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USERS' MANUAL FOR PROGRAM FOR CALCULATION OF KALKER'S LINEAR CREEP COEFFICIENTS

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16. Abstract

A program written in FØRTRAN IV is described that uses the Hertz theory of rolling contact between two bodies and Kalker's linearized theory of creep to determine the geometry of the contact patch between railway vehicle wheel and rail and the creep coefficients that characterize the linearized creep forces between wheel and rail. The program input, output and the subroutines used are described herein and the results are in the form of printout. The manual includes program listings, sample deck set ups and sample run outputs. Two other user's manuals for determination of creep forces and moments have been issued under this contract. These are "Users' Manual for Kalker's Simplified Nonlinear Creep Theory" by J.G. Goree and E.H. Law and "Users' Manual for Kalker's Exact Nonlinear Creep Theory" by J.G. Goree.

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I. INTRODUCTION AND PURPOSE

The program described in this report and its constituent subroutines were developed to calculate the geometry of the contact patch together with the linear creep coefficients that characterize the shear or frictional forces acting between a railway wheel rolling over a rail or roller.

The other Users' Manuals developed under this contract describe computer programs dealing with the creep forces between wheels and rails [1,2]. The programs described in these other Users' Manuals are FØRTRAN versions of ALGØL programs developed by Professor J. J. Kalker. The first, [1], implements Professor Kalker's simplified theory of rolling contact [3]. The second, [2], implements his complete theory of rolling contact [4]. Both theories are for nonlinear creep force-creepage characteristics. This manual, however, describes the program needed to calculate the linear creep coefficients that characterize linear creep force-creepage relationships.

The program has been written to first solve the Hertzian contact problem [5]. Then the linear creep coefficients are calculated using the linearized theory of creep developed by Kalker [4,6].

II. METHOD

The program consists of two parts.

1) Calculation of the Contact Patch Geometry and the Maximum Stresses. The calculation of the contact patch geometry and the maximum stress is based on the Hertzian theory of contact. The mathematical basis for the formulation and the procedure for the calculation of the contact patch geometry is described in detail in [5, 6, 7]. The procedure is briefly described here and a sample calculation is also shown below.

The normal force of contact between two contacting surfaces, their longitudinal and transverse radii of curvature, and the elastic properties of each of the bodies in contact are required in the form of input data for the calculation of the contact patch parameters. In [5], Timoshenko defines the semi axes of the contact ellipse as:

$$a' = m\ \{3\pi P/4)(k_1+k_2)/(A+B)\}^{1/3} \tag{1}$$

and

$$b' = n\ \{3\pi P/4)(k_1+k_2)/(A+B)\}^{1/3} \tag{2}$$

where P is the normal load across the contact area

$$k_1 = (1 - \nu^2)/(\pi E_1) \tag{3}$$

$$k_2 = (1 - \nu^2)/(\pi E_2) \tag{4}$$

ν_1, ν_2 are the values of Poisson's ratio and E_1, E_2 are the moduli of elasticity of bodies 1 and 2 respectively. The constants m and n depend on θ and are obtained from a table in [5], where $\cos\theta = |B-A|/(A+B)$. The parameters A+B and B-A are given by the relationships

$$A+B = (0.5)\{1/R_1+1/R_1'+1/R_2+1/R_2'\} \tag{5}$$

and $$B-A = (0.5)\{(1/R_1-1/R_1')^2+(1/R_2-1/R_2')^2+2(1/R_1-1/R_1')(1/R_2-1/R_2')\cos 2\psi\}^{1/2} \tag{6}$$

where $1/R_1$, $1/R_1'$ are the principal curvatures of body 1 at the point of contact.

$1/R_2$, $1/R_2'$ are the principal curvatures of body 2 at the point of contact.

ψ is the angle between the normal planes containing $1/R_1$ and $1/R_2$

In [5], the table given for the constants m and n as a function of θ extends from $\theta = 30°$ to $\theta = 90°$. However, as the value of θ may range from 0° to 90°, the table has been extended in the program to run from $\theta = 0°$ to $\theta = 90°$. Values for θ from 0° to 30° are given in [8]. From the tables given in [5, 8], it is noted that $m > n$ for all values of θ between 0° and 90°. Hence from equations (1) and (2)

$a' > b'$

The particular orientation of the contact ellipse relative to the contacting surfaces is not discussed in [5]. Knowledge of this orientation is essential for calculation of the creep coefficients. The procedure for finding the orientation is discussed below.

The principal radii of curvature and the angle ψ are defined in relation to the wheel/rail contact problem in Figure 1. Considering the wheel as body 1 and the rail as body 2, then

- R_1 is the principal rolling radius of the wheel
- R_1' is the principal transverse profile radius of the wheel
- R_2 is the principal longitudinal radius of the rail or roller
- R_2' is the principal transverse profile radius of the rail head or the roller head.

Equations (1) and (2) have been developed using a fixed sign convention for the radii of curvature R_1, R_1', R_2 and R_2'. As stated in [5] and shown in Figure 2, these are positive if the center of curvature at that point lies inside the body and negative if the center of curvature lies outside the body.

The angle $\psi \simeq 0$ and $\cos 2\psi \simeq 1$ as the yaw angle of the axle centerline with respect to the track centerline is at the most 1 or 2 degrees. A further discussion of this can be found in [9]. Equation (6) then reduces to

$$B-A \simeq (0.5)\ \{1/R_1-1/R_1'+1/R_2-1/R_2'\} \qquad (7)$$

The calculation procedure for the creep coefficients requires that the dimensions be specified for axes of the contact ellipse in the direction of rolling and transverse to the direction of rolling [1]. As indicated in [4, 7], when

$(1/R_1+1/R_2) \geq (1/R_1'+1/R_2')$

then the transverse semi-axis of the contact ellipse is greater than or equal to the longitudinal semi-axis; i.e.

ALØNG = b' = longitudinal (minor) semi-axis

BTRANS = a' = transverse (major) semi-axis

Conversely, if

$(1/R_1+1/R_2) \leq (1/R_1'+1/R_2')$

then the transverse semi-axis is less than or equal to the longitudinal semi-axis; i.e.,

ALØNG = a' = longitudinal (major) semi-axis

BTRANS = b' = transverse (minor) semi-axis

ALØNG and BTRANS are also the FØRTRAN symbols used in the program.

The maximum pressure at the contact ellipse is defined as

$$q_o = (3/2)(P/\pi a'b') \qquad (8)$$

where P, a' and b' are as defined previously.

The average normal stress at any point can be easily calculated. The average normal stress is defined as

$$\sigma_z = - q_o$$

and the maximum shear stress for a Poisson's ratio of 0.3 is

$$\tau_{max} = 0.31\ q_o \qquad (9)$$

The value of τ_{max} calculated in the program is valid only for a Poisson's ratio of 0.3. However, since the procedure required to calculate

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(1) For the problem of a railway wheel rolling or a rail or a roller, it can be shown that the major and minor axes of the contact ellipse are very nearly in the direction of rolling and transverse to the direction of rolling or vice versa.

the exact value of the shear stress is a fairly involved one, it is felt that this approximate value of τ_{max} gives a good estimate of the actual shear stress for materials used in the construction of railway rails and wheels.

A table giving the FØRTRAN equivalents of the symbols used previously to define the various variables involved in the calculation of the contact geometry is given in Table 1.

a) Sample Calculations.

A sample calculation is illustrated below for the same case as sample computer run, Problem (1). This is the case of a moderately worn AAR wheel on a new rail. The input data are as follows.

