Report # 9

REPORT NO. FRA/ORD-81/05

FUNDAMENTAL STUDIES RELATED TO WHEEL-RAIL CONTACT STRESS

BY

B. PAUL

JANUARY 1981

FINAL REPORT

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The technical monitor on this contract was Mr. Thomas P. Woll, Office of Research and Development, Office of Passenger Systems, at the agency address, phone (202) 426-9564.

16. Abstract
This Final Report summarizes the research performed and provides a brief review of the major results of the program.

The problems discussed include: the development of cost-effective methods for finding the wheel-rail contact patch, finding subsurface internal stresses, determining points where plastic flow will first occur, finding the distribution of surface shear stresses on the contact patch, finding the boundary between slip and adhesion on the contact patch, and finding the relationship between applied forces and wheel-rail creepage.

This work will be useful in explaining, and devising means of preventing various forms of stress-induced rail and wheel failures, as well as a whole complex of problems related to wheel-rail guidance and tractive forces. In particular, the dynamic behavior of rail vehicles can be analyzed relative to the forces developed at the rail-wheel interface.

17. Key Words	18. Distribution Statement
Rail-wheel Interaction, Contact stress, Conformal Contact, Elasticity, Creepage, Non-Hertzian Contact	Copies can be purchased from the National Technical Information Service (NTIS), Springfield VA 22161

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

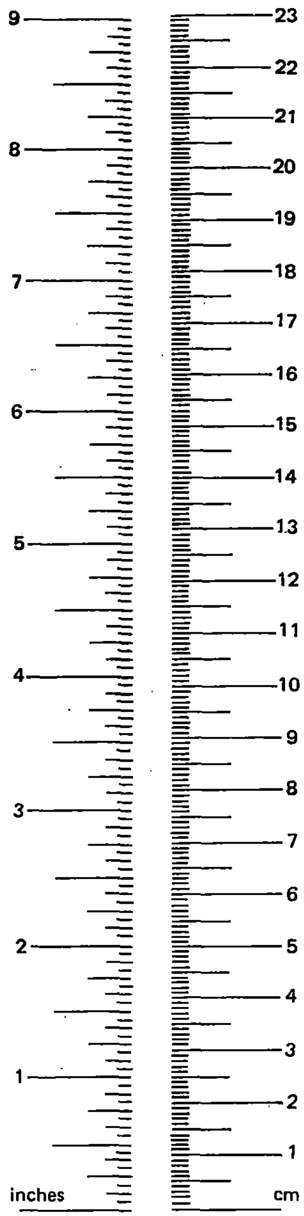
Form DOT F 1700.7 (8-72)

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

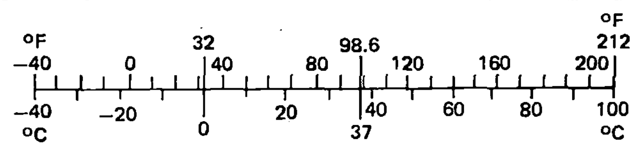
Symbol	When You Know	Multiply by	To Find	Symbol
	LENGTH			
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
	AREA			
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	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



FUNDAMENTAL STUDIES RELATED TO WHEEL-RAIL CONTACT STRESS

Final Report[1]

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January 1981

[1] on Federal Railroad Administration Contract DOT-OS-60144

TABLE OF CONTENTS

1. GOALS OF THE PROGRAM

The following information pertains to the project described in this Final Report:

Project Title: "Fundamental Studies of Phenomena Related to Wheel-Rail Contact Stress"

Contracting Agency: Federal Railroad Administration

Contract No: DOT-OS-60144

Contractor: University of Pennsylvania

Duration of Contract: 7/6/76 - 9/30/80

Principal Investigator: Burton Paul, Prof. of Mechanical Engineering

Contractor's Technical Representative: Thomas P. Woll, Manager, Signal & Controls

1.A Brief Definition of Problems Addressed

The research investigates the stresses (pressures and tractions) which exist at the wheel-rail interface or "contact patch." These problems include:

(i) The development of cost-effective numerical methods for finding the shape of the contact patch and the normal pressures acting on it. This capability is necessary for two classes of problems which arise in practice, namely for:

(a) antiformal (or counterformal) contact which occurs on new wheels at points well-removed from the throat of the flange.

(b) conformal contact which occurs on worn wheels especially near the throat of the flange.

(ii) Determination of the stresses inside the wheel and rail, just beneath the surface of the contact patch. It is these subsurface stresses which are the most critical.

(iii) Determining the location of and the magnitudes of those combinations of subsurface stresses which are most critical from the point of view of failure by plastic action which results in spalling (shelling), fatigue, and fracture.

(iv) Determining the distribution of tangential (shear) stresses on the contact patch.

(v) Determining the boundary line (separatrix) between those regions on the contact patch where sliding with frictional wear occurs, and those regions where adhesion (no relative slip) occurs.

(vi) Finding the relationship between the applied forces (normal and tractive) and the so-called "creepage" of wheel over rail that is known to control the dynamic behavior of rail vehicles.

1.B Relevance of the Research to the Railroad Industry

This work should be useful in explaining, and devising means of preventing, various forms of stress-induced rail and wheel failures, as well as a whole complex of problems related to wheel-rail guidance and tractive forces. In particular, the dynamic behavior of rail vehicles is very sensitive to the forces developed at the rail-wheel interface.

A better understanding of the wheel-rail interaction will contribute directly to a wide variety of current problems of rail research (e.g. noise; propulsion, braking, and power distribution; ride quality; derailment; reliability and maintenance; safety). For example, the noise due to wheel screech (on tight turns, braking and acceleration) and that due to flange impact (which is aggravated by the current trend towards the use of cylindrical, rather than conical wheels) originate at the wheel-rail interface. Propulsion and braking are adhesion limited in conventional rail systems. Power takeup, through third rail or catenary techniques, is limited, to a large extent, by maintenance of adequate but not excessive contact stress. Ride quality depends upon the system dynamics, the stability of which is governed by lateral and longitudinal creep (a contact stress dependent phenomenon). Derailment is often the end result of dynamic instability. The items "Reliability and Maintenance" and "Safety", are influenced by an improvement in rail-wheel understanding, due to the attendant possibility of improving wheel wear and roundness, track life, and the added understanding of dynamic factors entering into detailment problems.

There is a large worldwide effort now underway to develop computer programs which accurately predict the motion of realistic car and train configurations. It is now realized that the (heretofore used) Hertzian* analysis for contact stresses is inadequate for realistic worn wheels, that these stresses interact in a complex way with the dynamic motions of the vehicle, and that advances in the understanding of vehicle dynamics depends very much upon an improvement in the understanding of wheel-rail force and deformation patterns. This is particularly true for studies of the so-called lateral dynamics or hunting problem. Virtually all of the current generation of vehicle dynamics programs depend primarily upon numerical coefficients (creep coefficients) determined by J. J. Kalker of the Delft Technical University. But these coefficients were developed for a linearized theory that is unreliable for worn wheels or for contact of the wheels in the neighborhood of their flanges or near the gage corner of the rails.

The second generation computer programs now under development which are intended to analyze nonlinear vehicle motions (up to the limit of derailment) will require, as input, the information on rail wheel guidance forces of the type we are investigating. Current research on Vehicle Dynamics shows that this critically needed information must consider "realistic" curved or worn wheel and rail profiles, nonlinear creep, and contact patches near the limit of flange contact. All these considerations require a fundamental study of conformal contact stress problems of the type discussed in this report.

