD and AAR
Typical Running Time:
Availability: Restricted

NONLINEAR LOCOMOTIVE CURVING (CURVLOCO)

Category: Curving, nonlinear, locomotive
Sequence Number: 17
Program Title: CURVLOCO: Nonlinear Six Axle Locomotive Curving Model
Author: Law (Clemson University) & Cooperrider (Arizona State University)
Maintenance: Same
Date: 1978
Components Modeled: Vehicle
Type of Vehicle: Locomotive (6 axle)
Domain: Dynamic
Degrees of Freedom: 21 plus 6 axle rotation variables
Method: Integration
Linear/Nonlinear: Nonlinear
Creep/Friction Model: Extended Kalker
Wheel/Rail Profile: Arbitrary
Coupler Forces: Yes
Other: Deterministic track geometry can be superimposed.
Limitations and Restrictions: Geometry relations from preprocessor
Programming Language: FORTRAN
Documentation: User's Manual (brief)
Comments: Good
Input: Card: vehicle and track data, creep data
Data file: wheel-rail relationships
Output: Print, plot: states, forces, L/V ratios
Software Operation: Batch
Hardware: IBM 370
Usage: Heavy use by about 4 users, with various modifications
Typical Running Time: 30 min. (3031)
Availability: Arizona State (N. K. Cooperrider, 602-965-3797): Source Tapes
and User's Manual
Remarks: Corrections and modifications appear occasionally from ASU or TSC

FREIGHT CAR COVARIANCE (RVDCADET)

Category: Curving, nonlinear, freight car, stochastic
Sequence Number: 18
Program Title: RVDCADET.2: Freight Car Covariance Analysis
Author: The Analytic Sciences Corporation
Maintenance: Same
Date: 1978
Components Modeled: Vehicle
Type of Vehicle: Freight
Domain: Dynamic; steady-state option
Degrees of Freedom: 14
Method: Integration of Quasi-Linearized System
Linear/Nonlinear: Nonlinear
Creep/Friction Model: Linear with slip limit
Wheel/Rail Profile: Implicit arbitrary, idealized
Coupler Forces: Yes
Other: Trucks treated as parallelograms. May be operated in deterministic
or stochastic mode.
Limitations and Restrictions: Multiplicative, piecewise-linear flange force
representations; must be extracted from separate analysis.
Programming Language: FORTRAN
Documentation: None; available in 1980
Comments: Good

Input: Card image: vehicle characteristics, track geometry, covariances
Output: Print, plot: states, forces (time history of statistics)
Software Operation: Batch
Hardware: IBM 370 (3031)
Usage: TASC only
Typical Running Time: 30 min. (stochastic), 10 min. (deterministic), 2 min.
(steady state)
Availability: Late 1980, from TASC or TSC. Contact Dr. Fred Blader, TASC.
(617-944-6850)
Remarks: Time varying curvature treated as yaw offset plus differential
velocity of rails.

LINEAR STEADY CURVING (SSCURVE15)

Category: Curving, linear, steady
Sequence Number: 19
Program Title: SSCURVE15: 15-DOF Linear Steady Curving Model
Author: Charles Bell: MIT
Maintenance: Same
Date: 1979
Components Modeled: Vehicle
Type of Vehicle: Passenger
Domain: Steady
Degrees of Freedom: 15
Method: Solution of simultaneous linear equations
Linear/Nonlinear: Linear
Creep/Friction Model: Linear
Wheel/Rail Profile: Conical; linearized stiffness
Coupler Force: No
Other: Generalized shear and bending stiffness among wheelsets
Programming Language: FORTRAN
Documentation: User's Manual
Comments:
Input: Vehicle characteristics, track geometry, flange clearance.
Output: Maximum curvature for flange-free curving
Software Operation: Batch
Hardware: DEC VAX
Usage: About 4 users
Typical Running Time: Less than 0.5 sec. per case
Availability: Contact Charles Bell, 3-351, MIT, Cambridge, MA 02139
(617) 253-3772: Source Tapes

NONLINEAR STEADY CURVING

Category: Curving, nonlinear, steady
Sequence Number: 20
Program Title: 6-DOF Nonlinear Steady Curving Model
Author: Charles Bell: MIT
Maintenance: Same
Date: 1980
Components Modeled: Vehicle
Type of Vehicle: Passenger
Domain: Steady
Degrees of Freedom
Method: Iterative algebraic

Linear/Nonlinear: Nonlinear
Creep/Friction Model: Linear
Wheel/Rail Profile: Conical tread; hard flange
Coupler Forces: No
Other: Generalized shear and bending stiffness among wheelsets
Programming Language: FORTRAN
Documentation: None
Comments:
Input: Vehicle characteristics, track geometry, flange clearance
Output: States, forces
Software Operation: Batch
Hardware: DEC VAX
Usage: MIT only
Typical Running Time: Less than 1 sec. per case
Availability: Contact Charles Bell, 3-351, MIT, Cambridge, MA 02139
(617-253-3772): Source Tape
Remarks: Extension of No. 19. Development continues.

SUMMARY

A number of analytical and computer methods exist to study the behavior of rail vehicles in curves. Of these, only the friction center method has achieved any degree of general acceptance; the technique is used in several of the programs reviewed here, and it has been widely used as a design tool. Newer methods for steady curving analysis, which employ more detailed representations of the geometric and creep relationships, exist but are not readily available and useful to the industry. The situation with regard to dynamic curving is even less settled, because there is as yet no model of transient wheel-rail interaction which is sufficiently comprehensive and well validated to be relied upon.

In general, curving models are not well validated by experimental results. Steady curving analyses yield qualitatively correct behavior but should not be treated as better than about 20% accurate in predicting individual wheel/rail forces. Dynamic curving models are also accurate as to overall low-frequency response; their prediction of high frequencies and impacts varies tremendously with the details of the model, however, and cannot be trusted. Unfortunately, it is just this impact regime which dominates safety and track deterioration. Dr. Garg of Track-Train Dynamics and Professor Sweet of Princeton University have recently presented some informal results which show encouraging correlation between analytical and test data (field and laboratory, respectively). Nevertheless, transient curving analysis remains an underdeveloped but important area.

ACKNOWLEDGEMENTS

In compiling this information, I was greatly helped by discussions with Messrs. Donald Ahlbeck (BCL), Charles Bell (MIT), Paul Berry (TASC), Neil Cooperrider (ASU), V. K. Garg (AAR/TTD), Harry Law (Clemson), Harvey Lee (TSC), Robert Prause (BCL), and Herbert Weinstock (TSC).

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2.4 WHEEL/RAIL CONTACT

INTRODUCTION

This section contains descriptions of the programs CONFORM AND CONTACT and of the programs Kalker's Simplified Theory and Kalker's Exact Theory. A summary of the recent Kalker code DUVOROL is also included. CONFORM AND CONTACT are programs which compute Hertzian and non-Hertzian contact stress fields. The other three codes apply to rolling contact problems including creep; of the three, DUVOROL appears to be the most highly developed.

2.4.1 CONFORM and CONTACT

CONFORM

Program Summary

Program Name: CONFORM

Categories (Keywords): Wheel-Rail interaction; contact stress; conformal contact; non-Hertzian contact; elasticity.

Descriptive Program Title: CONFORMal contact stress problems.

Authors: B. Paul and J. Hashemi, University of Pennsylvania

Availability: B. Paul

University of Pennsylvania

111 Towne Bldg./D3

Philadelphia, PA 19104

(215) 243-7191

or

National Technical Information Service
Springfield, VA 22151

Maintenance: B. Paul

Availability Dates: June 1978 from B. Paul
November 1979 (estimated) from NTIS

Capability: CONFORM (Conformal Contact of Two Elastic Bodies) is an all FORTRAN Computer program for the analysis of contact stress between two elastic bodies in conformal contact. It is used to find the pressure distribution between the two bodies, the boundary of contact patch, and the total load corresponding to a given depth of penetration.

This program is a generalization of a previous program (CONTACT) which was restricted to the case of counterformal contact. This new program CONFORM will treat counterformal as well as conformal cases.

Built into the program are specialized subroutines which enable the user to conveniently specify the surface profiles for railroad wheels and railheads. By reading dimensional information from conventional engineering drawings of wheels and rails, the user need not do any programming. For wheel and rail profiles (e.g., worn wheels) which consist of other than straight lines and circular arcs (associated with standard new wheels and rails), the user may provide his own subroutines for describing the wheel-rail geometry.

Descriptions of the program variables, input, output, and method of analysis are given. Instructions for problem modelling, preparation of input data, and solutions of sample problems, are included.

Method: The user supplies an initial estimate of the contact patch boundary associated with a given "rigid body approach δ ," and the program corrects the boundary by an iterative method, described in Refs. A6 and A7.

Limitations and Restrictions: The program may be used for either counterformal or conformal contact, but program CONTACT is more efficient for the simpler case of counterformal contact.

Programming Language: FORTRAN IV

Input: (a) Modulus of elasticity and Poisson's ratio for both bodies.
(b) Rigid body "approach" of the two bodies.
(c) Information on the (x,y) coordinates of a user supplied estimated contact boundary, and on the user-desired meshwork of rectangular cells which this estimated contact patch is to be divided into.
(d) The user must provide an initial estimated contact patch which the program will refine by an iterative procedure. To establish this initial contact boundary, for the case of railroad wheels and rails, two programs called MIDSEP and INTERPEN may be used before running CONFORM. Complete instructions (and listings) of these "preliminary programs" are included in the User's Manual for CONFORM.
(e) The initial separation (before deformation occurs) of neighboring points on each of the two surfaces must be calculated in a subordinate called INSEP. When using this standard version, the user needs only to supply numerical data on the sets of straight lines and circular arcs which describe the profiles of arbitrary (unworn) wheels and rails. The user must also indicate that point on the wheel and that point on the railhead which make initial contact as loading begins.

Output: Output includes a reprint of all input data. Then for each iteration,

the following output data is printed.

- (a) Coordinates of a set of points along the boundary of the current contact boundary.
- (b) A table of the contact pressures at a set of points within the contact patch.
- (c) The resultant force (and moment, if any) of the contact pressures if the pressure is positive throughout the contact patch.

Software Operation: Program is suitable for batch or time-sharing progress.
Hardware: Tested on UNIVAC 90/70 (using BG-4 compiler); requires 120K storage
Precision: Double precision

Capabilities: CONFORM determines the shape of the contact region, the distribution of contact pressure, and the resultant force, on the surfaces of the two elastic bodies in conformal contact, with a specified approach (rigid body displacement). Dimensioned for maximum of 100 field points, with a maximum of 20 along the x-axis. Dimensions may be modified by changing the first four DIMENSION cards, and data according to the instruction given by comment cards.

Number of cards: Approximately 318 (exclusive of comment cards; the current version of CONFORM contains 192 comment cards), plus 390 in different subroutines of LEQTF (LEQTF is a subroutine for solving linear equations; it is part of the IMSL Library), plus 258 in standard subprograms.

Documentation: A User's Manual. Ref. A5, is available.

Example Problem Solved

Figure 1 shows a cross section through a Metroliner wheel and a standard rail; the initial contact point C is on the throat of the flange at a point where both the wheel and the rail experience jump discontinuities in curvature. Note that the contact is highly conformal with the radii of curvature of wheel and rail differing by only 0.03 in. to the left of point C and by 0.003 in. to the right of point C.

For an assumed "approach" of the two bodies by 0.003 in., the initial estimated contact boundary (and the corresponding grid arrangement) predicted by the supplied preliminary program INTERPEN is shown in Fig. 2 (only the upper half is shown in Fig. 2, since the contact patch is symmetric about the horizontal axis).

When program CONFORM was utilized to iteratively refine the contact boundary, the outline of the contact patch converged to that shown in Fig. 3 (b). The corresponding pressure distribution along the axis of symmetry is shown in Fig. 3(a).

COUNTACT

Program Summary

Program Name: COUNTACT

Categories: Wheel-Rail interaction; contact stress; counterformal contact; non-Hertzian contact; elasticity.

Descriptive Program Title: COUNTERforman and CONTACT of two elastic bodies

Authors: B. Paul and J. Hashemi. University of Pennsylvania.

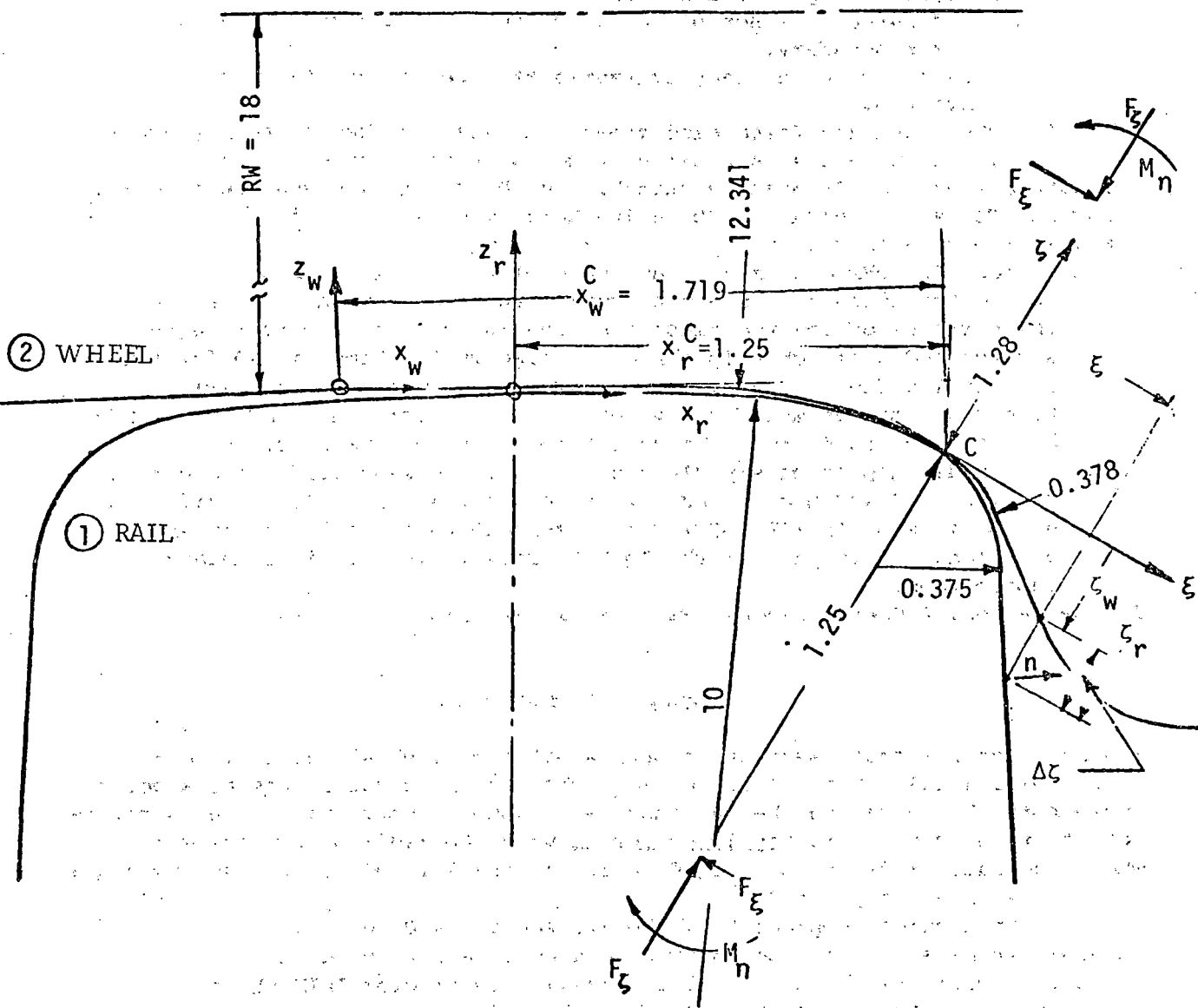


Fig. 1. Rail and wheel position, before deformation under applied load
 (x_w, z_w) wheel reference coordinate system
 (x_r, z_r) rail reference coordinate system
 (ξ, ζ) global coordinate system

