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PROJECT REPORT

LOG TRUCK GRADEABILITY ON CORNERS AND GRADES

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Project Report

P.R.38

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LOG TRUCK GRADEABILITY ON CORNERS AND GRADES

SUMMARY

This report covers LIRA's work to date on log truck gradeability. The project's aim has been to improve understanding of truck performance on adverse grades and corners so that better road constructions can be achieved. It has been estimated that a 2% increase in average grade for new roading over the next 10 years could save the forest industry $26M in construction costs.

Gradeability equations are developed for three common logging truck combinations used in New Zealand (Longs truck and trailer, Shorts truck and trailer and Bailey bridge[1]). Truck resistances such as rolling, air and cornering are based on existing published work. LIRA's work assembles the various components and applies them to typical New Zealand rigs climbing adverse grades with corners. To achieve a result without undue complexity or cost this model only applies to steady state conditions at low speed.

The completed model has been used to analyse a number of situations encountered in normal operation of a logging truck. Some of the more important conclusions from this work, for loaded trucks, are as follows :

- There is little difference in the climbing ability of any of the common New Zealand rig types on slippery road surfaces. It is more productive to try to improve the road surface or ease grades, than to be concerned with rig type.
- Corners with radii below 30 m cause significant additional resistance to movement. The grad on sharp steep corners should be eased by two to three percent.
- Positive superelevation (i.e. crossfall into the corner) reduces truck gradeability on corners. Pole trailer units and Bailey bridges are most affected. On sharp steep corners, zero or negative superelevation of 5 to 6 percent will improve gradeability.

Some relationships are presented which can help in designing road shapes to suit heavy trucks. Some of the predictions from the model have been checked and verified against actual experience in the field, particularly the matter of superelevation on corners. However full field vertification of the model is yet to be done to give confidence in the absolute values predicted. Further research work on field measurement of coefficient of traction and on the effect of truck suspension design is needed.

Solution of the equations and presentation of the results forms part of the report. To make the model readily available a personal computer spreadsheet programme has been utilised to both calculate and plot results. Copies of the spreadsheet to run on SUPERCALC 3 or 4 are available from LIRA under the name TRUKGRAD.

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1. Multiple stanchion semi-trailer

1.0 INTRODUCTION

The logging industry in New Zealand is moving towards harvesting forests on more difficult terrain. Both soil conditions and steepness will increase the costs of log transport by increasing road construction and maintenance costs and/or reducing truck productivity.

Roading and transportation already consume a large proportion of the forest's income. In some cases they will be too costly to allow a profit. It is this scenario that has prompted LIRA to investigate ROAD/TRUCK interaction with the aim of finding lower cost methods of transporting wood from skid to mill. Research is looking at both roads and vehicles to provide ways of assessing the most economic solution for each section of forest.

For critical sections of forest access, road builders are interested in the lowest standard of road that will allow satisfactory truck performance. It has been estimated (Wall, 1987) that a 2% increase in average grade for new roading over the next 10 years could save the forest industry $26M in construction costs.

"Roading through steep country can be difficult and costly"
(Wairau Forest, Malborough)

This report analyses the performance of typical NZ log truck configurations on grades and corners. It will be useful to road builders and truck operators who want to predict how a given truck specification will perform on critical sections of existing or proposed roads.

This analysis sets the various resistances to motion against the truck's ability to generate tractive effort. Equations for the resistance components have been taken from existing literature. Tractive effort has been developed taking into account load unbalance on the drive axles when cornering due to trailer in-swing and road super-elevation. To recognise super-elevation without undue complication, centripetal acceleration and the centre of mass above the drive axles have been calculated using the rig as a whole. This assumption provides acceptable accuracy at the speeds likely during critical climbing operations (0 - 10 km/hr).

The model developed by the analysis in this report has been called TRUKGRAD. Because manual calculation would be too tedious the model has been loaded into a personal computer spreadsheet labelled with the same name. Use of the computer programme is covered in the Appendix.