Rolling radius of the wheel, $r = 1.3690$ ft

Principal transverse or profile radius of wheel, $R_1' = -1.6487$ ft

Principal longitudinal rail radius, $R_2 = \infty$

Principal transverse or profile radius of rail, $R_2' = 0.24088$ ft

Wheel load, $P = 11080$ lb

Poisson's ratio for wheel, $\nu_1 = 0.24$

Poisson's ratio for rail, $\nu_2 = 0.24$

Modulus of Elasticity for wheel $E_1 = 30 \times 10^6$ psi

Modulus of Elasticity for rail, $E_2 = 30 \times 10^6$ psi

Contact angle, $\delta = 0.0$ radians

Although the actual contact angle is not zero, it is used only in the calculation of the principal rolling radius. The rolling radius, $r = 1.3690$ ft, is for this problem actually the principal rolling radius, R_1. Then using equations (5) and (7)

$$A+B = (0.5)[(1/1.3690) - (1/1.6487) + 0 + (1/0.24088)] = 2.1376 \text{ ft}^{-1}$$
$$= 0.17813 \text{ in}^{-1}$$

and

$$B\text{-}A = (0.5)[(1/1.3690 + 1/1.6487 - 1/0.24088)] = -1.4072\ ft^{-1}$$

$$= -0.1172\ in^{-1}$$

The argument for m and n is then $\theta = \cos^{-1}(1.4072/2.1376) = 48.82$ deg. Using tables in [5], and interpolating

$$m(48.82) = \{m(50) - m(45)\}\{(48.82 - 45)/(50-45)\} + m(45)$$

$$= (1.754 - 1.926)\{(3.82)/5\} + 1.926 = 1.7945$$

$$n(48.82) = \{n(50)-n(45)\}\{48.82-45)/(40-45)\} + n(45)$$

$$= (0.641-0.604)\{(3.82)/5\} + 0.604 = 0.6323$$

From equations (3) and (4)

$$k_1 = k_2 = (1-(0.24)^2)/\{(\pi)(30 \times 10^6)\} = 9.9992 \times 10^{-9}\ (psi)^{-1}$$

Substituting these values into equations (1) and (2)

$$a' = 1.7945\ \{(3)(\pi/4)(11080)(2)(9.9992 \times 10^{-9})/(0.17813)\}^{1/3} = 0.2568\ in$$

and

$$b' = 0.6323\ \{(3)(\pi/4)(11080)(2)(9.9990 \times 10^{-9})/(0.17813)\}^{1/3} = 0.09048\ in$$

Now

$$(1/R_1 + 1/R_2) = (1/1.3690 + 0) = 0.73046$$

and

$$(1/R_1' + 1/R_2') = (-1/1.6487 + 1/0.24088) = 3.5449$$

Hence

$$(1/R_2' + 1/R_1') > (1/R_1 + 1/R_2)$$

Therefore, ALØNG = a' = 0.2568 in, and BTRANS = b' = 0.09048 in.

The maximum contact pressure is determined from equation (10) as

$$q_o = (3/2)(11080)/\{(\pi)(0.2568)(0.09048)\} = 0.22768 \times 10^6\ psi$$

and the maximum shear stress is determined from equation (11) as

$$\tau_{max} = 0.31\ q_o = (0.31)(0.22768 \times 10^6) = 0.70582 \times 10^5\ psi$$

The ratio ALØNG/BTRANS is then

ALØNG/BTRANS = (0.2568/0.09048) = 2.838

and the contact area is

$$Area = \pi\ ab = (\pi)(0.2568)(0.09048) = 0.072995\ in^2$$

b) Results

These results differ slightly from those calculated with the program for Problem (1) due to round-off. Summarizing, the results are

A+B	=	2.1376 ft^{-1}	ALØNG	=	0.2568 in
B-A	=	-1.4072 ft^{-1}	BTRANS	=	0.09048 in
θ	=	48.82 deg	Area	=	0.072995 in^2
m	=	1.7945	ALØNG/BTRANS	=	2.838
n	=	0.6323	q_o	=	0.22768 x 10^6 psi
			τ_{max}	=	0.70582 x 10^5 psi

2) Calculation of the Linear Creep Coefficients: The linear creep coefficients are determined on the basis of Kalker's linear theory of creep. The details of this formulation can be found in [4, 6]. The procedure for the calculation of the linear creep coefficients is briefly described here and a sample calculation is shown.

The elastic moduli of the two bodies, the values of Poisson's ratio and the dimensions of the contact patch are needed as input data for the calculation of the linear creep coefficients. In [4, 6] Kalker defines the linear creepages as

$$F_x = c^2 G C_{11} \nu_x \tag{12}$$

$$F_y = c^2 GC_{22} \nu_y + c^3 GC_{23}\phi \tag{13}$$

and

$$M_z = - c^3 GC_{23} \nu_y + c^4 GC_{33}\phi \tag{14}$$

where F_x is the longitudinal creep force

F_y is the lateral creep force

M_z is the creep moment

ν_x is the longitudinal creepage

ν_y is the lateral creepage

ϕ is the spin creepage

C_{11} is the nondimensional longitudinal creep coefficient

C_{22} is the nondimensional lateral creep coefficient

C_{23} is the nondimensional lateral spin creep coefficient

C_{33} is the nondimensional spin creep coefficient

G is the combined modulus of rigidity and is defined as

$$G = \frac{2}{(1/G_1 + 1/G_2)} \tag{15}$$

where G_1, G_2 are the shear moduli of bodies 1 and 2 respectively.

and c is defined as

$$c = \sqrt{a\ b}$$

where a and b are the semi axes of the contact ellipse in direction of rolling and transverse to direction of rolling, respectively.

Equations (12), (13), and (14) can be rewritten as

$$F_x = f_{33}\ \nu_x \tag{12a}$$

$$F_y = f_{11}\ \nu_y + f_{12}\phi \tag{13a}$$

$$M_z = f_{12}\ \nu_y + f_{22}\phi \tag{14a}$$

where $f_{11} = c^2\ GC_{22}$ and is the lateral creep coefficient

$f_{12} = c^3\ GC_{23}$ and is the lateral spin creep coefficient

$f_{22} = c^4\ GC_{33}$ and is the spin creep coefficient

$f_{33} = c^2\ GC_{11}$ and is the longitudinal creep coefficient.

C_{11}, C_{22}, C_{23}, and C_{33} are tabulated in [4, 6] for different values of the a/b ratio and for σ, the combined Poisson's ratio, where σ is defined as

$$\sigma = (G/2)\ \{\nu_1/G_1 + \nu_2/G_2\} \tag{16}$$

a) Sample Calculations

The linear creep coefficients may be calculated for the problem considered previously. The tables of C_{ij} listed in [4, 6] are for values of σ of 0, 1/4, and 1/2. For each value of σ, values of the C_{ij} are given for $0.1 \leq a/b \leq 10$. These values are listed in a two part table. The first part is for $0.1 \leq a/b \leq 0.9$ while the second part is for $0.1 \leq b/a \leq 1.0$. For values of $a/b > 11.0$ ($b/a < 0.091$), asymptotic expansions may be used to calculate the C_{ij}.

The calculation of the values for the C_{ij} is implemented in the subroutine CØNST. This subroutine uses linear and quadratic interpolation for values of σ and a/b within the range of the tables and asymptotic expansions for the C_{ij} outside the range of the tables.

For our previous problem, equations (15) and (16) may be used to obtain $\sigma = 0.24$ and $G = 12 \times 10^6$ psi. Also, $a/b = 2.838$ or $b/a = 0.3524$. Thus, interpolation from the tables [6] gives

$$C_{11} = 5.8468 \qquad C_{22} = 5.8192 \qquad C_{23} = 3.6574 \qquad C_{33} = 0.72518$$

and, thus, for $c = (a\ b)^{1/2} = [(0.2568)(0.09048)]^{1/2} = 0.15243$ in.

$$f_{11} = c^2\ G\ C_{22} = 0.0232\ (12 \times 10^6)(5.8192) = 1.6225 \times 10^6 \text{ lb/wheel}$$

$$f_{12} = c^3\ G\ C_{23} = (3.5417 \times 10^{-3})(12 \times 10^6)(3.6574)/12$$
$$= 1.2954 \times 10^4 \text{ ft lb/wheel}$$

$$f_{22} = c^4\ G\ C_{33} = (5.3987 \times 10^{-4})(12 \times 10^6)(0.72518)/144$$
$$= 32.625 \text{ lb ft}^2\text{/wheel}$$

$$f_{33} = c^2\ G\ C_{11} = (0.0232)(12 \times 10^6)(5.8468) = 1.6302 \times 10^6 \text{ lb/wheel}$$

b. Results:

C_{11} = 5.8468 f_{11} = 1.6225 x 10^6 lb/wheel

C_{22} = 5.8192 f_{12} = 1.2954 x 10^4 lb-ft/wheel

C_{23} = 3.6574 f_{22} = 32.625 lb-ft^2 lb-ft^2/wheel

C_{33} = 0.72518 f_{33} = 1.6302 x 10^6 lb/wheel

All the calculations done here are in English units. For conversion from English to Metric units, see Table 2.

III. PROGRAM DESCRIPTION

1. Usage:

The usage of the program is not restricted to the analysis of a wheel on a rail. The program can be used to analyze a wheel on a roller or any other geometric shape, so long as the principal radii of curvature at the point of contact can be specified. Bodies constructed from different materials each having different but isotropic elastic properties can also be analyzed. A flow chart of the program is shown in Figure 3. Table 2 shows the FØRTRAN symbols corresponding to the algebraic symbols previously used.