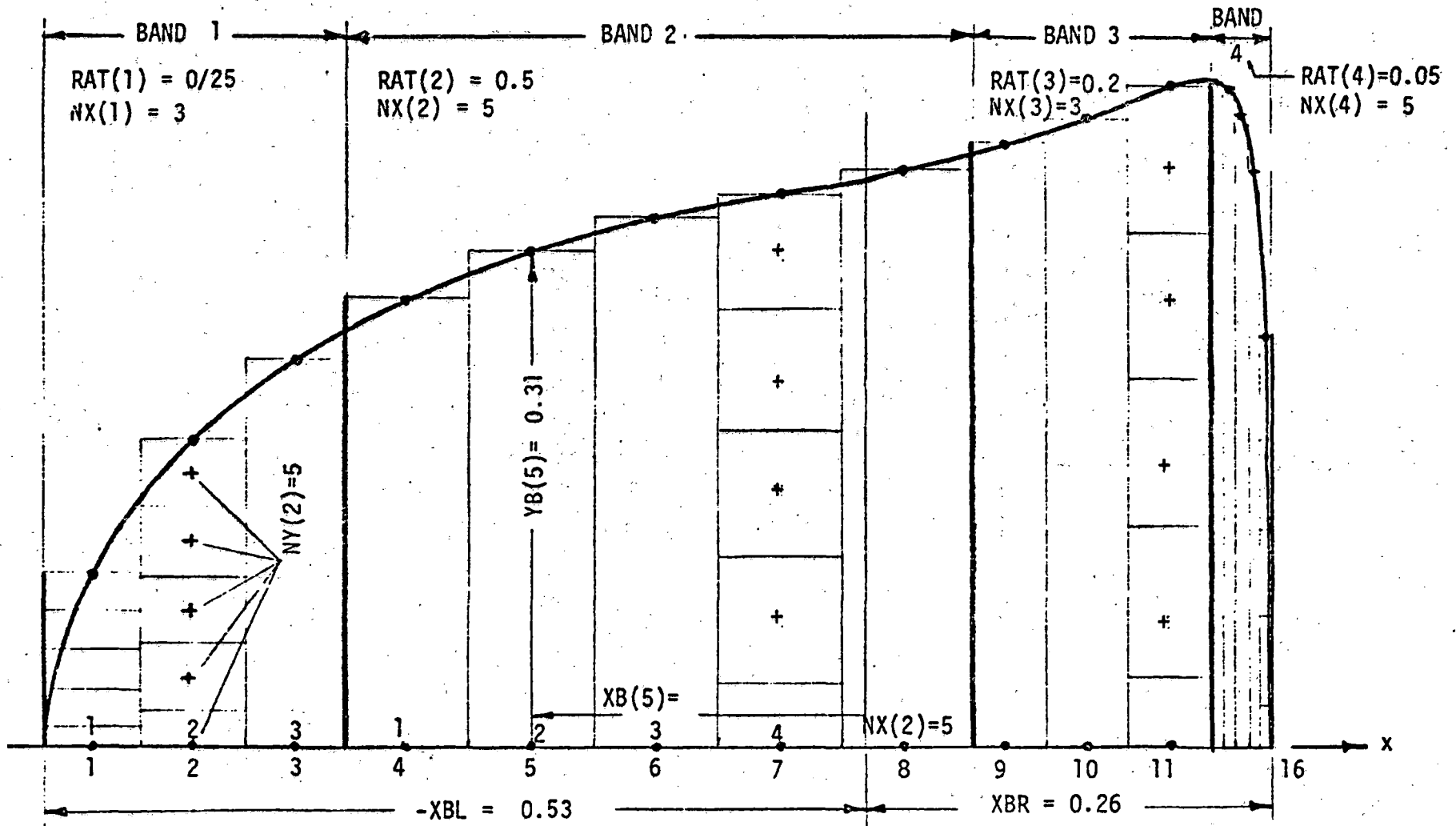


Fig. 2 Interpenetration curve used as initial candidate contact patch boundary, corresponding to Fig. 1, with $\delta = 0.003$ in. Curve is symmetric about x axis

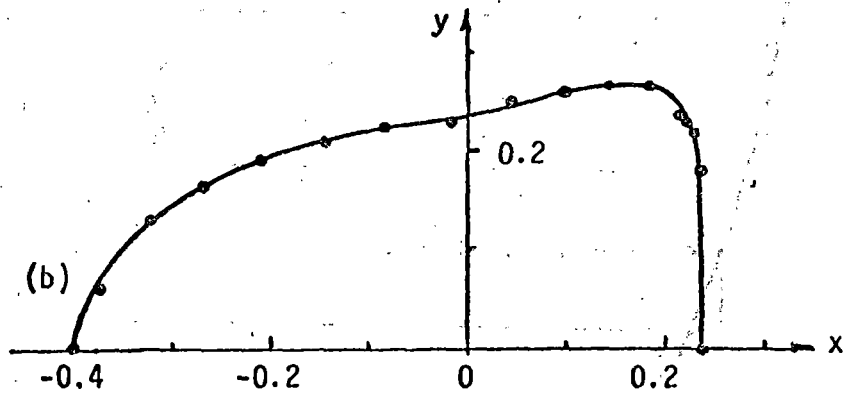
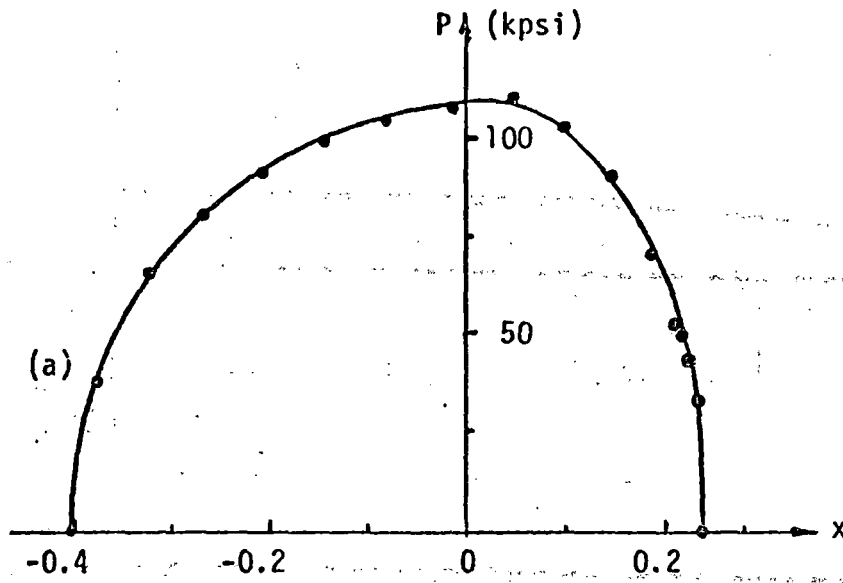


Fig.3 Example $\delta = 0.003''$
 (a) pressure distribution
 (b) contact patch (symmetric about x axis)

Availability: B. Paul
University of Pennsylvania
111 Towne Bldg./D3
Philadelphia, PA 19104
(215) 243-7191

or

National Technical Information Service
Springfield, VA 22151

Maintenance: B. Paul

Capability: COUNTACT (Counterformal Contact of Two Elastic Bodies) is an all FORTRAN computer program for the analysis of stress between two elastic bodies in counterformal contact. It is used to find the pressure distribution between the two bodies, the boundary of contact patch, and the total load corresponding to a given depth of penetration.

The program COUNTACT has two versions: COUNTACT-1 for those bodies with a contact patch having one axis of symmetry, and COUNTACT-2 for those bodies whose contact patch has two axes of symmetry.

Descriptions of the program variables, input, output, and method of analysis are given. Instructions for problem modelling, preparation of input data, and solutions of sample problems, are included. The general approach to writing a user supplied routine required by the program is discussed.

The program will treat both Hertzian cases (elliptical contact patches) and non-Hertzian cases (arbitrarily shaped contact patches), including situations where there is a jump discontinuity in the radii of curvature of the contacting bodies (such as in conventional unworn railroad wheels and railheads).

Method: The user supplies an initial estimate of the contact patch boundary associated with a given "rigid body approach δ ," and the program corrects the boundary by an iterative method, described in Ref. B3.

Limitations and Restrictions: The method used is valid when the contact patch dimensions are small compared to the smallest radii of curvature of the contacting surfaces. This will be true except for closely conforming bodies, such as a circular pin in a closely fitted hole.

Programming Language: FORTRAN IV.

Input: (a) Modulus of elasticity and Poisson's ratio for both bodies.

(b) Rigid body "approach" of the two bodies.

(c) Information on the (x,y) coordinates of a user supplied estimated contact boundary, and on the user desired meshwork of rectangular cells which this estimated contact patch is to be divided into.

(d) A user supplied subroutine which describes the initial separation $f(x,y)$ between points on the two surfaces (prior to deformation) having the same x and y coordinates.

Output: Output includes a reprint of all input data. Then, for each iteration, the following output data is printed:

(a) Coordinates of a set of points along the boundary of the current contact boundary.

(b) A table of contact pressures at a set of points within the contact patch.

(c) the resultant force (and moment, if any) of the contact pressures if the pressure is positive throughout the contact patch.

Software Operations: Program is suitable for batch or time sharing processing.

Machines: Tested on IBM 370/168 Computer (using FORTRAN G Compiler) and UNIVAC 90/70 (using BG-4 compiler)
Capabilities: Dimensioned for 100 field points, with a maximum of 20 along the x axis. These dimensions may be modified by changing the first three DIMENSION cards.
Number of Cards: Approximately 350, plus 390 in different subroutines of LEQTIF, plus a user supplied subroutine (typically containing about 15 cards).
Documentation: A User's Manual, Ref. A4, is available.

Example Problem Solved

Figure 4 shows a cross section through a Metroliner wheel and a standard rail which make initial contact at a point 0 where the railhead undergoes a jump in radius of curvature (from 1.25 in. to 10 in.). The contact patch predicted by program COUNTACT, as shown in Fig. 5, is very far from elliptic; hence, the problem is definitely non-Hertzian, although still conformal. The calculated pressure distribution, shown in Fig. 6, indicates a substantial pressure concentration. The complete input and output for this problem are described in the "User's Manual."

ACKNOWLEDGMENTS

The authors appreciate the support of the Federal Railroad Administration, U.S. Department of Transportation for supporting the development of this program.

LIST OF RELATED REPORTS AND PUBLICATIONS

A. FRA Technical Reports (Available from National Technical Information Service)

A1 Paul, B., "A Review of Rail-Wheel Contact Stress Problems," Technical Report No. 1, April 1975, FRA/ORD-76 141, PB 251238/AS, Contract DOT-OS-40093.

A2 Woodward, W., and Paul, B., "Contact Stresses for Closely Conforming Bodies - Application to Cylinders and Spheres," Technical Report No. 2, December 1976, DOT/TST/77-48, PB 271033/AS, Contract DOT-OS-40093.

A3 Paul, B., and Hashemi, J., "An Improved Numerical Method for Counterformal Contact Stress Problems," Technical Report No. 3, July 1977, FRA/ORD-78/26, Contract DOT-OS-60144. PB 286097/AS

A4 Paul, B., and Hashemi, J., "User's Manual for Program COUNTACT (COUNTERformal CONTACT stress problems)," Technical Report No. 4, September 1977, FRA/ORD-78/27, Contract DOT-OS-60144. PB 286097/AS.

A5 Paul, B., and Hashemi, J., "User's Manual for Program CONFORM (CONFORMal contact stresses between wheels and rails)," Technical Report No. 5, June 1978 FRA/ORD-78/40, Contract DOT-OS-60144, PB 288927/AS.

A6 Paul, B., and Hashemi, J., "Rail-Wheel Geometry Associated with Contact Stress Analysis," Technical Report No. 6, 1978, FRA/ORD-78/41, Contract DOT-OS-60144, (to be issued).

A7 Paul, B., and Hashemi, J., "Contact Stresses in Bodies with Arbitrary Geometry, Applications to Wheels and Rails," Technical Report No. 7, April 1979, FRA/ORD/79-23, Contract DOT-OS-60144.

A8 Paul, B., and Hashemi, J., "Numerical Determination of Contact Pressures Between Closely Conforming Wheels and Rails," Technical Report No. 8, July, 1979. Contract DOT-OS-60144, FRA/ORD-79/41.

B. Related Papers Published in Various Journals and Proceedings

B1 Singh, K. P., and Paul, B., "A Method for Solving Ill-Posed Integral Equation of the First Kind," Computer Methods in Applied Mechanics and Engineering, Vol. 2, 1973, 339-348.

B2 Singh, K. P., and Paul, B., "Numerical Solution of Non-Hertzian Elastic Contact Problems," Journal of Applied Mechanics, Vol. 41, Trans. of ASME, Series E, Vol. 96, June 1974, pp. 484-490.

B3 Singh, K. P., and Paul, B., "Stress Concentration in Crowned Rollers," Journal of Engineering for Industry, Trans. ASME, Series B. Vol. 97, No. 3, 1975, pp. 990-994.

B4 Paul, B., Singh, K. P., and Woodward, W., "Contact Stresses for Multiply-Connected Regions--The Case of Pitted Spheres," Proceedings of the Symposium on the Mechanics of Deformable Bodies, Delft University Press, 1975, pp. 264-281.

B5 Paul, B., "A Review of Rail-Wheel Contact Stress Problems," in Proceedings of Symposium on Railroad Track Mechanics, Pergamon Press, 1978, Ed. by A. Kerr, pp. 323-351. (Based on Ref. A1).

B6 Paul, B., and Hashemi, J., "An Improved Numerical Method for Counterformal Contact Stress Problems," in Computational Techniques for Interface Problems, AMD-Vol. 30, Ed. by K. C. Park and D. K. Gartlung, American Society of Mechanical Engineers, N.Y., 1978, pp. 165-180, (Same as Ref. A3).

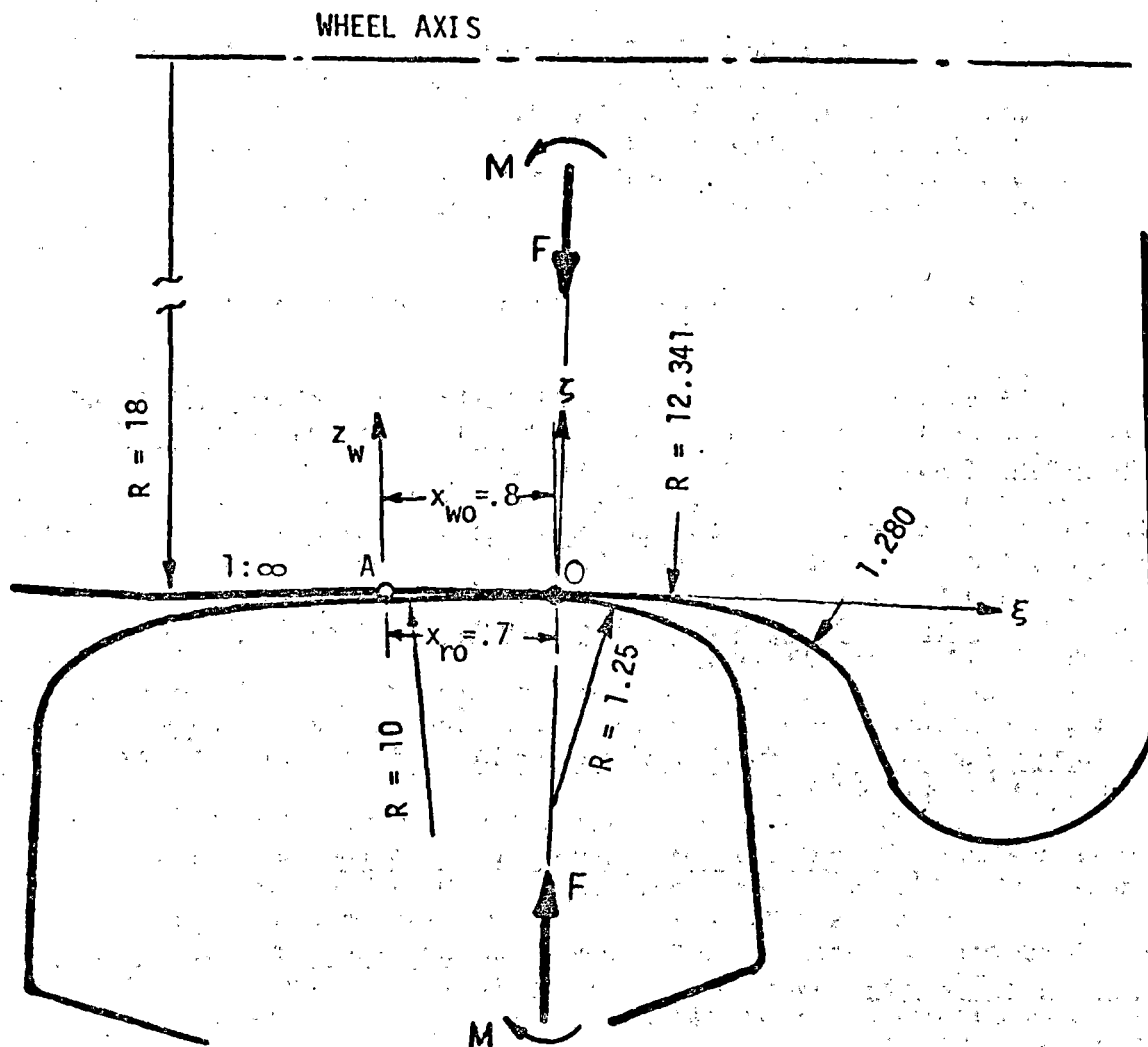


Fig. 4 Example
 Contact is non Hertzian. Note jump in rail
 curvature at point O.