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*"Hertzian" analysis refers to the solutions generated by Heinrich Hertz at the turn of the century. Unfortunately, these solutions are only valid when the wheel-rail contact patch has an elliptical shape. This Hertzian case is known to be very far from the truth for many wheel-rail geometries.

2. RESULTS ACHIEVED DURING DURATION OF CONTRACT

This section will be restricted to the results achieved during the period July 1976 through September 1980. Related results prior to that period have been reported upon earlier.*

2.A Classification of Relevant Contact Problems

A detailed and systematic classification of all contact stress problems (both static and dynamic) is given in the survey papers of Kalker (1980).** For present purposes, the following narrower classification scheme will suffice.

Elastic contact stress problems are classified as Hertzian if they satisfy the following five conditions:

1. The bodies are homogeneous, isotropic, obey Hooke's law, and experience small strains and rotations (i.e., the linear theory of elasticity applies).
2. The contacting surfaces are frictionless.
3. The dimensions of the deformed contact patch remain small compared to the principal radii of the undeformed surfaces.
4. The deformations are related to the stresses in the contact zones as predicted by the linear theory of elasticity for half spaces (Boussinesq's influence functions are valid).
5. The contacting surfaces are continuous, and may be represented by second degree polynomials (quadratic surfaces) prior to deformation.

Contact stress problems are also classified as:

a. Counterformal (or antiformal), if Condition 3 is satisfied, or
b. Conformal, if Condition 3 is violated.

2.B Reports and Publications

The state of the art at the beginning of the subject contract is summarized in the publications B1, B2, B3, B4, B5. Here we restrict our discussion to a brief outline of work done on the subject contract. Complete Documentation of this work will be found in the FRA Technical Reports (TR's) listed in Section 4A and in the publications listed in Sec. 4B.

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*See Refs. A1, A2, B1, B2, B3, B4 in Sections 4A and 4B respectively.

**Kalker, J. J. "Review of Wheel-Rail Rolling Contact Theories," in The General Problem of Rolling Contact, AMD-Vol. 40, Edited by A. L. Browne and N. T. Tsai, American Society of Mechanical Engineers, NY, 1980, pp. 66-92.

2.C Antiformal and Simple Conformal Geometries

In T.R. No. 3, Paul and Hashemi (Ref. A3, reprinted as B6), developed a method which enabled them to solve antiformal contact problems for virtually any geometries. To do this, they developed a computer program called COUNTACT (COUNterformal conTACT) described in depth in T.R. No. 4 (Paul and Hashemi, A4). A summary of the characteristics of COUNTACT is given in Appendix A. Using COUNTACT, they presented the first known solution for a realistic wheel and rail profile in a non-Hertzian configuration (see Fig. 2-1) arising from a discontinuity in wheel curvature at the point of contact (common for new wheels). The corresponding contact patch is shown in Fig. 2-2, and the distribution of contact pressure along the line of symmetry is shown in Fig. 2-3. Note the great deviation from the classical solution of Hertz which is only capable of predicting elliptical contact patches and elliptical pressure distributions.

A summary of Program COUNTACT is included as part of Ref. B7.

2.D Conformal Contact of Wheels and Rails

The next major advance in this research was the development of a theory and a computer program to find the contact pressure, and contact patch for the hitherto unsolved case of <u>conformal</u> contact in wheels and rails. The computer program, called CONFORM, is given in the User's Manual, T.R. No. 5 (Paul and Hashemi, A5). The theory is presented in T.R. No. 6 (Paul and Hashemi, A6), T.R. No. 7 (Hashemi and Paul, A7), and T.R. No. 8 (Paul and Hashemi, A8).

The validity of program CONFORM was checked by considering the case of Fig. 2-4 where the rail corner makes highly conformal contact within the throat of the wheel flange. For the extremely light load of 1413 lb, the pressure distribution (Fig. 2-5.a) and the contact patch (Fig. 2-5.b) are both close to elliptical (Hertzian) and are both predicted with equal accuracy by CONFORM and by COUNTACT; this is to be expected in this nearly Hertzian situation. However, when the load is increased to the more realistic level of 19,000 lb, the contact patch (see Fig. 2-6.b) becomes noticeably non-elliptical. For this highly <u>conformal</u> situation, program CONFORM predicts the reasonable looking smooth pressure distribution, shown in Fig. 2-6.a) whereas program COUNTACT, which is not expected to be

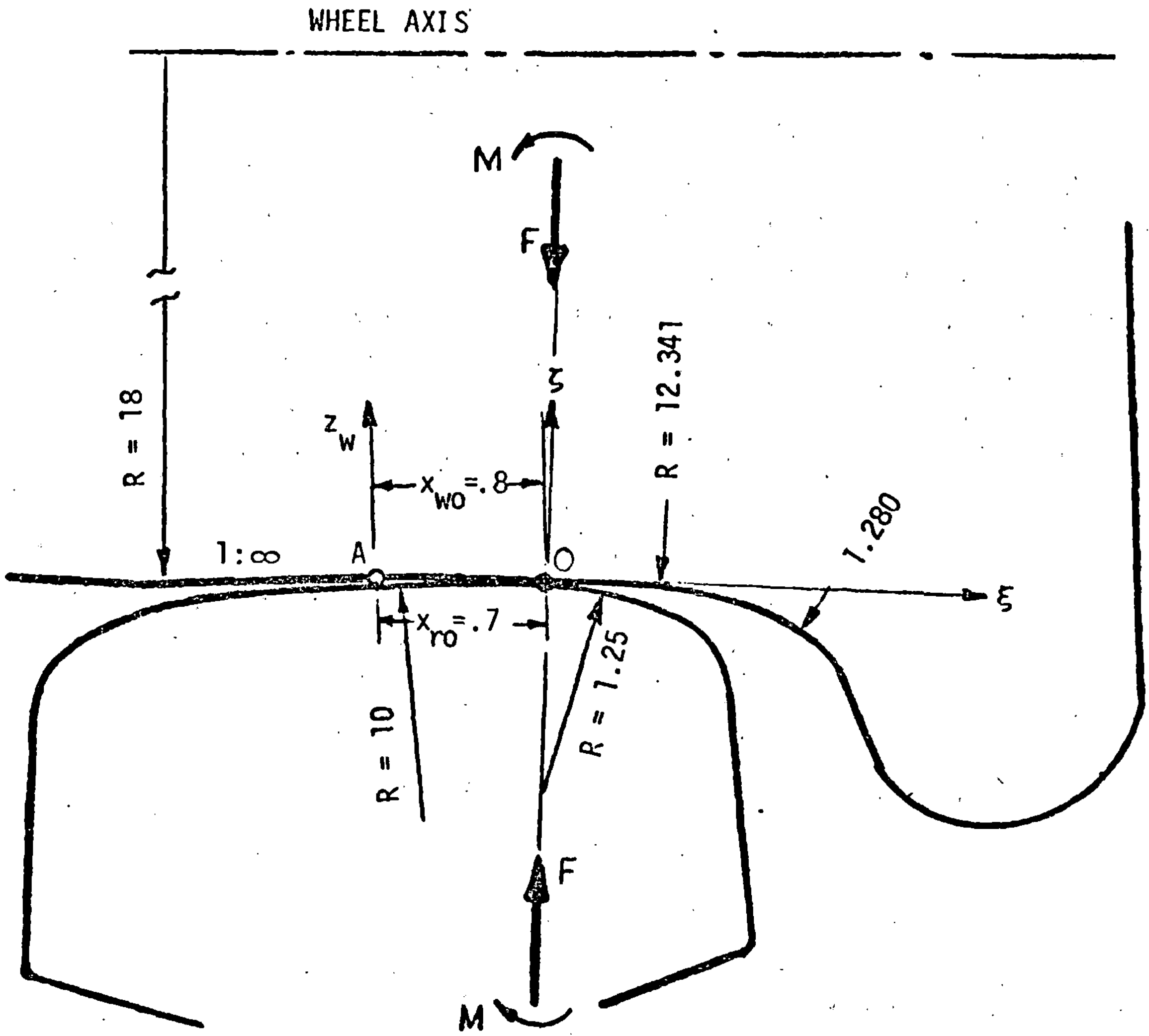


Fig.2-1.
Contact is non Hertzian. Note jump in rail curvature at point O. (From TR No. 4)