The program consists of a main program and two subroutines. Input is coordinated through the main program. Output is also through the main program. All calculations are performed in single precision. The main program reads in data pertaining to the elastic and geometric properties of the two bodies in contact. It then proceeds to calculate the dimensions and shape of the contact patch in terms of parameters A+B, B-A, ALØNG, BTRANS, THETA, M, and N. The parameters A+B and B-A are calculated using values of the principal curvatures of the two bodies at the contact point. The parameter THETA depends on the ratio of |B-A| to A+B and M and N are functions of THETA. Tabular data for M and N are stored in the data vectors VALM(I) and VALN(I), respectively. Values of M and N are obtained through linear interpolation using subroutine SLI. The interpolation is terminated if the argument value specified by the input is outside the range of the tables.

Subroutine CØNST calculates the nondimensional linear creep coefficients using XNU and the contact patch dimensions, ALØNG and BTRANS (obtained from the main program). For ratios of ALØNG/BTRANS greater than 11, an asymptotic expansion is used to calculate the nondimensional linear creep coefficients but for ratios less than 11 but greater than 0.1, tabulated data is used from [6]. The main program then calculates the average normal stress, the maximum normal pressure and the maximum shear stress in the contact patch together with the dimensional linear creep coefficients (using the nondimensional creep coefficients from CØNST).

2. Subroutines required:

SUBRØUTINE CØNST (A, B, XNU, C11, C22, C23, C33) calculates the nondimensional linear creep coefficients C11, C22, C23, C33. It uses the semiaxes of the contact ellipse, A, B, (ALØNG, BTRANS) and the constant XNU as input. The constant XNU is dependent on the moduli of rigidity of the two contacting bodies and their respective values of Poisson's ratios.

The subroutine outputs the nondimensional creep coefficients C11, C22, C23, and C33. For A/B ratios less than 11 but greater than 0.1 the subroutine uses tabulated data from Kalker's linearized creep formulation to obtain the nondimensional creep coefficients. For ratios of A/B > 11, the subroutine uses an asymptotic expansion to calculate the creep coefficients.

SUBROUTINE SLI (X, ARG, VAL, Y, NDIM, IER) is a subroutine used to interpolate a function value for a given argument value using a table of argument and function values. The main program provides the argument value X specified by input, the input vector of argument values, ARG, and the input vector of function values, VAL, as input to the subroutine. NDIM is an input parameter that lists the number of pairs of points in the table (ARG, VAL). The subroutine outputs the resulting interpolated function value Y. A straight line interpolation is used that is terminated if the argument value is outside the range of values given in the table. In the case where the argument value is outside the range of the table, the subroutine outputs an error parameter IER = 1 signifying the above condition. IER = 0 when the argument value is within the range of the table.

3. Parameter Description:

Input parameters:

RINV	1/wheel profile radius	1/ft
RPINV	1/rail head profile radius	1/ft
SMR	Wheel rolling radius	ft
RØLRI	1/roller radius (= 0 for actual rail)	1/ft
DELP	Increment in normal load on contact patch	lbs
P	Normal load on contact patch	lbs
E1	Young's Modulus for rail	psi

E2	Young's Modulus for wheel	psi
XNU1	Poisson's ratio for rail	
XNU2	Poisson's ratio for wheel	
G1	Shear Modulus for rail	psi
G2	Shear Modulus for wheel	psi
CTANGL	Angle between axle centerline and contact plane of wheel and rail.	radians
PMAX	Maximum value of P for which contact patch parameters are required.	lbs

4. Input Formats: The wheel profile curvatures, the railhead profile curvatures, the wheel rolling radius, the roller curvature, the normal load on the contact patch and the elastic properties of the wheel and the rail or roller are input to the program. The format required for input into the main program is as follows.

Card #	Col. #	Input Parameter	Format
1	1 - 14	RINV	5 E 14.5
	15 - 28	RPINV	
	29 - 42	SMR	
	43 - 56	P	
	57 - 70	DELP	
2	1 - 14	RØLRI	E 14.5
3	1 - 14	PMAX	E 14.5
4	1 - 14	XNU1	3 E 14.5
	15 - 28	E1	
	29 - 42	G1	
5	1 - 14	XNU2	3 E 14.5
	15 - 28	E2	
	29 - 42	G2	
6	1 - 14	CTANGL	E 14.5

5. Output Parameters: A sample output is given in the Appendix. The main program first prints out the input parameters under the heading INPUT DATA. The contact geometry parameters, A+B, B-A, ALØNG, BTRANS, and A/B are then printed out along with the constants M and N. Values for the contact area, the normal load and the average and maximum stresses are also given. Finally the program prints out the nondimensional creep coefficients (C11, C22, C23, and C33) and the linear, dimensional creep coefficients (F11, F12, F22, F33).

The output parameters are defined as follows.

ALØNG	Semi axis of contact ellipse in direction of rolling	in
BTRANS	Semi axis of contact ellipse transverse to direction of rolling	in
A+B	Constant depending on the principal radii of curvature	1/ft
B-A	Constant depending on the principal radii of curvature	1/ft
A/B	Ratio of the longitudinal and transverse axes of the contact ellipse	
C11	Non-dimensional longitudinal creep coefficient	
C22	Non-dimensional lateral creep coefficient	
C23	Non-dimensional lateral spin creep coefficient	
C33	Non-dimensional spin creep coefficient	
F11	Linear lateral creep coefficient	lb/wheel
F12	Linear lateral spin creep coefficient	lb-ft wheel
F22	Linear spin creep coefficient	lb-ft^2/wheel
F33	Linear longitudinal creep coefficient	lb/wheel
M	Constant, depending on THETA	
N	Constant, depending on THETA	
P	Wheel load normal to contact patch	lb
THETA	Constant, depending on ratio of $\|B-A\|$ to (A+B)	radians

6. User Requirements and Recommendations

The program requires the input data to be on cards. The format for the input is given above. Care should be taken in assigning values for the curvatures of the wheel and the rail. The convention followed for assigning positive or negative values to the curvatures is dependent on whether the center of curvature lies inside or outside the body (see Figures 1 and 2). Positive values are assigned to those curvatures whose centers lie inside the body and negative values to those whose centers lie outside the body. All inputs to the program are in English units For conversion of the output to metric units, refer to Table 2.

The wheel rolling radius SMR is required as one of the inputs to the program. The wheel rolling radius SMR is perpendicular to the axle centerline and is measured from the axle centerline to the contact point between wheel and rail (see Figure 2). The program also requires that the contact angle be provided. The program then proceeds to calculate the principal value of the wheel rolling radius. If, however, SMR is input as a principal rolling radius, then the contact angle, CTANGL, is equal to zero. If CTANGL is not set equal to zero, the program will recalculate a principal value of the wheel rolling radius leading to erroneous results. The other curvatures (RINV, RPINV, and RØLRI) are input into the program as principal curvatures. The program has the capability to determine the creep coefficients and the contact patch geometry for a number of different loadings in one execution. The user has to specify the increment in load, DELP, and the maximum load, PMAX, for which data is desired. The program goes through successive loops to calculate the necessary data and finally terminates when P > PMAX.

IV. TEST PROBLEMS

The following test problems are given to demonstrate the program. The calculations were performed on a IBM 370/3165 - II computer.

The CPU time for problem 1 was less than 3 secs. and for problem 2 was less than 4 sec. Results and sample outputs for these programs are given in the Appendix.

Problem (1)

Profiles: -	Moderately worn AAR wheel New AAR Rail		
Wheel Radii -	Transverse profile	-	-1.6487 ft.
	Rolling	-	1.36904 ft.
Rail Radii: -	Transverse profile	-	0.24088 ft.
	Longitudinal	-	∞
Normal Load:		-	11080.0 lbs.
Maximum Load:		-	11080.0 lbs.
Load Increment:		-	0.0 lbs.
Contact Angle		-	0.0 radians

Problem (2)

Profiles:	New 33" wheel Roller, new rail profile		
Wheel Radii:	- Transverse profile		∞
	Rolling		1.375 ft.
Roller Radii:	- Transverse profile		0.31927 ft.
	Longitudinal		1.75 ft.
Normal Load:		-	11080.0 lbs.
Maximum Load:		-	14860.0 lbs.
Load Increment:		-	1890.0 lbs.
Contact Angle		-	0.0693 radians

Results and sample outputs of these sample problems are given in the Appendix.