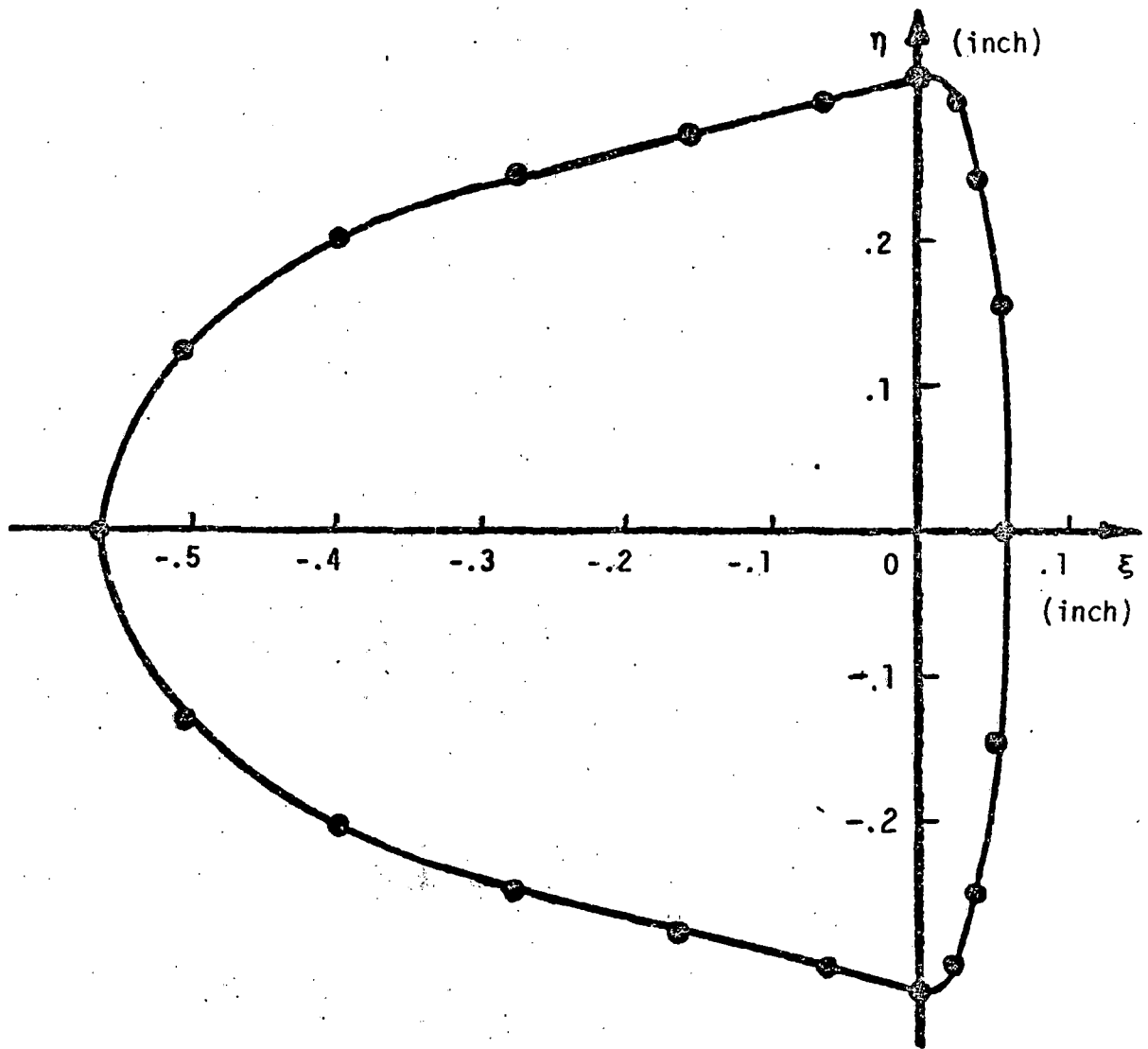


Fig. 5 Contact patch, $F = 33,946$ lb.,
 $\delta = 0.005$ " corresponding to
 Fig. 1.

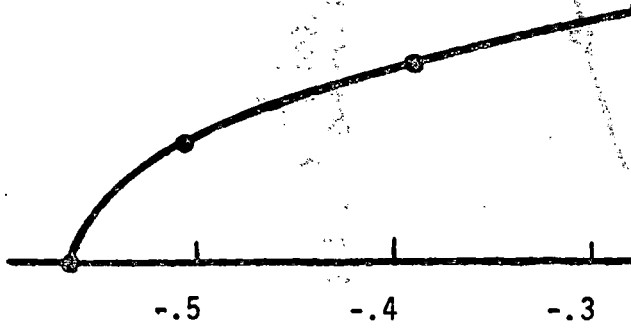
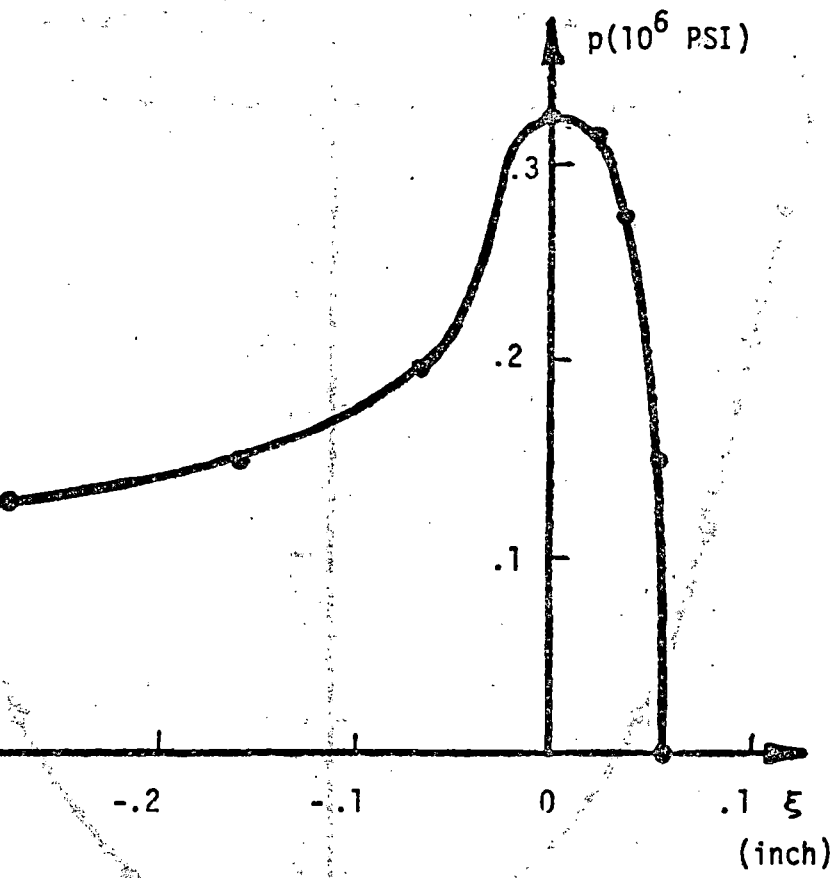


Fig.6



Pressure distribution
Load = 33,946 lb
Approach = 0.005"

2.4.2 Kalker's Exact Theory and Kalker's Simplified Theory

ABSTRACT OF KALKER'S EXACT THEORY

The conversion of the computer program, "A Programme for Three Dimensional Steady State Rolling" developed by Professor J. J. Kalker, from the Original Algol language to FORTRAN is considered. This program determines the resultant creep forces and moment for steady state rolling of two bodies of equal or unequal linearly elastic material properties.

A related manual for Kalker's "Simplified Theory of Rolling Contact" is considered in the report "User's Manual for Kalker's Simplified Nonlinear Creep Theory," by James G. Goree and E. Harry Law, FRA/ORD-78/06 Contract DOT- OS-40018, December, 1977. The program considered in the present report concerns the same problem except for the extension to unequal materials. It is found that, for equal materials, the "Simplified Theory" gives approximately the same results as the exact solution in most cases, and in those instances where some difference was noted, the simplified theory appears to be in better agreement with experimental results. In addition, the simplified theory reduces the computation time by a factor of approximately 50 to 100.

ABSTRACT OF KALKER'S SIMPLIFIED THEORY

The conversion of the computer program, "Simplified Theory of Rolling Contact," (used for calculation of a nonlinear creep force-creepage relationship) from the original Algol language to FORTRAN is considered. The Algol program was written by Professor J. J. Kalker and was derived from the paper, "Simplified Theory of Rolling Contact," Delft Program Rep., Series C; Mechanical and Aeronautical Engineering and Shipbuilding, 1 (1973), pp. 1- 10. A significant number of changes was made in the program for more convenient use; however, the fundamental equations remain unchanged. The results were checked in detail to insure agreement with the original solution. The program gives an appropriate solution for the resultant tangential creep forces and spin moment acting between two bodies of equal linearly elastic material properties. The creep forces and spin moment are due to lateral, longitudinal, and spin creepages. Assumptions corresponding to the Hertz contact theory are implied and two additional simplifying assumptions are made, resulting in a significant reduction in computation time as contrasted with previous solutions. Two separate computer codes were developed, the first being the general solution with extended input and output, and the second a shortened version primarily intended for use as a subroutines. Surprisingly good agreement is found to exist between the "Simplified Theory" and published experimental results for a wide range of contact ellipse eccentricity.

Kalker's Exact Theory

Program Summary

Category: Nonlinear creep, creepage, creep forces, spin, spin moment, steady-state rolling, Hertz contact, railroads

Descriptive Program Title: Kalker's Exact Nonlinear Creep Theory

Date: August, 1978 - has not been updated

Author: James G. Goree

Department of Mechanical Engineering

Clemson University, Clemson, SC 29631

Maintenance: Same

Availability: National Technical Information Service

Springfield, VA 22151

(703) 557-4600

Method: The user's manual available from NTIS contains some of the theory. The solution is based on work done by J. J. Kalker with the initial development covered in the thesis, "On the Rolling Contact Between Two Elastic Bodies in the Presence of Dry Friction," Ph.D. Thesis, Delft University of Technology (1967).

Language: FORTRAN

Input: Hertz contact dimensions; resultant normal load on the contact region; shear modulus for each material; longitudinal, lateral and spin creepages.

Output: Normalized resultant longitudinal and lateral forces and normalized resultant spin moment. Stresses over the contact area and relative velocities over the region of slip.

Kalker's Simplified Theory

Program Summary

Category: Nonlinear creep, creepage, creep forces, spin, spin moment, steady state rolling, Hertz contact, railroads

Descriptive Program Title: Kalker's Simplified Nonlinear Creep Theory

Date: December, 1977 - has not been updated

Author: James G. Goree and E. Harry Law

Department of Mechanical Engineering

Clemson University, Clemson, SC 29631

Maintenance: Same

Availability: National Technical Information Service

Springfield, VA 22151

(703) 557-4600

Method: The User's Manual available from NTIS contains some of the theory. The solution is based on the paper by J. J. Kalker, "Simplified Theory of Rolling Contact," Delft Progr. Ref., Series C: Mechanical and Aeronautical Engineering and Shipbuilding, Vol. 1 (1973), pp. 1-10.

Language: FORTRAN

Input: Hertz contact dimensions; Poisson's ratio; normalized longitudinal; lateral and spin creepages.

Output: Normalized resultant longitudinal and lateral forces and normalized resultant spin moment. Stresses over the contact area and relative velocities over the region of slip.

Documentation: Complete

2.4.3 DUVOROL

DUVOROL

Program Summary

Developer: Dr. J. J. Kalker
Delft University of Technology
Department of Mathematics
Julianalaan 132
2628 BL Delft
The Netherlands
telephone (015) 783512

Availability: The program is available for purchase from the author for the tape cost.

Program Description: The program calculates the total tangential wheel-rail force in dependence on creepage and spin. It is 100% effective.

Input: As input, one needs a.o. the ratio of the axes of the contact ellipse. There are no pre- or postprocessors.

Typical Time Required: For a "symmetric" case 2-4 sec are needed, and for an "asymmetric" case 8-12 sec are needed on an IBM 370/158.

Comments: The program has been verified.

2.5 FREIGHT VEHICLE DYNAMICS

INTRODUCTION

This section contains summaries of the program FRATE and of the IIT Freight Model. A comparison of the two programs is also included. Both programs are primarily intended for computing the response of cargo in freight cars subjected to excitation of track irregularities. These two programs are the only codes from the group which were reviewed.

FRATE

Program Summary

Category: Freight car vibration analysis, rock and roll, TOFC dynamic response, nonlinear model
Descriptive Program Title: Nonlinear, time domain solution for freight car dynamic response
Date: 1978
Author: Kachadourian, G., Sussman, N. E., Anderes, J. R.
The MITRE Corporation
1820 Dolley Madison Boulevard, McLean Virginia 22102
Maintenance: Office of Research and Development
Federal Railroad Administration
2100 2d Street, S. W.
Washington, D. C. 20590
(202) 755-1877

Availability: National Technical Information Service
Springfield, Virginia 22151

or

George Kachedourian
National Technical Information Service
Springfield, Virginia 22151

Program Description: Dynamic simulation of a TOFC freight car including certain nonlinearities. Solves in time domain by Runge-Kutta techniques for dynamic response to vertical and lateral input motions at the wheel/rail interface.

Method: Lumped mass model with synthesis of carbody flexibility normal modes. Equations of motion solved in time with numerical integration. Technical manual being prepared.

Limitations and Restrictions: Does not consider longitudinal degrees of freedom. Not valid at and above 20 cps.

Language: FORTRAN

Input: Control Parameters - defines type of run to be made and the output requirements.

Excitation Parameters - defines input forcing function motions.

Vehicle Parameters - defines the mechanical properties of the freight car

Modal parameters - defines the freight car body flexibility

Output: Time history - displacement, acceleration or force at selected locations in the vehicle. Printer plotted with 3 & 4 functions per plot.

Envelope - envelope of response of selected locations. Printer plotted against time/frequency. Can also be Calcomp plotted using CDC software.

Snapshot - deflection of the vehicle against time using CDC software.

Documentation: User's manual has been issued. There is a validation report, also.

Software Operation: Presently used on the CDC 7600 computer. Can be converted to IBM with line printer output only. Calcomp plots require CDC software.

Technical Summary of FRATE

The purposes with which FRATE was developed were to support full-scale freight car laboratory testing in the Rail Dynamics Laboratory and to provide a user-oriented simulation to determine the dynamic responses of a freight car and its cargo to rail profile irregularities. The following is a brief synopsis of the technical capabilities and aspects of the program.

Simulated Characteristics

- Carbody - 89 foot flatcar using normal modes for structural flexibility
50 ton boxcar assumed rigid
- Cargo - pallet-mounted cardboard shippers carrying canned goods;
simulated by masses flexibly connected to the carbody
- Track - tangent track; periodic and single pulse irregularities; road-
bed flexibility
- Trailers - highway trailers for TOFC; assumed rigid
- Trucks - single rigid masses
- Interconnections - linear suspension springs in trucks
friction snubbers
center plates
side bearings
wheel/rail separation
tandem/flatcar separation (TOFC)

External Dynamic Forces

The only external dynamic forces are those induced by rail profile vertical and lateral irregularities.

Topology

TOFC is simulated by 27 DOF for the flatcar and trailers, 12 DOF for the cargo, and up to 7 normal modes of the flatcar's flexibility.

The boxcar is simulated by 21 DOF and the cargo by 12 DOF.

Mass Assignment

	Number of Lumped Masses	
	TOFC	BOXCAR
Carbody	1	1
Cargo	4	4
Trucks	1(each)	1(each)
Trailers	1(each)	-
Tandems	1(each)	-

Coordinate Assignments

		Translation			Rotation		
		Long.	Lat.	Vert.	Pitch	Roll	Yaw
TOFC	Carbody		x	x	x	x	x
	Cargo		x	x		x	
	Trucks		x	x		x	
	Trailers		x	x	x	x	x
	Tandems		x	x		x	
BOX-CAR	Carbody		x	x	x	x	x
	Trucks		x	x		x	
	Cargo		x	x		x	

Model Aspects

- Responses only - natural frequencies and mode shapes not found
- No stability indications
- Equations of motion derived from F=MA
- Numerical integration using the 4th order Runge-Kutta method
- Time step maximized (=0.005 sec) to minimize computer costs
- Rail irregularities simulated by

Sine

Rectified Sine(Staggered joints)

Versine pulse

Fore and aft and side to side phasing included.

- Nonlinearities include truck coulomb damping, wheel/rail separation, bilinear center plate rotational stiffness, side bearing gap, no small angle assumption
- Forward speed either constant or variable; sweep frequency simulates either braking or acceleration

Computer Aspects

- FORTRAN language
- Stand-alone with the Calcomp Option; requires the CDC system with Calcomp option
- Output options;
 - .Complete time histories of preselected groups of responses
 - .Maximum values of the time histories with a swept sine simulates testing and provides a frequency response
 - .Complete response shape at specified times
- Remote batch operation on CDC system using the 7600

Miscellaneous Information

FRATE has been validated against laboratory testing of a full size TOFC. It is used by the TTX company to support the design effort of a new TOFC. There are MITRE reports illustrating the use of the analysis.

IIT FREIGHT MODEL

Program Summary

Descriptive Program Name: Dynamics of a Freight Element in a Railroad Freight Car

Author: K. L. Shum and T. Willis
Illinois Institute of Technology
Chicago, Illinois 60616

Availability: from Authors

Description: This program was developed to study the response of cargo in a typical freight car.

Language: FORTRAN

Hardware: Univac 1108

Output: Options include plotted time histories

Documentation: Not available

Technical Summary of IIT Freight Model

Simulated Characteristics

Carbody - 70 ton boxcar assumed rigid

Cargo - one rigid mass flexibly connected to the c.g. of the freight car

Track - tangent track; periodic rail profile and flexible roadbed

Trucks - two rigid masses

Interconnections - bilinear suspension springs to simulate bottoming
 bilinear lateral springs to simulate lateral gib
 friction snubbers
 side bearings
 wheel/rail separation
 couplers

External Dynamic Forces

Coupler forces and forces induced by rail profile irregularities.

Topology

The boxcar is simulated by 24 DOF; the freight element by 3 DOF.

Mass Assignment

	Number of Lumped Masses
Carbody	1
Trucks	1 (each)
Cargo	1

Coordinate Assignments

	Translation			Rotation		
	Long.	Lat.	Vert.	Pitch	Roll	Yaw
Carbody	x	x	x	x	x	x
Bolsters			x	x	x	x
Trucks		x	x	x	x	x
Cargo	x	x	x			

Model Aspects

- Responses only; no natural frequencies or mode shapes
- No stability indications
- Equations of motion derived using Lagrange's equation
- Numerical integration using the 4th order Runge-Kutta method
- Time step based on bolster bending flexibility frequency of 950 cps; time step is 0.00013 seconds
- Rail irregularities simulated by rectified sine

- Nonlinearities include coulomb truck damping, wheel/rail separation, lateral gib clearance, truck suspension spring bottoming, side bearing gap
- Constant forward speed

Other Information

This program has been validated against another model. There is a separate program written to calculate the Fourier coefficients to obtain a measure of the frequency content of the periodic response.