Verification of the predictions is needed but may take some time as discussed in the section on "Future research directions" later. Subjective comparison of results with field operations supports the general form of the relationships. An alternative to verification by research would be to slowly build up experience by using the model to help construct short sections of road or reconstruct corners. In this way confidence can be achieved without undue cost.

2.0 THE PRINCIPLES OF TRUCK/ROAD INTERACTION

How well a particular truck performs over a certain stretch of road depends on the <u>resistances</u> the road presents to the truck (1).

Resistances can be either :

DIRECT, i.e. physical forces to be overcome such as :

- tyre rolling resistance
- grade resistance
- cornering resistances

or influences on traction :

- tractor lean because of road super-elevation (crossfall) (causing weight transfer from the high side drive wheels across to the lower side)
- different super-elevations at the truck and trailer (causing weight transfer across the drive axles through stiffness of the load)
- loose surfaces

INDIRECT, i.e. factors which impede the truck, usually because of the driver's perception :

- lane and shoulder widths
- sight distance
- roughness
- special speed restrictions

These direct interactions have been reasonably well understood for many years. Formulae and tables can be found in many references such as S.A.E. J688 "Truck Ability Prediction", 1958 and "Trucks and Trailers and their Application to Logging Operations" 1975 (McNally, 1975). More recently D. Ljubic of FERIC has been testing and revising many of the resistance relationships (Ljubic, 1985). It is possible to take these equations and determine the force required at the truck wheels to proceed down the road.

The truck's ability to produce traction can be calculated using conventional mechanics of machines theory. With the total resistance and tractive force calculated it is possible to subtract one from the other to get the net force available to accelerate the truck at any position on the road (refer Fig. 1). This procedure is the heart of any truck performance prediction model.