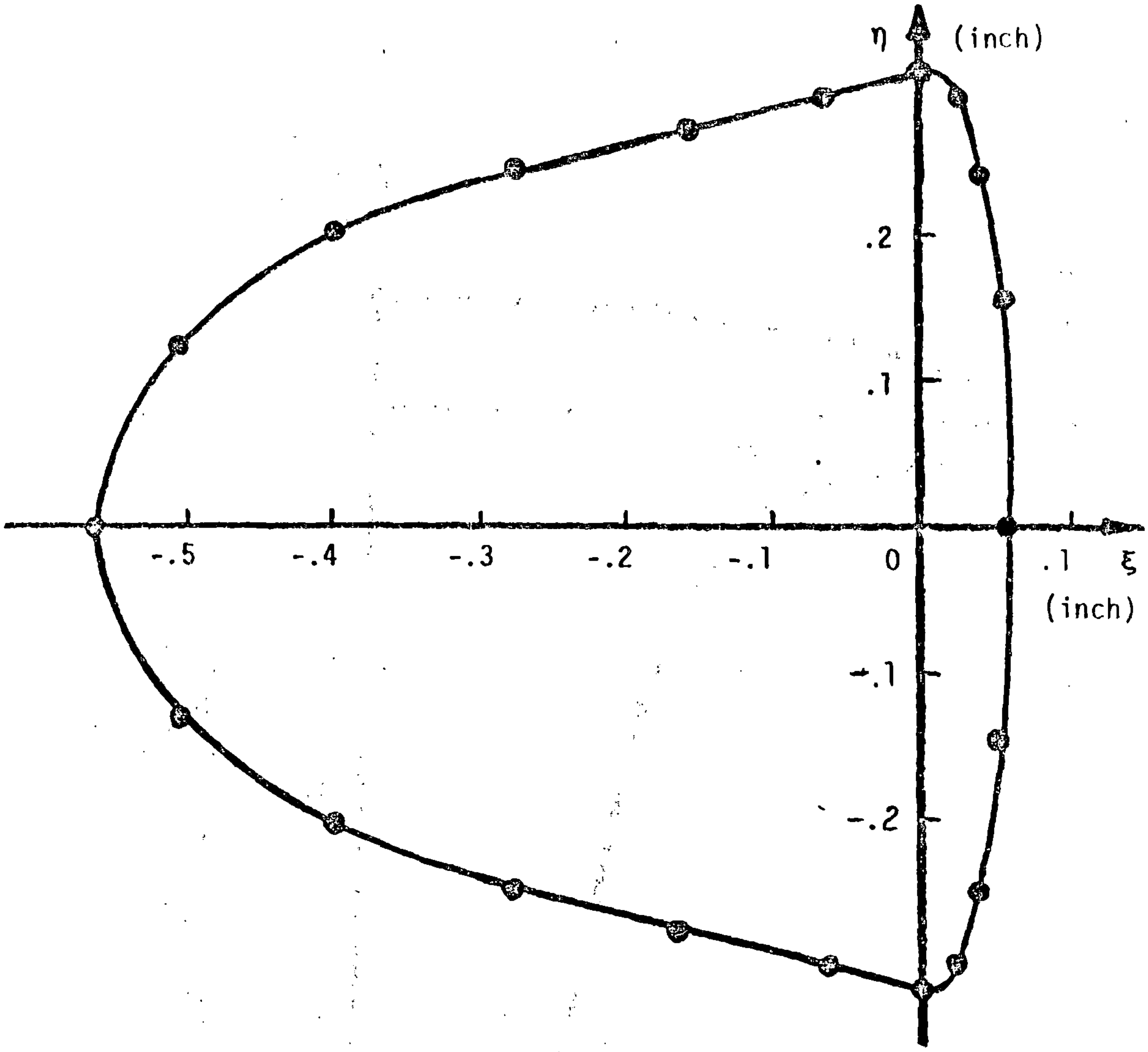


Fig. 2-2 Contact patch, F = 33,946 lb., δ = 0.005" corresponding to Fig.1. (From TR No. 4)

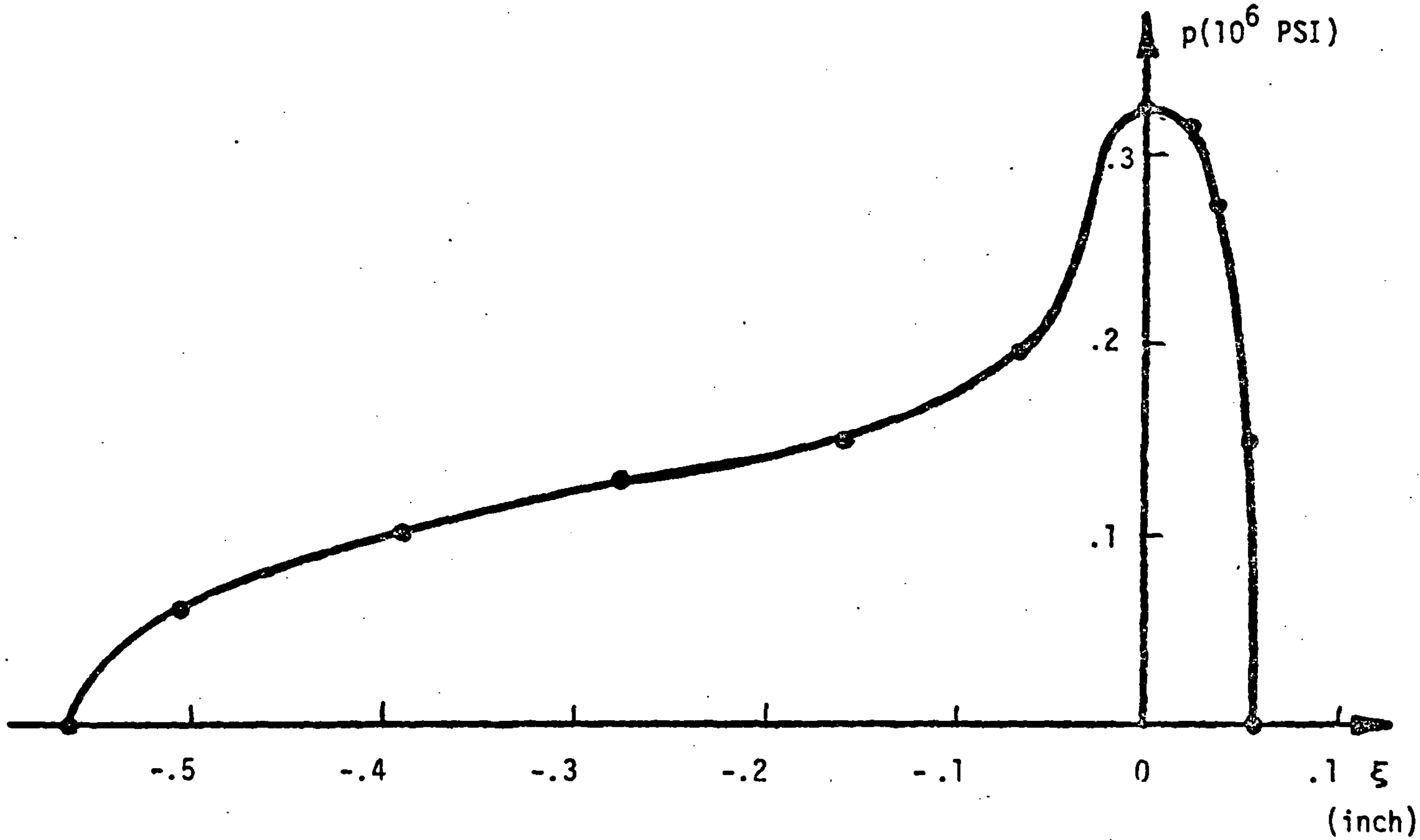


Fig.2-3. Pressure distribution
Load = 33,946 lb
Approach = 0.005" (From TR No. 4)