A COMPARISON OF FRATE AND THE IIT FREIGHT DAMAGE MODEL

These two programs are very similar in many fundamental aspects. They are both fundamentally motivated by the desire to calculate the response of cargo in typical freight cars traversing irregular track. Both their similarities and differences will be noted. In general, their differences are of a smaller magnitude than their similarities, but are critical for a potential user. This reviewer was closely associated with the development of FRATE and so the reader should be aware of possible bias.

The following attributes are similar to both simulations in that they both:

- 1 calculate time history responses only
- 2 use numerical integration of the nonlinear equations of motion using the 4th order Runge-Kutta method
- 3 simulate single freight cars excited by rail irregularities running on tangent track
- 4 contain cargo simulations
- 5 lack wheel/rail kinematically induced forces
- 6 incorporate periodic rail profile irregularities
- 7 provide for Coulomb damping in the trucks
- 8 simulate wheel/rail separation
- 9 are written in Fortran IV
- 10 incorporate roadbed flexibility
- 11 have side bearing gaps in the trucks
- 12 are stand-alone programs
- 13 have a frequency range of interest under 25 cps

In addition to these identical features they are roughly equivalent in that they are of the same order of complexity; 27 DOF for the IIT model and 33 DOF for the boxcar simulation of FRATE. The periodic track irregularities are equivalent though FRATE also provides for single pulse inputs. The coordinate coupling is approximately the same except that the IIT simulation allows longitudinal motion while FRATE does not.

The IIT simulation requires an integration time step which is about 40 times smaller than the one required by FRATE. This is due to the simulation of the lateral gib clearance and the vertical suspension Spring bottoming. Both require a bilinear spring of very high stiffness. This results, for the gib clearance, in a bolster natural frequency

of 950 cps which, in turn, requires a numerical time step of 0.00013 seconds based on 8 iterations per cycle. The FRATE truck simulation was designed to use one mass element only without vertical suspension spring bottoming or lateral gib clearance. It does include a bilinear roll spring to simulate "soft" centerplate motion and "hard" centerplate motion when the side bearing gap becomes zero. The potential user must decide if the lack of bottoming simulation and lateral side clearance outweighs the additional computer costs of including them.

The equations of motion developed for the IIT simulation include higher order terms because the Lagrange method is used. The FRATE simulation uses the Newtonian approach thereby eliminating them. Changes to the Lagrange-generated equations of motion are considered, by this reviewer, to be exceedingly difficult and of an order of magnitude more time consuming than similar changes to Newtonian-generated equations. Certainly changes to the IIT equations can be made, but the cost and time of doing so should be carefully considered.

The validation of dynamic simulations is always difficult. If a response validation is desired rather than a dynamic characteristic validation then the difficulties are greatly increased. (A dynamic characteristic validation is one where the natural frequencies and mode shapes are verified by test. A response validation is one where the responses are verified by test. A response validation requires the validation of the excitation function and structural damping as well as the dynamic characteristics.) The validation of FRATE against full-sized laboratory testing is documented. This effort was based on comparing the resonant frequencies, amplitudes, and response shapes found in tests with those calculated by FRATE. The validation of the IIT model is based on comparing its responses with those of another simulation, one which is not documented. Also, the IIT validation window is rock and roll only, while the FRATE validation window also incorporates bounce responses.

The IIT cargo simulation incorporated in its freight car program is a single mass element flexibly connected to the c.g. of the boxcar mass. It is not clear what physical situation is simulated. FRATE contains four mass elements simulating flexibly floor-mounted cargo, derived by development of realistic, pallet-mounted, cardboard shippers. The values used in the cargo simulation in FRATE were derived from special laboratory testing. The documentation is also available.

Other differences between these two models are:

- 1 The IIT model has provision for including limited coupler forces; the FRATE model does not.
- 2 The FRATE model has provision for including the structural flexibility of the freight car using normal modes; the IIT model does not. (The normal modes for the 89 foot flatcar are available in the TOFC simulation.)
- 3 FRATE provides an input option of a single versine pulse to simulate a grade crossing or roadbed stiffness discontinuity; the IIT model does not.
- 4 The IIT model includes suspension spring bottoming and lateral gib clearance; the FRATE model does not.

5 The level of documentation is larger and in greater detail for FRATE than for the IIT model.

The potential user trying to decide between these two models will certainly have preferences based on the needs of his specific problem. In the final analysis it is these needs which will determine the final choice.

2.6 ANALOG/HYBRID SIMULATION

INTRODUCTION

Analog Computer simulation has long been a viable and cost-effective tool for doing extensive studies of large scale nonlinear dynamic systems. This has been repeatedly demonstrated in the aerospace and other industries. The direct simulation of complex differential equations of motion using interconnected parallel mathematical building blocks available on the analog computer produces a speed, simplicity of computation, and experimental realism not easily obtained using digital techniques alone.

Analog computers have been used to simulate various aspects of railroad vehicle dynamic systems for many years. For example, in the early 1950's Pullman-Standard did extensive studies of vehicle dynamics using analog computers [1]. Since that time, many other analog simulations of varying complexity have been developed and studied by both industry and academia throughout the world. But just as digital computer programs written in the 1950's and early 1960's have passed into oblivion due to improvements in computer hardware and software, so have these analog simulation efforts. These past simulation activities were, in general, directed at specific problem areas and tailored to fit the relatively small complements of equipment then available.

Some of the shortcomings of the early analog computer were overcome in the mid-1960's when intelligent interfaces were developed to allow the analog and the digital computer to become effective partners in computation. The resulting hybrid computer became an even more powerful simulation tool. In the hybrid machine, the storage and control functions lacking in the stand-alone analog computer are provided by the attached digital computer. The hybrid machine configuration has proven far superior to analog-only systems, and is a significant part of many simulation facilities today.

Despite the apparent advantages of analog/hybrid simulation and its use in many industries for the study of large-scale dynamic systems, in the past decade it has not been extensively used as a design and analysis tool to study railroad vehicle dynamics. In those industries such as Aerospace where wide-spread use of analog/hybrid simulation has prevailed over a number of years, formalized simulation techniques have developed, such as extensive definition and verification of models, and

generalized system simulations unique to the needs of that industry. In the area of simulation of railroad vehicle dynamics, there has not been an extensive or even a concerted effort by industry or government to develop such tools on the hybrid computer. Therefore, little exists in the way of generalized analog/hybrid simulations to study rail system dynamics.

It would be most desirable, particularly in the context of the other chapters of this document, to be able to describe specific comparisons between different portable hybrid simulation programs for rail vehicle dynamics studies that one could obtain and run on the computer facility of his organization. This, unfortunately, is not possible due to the specific nature of analog/hybrid computer hardware, the necessary methods of implementation, and state of generalized hybrid simulations for rail dynamics as they exist today. One method does exist, however, to allow currently operational (or yet to be developed) rail vehicle simulations operating in existing hybrid facilities to be used by investigators located in other geographic areas. This method, called remote hybrid computation, allows the user to operate a simulation from a remote location over telephone lines. This type of operation assumes that both the simulation facility and the remote user have the proper equipment to support such an operation. The details of this will be expanded in a subsequent section.

WHAT IS HYBRID COMPUTATION?

Hybrid computation is a combination of two basically different types of computers brought together in one computing system. The computers used in such a system are the digital computer and one or more modern analog computers. The two types of computers are allowed to "talk" to each other through a sophisticated linkage and interface system which provides both data communication and control communication to and from each machine (see Fig. 1).

The digital computer is basically a sequential machine which is capable of only a little parallel processing. Most modern digital computers are very fast in doing individual operations, but due to the sequential nature of the operations the machine can become bogged down in the solution of problems where many, many operations are required. One such class of problems is the simulation of large scale nonlinear dynamic systems where it is necessary to integrate the equations of motion. Comprehensive, nonlinear, multi-degree-of-freedom rail vehicle simulations are in this class.

The modern analog computer is a parallel machine where mathematical electronic building blocks are patched (wired) together via a patch panel to simulate the dynamic equations of motion described by ordinary differential equations. The mathematical operations performed are addition, subtraction, multiplication, division, integration, logical comparisons, switching, and

HYBRID COMPUTER SYSTEM

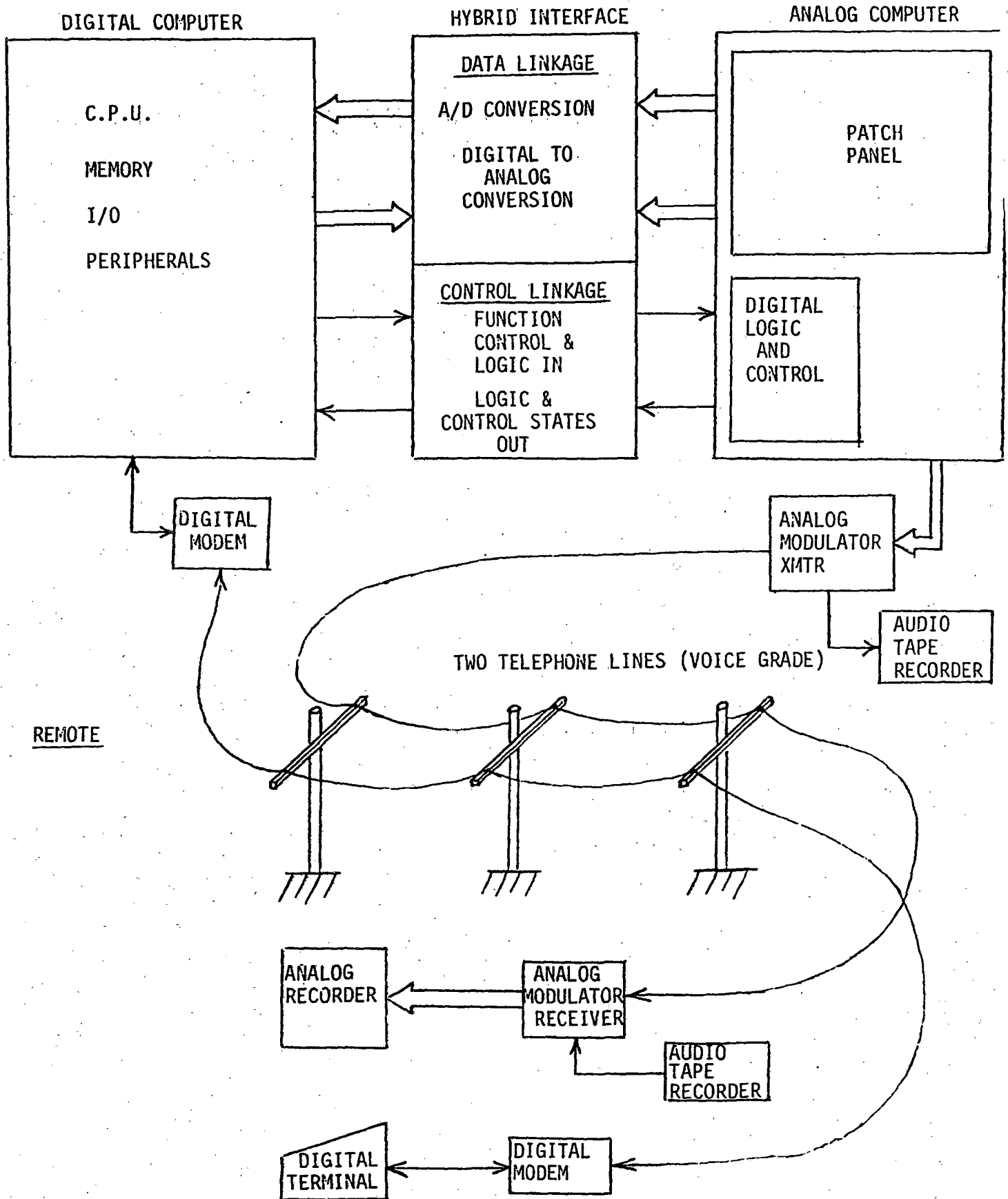


Fig. 1

nonlinear function generation. A voltage model of a physical system is constructed by wiring together these building blocks. A simulation on the analog computer appears to the investigator like an extremely well instrumented physical system which can be studied and manipulated with a degree of experimental realism very closely approximating the real world. Much can be learned about the physical system in a relatively short time on the computer in this interactive, hands on, mode of operation.

The interface system is divided into two major parts, as diagrammed in Fig. 1. One is the data interface and the other is the control interface. The data interface includes an analog to digital converter (ADC) with a multi-channel multiplexer on the input. The ADC converts voltages into digital words. In the opposite direction there are a number of multiplying digital to analog converters (MDACS) that change digital words back to voltages while multiplying by another voltage. The control interface provides facilities for the digital computer to perform under program control all of the normal operator functions for the analog computer such as mode control, setting potentiometers, addressing components, reading components, setting switches, etc. This allows for completely automated set up and check out of the analog computer(s). There are also several channels of single data bit communication in both directions to allow analog control over the digital program and logic communication from the digital to the analog machine.

WHY USE HYBRID?

The purpose of a hybrid computer system is to capitalize on the strong points of each type of computer and minimize the weak points of each, thus providing a high speed, cost effective computing system. The digital computer is a precise sequential calculating device, with stored program capability and high speed mass memory, but it is slow when considered in light of the needs for solving high speed, complicated dynamic system simulations. The analog computer, on the other hand, is a high speed parallel processing device which simulates equations of motion by direct analogy between physical variables and computer voltages. Mathematical integration is done directly in parallel, which does not involve sequential accumulations and approximations; therefore, solution speeds can be in real time or much faster than real time. The major analog computer shortcomings are limited computing precision resulting from only having a fixed voltage range, and limited storage for complicated nonlinear functions.

The speed of the analog computer in solving differential equations and the storage of the digital computer combine to form a unique computing tool for the simulation of complex dynamic systems. In a typical hybrid system, the analog computer is programmed to simulate the high speed equations of motion and interfaces to any real world hardware while the digital computer handles function storage and generation, simulation set-up, check-out, and control functions.

The hybrid computer system has several advantages over digital simulation techniques for many applications. Some of these advantages are: cost effective computing for the design and study of large scale dynamic systems where integration of the equations of motion and simulation of system nonlinearities is required; experimental realism and easy interaction with the simulated system; and inclusion of real world hardware to replace portions of the simulated system in order to verify hardware and simulation performance. Historically, hybrid computing has been demonstrated to be superior in both time and cost to digital simulations of complex nonlinear systems. Several references [2,3,4] report hybrid solution speeds and costs of from 10 to 100 times faster and cheaper than large digital implementations of similar types of models.

REMOTE OPERATION

One disadvantage the hybrid computer has suffered until recently, compared to modern digital computers, was the necessity to "go to" the hybrid machine to use it.

Hybrid simulations are not generally transportable in the same sense as purely digital simulations written in a high level language such as FORTRAN. There is a significant lack of standards for hybrid systems hardware configuration and operational software between facilities. Also, the analog portion of the simulation is usually implemented to take maximum advantage of the machine configuration available, making the simulation unique. Another degree of uniqueness is added by the interface configuration. Previously the primary options open to anyone who wanted to use an existing hybrid simulation were either to travel physically to the host facility or to use complete documentation of the simulation to re-program it at a different facility.

It is now possible, however, to use such a system remotely, via telecommunications, similar to the way digital computers are frequently used. This type of operation was demonstrated for railroad applications at the Conference on Advanced Techniques in Track/Train Dynamics and Design [5] in Chicago in September 1977. Figure 1 shows a schematic drawing of this process. The digital computer in the hybrid system is controlled over a phone line using standard digital communications techniques. The digital computer through the hybrid control interface is then able to set up, check out, and control the complete analog simulation (except for putting on the patch panel). The dynamic parallel analog results are transmitted from the simulation over another telephone line. This line is equipped with special transmitter and receiver hardware which allows up to eight parallel analog channels of up to 25 hertz frequency each to be transmitted over one phone line [6,7].

The implications of the remote use of the hybrid computer are quite important. This allows comprehensive dynamic rail vehicle simulations to be developed as cost-effective analytical tools for the railroad industry that can be implemented on existing hybrid computer systems in academic, government, and industry laboratories and used remotely. This approach will allow the industry to experiment with more cost-effective computing without large capital outlays.

REMOTE HYBRID CONFIGURATION

The hybrid computer was previously described as a digital and an analog computer interfaced to "talk" to each other. In order to operate such a system remotely, it is necessary to communicate with and control each computer and to receive output from each (refer again to Fig. 1).

The detailed requirements for remote operation were first reported by Martin Marietta Corporation, Orlando, Florida [6,7]. Remote input and output to a digital computer is standard today. The hardware included a digital modem that transmits and receives serial data bits over a voice grade telephone line by sending a stream of two level tones, representing a "0" level and a "1" level. In this manner, we can control and get output from the digital computer. This also allows for analog computer control through the control interface between the digital and analog machines. We can perform all operator functions required by the analog computer from the digital computer through this interface. To communicate with the digital computer over a telephone line it is necessary to have a digital modem on each end of the line. At the remote site there is a digital terminal with a keyboard that is used for computer input and a printing unit (either hardcopy or cathod ray tube) for computer output. For remote hybrid operation, a preferable (but not mandatory) type of digital computer terminal is a Tektronix 4000 Series graphics terminals, since the graphics display can be used to present summary results from several hybrid runs. This is particularly important if the simulation is running faster than real time.