V. REFERENCES.

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VI. APPENDIX

PROGRAM LISTING WITH INPUTS AND OUTPUTS FOR TEST PROBLEMS

1. Program Listing

```
          C     PROGRAM TO CALCULATE CONTACT AREA SHAPE AND AREA, AND LINEAR
          C     CREEP COEFFICIENTS
          C
          C     REFERENCE
          C         CONTACT AREA,  TIMOSHENKO + GOODIER,'THEORY OF ELASTICITY',
          C                  MCGRAW-HILL, 2ND ED., 1951
          C
          C         CREEP,  KALKER,J.J.,'THE TANGENTIAL FORCE TRANSMITTED BY TWO
          C                 ELASTIC BODIES ROLLING OVER EACH OTHER WITH PURE
          C                 CREEPAGE', WEAR II,1968, PP.421-430
          C
          C     PARAMETERS     RINV = 1/WHEEL PROFILE RADIUS,  1/FT
          C                    RPINV = 1/RAIL HEAD PROFILE RADIUS, 1/FT
          C
          C                    IF RINV,RPINV < 0 THEN THE CENTER OF CURVATURE
          C                    OF THE PROFILE IS OUTSIDE THE BODY
          C
          C                    SMR   = WHEEL ROLLING RADIUS, FT
          C                    ROLRI = 1/ROLLER RADIUS, 1/FT, = 0  FOR ACTUAL RAIL
          C                    P     = NORMAL LOAD ACROSS CONTACT PATCH, LB
          C                    E1 = YOUNG'S MODULUS RAIL, PSI
          C                    E2 = YOUNG'S MODULUS WHEEL, PSI
          C                    XNU1  = POISSON'S RATIO RAIL
          C                    XNU2  = POISSON'S RATIO WHEEL
          C                    G1 =  SHEAR MODULUS RAIL, PSI
          C                    G2 =  SHEAR MODULUS WHEEL,PSI
          C                    CTANGL = CONTACT ANGLE ON WHEEL
          C
          C
0001            DIMENSION ARG(23),VALM(23),VALN(23)
          C     ****************************************************************
          C     ARGUMENT RANGE FOR M,N HAS BEEN EXTENDED FROM 0.5 TO 30 DEG., SEE
          C     KORNHAUSER, J. APPL. MECH., SEPTEMBER, 1951
0002            DATA ARG/.5,1.,1.5,2.,3.,4.,6.,8.,10.,20./
          C     ****************************************************************
          C     LIST VALUES OF VALM(I), VALN(I) AFTER THIS CARD
0003            DATA VALM/61.4,36.89,27.48,22.26,16.5,13.31,9.79,7.86,6.604,3.813,
               A2.731,2.397,2.136,1.926,1.754,1.611,1.486,1.378,1.284,1.202,1.128,
               B1.061,1./
0004            DATA VALN/.1018,.1314,.1522,.1691,.1964,.2188,.2552,.285,.3112,
               A1.4123,.493,.53,.567,.604,.641,.678,.717,.759,.802,.846,.893,.944,
               B1./
          C     ****************************************************************
0005            IRD = 1
0006            IWT = 3
0007       3000 KK=0
0008            READ (IRD,1,END=5000) RINV,RPINV,SMR,P,DELP
0009            READ (IRD,3) ROLRI
0010            READ (IRD,3) PMAX
0011            READ (IRD,2) XNU1,E1,G1
0012            READ (IRD,2) XNU2,E2,G2
0013            READ (IRD,3) CTANGL
0014            WRITE (IWT,2000) RINV,SMR,RPINV,ROLRI,XNU1,E1,G1,XNU2,E2,G2,CTANGL
0015            G = 2./((1./G1)+(1./G2))
0016            XNU =(G/2.)*((XNU1/G1)+(XNU2/G2))
0017            XK1 =(1.-XNU1*XNU1)/(3.14159*E1)
0018            XK2 =(1.-XNU2*XNU2)/(3.14159*E2)
0019            WRITE (IWT,2007) G,XNU
```

```
               C
               C       REDEFINE WHEEL ROLLING RADIUS AS PRINCIPAL RADIUS
               C
 0020                  SMR=SMR/COS(CTANGL)
 0021                  WRITE(IWT,2001) SMR
 0022                  APB = 0.5*((1./SMR) + RINV + RPINV + ROLRI)
 0023                  BMA = 0.5*ABS((1./SMR) - RINV - RPINV + ROLRI)
 0024                  COST = BMA/APB
 0025                  THETA = ARCOS(COST) * 57.3
 0026                  DO 15 I=1,13
 0027                  AI=I
 0028                  K=I+10
 0029               15 ARG(K) = 25.+(5.*AI)
 0030                  CALL SLI(THETA,ARG,VALM,XM,23,IERM)
 0031                  CALL SLI(THETA,ARG,VALN,XN,23,IERN)
 0032             1000 CONTINUE
 0033                  TERM = 0.75*3.14159*P*(XK1+XK2)/(APB/12.)
               C
               C       ALONG AND BTRANS ARE IN INCHES, AREA IN INCHES**2
               C
 0034                  IF(((1./SMR) + ROLRI) - (RPINV + RINV)) 4000,4000,4005
               C       NOTE  IF (1./SMR) + ROLRI > RPINV + RINV, THEN BTRANS>ALONG
               C             IF (1./SMR) + ROLRI < RPINV + RINV, THEN BTRANS < ALONG
 0035             4000 ALONG = XM*(TERM**(1./3.))
 0036                  BTRANS = XN*(TERM**(1./3.))
 0037                  GO TO 4010
 0038             4005 ALONG = XN*(TERM**(1./3.))
 0039                  BTRANS = XM*(TERM**(1./3.))
 0040             4010 CONTINUE
 0041                  AREA = 3.14159*ALONG*BTRANS
 0042                  AVGBST = P/AREA
               C       MAX CONTACT PRESSURE = Q0, MAX SHEAR STRESS = 0.31*Q0
               C
 0043                  Q0 = 1.5*P/(3.1416*ALONG*BTRANS)
 0044                  TAUMAX = 0.31*Q0
 0045                  AOVERB = ALONG/BTRANS
 0046                  WRITE (IWT,2004)
 0047                  WRITE(3,2005)P,APB,BMA,THETA,XM,XN,ALONG,BTRANS,AREA,AVGBST,
                     1  AOVERB
 0048                  WRITE (IWT,2006)Q0,TAUMAX
 0049                  IF(KK-0)2025,2020,2025
 0050             2020 CALL CONST (ALONG,BTRANS,XNU,C11,C22,C23,C33)
 0051                  KK=1
 0052             2025 CONTINUE
 0053                  C = SQRT(ALONG*BTRANS)
               C       F11 IN LB/WHEEL, LATERAL
               C       F12 IN LBFT/WHEEL, LAT-SPIN
               C       F22 IN LBFT2/WHEEL, SPIN
               C       F33 IN LB/WHEEL, LONG.
 0054                  F11 = C*C*G*C22
 0055                  F12 = C*C*C*G*C23/12.
 0056                  F22 = C*C*C*C*G*C33/144.
 0057                  F33 = C*C*G*C11
 0058                  WRITE (IWT,2010) C11,C22,C23,C33,F11,F12,F22,F33
 0059                  P = P + DELP
 0060                  IF (P-PMAX) 1000,1000,1005
 0061             1005 GO TO 3000
 0062             2001 FORMAT(/ ,T16,'PRINCIPAL ROLLING RADIUS OF WHEEL =',E14.5,' FT',
```

```
                 1//)
0063             1 FORMAT (5E14.5)
0064             2 FORMAT (3E14.5)
0065             3 FORMAT (E14.5)
0066          2000 FORMAT(1H1,///,40X,'INPUT DATA'//
                 1      1H0,15X,'RINV  = ',E14.5,'  1/WHEEL PROFILE RADIUS, 1/FT'/
                 2      1H ,15X,'SMR   = ',E14.5,'  WHEEL ROLLING RADIUS, FT'/
                 3      1H ,15X,'RPINV = ',E14.5,'  1/RAIL HEAD PROFILE RADIUS, 1/FT'/
                 4      1H ,15X,'ROLRI = ',E14.5,'  1/ROLLER RADIUS, 1/FT'/
                 5      1H ,15X,'XNU1  = ',E14.5,'  POISSON RATIO, RAIL'/
                 6      1H ,15X,'E1    = ',E14.5,'  YOUNG S MOD RAIL, PSI'/
                 7      1H ,15X,'G1    = ',E14.5,'  SHEAR MOD RAIL, PSI'/
                 8      1H ,15X,'XNU2  = ',E14.5,'  POISSON RATIO, WHEEL'/
                 9      1H ,15X,'E2    = ',E14.5,'  YOUNG S MOD WHEEL, PSI'/
                 8      1H ,15X,'G2    = ',E14.5,'  SHEAR MOD WHEEL, PSI'/
                 7      1H ,15X,'CTANGL= ',E14.5,'  CONTACT ANGLE,RAD   ',///)
0067          2004 FORMAT(1H0,'************************************************'/)
0068          2005 FORMAT(20X,'CONTACT GEOMETRY PARAMETERS     P = ',E14.5,
                 1      ' LB (WHEEL LOAD NORMAL TO CONTACT PATCH)'//
                 2      1H0,15X,'A+B = ',E14.5,' 1/FT',     B-A = ',E14.5,' 1/FT',
                 3      '      THETA = ',E14.5/
                 4      1H ,15X,'M     = ',E14.5,'          N    = ',E14.5///
                 5      1H ,15X,'ALONG = ',E14.5,'          BTRANS = ',E14.5,' INCHES'/
                 6      1H ,15X,'AREA  = ',E14.5,' IN2 ',   AVG.NORM STRESS = ',E14.5,
                 7      ' PSI ','     A/B = ',E14.5///)
0069          2006 FORMAT (20X,'MAXIMUM CONTACT STRESSES,',
                 1 // ,T17,'MAX CONTACT PRESSURE = ',
                 2      E14.5,' PSI,          MAX SHEAR STRESS = ',E14.5,' PSI'//)
0070          2007 FORMAT (1H0,T16,'AVG SHEAR MOD,',T40,'G   = ',E14.5,' PSI'/
                 1           1H ,T16,'AVG POISSON S RATIO,',T40,'XNU = ',E14.5//)
0071          2010 FORMAT(20X,'CREEP PARAMETERS'//
                 1      1H0,15X,'C11 = ',E14.5,' C22 = ',E14.5,' C23 = ',E14.5,
                 2      ' C33 = ',E14.5//
                 3      1H ,15X,'F11 = ',E14.5,' LB/WHEEL, LATERAL'/
                 4      1H ,15X,'F12 = ',E14.5,' LB-FT/WHEEL, LAT-SPIN'/
                 5      1H ,15X,'F22 = ',E14.5,' LB-FT2/WHEEL, SPIN'/
                 6      1H ,15X,'F33 = ',E14.5,' LB/WHEEL, LONGITUDINAL'//)
0072          5052 FORMAT (20X,'ERROR CODES FOR SLI4, 0=OK ', 4(I2,','))
0073          5000 STOP
0074               END
```