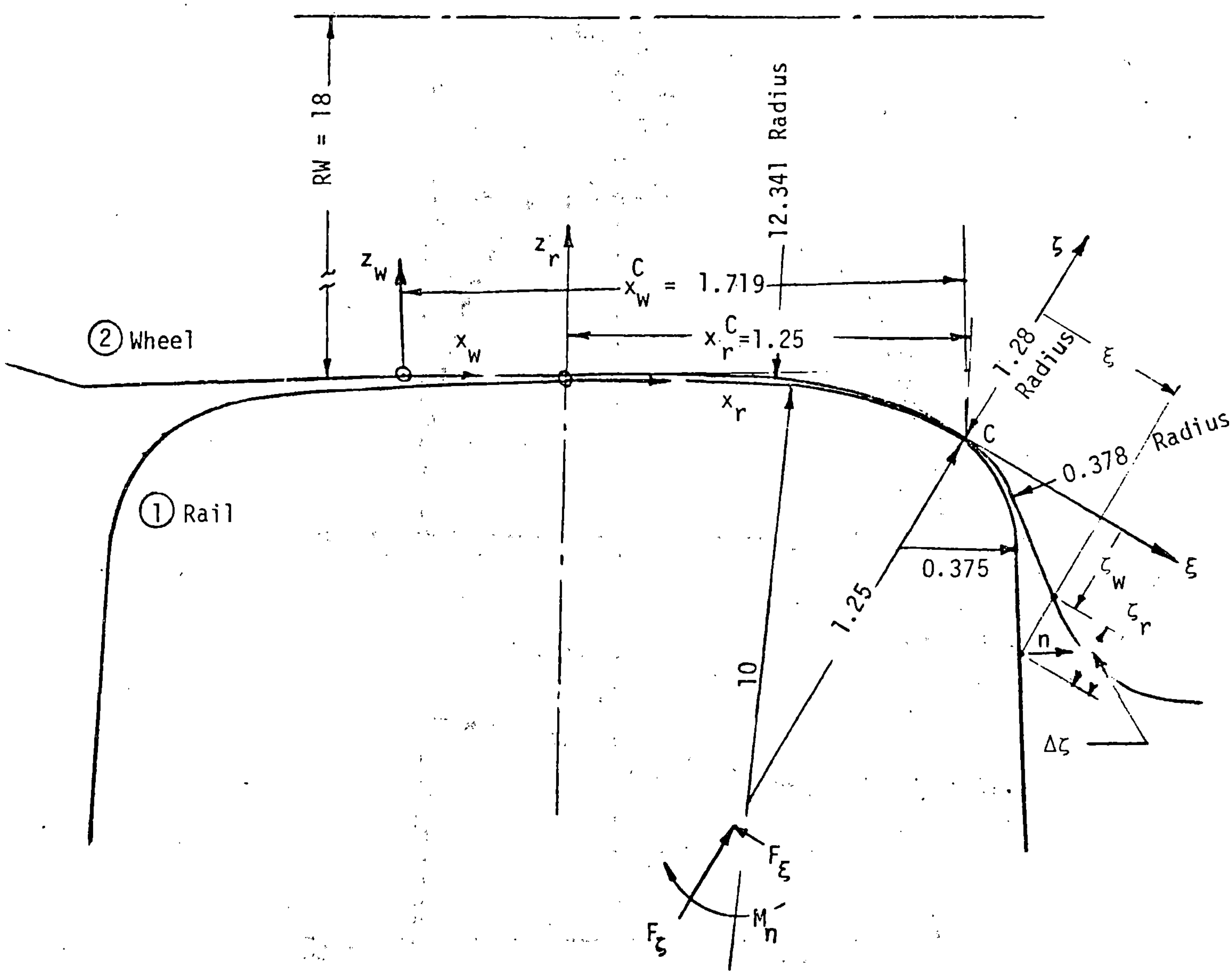


Fig. 2.4 Example of rail and wheel in conformal contact (unloaded case shown)
Numerical data is for 140RE rail (AREA designation) and for SIG Metroliner wheel (SIG=Schweitzerische Industrie-Gesellschaft)
(From TR No. 8)