To complete our remote site for hybrid operation, we need a way of getting parallel analog outputs transmitted over another telephone line. This is done by using a special transmitter box at the analog computer end and a matching receiver box at the remote site. The purpose of these boxes is to take up to eight parallel analog signals and frequency modulate (FM) and multiplex each signal onto its own center frequency within the audio band pass of the telephone line [7]. The frequency range of the phone line, the number of channels desired to transmit, and the frequency desired on each channel establish the constraints on the system. The maximum number of channels is eight, with a frequency on each channel of up to 25 hertz. Using fewer channels allows the possibility of higher frequencies. The analog signals which come out of the receiver can be connected to an eight channel strip chart recorder for parallel output. An X-Y plotter can also be driven with these signals. An additional capability is provided on both the transmitter and receiver boxes for either tape recording the FM multiplexed audio signal or playing back a previously recorded audio tape. To enhance this capability the system also records a ninth analog channel which is used to reject wow and flutter noise induced by the audio recorder when and recorded signal is played back. The importance of this recording the playback capability is that it allows important runs to be conveniently and cheaply saved. Under certain conditions the audio tapes can also be a means of communication between users without tying-up additional computer time.

CONTRASTS BETWEEN SIMULATION ON ANALOG AND DIGITAL MACHINES

It is important to understand the differences between analog and digital simulation techniques brought about by the basic difference in structure of the two types of computers. The analog is parallel and the digital is sequential.

An analog simulation, on one hand, requires more components or mathematical building blocks as the simulation grows or becomes more complex. This is due to the parallel nature of the machine. The time of solution does not increase in this process, but the number of components and patching complexity does. This parallel structure and nondependence of solution time on problem complexity makes the analog ideal for simulating physical components with high frequency response characteristics. Such systems cause excessive run times and costs for digital simulation.

The size of an analog computer is finite; therefore there is some upper limit to the complexity of simulation that can be implemented on one or even several machines. It is very common to have several analog machines (or consoles) tied together to act as one large simulation machine. A large simulation requires several patch boards, a set for each console used in the simulation. The removable patch boards and leads that interconnect the components are the facility by which a simulation is stored. The costs of this physical hardware are a significant expense item in the storage or analog simulations.

The digital computer, on the other hand, is a stored program, sequential processing machine which requires additional time rather than components to complete a more complex computational task. This dependence of problem execution time on computational complexity can be very important in the simulation of physical systems for several reasons. First, for nontime critical applications, the additional computational time will increase computational costs and slow down the analysis process. It is frequently necessary to avoid simulating devices in the physical system that have high frequency components because of the significant time and cost increases derived from a faithful simulation. Second, when time-critical processes are implemented on the digital computer, it is necessary to complete all computations in the process in a prescribed amount of elapsed time in order to maintain simulation integrity. If such a process becomes more complex, i.e., requires more time, it is very possible that the computations cannot be completed in the allotted time, causing serious consequences in the simulation results.

For any type of comprehensive computer simulation - analog, digital, or hybrid - there are numerous constraints to be considered in both the model development and computer implementation. The size and complexity of the simulation may need to be constrained due to limitations in equipment, funds, computing time, or analysis time. The limitations can also hinge on exercising sound engineering judgement about the current level of understanding of the physical system under study. At this point, the common practice is to define the mathematical model to include only the most important dynamic characteristic-eliminating incidental, secondary, and/or complicating effects. The model is then implemented on the appropriate computer. The resulting simulation then has one significant thing in common

with all others: all computer simulations are based on some set of simplifying assumptions which should be, but are not always, known to the user. This is particularly troublesome for digital simulations transported to other facilities where the users are far removed from the developer(s) and documentation never seems to be complete enough. Hybrid simulations, though not very transportable, are generally available in the facility where they were developed and are supported for some active period by the original developer of the model or simulation engineers in the hybrid facility.

Table 1 indicates the approximate equipment required for a progression of representative hybrid simulations starting with a 2-DOF wheelset model. The amount of equipment depends on the degrees of freedom (DOF) of the model, the nonlinearities involved, and the complexity of the system forcing functions. All models in this table represent the lateral dynamics of a single freight vehicle on a rigid track structure. The first three represent portions of a complete vehicle, and the first four assume rigid components and a relatively simple suspension. A generalized vehicle model 9,10 with 17 to 23 DOF includes flexible components and a refined suspension and would require up to four analog consoles and a digital processor with a relatively large (64K - 128K 16-bit words) memory coupled to a hybrid interface capable of handling numerous multivariable functions.

DESCRIPTIONS OF AVAILABLE HYBRID SIMULATIONS

The hybrid simulations described are representative of the efforts going on in the United States and other countries. Since hybrid simulations are not generally portable for reasons discussed previously, these profiles primarily serve to indicate the type, level, and location of some recent rail vehicle dynamics simulation activity.

Rail Vehicle Wheel Profile Optimization

Category: Wheel profiles, lateral dynamics, curving, wear

Descriptive Program Title: Rail Vehicle Wheel Profile Optimization

Using Hybrid Simulation

Date: May 1979

Author: Rainer Heller

Department of Electrical and Computer Engineering
Clemson University
Clemson, SC 29631

Maintenance: Author

Availability: College of Engineering Computer Laboratory
Clemson University
Clemson, S.C. 29631

Program Description: Equations evaluation include degrees of freedom for car body and wheelset. Large angles between wheel and rail are included. Nonlinear creep forces are calculated. Travel on tangent and curved track is included. Rail wear factors are calculated. Asymmetric wheel rail profiles.

Method: Dynamic simulation of the equations of motion on analog.

Nonlinear wheel/rail profile functions, large contact angle calculations, wear calculations, and optimization determinations computed on digital

TABLE 1

HYBRID COMPUTING EQUIPMENT REQUIREDREPRESENTATIVE RAIL VEHICLE SIMULATIONS

System being Simulated	Degrees-of-Freedom of the Model	Size of Hybrid System Required*	
		Digital**	Analog
<u>Wheelset</u> (Rigid body)	2	small-medium	.5 console
<u>Freight-Truck</u> 2 wheel sets, 2 side frames, and bolster	3	medium	1 console
<u>Roller Rig Car Model</u> Half car body on single 3 DOF Truck	5	medium	1-1.5 consoles
<u>Freight Car with 2 Roller Bearing Trucks</u> Car Body (3 DOF) 2 Trucks (3 DOF each)	9	medium	1-2 consoles
<u>Generalized Rail Vehicle</u> Car Body (3-5 DOF) Trucks (3 DOF each) Wheelsets(2-3 DOF each)	17 - 23	medium-large	3-4 consoles

*The hybrid system is assumed to be configured with a digital processor with at least a 16 bit word, 24K - 32K memory, with disk storage and a comprehensive data and control interface. One analog/hybrid console in the system is assumed to have at least 120 amplifiers, 30 integrators, and a reasonable complement of nonlinear components and parallel logic.

**The use of MVFG hardware for complex function generation can reduce the digital processor size requirements(8).

Limitations and Restrictions: Simplified slab body on a single wheelset
Hardware Appropriate: PDP-15 Digital/EAI 680 analog/EAI 693 Interface.
24K memory, 20 integrators, 65 amplifiers, 60 ports, 16 channel MUX/ADC,
12 MDACS, 20 DCAs
Language: Analog wiring and FORTRAN.
Software Operation: PDP-15/DOS - remote operation possible
Usage: Doctorial Research
Typical Running Time: 10 times slower than real time
Documentation: Current

Five Degree-of-Freedom Half-Car Body
on a Single Freight Truck

Category: Freight car trucks, nonlinear rail vehicle models, lateral
dynamics, wheel profiles

Descriptive Program Title: Five Degree-of-Freedom Half-Car Body on a
Single Freight Truck

Date: June 1976 - August 1979

Author: Carl W. Malstrom, Rainer Heller, M. S. Khan, E. H. Law
Department of Electrical and Computer Engineering and
Mechanical Engineering
Clemson University
Clemson, S.C. 29631

Maintenance: Authors

Availability: College of Engineering Computer Laboratory
Clemson University
Clemson, S.C. 29631

Program Description: 5-DOF total including body lateral displacement and
roll and truck yaw, roll and warp. Nonlinear wheel/rail profiles
are generated. Four sources of coulomb friction are included at
vertical sideframe-to-bolster, lateral sideframe-to-bolster, and
truckframe warp. Effects of vertical motion on breakout levels are
included. Track noise input from field test spectra are included.

Method: The five nonlinear, second order equations are implemented on
the analog. The nonlinear wheel/rail profile functions are generated
on the digital. External noise source is shaped and used for track input.

Limitations and Restrictions: One half of the car body on a single truck
lacks proper geometry of a full vehicle. Tangent track only. Small
angle approximations for wheel/rail contact geometry. Linear creep.

Language: Analog wiring and FORTRAN

Hardware Appropriate: PDP 15 digital/EAI 680 Analog/EAI 693 interface,
24K memory, 20 integrators, 65 amplifiers, 60 ports, 16 channel MUX/ADC,
12 MDACS, 20 DCAs

Software Operation: PDP-15/Disk Operating System - remote operation
checked out and operational

Usage: Research for F.R.A. and graduate research

Typical Running Time: Five times slower than real time

Documentation: Current

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2.7 TRAIN DYNAMICS

INTRODUCTION

One major area of concern to the railroad industry, the supply industry, and the government is the safe operation of the rail system. The railroad has suffered losses of many millions of dollars worth of equipment, lading damages and losses, and personal injuries every year from accidents, derailments, and over-the-road and yard operations. Concerned parties, including the Federal Railroad Administration, the Association of American Railroads, the Railway Progress Institute, the Transportation Development Agency, universities, and railroad and supply industries, have pooled their resources for the formation and development of the Track Train Dynamics Programs, which have been functioning for about ten years. The Track Train Dynamics Program has addressed itself to many facets of the railroad problem; the computer modelling of train dynamics is one of the many areas that has achieved considerable success.

A moving freight train interacts with the track in three directions: longitudinal, lateral, and vertical. Locomotives provide tractive efforts for train motions, while braking provides for retardations. Couplers transmit drafting or buffing forces to cars from locomotives and maintain the trains intact. Starting and stopping, accelerating or braking, the existence of slacks, coupled with varying resistances due to grade and/or curvature changes set up differential velocities among neighboring vehicles. These phenomena of run-in or run-out actions generate in-train dynamic forces which, when high enough, can result in train separation, lading and equipment damage, derailments, and/or personal injuries.

Railroads have train operations over curvatures, turn-outs, and cross-overs on main lines and in-yard services. Some have relatively higher running speeds on level tangent territories than others. The lateral stability of trains in curve negotiations or in diverging on a turn-out or cross-over is a subject of concern. Hunting is a phenomenon which involves the lateral stability of equipment above certain critical speeds. Occasionally there is a train derailing on a curve, a cross-over, or a turn-out that many other trains have successfully negotiated. On-site

derailment investigations may not always be able to uncover the exact cause or causes of accidents. A life reconstruction of the sequence of events for the derailment may be costly and impractical and will introduce further delays in the traffic flow. Moreover, it may not always be possible to gain additional information to explain the cause of the accident through this kind of endeavor; therefore, recommendations for preventing similar happenings are not always be available.

Railroads are interested in learning of the results of tests or analyses which can compare the performance of one design with another. For example, in hump yard operations, thousands of freight cars every day experience impact forces in the process of recoupling during classifications. The amount of lading and/or equipment damage could potentially be reduced through selection of the optimum suspension characteristics and shock absorbing devices for controlling the bouncing, pitching motions and the impact forces on the car body. Even over-the-road in train dynamic forces could set up car body vertical motions and vibrations which can be responsible for many consealed damages on lading shipped over the rail.

The railroad and the supply industry are faced with the need for analysis tools which can shed more insight into the many problems of railroad operations. Specifically, computer modelling of train stabilities offers a better understanding of the interactions of train handling, train make up, and equipment and track designs for a safer and a more profitable operation of the rail service.

Train Dynamics Models

The Train Dynamics Models developed through the Track Train Dynamics Program, the FRA, and other research efforts may be classified into three areas:

1. Models which specifically address the longitudinal train dynamics
2. Models which deal with the lateral dynamics
3. Models which cover areas of vertical dynamics.

Table 1 summarizes various computer models in the area of train dynamics with a brief description of the basic applications of each mode. An in-depth discussion of each computer model follows.

PROGRAM SUMMARIES

Train Operations Simulator (TOS)

Categories: Freight train performance, diesel-electric locomotives,

longitudinal coupler force, L/V ratio, speed and distance

Descriptive Program Title: Train Operations Simulator (TOS)

Authors: N. W. Luttrell, R. K. Gupta, R. M. Low G. C. Martin

Association of American Railroads

3140 South Federal Street

Chicago, Illinois 60616

Maintenance: Association of American Railroads

Date: Currently available

Table 1 Train Dynamics Models

Train Dynamics	Model	Model Application	Program Language	Core Space Execution (K Bytes)	Availability
Longitudinal	Train Operations Simulator (TOS)	Train handling and train make-up analyses; derailment investigation; track and signal spacing design.	Fortran	216	AAR
	Detailed Longitudinal Train Action	Same as TOS model; evaluation of shock absorbing devices such as EOC and sliding sills in controlling train actions.	Fortran	About 400	AAR*
	Quasi-Static Lateral Train Stability Model (QLTS)	Establish train make-up guidelines; designs for curvature, cross-overs, turn-outs, minimum tangent length in reverse curves and spiral lengths.	Fortran	292	AAR
Lateral	Detailed Lateral Train Stability Model	Train operation and train make-up guidelines; track design evaluation.	Fortran	—	AAR*
	Detailed Vertical Train Stability Model	Evaluation of suspension characteristics in controlling vertical stability lading acceleration analysis.	Fortran	156	AAR*
Vertical	Longitudinal Vertical Train Action	Same as Detailed Vertical Train Stability Model; study of effect of impacts on train vertical stability.	Fortran	64	WU,** FRA

* - Model being finalized at the Association of American Railroads;
 ** - WU - Washington University; FRA - Federal Railroad Administration.

Capability: This program can simulate the performance of a freight train powered by diesel-electric locomotives over a piece of railroad with any combination of curvature and grades. Operation capabilities include any combination of throttle and various modes of braking manipulations. The program has been applied for derailment investigation, train make-up studies, power selection, a train handling training tool, signal spacing, and track layout designs.

Method: Based on the available tractive effort from locomotives and the total resistance acting against the train using the Davis Resistance formula, dynamic braking characteristics, and air brake forces from WABCO's freight train braking characteristics, the net force on the train is calculated. This net force determines whether the train will accelerate, decelerate, or remain at a constant speed. By numerical integration, train velocity and distance are determined. The relative velocities between neighboring vehicles, together with the amount of coupler slack, govern the buff and draft actions in the train and the magnitude of draw bar forces calculated according to draft gear characteristics.

Limitations and Restrictions: The draw bar forces and L/V ratios are quasi-dynamic and are good approximations. They should not be considered as being absolutely exact.

Only one remote consist may be placed within the train close to the rear end. Only ABD valves are correctly handled during brake release. The program shows much quicker than actual release on AB valves. It does not have the provision for ABDW brake valves. Simulation of cyclic braking involving complete release is not accurate, and brake pipe leakage is assumed to be evenly distributed throughout train.

An undesired emergency with remote-control units cannot be simulated. The program cannot give correct results simulating an undesired emergency after a partial service brake application without having the previous brake application completed on the whole train.

The program does not give a complete echo of the input data.

The user should not assume that data as input are absolutely correct.

Programming Language: FORTRAN

Documentation: Users, Technical, and Programming Manuals are available. The Users Manual is written to be user oriented. However, due to the complexity of data for the Standard Library, locomotive and freight car characteristics, train handling commands, and track curvature and profile data, beginning users without railroad background may find it difficult to prepare data for simulation.

Input: Input may be divided into four areas:

1. **Track Data:** Curvature data includes degree of curve, length of spiral and curve, and superelevation. Profile data includes mileage and elevation.
2. **Train Consist Data:** Data required are for locomotive and freight cars. If different from those in the Standard Library (which comes with the program) the user must input various geometric parameters as well as the brake valve type, brake shoe type, and forces. For locomotives not in the Standard Library, data such as tractive effort and dynamic braking characteristics are required.
3. **Train Operations Command:** These include commands such as speed, throttle, and brake pipe reductions and brake releases, independent and dynamic brake application, etc.

4. Title Information: This is one card stating the title that the users wish to appear on output.

Output: This is given in three sections:

1. Train Consist Data: The number of locomotives, number of cars, train length, and tonnages and a list of primary characteristics of each vehicle.
2. Power Summary: The tractive effort and dynamic braking characteristics including HP on rail and transition speed.
3. Performance Printout:
 - (a) Time, station name, and mile post location of front end of train
 - (b) Speed limit and actual train speed
 - (c) Locomotive throttle setting and amperage
 - (d) Train brake setting, brake pipe and brake cylinder pressures
 - (e) Maximum value and location of drawbar and L/V ratio
 - (f) Fore and aft drawbar forces and L/V ratios on vehicles selected by user for each print interval
 - (g) A summary for maximum buff, draft, and L/V with corresponding location in train for the simulation
 - (h) An indication of whenever there are changes in operation commands, grade, and/or curvatures.

Software Operation: The program is available for both batch and time-sharing modes. For the batch mode all input data with the necessary Job Control Language are on punched cards. The time-sharing option is available on the DEC-20 computer located in-house at the Technical Center of the AAR in Chicago. To adopt the time-sharing mode on other computers may require slight modifications.