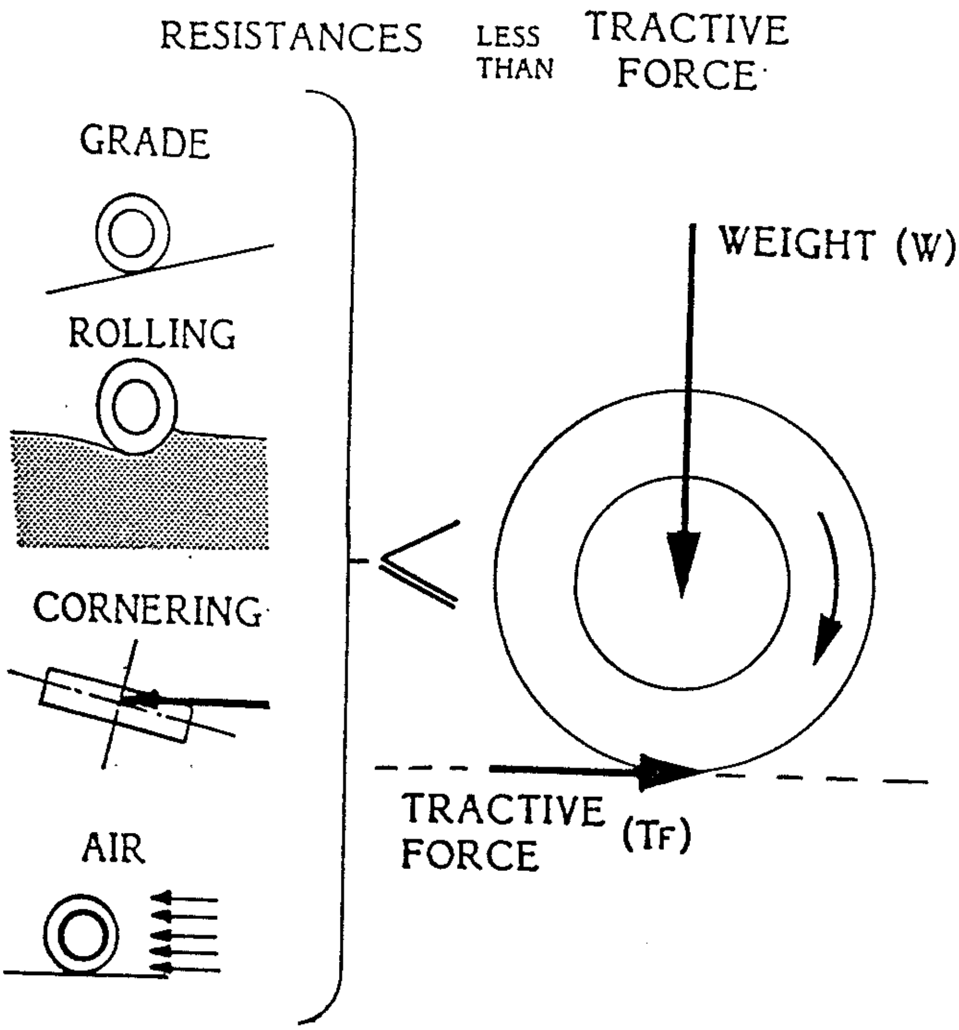


Figure 2.1 : Direct Resistances versus Tractive Force

The remainder of this section discusses the formulae used in the TRUKGRAD gradeability model.

Note :

(1) Sections 2.1 to 4.5 provide a detailed analysis. *Some readers may wish to leave this and go directly to Section 5 on results.*

(2) Terminology is assumed to be consistent unless otherwise stated. Some anomolies occur between truck types, i.e. common terms identify similar but not identical dimensions. This has been done to facilitate a parallel spreadsheet layout. Figures included later will clarify how dimension symbols apply to each rig.

2.1 ROLLING RESISTANCE (R_R) :

Based on FERIC's current research into log transport productivity and efficiency (Ljubic, 1985).

$$R_R = W_{(i)} \times \{ CR_1 + [CR_2 \times V^2]\}/100 \quad kN$$

$W_{(i)}$ Weight on axle(s) considered (Tonnes)

CR_1 Coefficient of rolling resistance No 1

CR_2 Coefficient of rolling resistance No 2

V Truck Velocity (Metres/second)

FERIC values for CR_1 and CR_2 when travelling on gravel road are 7.25 and .01692 respectively.

2.2 AIR RESISTANCE (R_A) :

Air resistance is defined by the well accepted equation (McNally, 1975);

$$R_A = K \times A \times V^2 \quad (N)$$

A Frontal area of truck (Sq. metres)

K Drag coefficient

K = .0611 when converted to metric units.

2.3 CORNERING RESISTANCE (R_C)

Vehicles negotiating a corner experience an added drag force. This resistance has two main factors; centripetal acceleration and scuff of multiple axle groups. Empirical studies indicated that this drag was generally greater than air and rolling resistance combined. This conclusion was further supported in later analytical work by the same author, Smith (1970), and the equations shown in Sections 2.3, 2.4, 3.1 and 3.2 are from this reference.

(i) The centripetal acceleration factor is :

$$R_{cc} = Fe\{(1 / [4.86 \times n \times C_c]) \times ([W \times S^2] / [427.8 \times R])^2\}$$

(ii) The group axle scuff :

$$R_{cs} = Fe\{ Mu_c \times W_a \times L_a / (2 \times R)\}$$

$$Fe = 0.01 \times (1 - \{ 127.28 * R * E / [S^2]\})$$

S Vehicle speed (km/Hr)

W Gross weight on the axles being considered (kg)

W_a Pavement load under the axle group being scuffed (kg)

L_a First to last axle distance for axle group being scuffed (metres)

n Number of tyres in the group being considered (All tyres count eg. Twin tyred axle = 4 tyres)

E Super-elevation of the road

Mu_c Coefficient of friction for cornering scuff (suggested value 0.2 Smith, 1970)

C_c Tyre cornering coefficient 200 kg / degree loaded; 85 kg / degree unloaded

Fe Factor to take account of super-elevation . At speeds of 0 - 20 k.p.h. this factor can be taken as 1.0 .Smith,1970 gives the following equation for all speeds ;

$$Fe = 0.01 (1 - [\{127.28 \times R \times E \}/\{S^2\}])$$

Note: The numerical constants have been calculated to suit the metric system and so they vary from those shown in the text of Smith, 1970.