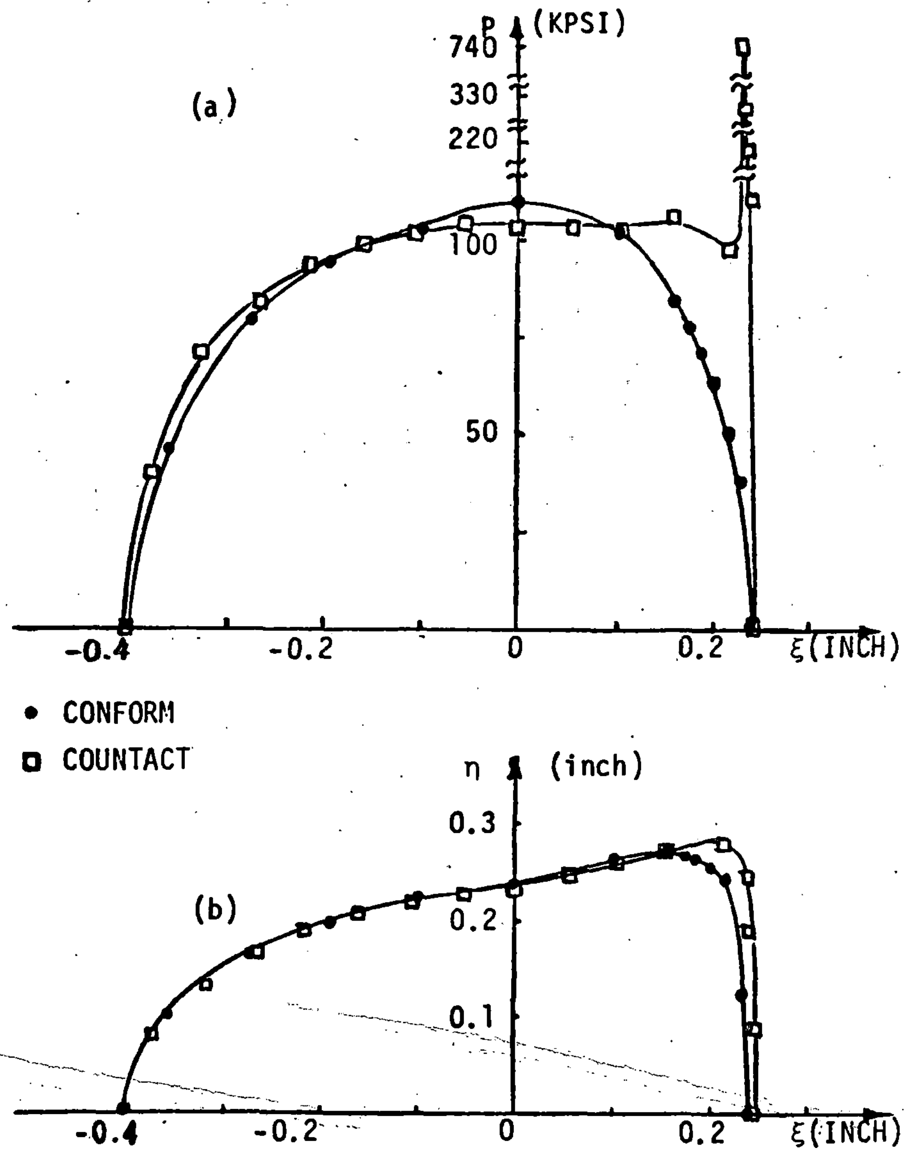


Fig. 2.5 Comparison of Programs CONFORM and COUNTACT for $\delta = 0.003''$
F = 20550 lb (COUNTACT), F = 19000 lb (CONFORM)
(a) Pressure distribution along the ξ axis
(b) Contact patch
(From TR No. 8)

accurate for such a highly conformal case, does indeed predict an unrealistic high pressure spike.

These examples show that we should expect to see situations in realistic wheels and rails where highly non-Hertzian contacts occur--either conformal or antiformal--depending on the transverse location of the wheel on the railhead; and that the programs developed can cope with all such cases.

2.E Critical Subsurface Stresses

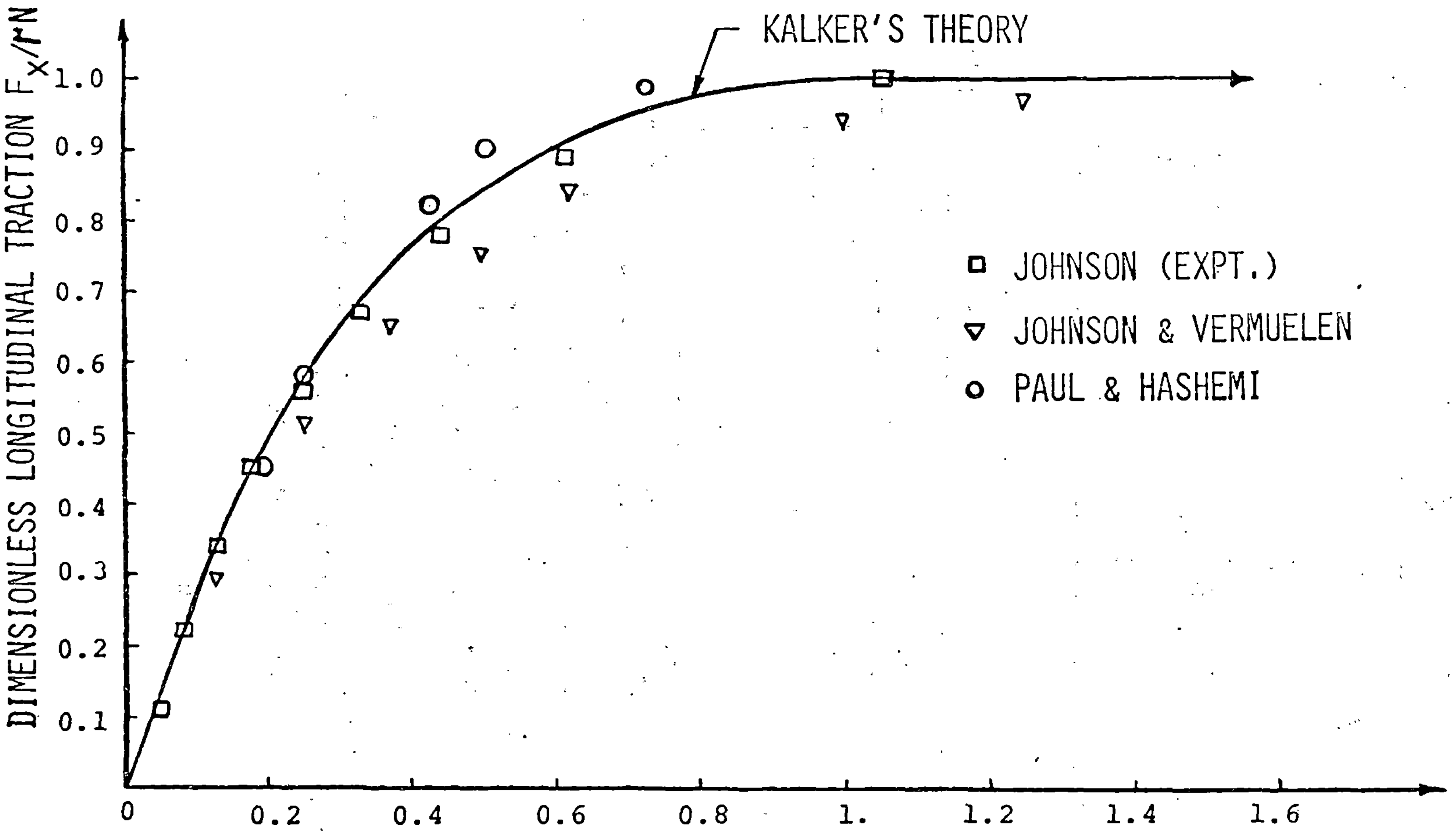
It is well known that, in the Hertzian case, the most critically stressed point does not lie on the contact surface; but just beneath the surface point where the contact pressure is a maximum. Furthermore, we know that the presence of friction can raise the critical point closer to the surface. Therefore, it is natural to suspect that a similar subsurface point is critical for non-Hertzian contact problems as well. To locate the critical point and determine the magnitude of the stress components at that point, we have generated a computer subroutine called SUBSIG which can find all six components of stress at any selected subsurface point when a surface of any shape (not just a plane) is loaded over an arbitrary region by an arbitrary distribution of normal and shear tractions. This subroutine can be used with program CONFORM to find subsurface points of greatest susceptibility to yielding or fracture. It can also be used for a similar purpose to find the influence on yielding of frictional forces generated during the process of rolling with creepage. Subprogram SUBSIG may be integrated with main programs CONFORM and COUNTACT.

2.F Rolling-Creepage Effects

The most important contribution of wheel-rail contact research to the problem of rail-vehicle dynamics is the determination of reliable information on the force-creepage relationships at the wheel-rail interface. For purely Hertzian contact we may draw on the excellent body of work on this subject by J. J. Kalker (Loc. Cit.). However, for non-Hertzian cases it has been necessary to develop a new approach to this mathematically difficult subject. At the present time, we have worked out such an approach and have developed a corresponding computer program (currently called

CREEPAUL-1) for the case of longitudinal creepage for arbitrary antiformal (Hertzian or non-Hertzian) contact. For example, Fig. 2-6 shows how favorably our numerical results compare (in the Hertzian case) with experimental results and with the simplified theory of Kalker.