Hardware: The program was developed on an IBM 370/158 machine requiring 216 K bytes of core storage. This program can be run on other computers with minor modifications.

Usage: To date, more than 50 organizations, including government agencies, the supply industry, research organizations, universities, and railroads have purchased this program. It has been used extensively by several major railroads in the United States. Some comments by users are given in Section 3.0 of this report.

Typical Running Time: A typical stopping simulation for a freight train at 50 to 60 MPH requires about 1 minute of IBM 360/168 CPU time. Simulation using the automatic mode requires approximately twice as much time as the manual modes. A typical simulation consumes about 1/3 as much CPU time as simulation time on an IBM 360/168 computer.

Availability: TOS is available to the general public for a fee of \$50.00.

Contact: Director - Technical Center
Association of American Railroads
3140 South Federal Street
Chicago, Illinois 60616

The fee covers the magnetic tape of the program and the documentation available at the time of the purchase.

Quasi-Static Lateral Train Stability Model (QLTS)

Categories: Train consists in curve negotiation, lateral stability, L/V ratio, coupler angles, buff and draft

**Descriptive Program Title: Quasi-Static Lateral Train Stability Model
(QLTS)**

Authors: L. R. Thomas. R. D. MacMillan. G. C. Martin
Association of American Railroads
3140 South Federal Street
Chicago, Illinois 60616

Maintenance: Association of American Railroads

Date: Currently available. Updated versions are only available to individual railroads accessing the AAR computer.

Capability: The program simulates the lateral stability of a train consist in curve negotiations under buff or draft drawbar forces. It calculates derailment tendencies through L/V ratios of rail-roll-over and wheel climb and coupler lateral angles. The program can be used for evaluation of long car - short car, loaded and empty combinations of train consists. It has been used for the determination of minimum tangent lengths between reverse curves, the effect of spiral lengths in curve negotiation, and the establishment of guidelines for train make-up, and it has been applied as a design tool for freight car geometric considerations.

Method: Based on the geometric interaction of track configuration with vehicle arrangement, the amount of buff or draft forces, the train speed and the amount of superelevation in a curve, this program computes the equilibrium condition using a coupler model and a vehicle model. The resultant lateral loading at bolster centers at equilibrium is used to calculate L/V ratios of rail roll-over and wheel climb.

Limitations and Restrictions: This is a quasi-static model which does not provide for inertial force considerations. A maximum of 2500 feet of track and 100 vehicles can be simulated. The only available alignment control types for locomotives is M380/381 and for freight cars is on E-60 square-butt coupler with M-17A draft gear and an F-butt type coupler. Maximum drawbar force on vehicles must be less than 450,000 lbs. There is no lateral coupler swing limit and the user must manually check each calculation of the coupler angle against the maximum allowable for the equipment. The L/V ratios calculated do not take into account the coupler arm's contacting strikers.

Programming Language: FORTRAN IV

Documentation: User's Technical and Programming Manuals are available through the Association of American Railroads. Due to the simplicity of the model, all documentation is self-explanatory. These manuals are easy to follow for those users who have some background in freight car geometric parameters and spirals and super elevation of curves.

Input: The input is in three parts:

- 1. Track Data: Requires lengths of tangent, lead and trail spirals, length and degree of curve, and amount of superelevation**
- 2. Train Operation Data: Includes speed of train, draw bar force, start and stop times, and interval of simulation**
- 3. Train Consist Data: Includes bolster (truck) center distance, length between bolster center and coupler pin, coupler length, maximum lateral offset of bolster center from track center line, type of alignment control, vehicle weight, and the net lateral load at the leading outer wheel of each vehicle.**

Output: There are two sections of output:

1. **Track Generator:** The track generator gives an echo of the input data and generates the X-y coordinates, and the angle to the origin of the track centerline. It shows the radii of curvature and the superelevation for every chord length as defined by the user.
2. **Results of Equilibrium:** Every calculation time-step gives an echo of the input geometry of each vehicle. In addition, the following are calculated:
 - (a) Location of vehicle on track
 - (b) Bolster lateral displacement and reactions
 - (c) Coupler lateral angles and couple pin reactions
 - (d) Centrifugal and superelevation forces
 - (e) Alignment control moments if present
 - (f) Draw bar force on each vehicle and L/V ratios for rail roll-over and wheel climb

Software Operation: Both batch and time-sharing modes are available.

Hardware: This program was developed on the IBM 370/158 machine requiring 292 K bytes of core for execution. Only minor modifications, if any, are required to operate on other computers.

Usage: There are relatively few users for this program. They are mainly from railroads. At one time, this program was heavily used to determine critical consists in train make-ups, minimum tangent length, and effect of spiral lengths in curves. The Transportation System Center has used a modified version of this program to generate a Buff Stability Index and the Southern Pacific Transportation Company has utilized information generated from this program to improve train make-up.

Typical Running Time: Typical running time on an IBM 370/158 machine varies from a few CPU seconds to over a minute, depending on the length of the train consist, the train speed, and the calculation interval specified by the user.

Availability: This program is available to the general public for \$50 contact: Director

Technical Center of the Association
of American Railroads
3140 South Federal Street
Chicago, Illinois 60616

The fee covers the cost of the program on magnetic tape with sample input data, and the costs of all documentation available at the time of purchase.

Detail Vertical Train Stability Model (VTS)

Categories: Vertical train stability, vertical forces, motions and displacements

Descriptive Program Title: Detailed Vertical Train Stability Model

Authors: T. B. Raidt, K. L. Shum, G. C. Martin, V. K. Garg
Association of American Railroads
Track Train Dynamics Phase II
3140 South Federal Street
Chicago, Illinois 60616

Maintenance: Association of American Railroads

Date: Currently unavailable. The program is being finalized.

Capability: The program can be used as an analysis tool for the vertical forces and motion due to the longitudinal in-train dynamic forces which, when they become larger, could cause vertical coupler disengagement and/or car body separation from trucks. It can be used for train make-up evaluations in terms of vertical stability.

Method: This is a two-dimensional model developed to study the vertical and pitching motions and forces of loadings and trucks in a train consist under the action of in-train longitudinal forces. Car bodies, trucks, and loading are assumed to be rigid masses interconnected by a nonlinear spring and damper system. The equations of motion describing the force-acceleration relationship are numerically integrated using a modified Euler's method which yields velocities and displacements.

Limitations and Restrictions: The current version of the program does not have the capability of train operation simulation. In train dynamics, drawbar forces can be obtained through simulations using either the Train Operations Simulator (TOS), or the Detailed Train Action Model (DTAM), or tests. These forces may then be used as input horizontal coupler forces. Not more than ten vehicles in a train consist can be simulated.

Programming Language: FORTRAN IV

Documentation: To date, only the User's and Technical Manuals are available. The User's Manual is fairly easy to follow. The use of sample input cards and illustrations and suggested values for various input parameters is advantageous. A Technical Manual with illustrations helps the user gain insight into the model. It also compares the simulation results versus test.

Input: There are four sections of input:

1. Consist data which includes the number of cars, first and last car numbers, and train speed
2. Car data by geometry, weight, stiffness, and snubber damping force, coupler slacks, mass moment of inertia in pitching, and coefficient of friction
3. Horizontal coupler force acting at the front and rear end of simulated consist as a function of time
4. Simulation data, which includes time duration of simulation, integration time step, and plot option

Output: There are seven sections of output:

1. Echo of input data
2. Car body acceleration, velocity, and displacement
3. Coupler horizontal and vertical force and vertical slippage
4. Truck horizontal and vertical reactions and vertical displacement
5. Loading acceleration, velocity and displacement, friction, and end wall
6. Plot option echo
7. Draft gear characteristics.

Plot output is also available if desired.

Software Operation: Batch modes in cards. No pre- or postprocessors are available.

Hardware: The program was developed on an IBM 370/158 computer requiring 156 K bytes of core for execution. A total of five input, output, logical units are required in this program.

Usage: There are a limited number of users from railroads.

Typical Running Time: A typical 1 second run-in simulation on a seven car consist uses about 20 seconds of IBM 370/158 CPU time.

Availability: The program is being finalized. It will be available soon for \$50 through the Director - Technical Center
Association of American Railroads
3140 South Federal Street
Chicago, Illinois 60616

The fee covers costs of the magnetic tape of the program and all documentation available at the time of purchase.

Detailed Longitudinal Train Action Model (DTAM)

Categories: Longitudinal coupler forces, train operation, speed, distance

Authors: G. C. Martin, W. E. Plouffe, S. Ahmed, H. Antezak and H. Tideman
Association of American Railroads
3140 South Federal Street
Chicago, Illinois 60616

Maintenance: Association of American Railroads

Date: Currently unavailable. The program is being finalized.

Capability: The program handles simulations of freight train longitudinal train actions due to train handling, profile, and grade changes. The program can be used for performance evaluation of end-of-car cushioning devices and sliding sill equipment in controlling in-train dynamic forces.

Method: The program can be classified into 3 sub-programs by function. The Standard Library Program prepares vehicle data for standard locomotives and freight cars and stores the characteristics of equipment in the Standard Library, which may be saved for future runs. The Run Library Program constructs files for profile, curvature, consist, and station data. All data prepared by the Standard Library and Run Library Programs are input to the Detailed Train Action Model's Forward Integration Program which computes the acceleration of the train for each time step based on the net force and mass of the system. Numerical integration for velocity and displacement can be utilized through Hamming's, Runge-Kutta fourth order, or Beta method of integration. Relative velocities of neighboring vehicles, together with the amount of coupler slack form the basis for computing longitudinal coupler forces from draft gear characteristics.

Limitations and Restrictions: The program does not consider effects of track irregularities, worn wheels, and stuck brakes. All draw bar forces are assumed to be acting only in the direction of travel of the train. Only Mark-50 draft gear characteristics have been modelled in the program. Users, however, have been provided the option of inputting characteristics of any cushioning device.

Programming Language: FORTRAN IV

Documentation: User's Technical and Programming Manuals are available. The DTAM User's Manual describing the Standard Library, the Run Library, and the Forward Integration program, is somewhat confusing to first-time users, not because of the way the manual was written, but because of the complexities of the idea of three programs in one. Beginning users without prior exposure to the concept of a Standard

Library are strongly urged to attend one of the AAR-TTD seminars for further explanation of the program. The Technical Manual is quite technical and contains the validation of the DTAM program against SP Steel Coil Train Tests comparing stop distance, time, and coupler forces. The section illustrating tested draw bar forces versus relative car positions indicated a high degree of nonlinearities of energy dissipation exhibited by draft gears and hence explains why it is as difficult to accurately model a draft gear. The Programming Manual is voluminous and attempts to illustrate program logic in great detail.

Input: The Standard Library data should be available as part of the program package. Unless this is missing from the magnetic tape delivered, it is not necessary to input any data for the Standard Library Program. Input to the Run Library Program consists of track data including station name and speed limit, curvature and profile data, vehicle geometric and brake characteristics, train brake pipe pressure, and tractive effort and dynamic characteristics for non-standard power units. Input to the forward integration simulator includes the number of vehicles in the train, speed, throttle, and brake handling sequence, the condition of the rail, the integration time step, and instructions for how often braking and grade routines should be called.

Output: Output consists of an initial echo of input data including station and speed limit, curvature and profile data, train brake characteristics, and the vehicle listing showing all data used; this is followed by program debugging aids of initial forces and displacements of vehicles and various indices for error analysis. The main output of the DTAM are time and speed of the train and the mile post and distance reached by the front locomotives, throttle setting and amperage reading on locomotives, train line pressure, and independent brake setting. On vehicles specified by the user, the program outputs the vehicle location with the grade and curvature information, brake pipe and cylinder pressure, maximum and minimum front and rear draw bar forces. The program also indicates the maximum draw bar force and the location for each print interval. Plot outputs are also available.

Software Operation: Batch mode only; all input data is on punched cards; no pre- or postprocessors are available.

Hardware: The program was developed on an IBM 370/158 machine requiring about 400 K bytes of core for execution.

Usage: There are limited users only because the program is still not released.

Typical Running Time: DTAM requires about 15-20 IBM 370/158 CPU minutes for typical stopping simulations on a medium length train using the R-K integration scheme. Simulation time increases with train length and decreases with the use of Hamming's method and bigger time-steps for integration. However, the user is advised not to sacrifice program accuracy and integration stability by going to too large an integration time step, nor should he decrease the integration time-step unnecessarily, which will end up with cumulative truncation errors.

Availability: This is not currently available to the public. The program is in its final stage before release. When approved, the program

should be available through the
Director
Technical Center of the Association
of American Railroads
3140 South Federal Street
Chicago, Illinois 60616

Longitudinal - Vertical Train Action Model

Categories: Railroads, accident, collision, derailment, coupler override.

Descriptive Program Title: Longitudinal - Vertical Train Action Model

Author: K. Y. Sheng

Maintenance: School of Engineering and Applied Science
Washington University
St. Louis, Missouri 63130

Date: June, 1976

Capabilities: The program can be used for the simulation of the longitudinal - vertical motion of railroad cars during impact. The model is capable of modelling friction draft gears and hydraulic cushioning devices.

Method: Each freight car is modelled as rigid masses connected by springs and dampers having degrees of freedom in the longitudinal, vertical, and pitching directions. The underframe of each car is represented by a linear spring in series with the draft gear spring, which is represented by a hysteresis loop with different loading and unloading stiffnesses. Depending on the amount of coupler slack and the displacement, the horizontal coupler force is calculated from the draft gear characteristics. Vertical coupler force, vertical and horizontal truck forces, and lading dynamics are also computed. The program utilizes the fourth order Runge-Kutta for numerical integrations.

Limitations and Restrictions: The program does not provide for the consideration of plastic deformation of underframes under impact conditions.

Programming Language: FORTRAN

Documentation: Theoretical Manual and User's Guides are available. Both theoretical and user's sections of the manual are relatively straightforward, except the user is required to translate program variable names into English.

Input: There are three types of data to be input:

1. Train Consist Data: Total number of cars and number of impacted cars with selection of degree of freedom, coulomb of viscous for track vertical damping, and plot option
2. Simulation Data: Impact speed, program input boundaries, time steps for point and plot outputs.
3. Vehicle Geometric, Weight Data: Inertia and stiffness parameters

Output: Output is in three sections.

1. I/O logical units and word storage size
2. Echo of the input data including total number of cars, impact car, and impact speed. Simulation control data including step size, initial and final time, print and plot time steps. Vehicle parameters for all the cars, and draft gear and underframe characteristics.

3. For each print step it gives the horizontal coupler force, coupler displacements, relative displacements between adjacent cars, horizontal and vertical truck forces, coupler offsets, and truck separations and coupler disengagement, if any.

Software Operation: Batch mode

Hardware: This program was developed on an IBM 360/65 computer requiring 64 K bytes for execution with NSIZE = 1000. No pre- or postprocessor is available.

Usage: The number of users is unknown.

Typical Running Time: For a 0.04 second simulation, it took about 2.8 IBM 360/65 CPU seconds for execution.

Availability: A document which contains the listing of the program is available from

National Technical Information Service
Springfield, Virginia 22161

2.8 SOME EUROPEAN PROGRAMS

2.8.1 German Programs

This section is a translation of a German report entitled "Anhang - Synopse über Rechenprogramme zur Simulation der Fahrzeug-Fahrweg-Dynamik"

Computer Program 20807 (KIS)

Objective: Evaluation of parameter-dependent eigenvalues of linear, time-invariant differential equations. The eigenvalues of given system matrices for single wheel-sets, bogies or complete vehicles are computed as functions of velocity; in this way, the critical velocity of wheel/rail systems can be ascertained within the framework of a linearized wheel-set model.

Computer Program M 20210 (KIS) NISIRA (THL)

Objective: Intregation of the linear and nonlinear equations of motion for single wheel-sets to investigate stability under varying roadway boundary conditions and the effects of misalignment and other track irregularities (e.g. switch crossings).

Computer Program FRQ 240 VO 3 (German Federal Railway)

Objective: Determination of the vehicle data which fix the dynamical behaviour in the vertical direction. Small wheel forces and accelerations in the body of the vehicle are considered. The purpose is to define a wheel/rail test-base. In particular, assertions regarding

1. the geometry of the vehicle
 2. the distribution of masses, and
 3. the stiffness and damping in the first and second modes
- are developed.

Computer Program DIGSI (Technical University of Braunschweig)

Objective: Investigation of the influence of spring and damping elements in the coupling of three-car trains to increase ride comfort and safety.

Computer Program QUERSI (Technical University of Braunschweig)

Objective: Investigation of the influence of

1. the elasticity of the track
2. rail disturbance functions, and
3. vehicle data

on the behaviour of a two-axled vehicle by analyzing the lateral movements and rotations around the vertical axis. A comparison is made between the simulation results and actually measured system data.

Computer Programs TZX 245 and TZL 245 (Technical University of Hannover)

Objective: The effect of vertical track disturbances on the smooth running of the vehicle is investigated using a three-dimensional vehicle/rail model developed for this purpose. The vehicle and track data that are disturbance variables in the model are determined and their influence is investigated by means of the computer programs.

Computer Program STADYN (SNCF)

Objective: Investigation of the kinematic behavior of a bogie traveling in a straight line or along a curve as a function of the construction parameters and inaccurate positioning of the track.

Computer Program H-SRS (MAN-NT)

Objective: The following problem areas of wheel/rail and levitation systems are investigated:

1. adaptive regulator with regard to optimal response to disturbances
2. evaluation of the control forces and the required output of the regulator, and
3. simulation of real track irregularities.