```
      C      *****************************************************************
      C
      C      SUBROUTINE SLI
      C
      C
      C      PURPOSE
      C          TO INTERPOLATE FUNCTION VALUE Y FOR GIVEN ARGUMENT VALUE X
      C          USING GIVEN TABLE (ARG,VAL) OF ARGUMENT AND FUNCTION VALUES
      C
      C      PARAMETERS
      C          X    - ARGUMENT VALUE SPECIFIED BY INPUT
      C          ARG  - INPUT VECTOR OF ARGUMENT VALUES (DIMENSION NDIM)
      C          VAL  - INPUT VECTOR OF FUNCTION VALUES (DIMENSION NDIM)
      C          Y    - RESULTING INTERPOLATED FUNCTION VALUE
      C          NDIM - INPUT VALUE, NO OF POINTS IN TABLE (ARG,VAL)
      C          IER  - ERROR PARAMETER
      C
      C      REMARKS
      C          (1) TABLE(ARG,VAL) SHOULD BE STORED SUCH THAT ARG(I+1)-ARG(I)
      C              IS POSITIVE
      C          (2) INTERPOLATION IS TERMINATED IF X IS OUTSIDE RANGE
      C              (ARG(1),ARG(NDIM)). IER = 1 IN THIS CASE. IF X IS WITHIN
      C              THE ARG RANGE, IER = 0.
      C
      C      METHOD - STRAIGHT LINE INTERPOLATION
      C
      C      *****************************************************************
      C
0001         SUBROUTINE SLI(X,ARG,VAL,Y,NDIM,IER)
0002         DIMENSION ARG(NDIM),VAL(NDIM)
0003         IER = 0
0004         J = 0
0005         IF ((X.LT.ARG(1)).OR.(X.GT.ARG(NDIM))) GO TO 40
0006         DO 10 I = 1,NDIM
0007         IF (X-ARG(I)) 20,20,10
0008      20 J = I
0009         GO TO 30
0010      10 CONTINUE
0011      30 IF (X.EQ.ARG(J)) GO TO 25
0012         Y = ((VAL(J)-VAL(J-1))/(ARG(J)-ARG(J-1)))*(X-ARG(J-1))+VAL(J-1)
0013         GO TO 35
0014      25 Y = VAL(J)
0015         GO TO 35
0016      40 IER = 1
      C      IER = 1 REFERS TO CASE WHEN X IS NOT IN RANGE ARG(1),ARG(NDIM)
0017      35 RETURN
0018         END
```

```
      C     *****************************************************************00002070
0001          SUBROUTINE CONST(A,B,XNU,C11,C22,C23,C33)                        00002080
0002          DIMENSION AL(4),BE(4),D(12),E(12,20),AR(20),CNT(4),D1(12,9),     00002090
             1    D2(12,9),D3(12),D4(12)                                       00002100
      C     *****************************************************************00002110
      C     SUBROUTINE CONST CALCULATES THE KALKER LINEAR CREEP COEFFICIENTS BY 00002120
      C                                                                        00002130
      C          (A) LINEAR AND QUADRATIC INTERPOLATION FOR 0 < XNU <0.5       00002140
      C                                                                        00002150
      C              AND 0.1 < A/B < 11.0                                      00002160
      C                                                                        00002170
      C          (B)  CALCULATION FROM ASYMPTOTIC EXPANSIONS FOR A/B > 11.0    00002180
      C                                                                        00002190
      C          A = SEMI AXIS OF ELLIPSE IN ROLLING DIRECTION                 00002200
      C                                                                        00002210
      C          B = SEMI AXIS OF ELLIPSE IN TRANSVERSE DIRECTION              00002220
      C                                                                        00002230
      C     *****************************************************************00002240
0003          REAL NU                                                          00002250
0004          DATA D1/                                                         00002260
             $  2.51, 3.31, 4.85, 2.51, 2.52, 2.53, 0.334, 0.473, 0.731, 6.42, 00002270
             $ 8.28, 11.7,                                                     00002280
             $ 2.59, 3.37, 4.81, 2.59, 2.63, 2.66, 0.483, 0.603, 0.809, 3.46,  00002290
             $ 4.27, 5.66,                                                     00002300
             $ 2.68, 3.44, 4.80, 2.68, 2.75, 2.81, 0.607, 0.715, 0.889, 2.49,  00002310
             $ 2.96, 3.72,                                                     00002320
             $ 2.78, 3.53, 4.82, 2.78, 2.88, 2.98, 0.720, 0.823, 0.977, 2.02,  00002330
             $ 2.32, 2.77,                                                     00002340
             $ 2.88, 3.62, 4.83, 2.88, 3.01, 3.14, 0.827, 0.929, 1.07, 1.74,   00002350
             $ 1.93, 2.22,                                                     00002360
             $ 2.98, 3.72, 4.91, 2.98, 3.14, 3.31, 0.930, 1.03, 1.18, 1.56,    00002370
             $ 1.68, 1.86,                                                     00002380
             $ 3.09, 3.81, 4.97, 3.09, 3.28, 3.48, 1.03, 1.14, 1.29, 1.43,     00002390
             $ 1.50, 1.60,                                                     00002400
             $ 3.19, 3.91, 5.05, 3.19, 3.41, 3.65, 1.13, 1.25, 1.40, 1.34,     00002410
             $ 1.37, 1.42,                                                     00002420
             $ 3.29, 4.01, 5.12, 3.29, 3.54, 3.82, 1.23, 1.36, 1.51, 1.27,     00002430
             $ 1.27, 1.27/                                                     00002440
0005          DATA D2/                                                         00002450
             $ 3.40, 4.12, 5.20, 3.40, 3.67, 3.98, 1.33, 1.47, 1.63, 1.21,     00002460
             $ 1.19, 1.16,                                                     00002470
             $ 3.51, 4.22, 5.30, 3.51, 3.81, 4.16, 1.44, 1.59, 1.77, 1.16,     00002480
             $ 1.11, 1.06,                                                     00002490
             $ 3.65, 4.36, 5.42, 3.65, 3.99, 4.39, 1.58, 1.75, 1.94, 1.10,     00002500
             $ 1.04, 0.954,                                                    00002510
             $ 3.82, 4.54, 5.58, 3.82, 4.21, 4.67, 1.76, 1.95, 2.18, 1.05,     00002520
             $ 0.965, 0.852,                                                   00002530
             $ 4.06, 4.78, 5.80, 4.06, 4.50, 5.04, 2.01, 2.23, 2.50, 1.01,     00002540
             $ 0.892, 0.751,                                                   00002550
             $ 4.37, 5.10, 6.11, 4.37, 4.90, 5.56, 2.35, 2.62, 2.96, 0.958,    00002560
             $ 0.819, 0.650,                                                   00002570
             $ 4.84, 5.57, 6.57, 4.84, 5.48, 6.31, 2.88, 3.24, 3.70, 0.912,    00002580
             $ 0.747, 0.549,                                                   00002590
             $ 5.57, 6.34, 7.34, 5.57, 6.40, 7.51, 3.79, 4.32, 5.01, 0.868,    00002600
             $ 0.674, 0.446,                                                   00002610
             $ 6.96, 7.78, 8.82, 6.96, 8.14, 9.79, 5.72, 6.63, 7.89, 0.828,    00002620
             $ 0.601, 0.341/                                                   00002630
0006          DATA D3/                                                         00002640
```

```
     $ 10.7, 11.7, 12.9, 10.7, 12.8, 16.0, 12.2, 14.6, 18.0, 0.795,
     $ 0.562, 0.228/
      DATA D4/
     $ 11.08, 12.01, 13.10, 11.08, 13.38, 16.90, 13.72, 16.34, 20.20,
     $ 0.785, 0.552, 0.208/
      DATA AR / 0.1,0.2,0.3,0.4,0.5,0.6,0.7,0.8,0.9,1.0,1.111111,
     $1.25,1.428571,1.666667,2.0,2.5,3.333333,5.0,10.0,11.0/
      NU=XNU
      DO 6 I=1,12
      DO 5 J=1,9
      E(I,J)=D1(I,J)
    5 E(I,J+9)=D2(I,J)
      E(I,19)=D3(I)
    6 E(I,20)=D4(I)
      PI=3.14159
      RG=A/B
      IF(RG.GT.11.0) GO TO 14
      GO TO 15
C     ****************************************************************
C
C      CALCULATIONS FOR A/B.GT.11.0
C
C     ****************************************************************
   14 SG=B/A
      GAM=ALOG(16.0/(SG*SG))
      C11=2.0*PI/(SG*(GAM-2.0*NU))*(1.0+( 1.613706   )/(GAM-2.0*NU))
      C22=(( 1.613706 )*(1.0-NU))/(2.0*NU+GAM*(1.0-NU))
      C22=2.0*PI*(1.0+C22)/(SG*(2.0*NU+GAM*(1.0-NU)))
      C23=2.0*PI/((SQRT(SG)*SG*3.0)*((1.0-NU)*GAM-2.0+4.0*NU))
      C33=PI/4.0*(GAM*(1.0-2.0*NU)-2.0+6.0*NU)/(GAM*(1.0-NU)-2.0+4.0*NU)
      GO TO 80
C     ****************************************************************
C
C      INTERPOLATION FROM TABLES FOR A/B.LE.11.0 AND A/B.GE.0.1
C
C     ****************************************************************
   15 DO 20 I=2,20
      IF(RG.LE.AR(I)) GO TO 25
   20 CONTINUE
   25 J=I
      DO 30 I=1,12
   30 D(I)=E(I,J-1)+(E(I,J)-E(I,J-1))*(RG-AR(J-1))/(AR(J)-AR(J-1))
      DO 40 I=1,5
      AL(I)=8.0*(D(3*I)-2.0*D(3*I-1)+D(3*I-2))
      BE(I)=2.0*(-D(3*I)+4.0*D(3*I-1)-3.0*D(3*I-2))
   40 CNT(I)=AL(I)*NU**2+BE(I)*NU+D(3*I-2)
      C11=CNT(1)
      C22=CNT(2)
      C23=CNT(3)
       C33=CNT(4)
   80 CONTINUE
      RETURN
      END
```