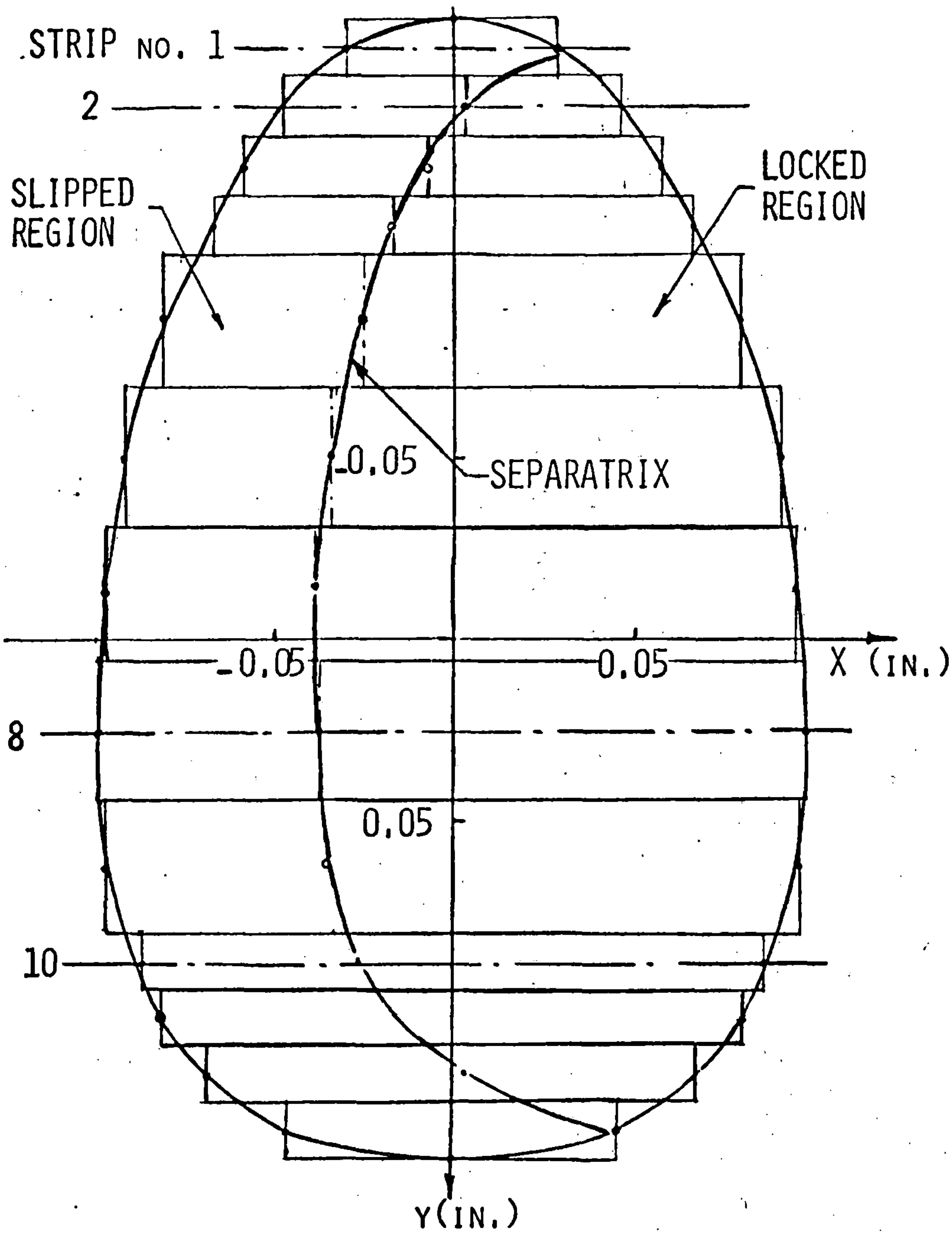
The great advantage of our method is that it is valid for any shape of contact patch and any contact pressure distribution--not just for the elliptical shapes required by all previous works on this subject. As an example of the generality of our approach we show, in Fig. 2-7, a typical non-Hertzian rail-wheel contact patch to which our method has been applied. The "separatrix" curve shown is one of the major results generated by our program. This curve separates the contact patch into a "locked" region where "pure rolling" action occurs and a "slipped" region where the wheel surface actually slides over the railhead surface. In Fig. 2-8, a corresponding set of curves shows how the longitudinal frictional force (shear traction) is distributed over the contact patch. So far as we know these are the first results ever to be reported on creepage calculations for non-Hertzian contact problems.



DIMENSIONLESS LONGITUDINAL CREEP $\bar{\nu}_x = \frac{E\,a\,b\,C_{11}}{3\mu N}\,\nu_x$

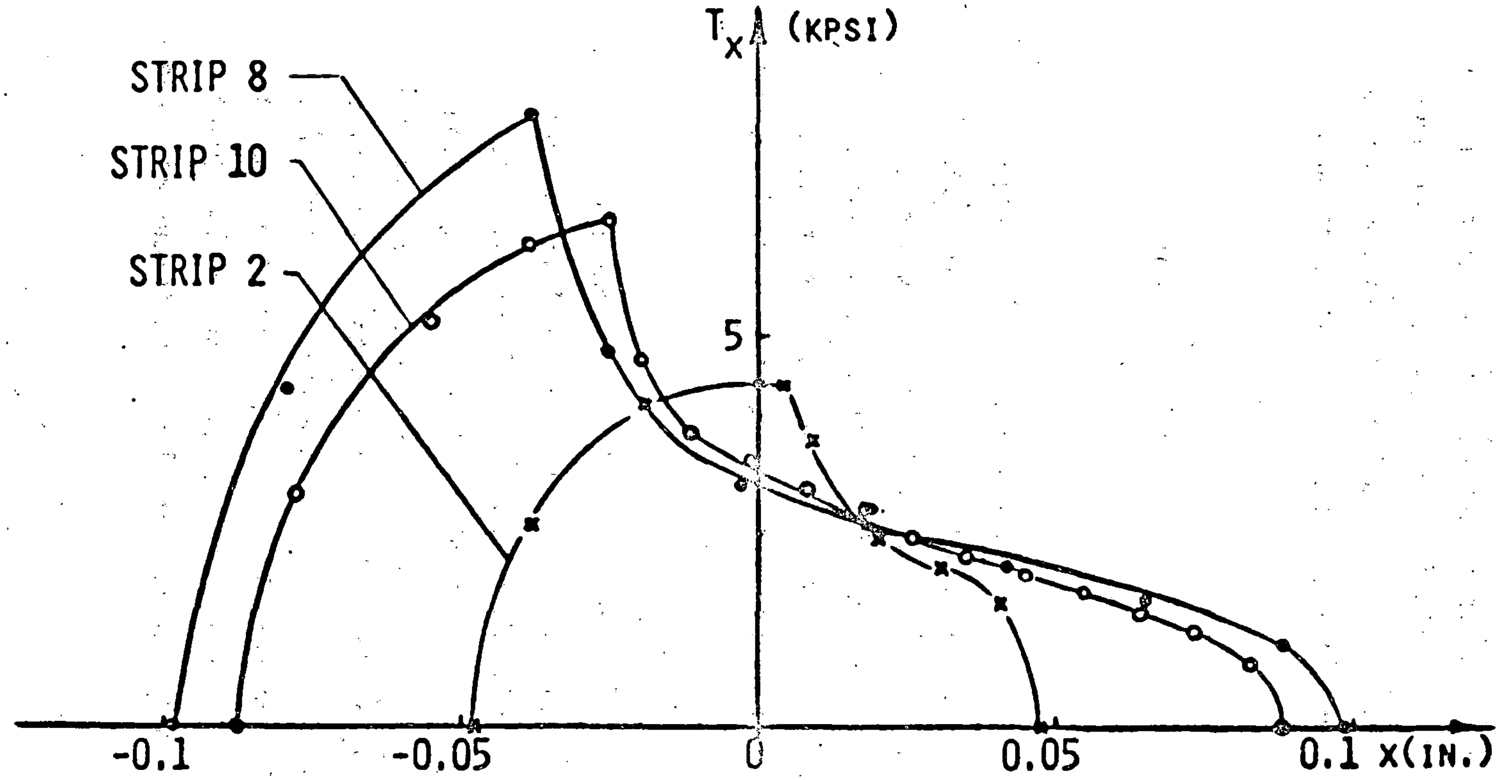
FOR HERTZIAN CONTACT (ELLIPTIC PATCH)