All equations in this section have been taken from Smith (1970) and converted to metric.

2.4 GRADE RESISTANCE (R_G)

Grade resistance is simply the component of weight acting parallel to the slope.

$$R_G = W \times \mathrm{Sin}(A)$$

W Weight on axle(s) considered.

A Slope of road under axle(s).

In the case of a complete logging rig each axle group follows a path with a different slope when negotiating a corner. Further if the pavement load normal to the surface under each axle(s) is known then grade resistance can be expressed as :

$$R_G = \{ N_T \times \mathrm{Tan}(A_3) + N_D \times \mathrm{Tan}(A_2) + N_F \times \mathrm{Tan}(A) \} \times 9.81 \quad \mathrm{kN}$$

N_T Pavement load under trailer (Tonnes)

N_D Pavement load under drive axle group (Tonne)

N_F Pavement load under the trucks' front axle (Tonnes)

2.5 INERTIA RESISTANCE (R_I)

All moving objects have energy by virtue of their motion (kinetic energy). If the rate of motion is changed the energy level changes, e.g. a truck slowing down as it negotiates a grade reduces its kinetic energy but this energy change assists the truck up the hill. In accelerating a truck additional energy is needed on top of that required for steady resistance, to provide the increase in kinetic energy. These changes in kinetic energy can be thought of as INERTIAL RESISTANCE, positive when speeding up and negative when slowing down.

In this model steady state conditions have been assumed so inertia resistance is zero.

3.0 TRACTIVE EFFORT (T_F)

Tractive effort is the force available at the tyre surface to propel the vehicle along the road. Past studies on typical North American logging rigs has shown that at low speed this force is limited by surface conditions not engine and transmission characteristics (Stryker, 1977). New Zealand logging rigs are specified similarly and will also be surface limited for traction. Normal operation of a laden logging rig on an adverse grade would not include engaging the differential lock if fitted. This means that the factor limiting traction is either the most lightly laden wheel or the tyre contacting the most slippery surface at the time. For this case, consistent road surface conditions are assumed. At low speed there are two factors which cause significant side loading of the drive bogie and hence uneven drive tyre loads : trailer inswing and road super-elevation.

3.1 TRAILER IN-SWING

Trailer drag on a corner pulls at an angle to the longitudinal axis of the truck. This can be resolved to give forces both along and across the truck. The transverse force is significant in shifting weight to the inside drive wheels on both Bailey bridges and Longs combinations.

The amount of weight shifted from the drive tyres on the outside of the corner to those on the inside is :

$$N_I = T_H \times \text{Sin}(P) \times Y_2 / T_R$$

3.2 SUPER-ELEVATION

Typical super-elevations seen in New Zealand forests cause significant weight shift to the low side drive wheels at low speed, especially on laden trucks. In this analysis the amount of weight shift has been calculated from the excess super-elevation, i.e. actual super-elevation less super-elevation required to balance centripetal force.

Figure 3 - Excessive superelevation.
Superelevation is often designed more to keep a vehicle at speed on the road than to assist a loaded truck climb a grade.

The amount of weight shifted from the drive wheels on the high side of the truck to those on the low side is :

$$N_E = N_D \times Y_M \times (E - E_C) / (T_R \times 100)$$

Using these two equations, the tractive effort available is defined by :

$$T_F = 2 \times Mu \times (N_D / 2 - N_I - N_E)$$

T_H Co planar force applied to the truck bolster (or 5th wheel) by the trailer.