2. Problem (1) Input and Output

INPUT DATA

```
RINV   =   -0.60650E+00  1/WHEEL PROFILE RADIUS, 1/FT
SMR    =    0.13690E+01  WHEEL ROLLING RADIUS, FT
RPINV  =    0.41514E+01  1/RAIL HEAD PROFILE RADIUS, 1/FT
ROLRI  =    0.0          1/ROLLER RADIUS, 1/FT
XNU1   =    0.24000E+00  POISSON RATIO, RAIL
E1     =    0.30000E+08  YOUNG S MOD RAIL, PSI
G1     =    0.12000E+08  SHEAR MOD RAIL, PSI
XNU2   =    0.24000E+00  POISSON RATIO, WHEEL
E2     =    0.30000E+08  YOUNG S MOD WHEEL, PSI
G2     =    0.12000E+08  SHEAR MOD WHEEL, PSI
CTANGL=     0.0          CONTACT ANGLE,RAD


AVG SHEAR MOD,            G   =    0.12000E+08 PSI
AVG POISSON S RATIO,      XNU =    0.24000E+00


PRINCIPAL ROLLING RADIUS OF WHEEL =    0.13690E+01 FT


****************************************************

     CONTACT GEOMETRY PARAMETERS    P =    0.11080E+05 LB (WHEEL LOAD NORMAL TO CONTACT PATCH)


A+B =    0.21377E+01 1/FT    B-A =    0.14072E+01 1/FT    THETA =    0.48834E+02
M   =    0.17941E+01         N   =    0.63237E+00


ALONG =    0.25675E+00       BTRANS =    0.90497E-01 INCHES
AREA  =    0.72995E-01 IN2   AVG.NORM STRESS =    0.15179E+06 PSI      A/B =    0.28371E+01


     MAXIMUM CONTACT STRESSES,

MAX CONTACT PRESSURE =    0.22769E+06 PSI,         MAX SHEAR STRESS =    0.70583E+05 PSI

     CREEP PARAMETERS

C11 =    0.58468E+01 C22 =    0.58192E+01 C23 =    0.36574E+01 C33 =    0.72518E+00

F11 =    0.16225E+07 LB/WHEEL, LATERAL
F12 =    0.12954E+05 LB-FT/WHEEL, LAT-SPIN
F22 =    0.32625E+02 LB-FT2/WHEEL, SPIN
F33 =    0.16302E+07 LB/WHEEL, LONGITUDINAL
```