Figure 2.6



CONTACT PATCH OF NONHERTZIAN RAIL AND WHEEL,
(EX. 1 OF CONFORMAL MANUAL)

Figure 2.7



Longitudinal Traction Distribution for Typical Strips of NonHertzian Rail and Wheel Contact Problem . ν_x = 0.0003, N = 1400 lb, $F_x/\mu N$ = 0.6, μ = 0.2

Figure 2.8

3. DISSEMINATION OF THE RESEARCH

3.A FRA Reports

Six formal reports (Technical Reports Nos. 3 through 8 listed in Section 4A) have been generated on this contract as part of a continuing series of FRA reports. These reports (or announcements of them) have been distributed by FRA via the project's mailing list of approximately 300 domestic and foreign industrial, governmental, and educational organizations.

3.B Published Papers

Five papers generated on this contract that were published externally are listed in Section 4B as item B6 - B10.

3.C Presentations and Meetings

During the course of this contract, numerous oral presentations of results were made at meetings of the American Society of Mechanical Engineers, at Special Seminars called by FRA (both in Washington and in Boston) and at seminars at various Universities. In addition, the principal investigator has been in correspondence with numerous people within the USA and abroad, who have requested information on the research.

3.D Computer Programs

The computer programs generated are available to the public through the Technical Reports, from NTIS, and from the principal investigators. Among the researchers who have used these programs is British Rail. According to a private communication from Mr. R. J. Gostling of the Railway Technical Centre of the British Railways Board, they have run a comparison test case of program CONFORM with a computer program of their own (unpublished), and have found very good agreement. In addition, Mr. A. Jaschinski of DFVLR (the West German counterpart of our NASA) has volunteered to run an extensive series of cases on program CONFORM in conjunction with his research on wheel-rail contact forces and creepage.

4. Technical Reports and Published Papers Generated Under this Contract

4.A List of FRA Reports Generated on Contract*

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 286228/AS.

A4. Paul, B., and Hashemi, J., "User's Manual for Program COUNTACT COUNTer-formal 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, September 1979, FRA/ORD-78/41. Contract DOT-OS-60144.

A7. Hashemi, J., and Paul, B., "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, PB 299409/AS.

A8. Paul, B., and Hashemi, J., "Numerical Determination of Contact Pressures Between Closely Conforming Wheels and Rails", Technical Report No. 8. July, 1979, FRA/ORD-79/41, Contract DOT-OS-60144, PB 80120462.

*Items A1 and A2 were generated on an earlier contract, but are listed here for convenience.

4.B List of Externally Published Papers Associated with Contract*

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., K. P. Singh., 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 Report 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 Report A3).

B7. Paul, B., "Description of Program COUNTACT," in Review of Track-Train Dynamics Computer Programs, A Report to FRA by W. Pilkey, (c. 1980).

B8. Paul, B., "Description of Program CONFORM," in Review of Track-Train Dynamics Computer Programs, A Report to FRA by W. Pilkey, (c. 1980)

B9. Paul, B., and Hashemi, J., "Contact Pressures on Closely Conforming Elastic Bodies," in Solid Contact and Lubrication, AMD-Vol. 39, Ed. by H. S. Cheng and L. M. Keer, American Society of Mechanical Engineers, NY., 1980, pp. 67-78.

B10. Paul, B., and Hashemi, J., "Contact Geometry Associated with Arbitrary Wheel and Rail Profiles," in The General Problem of Rolling Contact, AMD-Vol. 40, Ed. by A. L. Browne and N. T. Tsai, American Society of Mechanical Engineers, NY., 1980, pp. 93-105.

*Items B1-B5 were generated on an earlier contract, but are listed here for convenience.

APPENDIX A

A SUMMARY OF PROGRAM "COUNTACT"

1. Program Name: COUNTACT

2. Categories (Keywords):

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

3. Descriptive Program Title:

   COUNTerformal contACT of two elastic bodies

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

5. 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).

6. 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. B6.

A User's Manual, Ref. A4, is available.

7. 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.

8. Programming Language:

FORTRAN IV.

9. 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.

10. 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 pressuresat 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 throught the contact patch.

11. Software Operation:

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)

Precision: Double precision

Storage Requirements: 2400 K

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 LEQT1F, plus a user-supplied subroutine (typically containing about 15 cards).

12. Example Problem Solved:

Fig. 2-1* 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. 2-2 is very far from elliptic; hence the problem is definitely non-Hertzian, although still conformal. The calculated pressure distribution, shown in Fig. 2-3 indicates a substantial pressure concentration. The complete input and output for this problem are described in the "User's Manual," (A4).

*Figures are located in Sec. 2 of this report.

APPENDIX B

A SUMMARY OF PROGRAM "CONFORM"

1. Program Name: CONFORM

2. Categories (Keywords):

   Wheel-Rail interaction; contact stress; conformal contact; non-Hertzian contact; elasticity.

3. Descriptive Program Title:

   CONFORMal contact stress problems

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

5. 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 (COUNTACT) 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.

6. 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. A8 and A7.

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

7. Limitations and Restrictions:

The program may be used for either counterformal or conformal contact, but program COUNTACT is more efficient for the simper case of counterformal contact.

8. Programming Language:

FORTRAN IV

9. 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 (A5).

(e) The initial separation (before deformation occurs) of neighboring points on each of the two surfaces must be calculated in a subroutine called INSEP. For arbitrary cases, the user must supply this subroutine, but for railroad wheels and rails, the program CONFORM contains a standard version of 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.

10. 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.

11. Software Operation:

Program is suitable for batch or time-sharing progress.

Machines: Tested on UNIVAC 90/70 (using BG-4 compiler)

Precision: Double precision

Storage Requirements: 120 K

Capabilities: CONFORM determines the shape of the contact region, the distribution of contact pressure, and the resultant force, on the surfaces of 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*), plus 390 in different subroutines of LEQT1F†, plus 258 in standard subprograms.

12. <u>Example Problem Solved:</u>

Fig.2-4** shows a cross-section through a Metroliner wheel and a standard rail, where the initial contact point C is on the throat of the flange at a point where both the wheel and rail experience jump discontinuities in curvature. Note that the contact is <u>highly conformal</u> 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.B-1 (only the upper half is shown in Fig.B-1, 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.B-2(b). The corresponding pressure distribution along the axis of symmetry is shown in Fig. B-2(a).

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*The current version of CONFORM contains 192 comment cards.

†LEQT1F is a subroutine for solving linear equations; it is part of the IMSL Library.