P Plan angle between truck and trailer axes

Y_B Height of truck bolster

T_R Track of drive axle

N_D Pavement load under drive bogie

Y_M Height of centre of mass producing N_D. For simplicity this has been taken as the CofG height of the rig as a whole;
$(W \times Y_1 + P_L \times Y_4 + W_T \times Y_T) / (W + P_L + W_T)$

E Super-elevation (%)

E_C Neutral super-elevation (i.e. the super-elevation needed to balance centripetal acceleration $(V^2 / R \times g)$ (%)

Mu Coefficient of traction

V Truck velocity

R Corner radius

g Gravitational acceleration (9.81 m/sec^2)

4.0 EQUATIONS OF MOTION

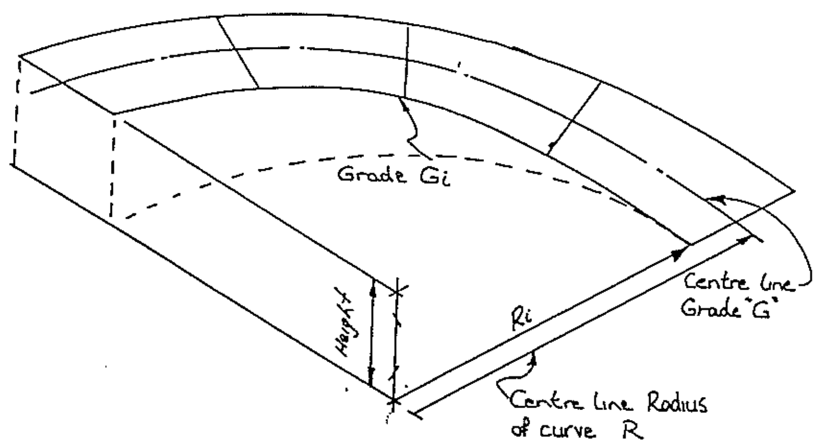
Using the equations in Sections 3 and 4 it is possible to combine maximum tractive effort and the various resistances to find surplus rim-pull.

Already in the sections above some assumptions have been made to avoid undue complexity and cost. It has also been necessary to define corner geometry as follows. Transitions between straight and curve are ignored.

4.1 CORNER GEOMETRY

The grade on any circular arc is assumed to be inversely proportional to radius (i.e. for a given angle of rotation the same height increase is achieved regardless of the arc followed).

Super-elevation can then be superimposed on this base geometry.



$$G_i = G \times R / R_i$$

Figure 4.1 : Corner Geometry

4.2 VERTICAL ANGLES

When cornering each bogie follows a different arc. But as discussed in 5.1 each arc has a different grade so grade resistance must be calculated for each bogie.

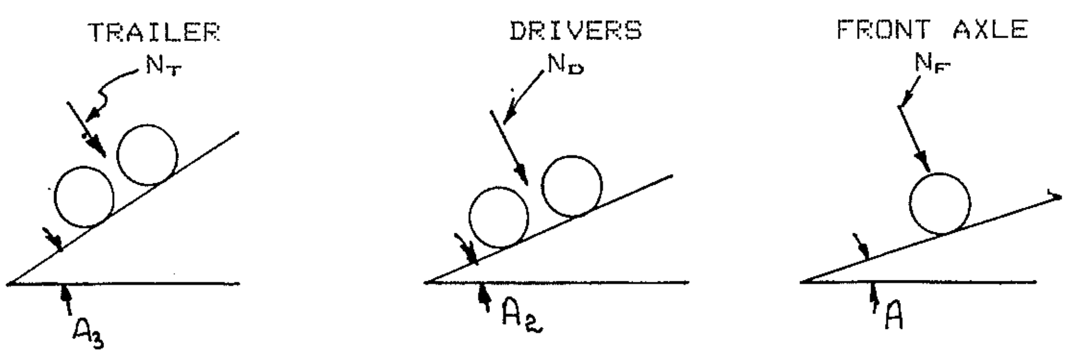


Figure 4.2 : Grades for each Axle Group

4.3 LONG LOG RIG : TRACTION EQUATIONS

Traction as discussed earlier is affected by many factors, including :

- super-elevation
- speed
- side pull component from trailer
- weight distribution on the drive axle.