3. Problem (2) Input and Output

INPUT DATA

```
RINV   =    0.0           1/WHEEL PROFILE RADIUS, 1/FT
SMR    =    0.13750E+01   WHEEL ROLLING RADIUS, FT
RPINV  =    0.31324E+01   1/RAIL HEAD PROFILE RADIUS, 1/FT
ROLRI  =    0.57140E+00   1/ROLLER RADIUS, 1/FT
XNU1   =    0.24000E+00   POISSON RATIO, RAIL
E1     =    0.30000E+08   YOUNG S MOD RAIL, PSI
G1     =    0.12000E+08   SHEAR MOD RAIL, PSI
XNU2   =    0.24000E+00   POISSON RATIO, WHEEL
E2     =    0.30000E+08   YOUNG S MOD WHEEL, PSI
G2     =    0.12000E+08   SHEAR MOD WHEEL, PSI
CTANGL=     0.69320E-01   CONTACT ANGLE,RAD


AVG SHEAR MOD,          G   =    0.12000E+08 PSI
AVG POISSON S RATIO,    XNU =    0.24000E+00


PRINCIPAL ROLLING RADIUS OF WHEEL =   0.13783E+01 FT


***************************************************

    CONTACT GEOMETRY PARAMETERS    P =    0.11080E+05 LB (WHEEL LOAD NORMAL TO CONTACT PATCH)


 A+B =    0.22147E+01 1/FT    B-A =     0.91774E+00 1/FT    THETA =    0.65524E+02
 M   =    0.13682E+01         N   =     0.76350E+00


 ALONG =    0.19350E+00       BTRANS =    0.10798E+00 INCHES
 AREA  =    0.65641E-01 IN2   AVG.NORM STRESS =    0.16880E+06 PSI     A/B =    0.17919E+01


    MAXIMUM CONTACT STRESSES,

 MAX CONTACT PRESSURE =    0.25319E+06 PSI,         MAX SHEAR STRESS =    0.78490E+05 PSI


    CREEP PARAMETERS


 C11 =    0.48657E+01 C22 =    0.46292E+01 C23 =    0.23659E+01 C33 =    0.87009E+00

 F11 =    0.11607E+07 LB/WHEEL, LATERAL
 F12 =    0.71456E+04 LB-FT/WHEEL, LAT-SPIN
 F22 =    0.31655E+02 LB-FT2/WHEEL, SPIN
 F33 =    0.12200E+07 LB/WHEEL, LONGITUDINAL


***************************************************

    CONTACT GEOMETRY PARAMETERS    P =    0.12970E+05 LB (WHEEL LOAD NORMAL TO CONTACT PATCH)
```

```
A+B =     0.22147E+01 1/FT     B-A =     0.91774E+00 1/FT     THETA =     0.65524E+02
M   =     0.13682E+01          N   =     0.76350E+00

ALONG =     0.20393E+00        BTRANS =     0.11380E+00 INCHES
AREA  =     0.72908E-01 IN2    AVG.NORM STRESS =     0.17790E+06 PSI     A/B =     0.17919E+01


    MAXIMUM CONTACT STRESSES,

MAX CONTACT PRESSURE =     0.26684E+06 PSI,          MAX SHEAR STRESS =     0.82721E+05 PSI

    CREEP PARAMETERS

C11 =     0.48657E+01 C22 =     0.46292E+01 C23 =     0.23659E+01 C33 =     0.87009E+00

F11 =     0.12892E+07 LB/WHEEL, LATERAL
F12 =     0.83644E+04 LB-FT/WHEEL, LAT-SPIN
F22 =     0.39051E+02 LB-FT2/WHEEL, SPIN
F33 =     0.13550E+07 LB/WHEEL, LONGITUDINAL

****************************************************

    CONTACT GEOMETRY PARAMETERS     P =     0.14860E+05 LB (WHEEL LOAD NORMAL TO CONTACT PATCH)

A+B =     0.22147E+01 1/FT     B-A =     0.91774E+00 1/FT     THETA =     0.65524E+02
M   =     0.13682E+01          N   =     0.76350E+00

ALONG =     0.21339E+00        BTRANS =     0.11908E+00 INCHES
AREA  =     0.79829E-01 IN2    AVG.NORM STRESS =     0.18615E+06 PSI     A/B =     0.17919E+01


    MAXIMUM CONTACT STRESSES,

MAX CONTACT PRESSURE =     0.27922E+06 PSI,          MAX SHEAR STRESS =     0.86558E+05 PSI

    CREEP PARAMETERS

C11 =     0.48657E+01 C22 =     0.46292E+01 C23 =     0.23659E+01 C33 =     0.87009E+00

F11 =     0.14116E+07 LB/WHEEL, LATERAL
F12 =     0.95833E+04 LB-FT/WHEEL, LAT-SPIN
F22 =     0.46817E+02 LB-FT2/WHEEL, SPIN
F33 =     0.14837E+07 LB/WHEEL, LONGITUDINAL
```

TABLE 1. Equivalent Algebraic — FØRTRAN Symbols

Algebraic	Fortran
a	ALØNG
b	BTRANS
a/b	A/B
A+B	A+B
B-A	B-A
C_{11}	C11
C_{22}	C22
C_{23}	C23
C_{33}	C33
E_1	E1
E_2	E2
f_{11}	F11
f_{12}	F12
f_{22}	F22
f_{33}	F33
G_1	G1
G_2	G2
m	M
n	N
p	P
r	SMR
$1/R_1'$	RINV
$1/R_2$	RØLRI
$1/R_2'$	RPINV
θ	THETA
δ	CTANGL
ν_1	XNU1
ν_2	XNU2
σ	XNU

TABLE 2. Conversion Factors for English to Metric Units

To Convert	To	Multiply By
inches (in)	meters (m)	0.0254
feet (ft)	meters (m)	0.3048
square inches (in^2)	square meters (m^2)	0.0006452
pounds-force (lbf)	Newtons (N)	4.44822
pounds force/sq inch (psi)	kilonewtons/meter^2 (KN/m^2)	6.894757
pounds force/sq foot (psf)	Newtons/meters^2 (N/m^2), or Pascal (Pa)	47.880