These problems are investigated using a hybrid computer. The advantage of the analogue simulation is the real time computer speed. In a short time, numerous parametric investigations can be run. If the real track irregularities are stored on tape, the dynamic behaviour can be simulated over large time periods.

GENERAL COMPUTER PROGRAMS FOR MULTI-BODY VEHICLES

Computer Program FRQ V 05 (German Federal Railway)

Objective: Determination of the normal acceleration of the vehicle body as well as the dynamic normal forces on the wheels when crossing a bridge; a three dimensional FFD model is used. The data can be used to evaluate and compare the comfort and safety of various vehicle types and configurations. In addition, specifications for the damping, stiffness and other characteristics of the bridge can be determined.

Computer Program T 06 488 (German Federal Railway)

Objective: This program can be used to calculate the instantaneous position (bounce and pitch) and the accelerations of the vehicle body at the centroid and also over the axle bearings. In addition, the temporal mean square accelerations are constructed. Maximum and minimum values of these variables, as well as the vertical axle forces, bridge deflections for specified cross sections, etc., are determined. Finally, the ratio of the maximum dynamic deflection to the maximum static deflection (i.e. the "magnification factor") is calculated.

The calculations are based on a vertical model of a constant velocity train/rail/bridge system. Earlier, less complex versions of this program were used to investigate the bridge "magnification factor" in development work for the uniform international railway force profile UIC-71.

Computer Program FADYNA (DFVLR)

Objective: The computer program FADYNA was developed by ASIMO for the following problems:

1. Trade-off studies for the development and optimization of complete vehicle/roadway dynamical systems with regard to system components and parameters (e.g. studies to reduce the requirements placed on the roadway).
2. Comparison of the operating dynamics of various proposed systems (e.g. relative stability, comfort, loss of contact).
3. Verification of the results from design simulations and attendant assumptions; also, to investigate the effects of perturbations and variable inaccuracies on the simulation model.
4. Prediction of the overall dynamics of the AVF's in order to define experimental programs and to relate the experimental programs to the simulation model (model verification).

The following vehicle/roadway system interactions can be simulated:

1. rigid and elastic vehicles with levitation or wheel/rail systems,
2. active and passive, as well as linear and nonlinear vehicle suspensions,
3. rigid, prestressed and elastic column-supported roadways for a number of simulation cases,
4. straight-line operation, suspended operation,
5. travel over weight-dependent track irregularities,
6. operation on curved sections and operation with variable velocity,
7. emergency situations,
8. behaviour of the vehicle due to random disturbances.

Computer Program LINDA (Technical University of Berlin)

Objective: The analysis of free, periodically forced and randomly forced vibrations of arbitrary rail vehicles modeled as linear, multi-mass systems.

The following problems have been considered to date:

1. stabilizing modifications for a two-car subway train;
2. the influence of vehicle body elasticity on stability;
3. investigation of the stability of the model for a modern, high-speed coach;
4. systematic parametric studies of a four-axle railroad car with an elastic body;
5. periodic, vertical excitation of a four-axle railroad car with an elastic body.

Investigations of the following problems are either completed, in progress or planned:

1. estimation of natural frequencies (viz. eigenvalues and characteristic equations) (completed);
2. estimation of stability limits (completed);

3. determination of the influence of construction parameters on the running stability and the characteristic equations by automatic parameter variation (completed);
4. optimization with regard to maximum limiting stability velocity (completed/ in progress);
5. estimation of vertical vibrations due to periodic excitations (completed);
6. estimation of horizontal vibrations due to periodic excitations (planned);
7. estimation of the effect of vertical, randomly excited vibrations on ride comfort (planned);
8. estimation of the effect of vertical, randomly excited vibrations on horizontal comfort (planned);
9. quasi-linearization for the approximate treatment of geometric nonlinearities (planned).

Computer Program LINSYS (MAN-NT)

Objective: The standardized simulation of rigid-body, multi-mass systems. The eigen-behaviour (root-locus) and the time and frequency response can be investigated for

1. wheel/rail vertical systems
2. wheel/rail lateral systems
3. levitation systems.

The program can be used to design active components for wheel/rail vehicles.

Computer Program RADSCHI (MAN-NT)

Objective: The program can be used to investigate the influence of special construction variations on the behaviour of guided vehicles in the presence of realistic disturbances (e.g. non-linear coupling between the vehicle body and the running gear, nonlinear rotational constraints, nonlinear lateral wheel forces, localized contact stresses).

The following problems have been investigated to date:

1. simulation of the behaviour of general, guided vehicles on elastic track in the presence of disturbances,
2. special questions regarding the operating dynamics of the high-speed coach ET 403,
3. dynamics of the rolling modes of EDS-AVF,
4. levitation vehicles.

Computer Program APLDYN (APL/JHU)

Objective: Dynamic simulation of multi-mass vehicles traveling on the ground or on elastically supported guideways. The program can be used for prototype development. The equations of motion are constructed from the input data by preprogrammed subroutines. Translational and rotational (linearized) motions with up to three degrees of freedom are allowed, as are linear and nonlinear couplings between the masses.

REFERENCE

Anhang

Synopse über Rechenprogramme zur Simulation der Fahrzeug-Fahrweg Dynamik

2.8.2 South African Program

Computer Program R VEH 17 (South African Railways)

Objective: Comparison of various suspensions for wheel/rail vehicles with regard to their stability. The eigenvalues of the system matrix of the linearized system are calculated. The system matrix is derived using linear closed link theory.

2.8.3 British Programs

A description of three main programs used in England was supplied by:

Mr. T. G. Pearce
The Railway Technical Centre
London Road
Derby 49203
England

JAR53EV

This program computes the eigenvalues and eigenvectors of the matrix equation

$$[A]\ddot{q} + \left(\frac{[B]}{V} + [D] \right) \dot{q} + [C]q = 0$$

The eigenvalue calculation is carried out using the QR algorithm in the IVM Scientific Subroutines Library. This general form of matrix solution is preferred to the more specific vehicle model formulation as being more applicable to a research environment where many forms of vehicle model are explored.

Reference: BR. R&DD Technical Note MATH .1
Program Specification and Users Guide to the
Eigenvalue Program
by D. J. Evans and M. Ruhlmann
April 1970

JAR13

This program computes the frequency response and random response of the matrix equation:

$$[A]\ddot{q} + \left(\frac{[B]}{V} + [D] \right) \dot{q} + [C]q = [P]q_t + \left(\frac{[Q]}{V} + [R] \right) \dot{q}_t$$

where $\dot{q} = i\omega q$ and q is a complex variable.

Reference: BR R&DD Technical Note MATH 15
Users Guide to Program JAR13
by Mrs. S. Athey. May 1971.

JARDIPN

This program computes the time history of the response to a discrete

irregularity. It requires the Fourier transform of the irregularity, and the frequency response of the vehicle from Program JAR13. Conversion back from the frequency domain to the time domain is carried out by inverse Fourier transformation.

Reference: BR R&DD Unpublished Report
Programs Description and Users Guide to Program JARDIPN.
by J. M. Kimpton. July 1971.

3.0 SUMMARY OF RESPONSES TO USERS QUESTIONNAIRE

Questions: What programs do you use; what problems do you solve with the programs; how efficient are the programs; and how reliable are the computed results.

Responses:

STRU DL, NASTRAN, FASTDRAW

The user has written a FORTRAN program to study the transmissibility of suspension systems; the program is a two-degree-of-freedom time domain simulation which uses energy equations to model nonlinear springs and dampers. The results of the program have been verified as accurate for some rubber springs and friction dampers.

MSC/NASTRAN

The program is used to perform nonlinear transient dynamic analysis applying the super element approach for substructuring. A quarter of a tank car was modeled and mirror-imaged to produce a full car; a static analysis of the car was run using a million-pound static squeeze at the rear draft lugs; a modal analysis of the car was performed simulating the gaps between the centerplate, bowl, and sidebearings with nonlinear elements. The accuracy of results has not been checked.

Train Operation Simulator (TOS)

1. The program is used in derailment investigations. The force conditions at the moment of derailment are found for various conditions of train makeup train weight, track profile, and train speed. The user has little faith in the computed results and relies mainly on road tests and rock and roll tests.
2. The user has indirectly used the AAR Train Operation Simulator for locomotive fuel consumption computations. He believes some "bugs" are present in the program but does not elaborate.
3. The user has a copy of TOS but gives no further information.

4. The program is used for derailment analyses. The user believes the program is fairly effective, but thinks the amount of time necessary to accumulate and prepare input data is a deterrent to use of the program. He states that computer programs are the only way to settle questions of slack action effects in a train.
5. The program is used to find lateral forces, probably speed, braking distances, and buffing and drawbar forces.
6. The program is used for analysis of derailments and of train handling techniques. The program appears to give useful results, but the results will have not been fully validated. Better results are obtained if tractive effort is reduced 20 to 30%, wind resistance increased 200%, other train resistance coefficients increased to those of Daves formula. Nominal brake force was reduced 40 to 75% from vehicle library values in stopping tests.
7. The program is used for routing coal trains, computing track layouts, and investigating accidents. No validation of the results has been yet done.
8. The program is used to determine longitudinal drawbar forces between cars and locomotives operated in freight train service; it is used to determine lateral forces applied to track by cars in freight train operation; it is used to determine stopping distances of freight trains for accidents; and it is used to determine speed and distance traveled for individual cars and cuts of cars for switching yard design profile determination for yard re-design. As far as the user knows, lateral force computations have not been verified. Stop distance calculations were verified by Westinghouse Air Brake.
9. The program is used for analysis of train handling, derailments, stopping distance, and tonnage ratings. The program works well, but some minor problems exist. The accuracy of computed results has been verified by field measurements using strain gauge cars. The user considers the program inefficient for general tonnage ratings.
10. User has applied TOS in the past; he plans to use the AAR vehicle model to analyze derailments attributable to excessive lateral instability on rock and roll phenomena.
11. The program is used to investigate wheel/rail action at derailment sites. Some success has been achieved in running the program.
12. The program was useful in determining the gross effects of coupler force in specific train situations. The program was easy to gain access to and the runs were efficient. The user also runs a number of proprietary vehicle dynamics programs. His proprietary truck hunting program was validated using a combination of test results and Cooperider and Law's work on wheel/rail interface and freight car response.

AAR/TTD Nonlinear Flexible Car Body Vehicle Model (FVEH & DYCAR)

1. The program is used to find car design dynamic characteristics which involve roll angle and bounce under varying conditions of track cross-elevation, truck centers, and center-of-gravity.

2. The program is used for derailment analysis and for determining effects of various nonstandard dimensions of crosslevel and sidebearing clearance. The major shortcoming of the program is the lack of data on bending and twisting coefficients of various freight cars.
3. The program has been run but no use has been made of the results yet.
4. The program is used to analyze wheel lift and rock-off derailment potential of an individual car in a train. User has performed no validation of results but remarks that AAR has done some checking of results.
5. The program is used for optimization of suspension elements to give best performance in terms of roll angle and bounce accelerations. The user questions the application of two-section car body to flat car body. He has not verified the computed results.
6. The program is used for derailment analysis and to study the effects of equipment modification on derailment tendencie. The computed results have been verified with test track data.
7. User has found that considerable effort is needed to prepare input data and to interpret the computed results. The programs are used to investigate accidents and to check car design.
8. The program produces useful results, but difficulties exist in obtaining stiffness and initial data and the runs are expensive.
9. The program (FVEH) is used to study the effects of surface defects in track. The program gives reasonable results, but hte input is too complex. The program is expensive to run for parametric studies.

STRU DL II

The program is used to perform track structure component (rail, tieplate) stress analyses, freight car wheel design, and thermal input. The responder believes the results are good, but too much time is required to prepare the input and interpret the program output. He has verified his results with sample problems in plane-strain and by comparing results with other companies doing similar work but using different programs (Abex-ANSYS AAR Battelle).

STARDYNE (Version 3)

The program is used to perform a full range of static and dynamic structural analysis by the finite element method. The STAR program provides static load analysis and modal analysis, and DYNRE provides vibration and shock analysis. The user considers the program excellent for linear analysis; he has verified the results with test analyses of the AMTRAK bi-level coach carbody. The program operates efficiently for problems with 600 to 700 modes, but foru larger models the Lanczos extraction method is used to hold costs down.

Vehicle Dynamics Simulator (DYNSIM)

The program is used to analyze dynamical problems of rail vehicles. It numerically integrates many linear and nonlinear systems of differential equations. The program appears to give meaningful results for the response of 3-axle locomotive trucks to random irregularities in curved track. The computed results are in general agreement with experience and with linear eigenvalue analysis. The coding appears to be very efficient.

Generation of 3-Dimensional Elements (GRIDGN)

The program is used to generate and develop 3-dimensional elements of wheel designs. Considerable manual effort is required to augment the computer analysis. The computed results have been verified against a draftsman's layout.

Transcendent and Steady-State Temperature Distribution in Multi-Dimensional Systems (TRUMP)

The program is used to analyze the temperature distribution in wheels subjected to braking action. The program is very effective, and the computed results have been verified by empirical data.

Elastic Finite Analysis Stress Analysis (WHEEL)

The program is used to compare wheel designs with various axle loads and braking forces. The computed results have been verified against empirical data. The use of the program enables the designer to evaluate his designs without producing expensive prototypes.

WHRAILA Nonlinear Wheel/Rail Geometric Constraints

1. The program is used to find wheel/rail contact geometry functions for the scale model rail vehicle test program. The program gives generally good results, but the user believes the curvature results are suspect, especially when the wheel and rail curvatures are nearly conformal. The plotting subroutines are useful for only a specific machine, and problems may occur if the FORTRAN compiler will not handle extended dimensional statements. The computed results have been indirectly validated by experimentally measured wheelset forces.
2. The program is used to study the effects of surface defects in track. The program gives reasonable results, but the input is too complex. The program is expensive to run for parametric studies.
3. The program is used for derailment analysis and to study the effects of equipment modification on derailment tendencies. The computed results have been verified with test track data.

FORCES

The program is used to compute wheel/rail contact forces. The computed results have been experimentally confirmed.

Quasi-Static Lateral Train Stability Model (QLTS)

1. The program is used to study the effect of car configuration on curve negotiation. The programs appears to give good results, but the accuracy has not been verified.
2. The program is applied to jackknifing problems in which derailment is caused by high lateral forces created by high buff conditions interacting with the car geometry. The program was also applied as the design tool for the 3-unit articulated automobile carrier (autoguard). The program reliably predicts derailments caused by high L/V ratios.

Eight respondents reported they did not use dynamics programs.

Questions: What programs would you like to know more about, and in what areas do you think future program development should be concentrated?

Responses:

1. The user would like to run hunting and curving models of new truck designs, but current programs are fixed to the 3-piece truck and cannot be adapted. He would like a program to study single, fixed axle railcars. Existing programs should have features for inputting characteristics of nonlinear springs and dampers.
2. The user states that existing models ignore the varied inputs from the six different classes of FRA track. More attention should be directed to the differences between freight cars, locomotives, passenger cars, and rapid transit cars. He believes there is an overemphasis on the study of creep regarding freight cars as opposed to the study of truck and track behavior. He feels that knowledge of critical speeds is of limited usefulness to the designers. Programs which he believes he might use are Wyle Freight Car Hunting Model, AAR/TTD Nonlinear Hunting Model, Clemson Freight Car 5 and 9 Hunting Models, AAR 2-, 3-, and 4-axle Rigid Truck Curve Negotiation Model, ENSCO Rock and Roll Model, and Program FULL, FLEX, HALF, LATERAL.
3. The user would like a program for fatigue analysis of freight car components under various service conditions; however, he believes the present need is to apply fully the existing programs. He also is interested in finite element analysis of freight car structural components.
4. The user would like a single program that models all major dynamical phenomena.
5. The user would like programs for linear and nonlinear vehicle dynamics, especially lateral response and stability.
6. The user would like a program to study inelastic behavior of wheels in service and to study crack propagation as it is affected by design. He would like to learn more about statistical analysis programs.

7. The user would like a model that includes the effect of grade, curvature, in-train dynamics, acceleration or deceleration, and non-regular irregular cross-level. That is, he would like to be able to input irregular cross-level other than as a uniform 3/4 in. He believes that the lack of input data for carbody characteristics and the large amount of time necessary for gathering input data impede the applications of existing programs.
8. The user believes the lack of accurate input data limits the usefulness of programs. In particular he cites moments of inertia and locations of mass centers of modified carbody masses, stiffnesses between carbody masses, lateral and vertical track stiffnesses, and damping coefficients as constants which are difficult to ascertain.
9. User would like an impact model for a TOFC configuration.
10. User would like to study track structure force/deflection response to dynamic loadings. He believes he could apply track and roadway cost models, rail wear/fatigue life prediction models, wheel/rail contact geometry and force models, car and locomotive truck hunting and curving models, train operations simulator, and train action models.

4.0 CONCLUSIONS

The response to the users questionnaires indicated that the most widely applied programs are Train Operations Simulator (TOS), Quasi-Static Lateral Train Stability Model (QSLTS), and Nonlinear Flexible Car Body Vehicle Model (FVEH). The majority of the available codes are not in use; only eleven of a list of seventy codes were reported as being applied by at least one of the thirty-three responding users. Some programs which were not developed specifically for railroad applications are being used to analyze trains and rail cars, e.g., STRUDL, NASTRAN, and STARDYNE.