**Fig. 2-4 is located in Sec. 2 of this report.

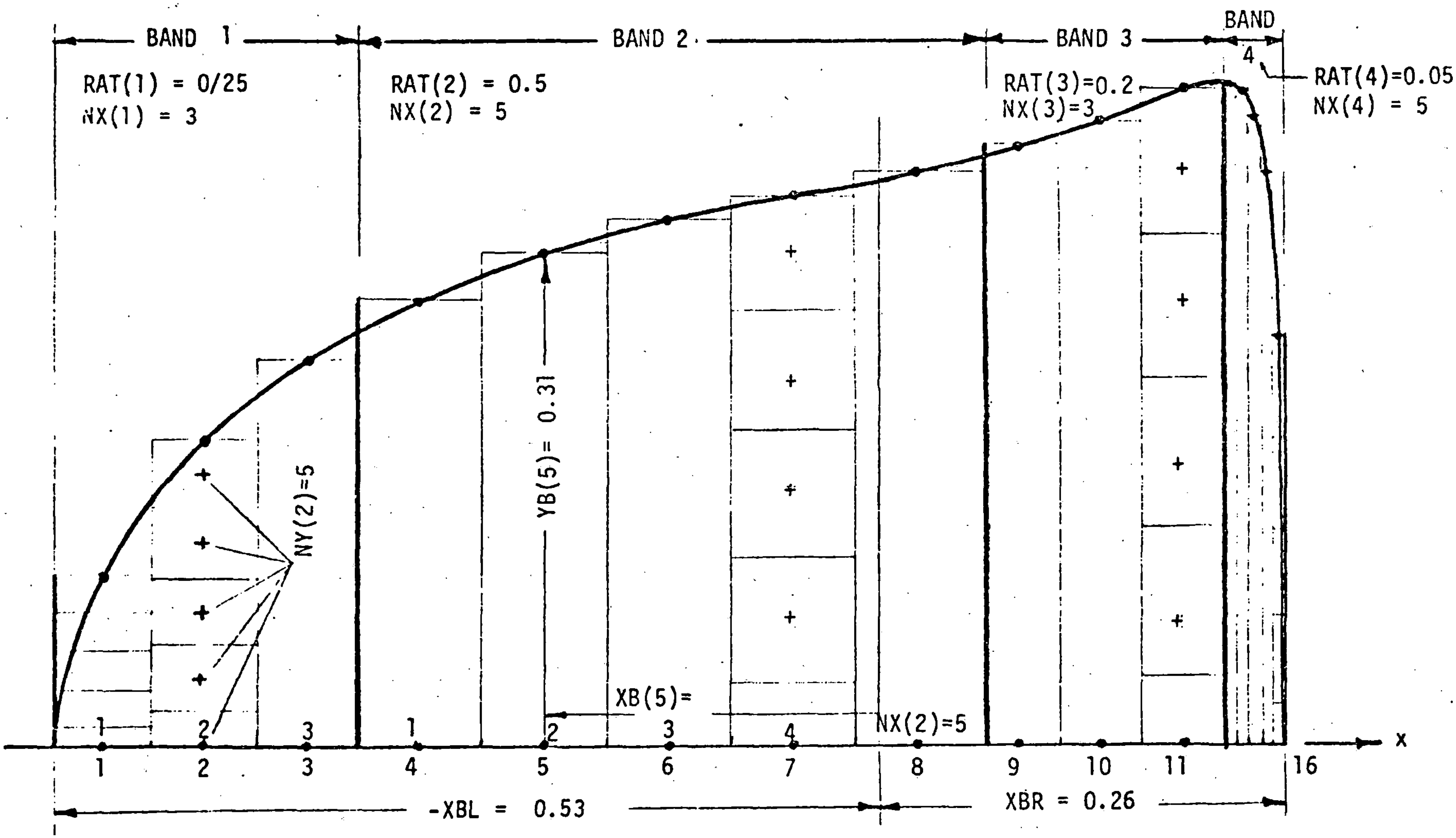

Fig. B-1 Interpenetration curve used as initial candidate contact patch boundary, corresponding to Fig. 1 , with δ = 0.003 in. Curve is symmetric about x axis

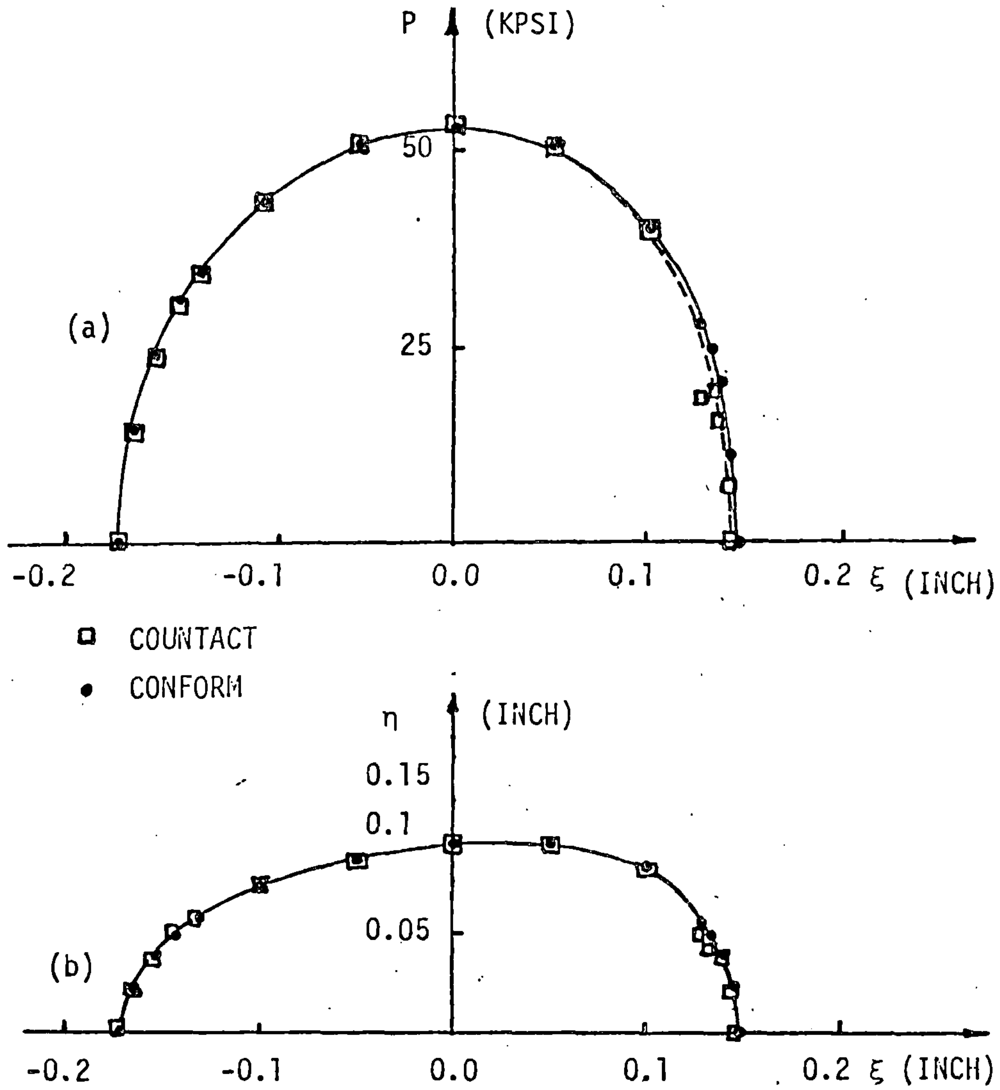

Fig. B-2. Comparison of Programs CONFORM and COUNTACT for δ = 0.0005."
The corresponding forces are: F = 1413 lb (CONFORM),
F = 1434 lb (COUNTACT)
(a) Pressure distribution
(b) Contact patch

Fundamental Studies Related to Wheel Rail Contact Stress (Final Report), 1980
US DOT, FRA, B Paul