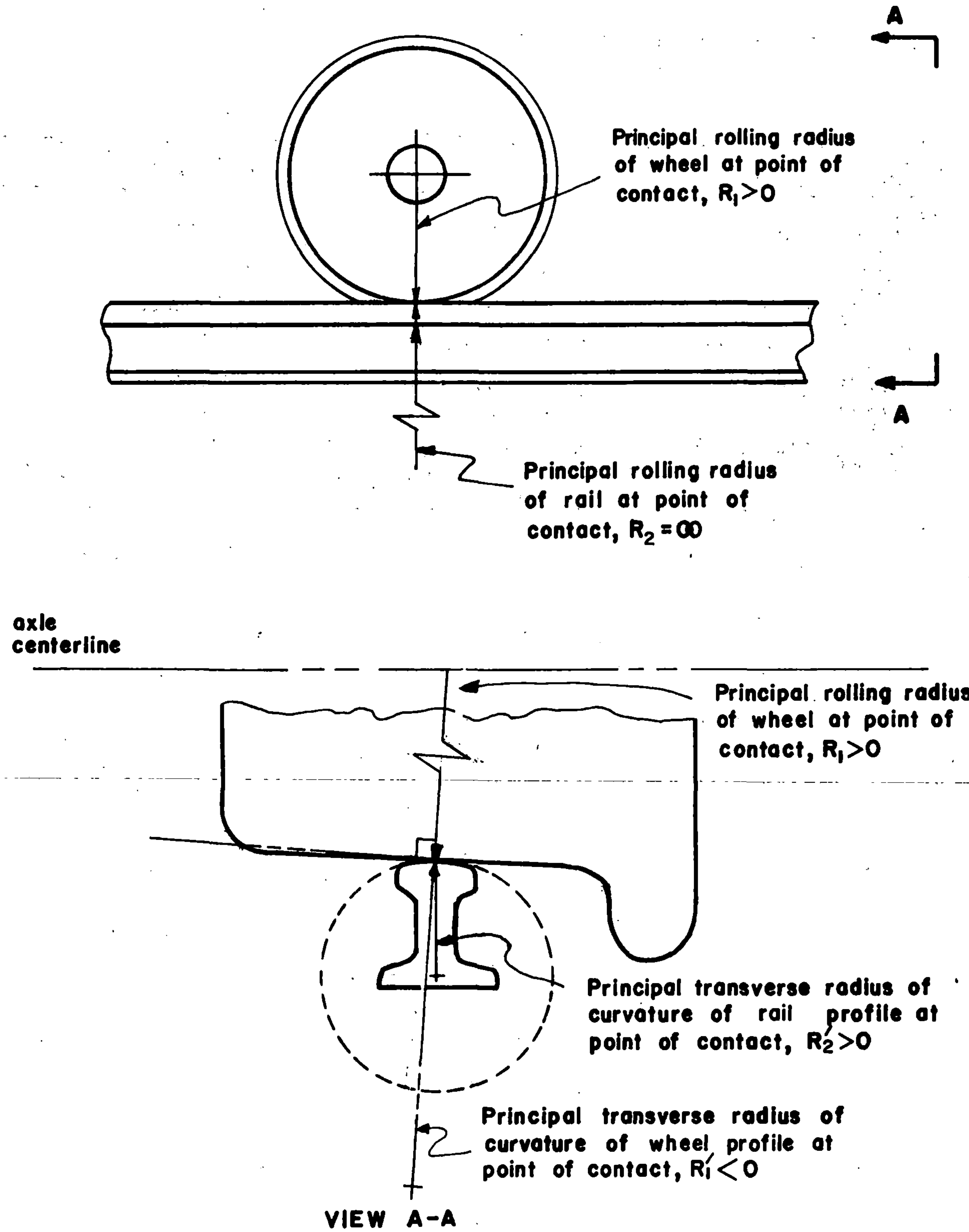
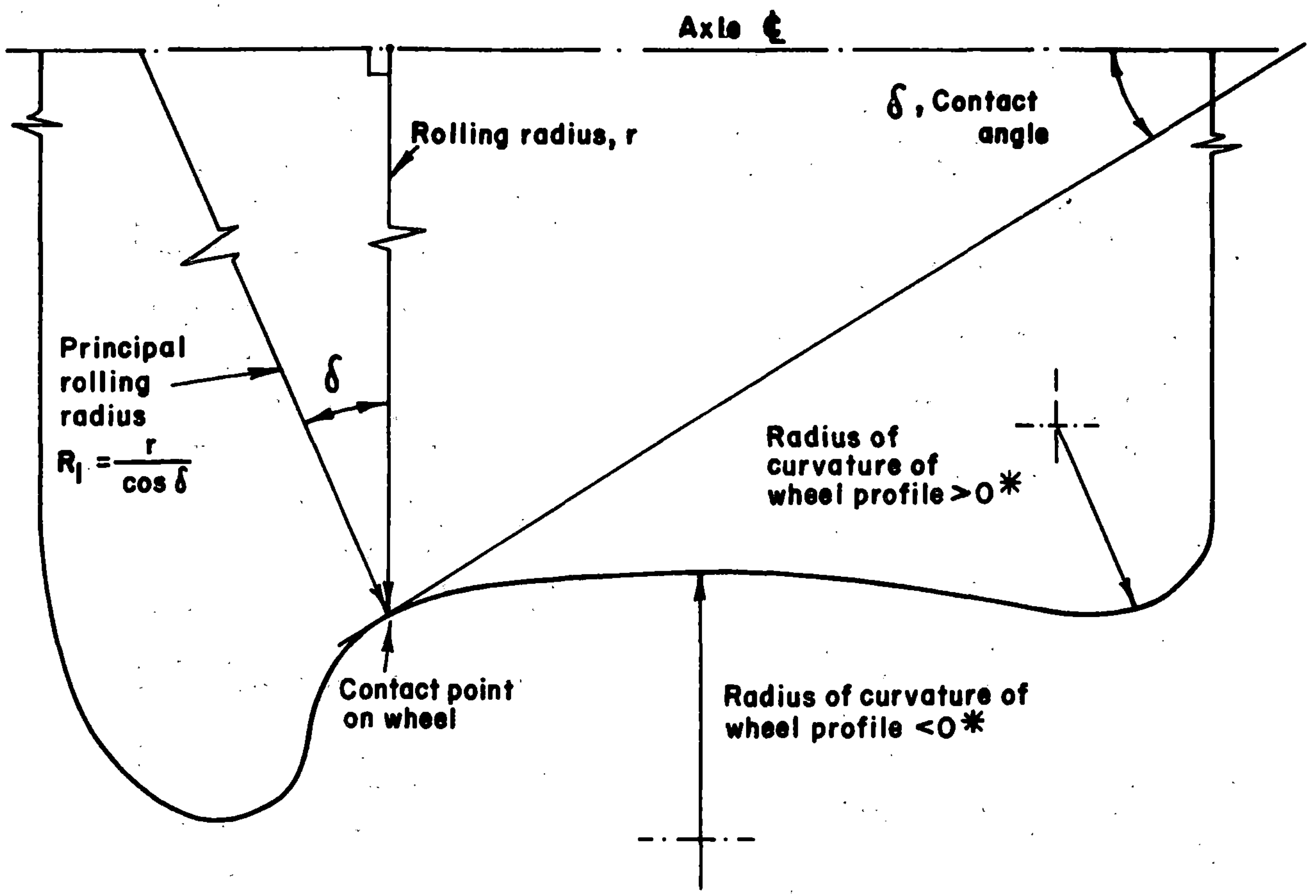
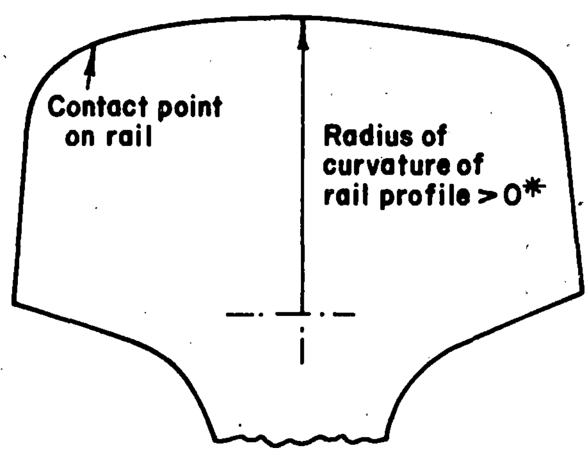


FIGURE. I Wheel and Rail Radii of Curvature





* If contact occurs in this region, sign of radius of curvature is as indicated.

FIGURE 2. Sign Convention for Radii of Curvature

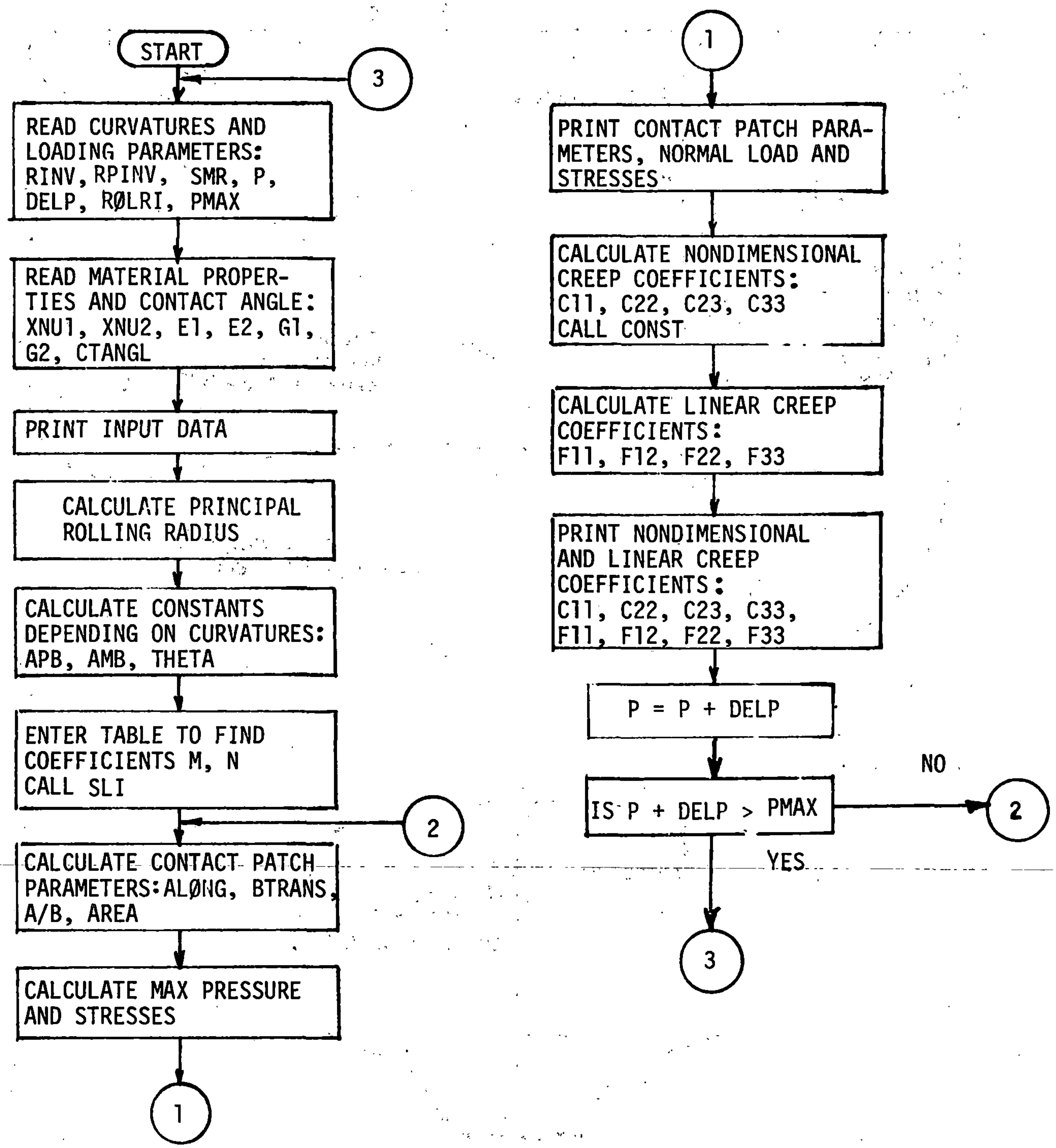


FIGURE 3. Flow Chart

Users' Manual for Program for Calculation of Kalker's Linear Creep Coefficients (Interim Report), 1979
US DOT, FRA