A limited amount of experimental and analytical verification of computed results has been done; most users felt that the programs gave reasonable results and that they executed efficiently. The complaint was frequently voiced that input data was difficult to obtain and organize. Many programs lack complete documentation; they were developed for specific tasks and are not suitable for general use.

Wear, fatigue, fracture, inelastic behavior, and impact were mentioned as areas in which computer programs might advantageously be applied. A pressing need appears to exist to apply existing codes more widely and effectively. Because of relatively wide application, programs TOS, QSLTS, and FVEH seem the best choices to be objects of improvement and validation programs.

The editors of this volume believe there is a technical deficiency in some of the eigenvalue programs, e.g., for lateral stability. None of these programs take advantage of available reanalysis technology which permits very efficient eigenvalue analyses to be performed. For example, improved efficiency would permit stability analyses to be performed over a speed range.

APPENDIX A

LIST OF RESPONDENTS TO THE
USERS QUESTIONNAIRE

Jeff P. Sandys
The Paton Corporation

J. J. Engle
Southern Railway System

M. F. Hengel
Missouri Pacific Railroad Co.

W. J. Bolla
Illinois Central Gulf Railroad

G. E. Dahlman
AT & SF Railway Company

J. A. Sivak
Union Tank Car Co.

M. Katz
Pullman Standard Company

L. C. Staten
FRA/TTC, Pueblo

H. A. List
REA Inc.

Larry M. Sweet
Princeton University

Timothy J. Devine
Griffin Wheel Company

John Baskin Harper
Rock Island Railroad

Robert M. Kionka
Chicago & Northwestern Transp.

Thomas H. Nixon
C & NW Transportation

Rao V. Dukkupati
National Research Council, Canada

Fred R. Sasser
Chicago Freight Car Company

Thomas J. Schoenleben
AAR

Steven J. Hakanson
Transportation & Distribution Association

James W. Hubbel
Elgin Joliet and Eastern Railroad

Ronald R. Newman
SLSF Railway

Gary Wolf

R. Yu
Canadian Pacific Railway

Eric Wolf
Trailer Train Company

J. R. Lundgren/W. J. Cruse
AAR Test Operations/TTC

R. W. Carman
Southern Railway

E. H. Waring/K. W. Bradley
D & RGW

P. L. Montgomery
Norfolk & Western Railway

E. Q. Johnson
Chessie System

V. Terrey Hawthorne
Railroad Dynamics Inc.

E. T. Franzen
Missouri Pacific Railroad

T. Hirai
Railway Technical Research Institute, Japan

M. Rougas
Bessemer and Lake Erie Railroad

R. F. Bush
Consolidated Rail Corporation

APPENDIX B

REMARKS ON THE USERS SURVEY

List of Programs Used as Indicated by the
Questionnaires Returned by the Program Users

Program	Number of Users
TOS	13
FVEH & DYCAB	9
QSLTS	3
WHRAILA	1
FORCES	1
DYNSIM	1
DLTAM	1
Train Dyn. Analy. (TDA)	1
GRIDGN	1
TRUMP	1
WHEEL	1

APPENDIX C

COMPUTER PROGRAMS LISTED BY CLASSIFICATION AND ORIGINATOR

Part I Classification of Programs*

A Lateral Stability Models

1. DYNALIST II
2. Battelle Truck and Car Hunting Programs TRKHNT, CARHNT, TRKV
3. Freight Car Lateral Stability (9, 17, 19, and 23 dof) Model (Clemson and Arizona State)
4. Arizona State Freight Car Hunting quasi-linear (9 dof) Model
5. Wyle Freight Car Hunting Model (nonlinear)
6. AAR/TTD Linear Hunting Model
7. AAR/TTD Simplified Nonlinear Hunting Model
8. AAR/TTD Nonlinear Hunting Model
9. AAR/TTD Hunting Model for Locomotives and Locomotive Trucks
10. Clemson Freight Car 5 and 9 dof Hunting Models (nonlinear time domain integration)

B Curving Dynamics Models

1. Steady state curving of two car bodies (Nichio)
2. Steady state curving of flexible truck (Newland and Boocock)
3. Battelle steady state curving analysis
4. Side thrust of curving wheels (Kuneida)
5. AAR Dynamic Freight Car curving model
6. AAR/TTD Phase II dynamic curving model of 6-axle locomotive with or without car
7. GEMD Quasi-static locomotive truck curving model
8. IIT freight car (43 dof/model - tangential track, transition curve, const. radius curve)
9. Clemson 9 dof freight car nonlinear steady state curving model
10. Clemson 17 dof rail car nonlinear steady state curving model
11. Arizona State nonlinear curve entry 9 dof model of half car
12. Arizona State nonlinear curve entry 27 dof 6-axle locomotive (CURVELCO)
13. AAR 2, 3, and 4-axle Rigid Truck Curve Negotiation Model (RTCN)

* References for these programs are given with the program listing under the originators' name (in the next section of this appendix). Most AAR/TTD programs are listed under V. K. Garg's name.

C Vertical Dynamics Models**

1. Dynamic Railcar Simulation Program (Melpar)
2. Battelle nonlinear freight car model
3. AAR/TTD nonlinear flexible car body vehicle model FVEH and DYCAB
4. ENSCO rock and roll model
5. Simple models for rock and bounce of freight car
6. Wyle lab model for response of flat car
7. AAR 6-axle locomotive model (LRM) (39 dof)
8. Program, FULL, FLEX, HALF, LATERAL (TSC)
9. Rail vehicle model (TRW)
10. Battelle linear vehicle model
11. Battelle vehicle/tract interaction model
12. Metroliner ride improvement model (Budd)
13. Rail car dynamic response (NASA)
14. Clemson freight car models: Linear 9 dof; Nonlinear 5 dof; Nonlinear 9 dof
15. Freight car response to driving functions, TDOP-model (Southern Pacific)

D Wheel/Rail Contact Geometry and Force Models

1. Dynamic loading in rail joints (BR)
2. Battelle model on vertical rail load
3. Variation of wheel load (Hirano)
4. Clemson wheelset model (linear)
5. Clemson wheelset dynamic response (nonlinear)
6. WHRAIL: Nonlinear wheel/rail geometric constraints (Arizona State University)
7. WHEELDAT (TASC): Generates simplified wheel and rail profile data (round rail, flanged-coned wheel) for use by WHRAIL
8. WHRAILA: Nonlinear wheel/rail geometric constraints (assymetric wheels, rails, and roadbed) (Clemson University)
9. CREEP: Calculates wheel/rail contact ellipse given profile and rolling radii; uses Kalker's tables to calculate creep coefficients (Clemson University)
10. FORCES: Calculates creep coefficients by Kalker's Simplified Theory of Rolling Contact given contact patch geometry; calculates creep forces given creepage (Clemson University)
11. FORCES - II (Clemson University)
12. CONFORM and COUNTACT: Calculate wheel/rail contact stress for conformal and counterformal contact problems
13. Lateral/Vertical Force Model: Simulates the dynamic response of a freight car truck and flanged wheels with emphasis on wheel/rail interaction (AAR)

E Freight Dynamics and Other Models

1. "FRATE" lading and vehicle model (Mitre)
2. AAR freight impact model
3. IIT/AAR freight damage model
4. FLA: Fatigue Life Analysis Model - freight car service life calculation (AAR) - TASC

**No review was received for this group of programs

5. Passenger truck model (LTV)
6. High speed passenger truck model (Battelle)
7. MIT Freight Car Response Model

F Analog/Hybrid Simulation Models

1. Clemson Hybrid, Nonlinear 5 dof Freight Car Hunting Model

G Train Dynamics Models

1. TOS: Train Operation Simulator (AAR)
2. EQUIP: generates standard vehicle data base for TOS (AAR)
3. DLTAM: Longitudinal train action model (AAR)
4. VEHICLE: generates standard vehicle data base for DLTAM (RUN) (AAR)
5. RUN: generates run-time files for DLTAM (SIM) (AAR)
6. Detailed Lateral Train Stability Model (AAR)
7. Vertical Train Stability Model (AAR)
8. QSLTS: quasi-static lateral train stability model (Track/Train, AAR)
9. Rail vehicle impact program (Washington University)

Part II List of Program Originators and Programs

Dr. V. K. Garg
Association of American Railroads
Research Center
3140 South Federal Street
Chicago, Illinois 60616

Hunting Model

Simplified Nonlinear Hunting Model [1]* - A7**
Linear Hunting Model for Freight Carts [2] - A6
AAR/TTD Hunting Model for Locomotives and Locomotive Trucks [3] - A9
Dynamic Freight Car curving model [4] - B5
Dynamic curving model of 6-axle locomotive with or without car [5] - B6
GMEMD Quasi-static locomotive truck curving model [6] - B7
2, 3, and 4-axle Rigid Truck Curve Negotiation Model (RTCN) [4] - B13
FVEH and DYCAR: AAR/TTD nonlinear flexible car body vehicle model [7,8] -
C3
6-axle locomotive response model (LRM) (39 dof) [9] - C7
Non-Linear Freight Car Hunting Model [10] - A8
Locomotive Dynamic Curving Model [5] - B6
Locomotive Response to Random Track Irregularities
Lateral/Vertical Force Model (AAR): Simulates the dynamic response of a
freight car truck and flanged wheels with emphasis on wheel/rail
interaction - D13
TOS: Train operation simulator [11,12] - E1
EQUIP: Generates standard vehicle data base for the TOS - E2
DLTAM: Longitudinal train action model [13,14,15] - E3
VEHICLE: generates standard vehicle data base for DLTAM (RUN) - E4
RUN: generates run-time files for DLTAM (SIM) - E5
Detailed lateral train stability model (AAR) [16] - F6
Vertical train stability model [17] - E7
QSLTS Mod: Quasi-static lateral train stability model [18] - E8
AAR freight impact model [19] - F2
FLA: Fatigue Life Analysis Model - freight car service life calculation -
F4

Dr. Robert Jeffcoat
The Analytic Science Corporation
6 Jacob Way
Reading, MA 01867

WHEELDAT: generates simplified wheel and rail profile data (round rail,
flanged-coned wheel) for use by WHRAIL - D7
RVCADDET: generates mean and covariance time histories (and steady state
values) given nonlinear vehicle equations and track geometry statistics.

* Square brackets indicate the reference for the program. The list of
references is found at the end of this section of this appendix.
** Refers to the program location in the previous section.

Dr. T. Yang
Chief Engineer
ENSCO
5408A Port Royal Road
Springfield, VA 22151

ENSCO rock and roll model - C4

Steward Esten
Duncan Sheldon
Kentron Hawaii, Limited
Cambridge, MA

Modified Quasi-Static Lateral Train Stability Model (QLTS)
Programs FULL, FLEX, HALF, LATERAL [20] - C8
FULL [21] - C8
FLEX [22] - C8
HALF [23] - C8
LATERAL: (Duncan Sheldon and Craig Schweinhart) [24] - C8

Melpar - An American Standard Co.

Dynamic Railcar Simulation Program [25] - C1

No developers name available

Rail Vehicle impact program [26] - E9

D. R. Ahlbeck
Battelle Columbus Laboratories
Applied Dynamics and Acoustics Section
505 King Avenue
Columbus, Ohio 43201

Truck and Car Hunting Programs TRKHNT, CARHNT, TRKV [27,28,29,30,31] - A2
Steady state curving analysis [32] - B3
Nonlinear freight car model [33] - C2
Linear response vehicle models [32] - C10
Vehicle/track interaction model [30,34] - C11
High speed passenger truck model - F6
Model on vertical rail load [32] - D2

Dr. T. Willis
Engineering Dept.
Portland State University
Portland, Oregon

Dr. Sudhir Kumar
Illinois Institute of Technology
Dept. of Mechanics and Mechanical and
Aerospace Engineering
3110 S. State Street
Chicago, Illinois 06016

Freight car (43 dof/model) - tangential track, transition curve, const.
radius curve [35] - B8
Freight damage model [36] - F3
Model for Rock and Bounce of Freight Car [37] - C5

Mr. J. Mitteering
Budd Co.
The Railway Division
Philadelphia, PA 19115

Metroliner ride improvement model [38,39] - C12

T. K. Hasselman
J.H. Wiggins Company
1650 South Pacific Coast Highway
Redondo Beach, CA 90277

Dynalis II [40] - A1

Mr. N. Sussman
The Mitre Corporation
1820 Dolly Madison Boulevard
McLean, VA 22101

"FRATE" lading and vehicle model [41] - F1

Mr. Karl Smith
Electromotive Division
General Motors Corporation
9301 West 55th Street
LaGrange, Illinois 60525

Quasi-static locomotive truck curving model [42] - B7

Burton Paul
University of Pennsylvania
Dept. of Mech. Engr. and Appl. Mech.
111 Towne Building
Philadelphia, PA 19104

CONFORM and COUNTACT: calculates wheel/rail contact stress for conformal
and counterformal contact problems [43,44,45] - D12

E. H. Law
Clemson University
Dept. of Mech. Engr.
Clemson, South Carolina 29631

Freight Car Lateral Stability (9,17,19, and 23 dof) Models [46,47,48,49] -
A3
Freight Car Hunting Quasi-Linear (9 dof) Model [50,51] - A4
Freight Car 5 and 9 dof Hunting Models (nonlinear time domain integration
[46,49] - A10
9 dof Freight Car Nonlinear Steady State Curving Model [52] - B9
17 dof Rail Car Nonlinear Steady State Curving Model [52] - B10
Nonlinear 5 D.O.F. Freight Car Forced Response Model [46,53] - C14
Nonlinear 9 D.O.F. Freight Car Forced Response Model [46,53] - C14
WHRAILA: Nonlinear wheel/rail geometric constraints (asymmetric wheels,
rails, and roadbed) [54] - D8
CREEP: calculates wheel/rail contact ellipse given profile and rolling
radii; uses Kalker's tables to calculate creep coefficients [55] - D9
FORCES: calculates creep coefficients by Kalker's Simplified Theory of
Rolling Contact given contact patch geometry; calculates creep forces
given creepage [55] - D10
FORCES-II [56] - D11
Clemson wheelset model (linear) [46] - D4
Clemson wheelset dynamic response (nonlinear) [57] - D5
Hybrid, Nonlinear 5 dof Freight Car Hunting Model [58,59] - G

Dr. Karl Hedrick
Mechanical Engineering Dept.
Massachusetts Institute of Technology
Cambridge, MA 02139

Freight Car Response Model [60,61] - F7

M. J. Healy
Wyle Laboratories
Colorado Springs Facility
4620A Edison Street
Colorado Springs, CO 80915

Freight Car Hunting Model (nonlinear) [62,63] - A5
Model for response of flat car [64] - C6

N. K. Cooperrider
Arizona State University
Dept. of Mech. Engr.
Tempe, AZ 85281

Freight Car Lateral Stability (9,17,19 and 23 dof) Models [54,55,56,57] -
A3

Freight Car Hunting quasi-linear (9 dof) Model [58,59] - A4

Nonlinear curve entry 9 dof model of half car [60] - B11

Nonlinear curve entry 27 dof 6 axle locomotive (CURVELCO) [60] - B12

Linear 9 D.O.F. Freight Car Forced Response Model [58,60] - C14

WHRAIL: Nonlinear wheel/rail geometric constraints [55] - D6

N. W. Luttrell
Southern Pacific Transportation Co.
One Market Street
San Francisco, CA 94105

Freight car response to driving functions, TDOP-model [62,65] - C15

TOS: Train Operation Simulator [11] - E1

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Part III List of Responding Program Originators

Program Originator

Programs Described

M. J. Healy
Wyle Laboratories
Colorado Springs Facility
4620A Edison Street
Colorado Springs, CO 80915

- i) Nonlinear model for response of flexible freight car (FRATE 11, FRATE 17).
- ii) Wyle Freight Car Hunting Model (HUNTCT)

Milton R. Johnson
IIT Research Institute
10 West 35th Street
Chicago, IL 60616

"Evaluation of Analytical and Experimental Methodologie for the Characterization of Wheel/Rail Loads"

Dr. Sudhir Kumar
Illinois Institute of Technology
Dept. of Mechanics and Mechanical and Aerospace Engineering
3110 S. State Street
Chicago, ILL 60616

- i) Freight car (43 dof) curving Model [47]
- ii) Freight Car Damage Model [50]
- iii) Model for Rock and Bounce of Freight Car [40]

T. K. Hasselman
J.H. Wiggins Company
1650 South Pacific Coast Highway
Redondo Beach, CA 90277

Dynamics of Articulated Linear Systems (DYNALIST II)

J. J. Kalker
Delft University of Technology
Dept. of Mathematics
Julianalaan 132
2628 BL Delft
The Netherlands

Tangential wheel-rail force calculation (DUVOROL)

George R. Doyle, Jr.
Research Engineer
Applied Dynamics and Acoustics Section
Battelle Columbus Laboratories
505 King Avenue
Columbus, Ohio 43201

- i) Two-Axle Steady State Curving (SSCUR2)
- ii) TRKVPSD Mod II B
- iii) Railroad Freight Car Simulation
- iv) Truck Hunting (TRKHNTII)
- v) Passenger Car Hunting (CARHNTII)
- vi) Rail Flaw Carriage (CARR)
- vii) Passenger Comfort in Spirals (SPICOM)
- viii) Vehicle Safety in Spirals (CRVENT)
- ix) 23 Degree-of-Freedom Rail Vehicle Model (23-DOF)
- x) 11-Degree of Freedom Railway Vehicle Model (11-DOF)

**Review and Summary of Computer Programs
for Railway Vehicle Dynamics (Final Report),
1981**
US DOT, FRA, Walter D Pilkey and Staff

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