The following calculations take these factors into account within the bounds of the various assumptions already stated.

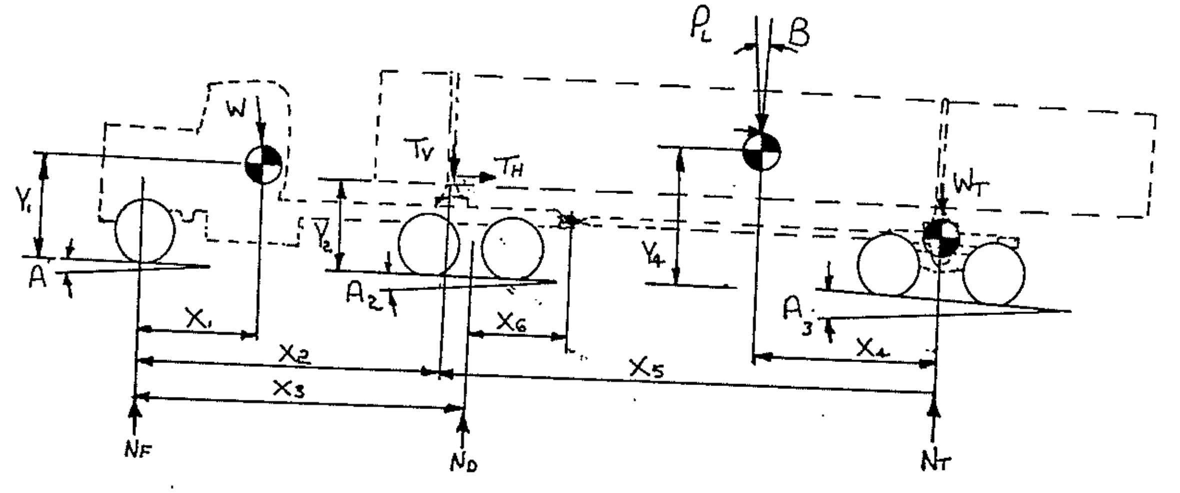


Figure 4.3 : Long Log Rig

Long Log Rig

Calculate the trailer pavement load first by taking moments about the front bolster.

N_T x X_5 = W_T x Cos(B) x X_5 +(X_5-X_4) x P_L x Cos(B) +

(Y_4-Y_2) x P_L x Sin(B) -

R_T x Y_2 / COS (P_3) kN Equation A

R_T = Trailer Resistance

= Rolling Resistance (R_R)

+ Grade Resistance Component (R_{GT})

+ Corner Resistance (R_{CT})

R_{RT} = N_T x C_R

R_{GT} = N_T X (A_3 - B) Note: A_3 & B are small so Sin X approx = X

R_{CT} = CORNER CENTRIFUGAL RESISTANCE (R_{CTC})

+ CORNER SCUFF RESISTANCE (R_{CTS})

R_{CTC} = {Fe / 4.86 x C_C x n_2} x 1000 x

{(N_T x S^2) / (427.8 x R)}^{2}

R_{CTS} = {Fe x Muc x N_T x n_3 x l_2} /(2 x R_C x n_2)

Note : Weight on tandem being scuffed is aproximated by :

(n_3/n_2) x N_T

R_{CTC} can be simplified to get rid of the N_T^2 term by assuming that the standard axle weight of 7000 Kg is carried and multiplying by the number of axles on the trailer.

So R_{CTC} = (Fe x N_T^2) / (4.86 x C_C x n_2) x 1000 x

({S^2} / {427.8 x R})^2

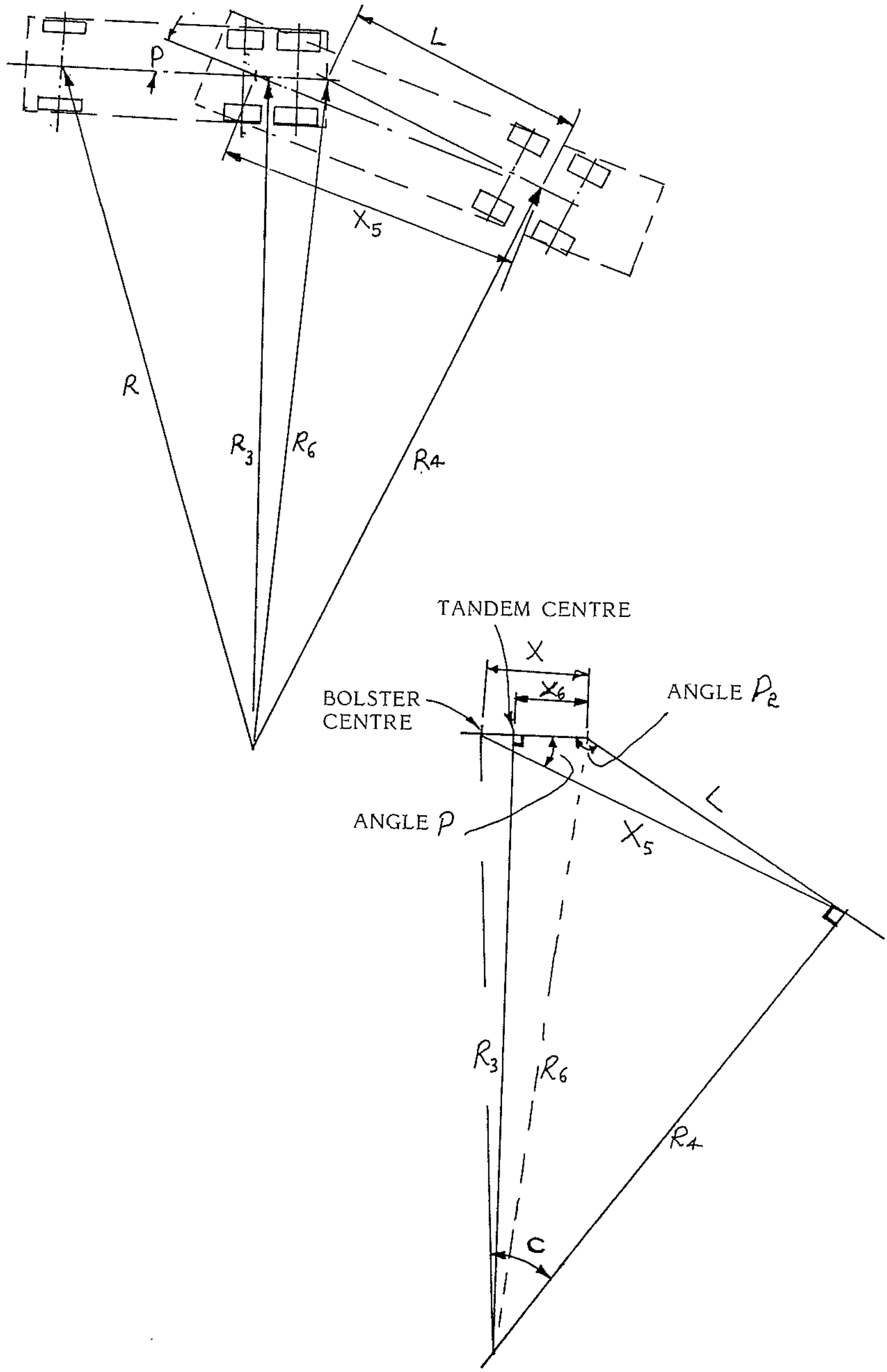


Figure 4.4 : Cornering Geometry for Long Log Rigs

Becomes:

$$R_{CTC} = (Fe \times 7000 \times n_m N_T) / (4.86 \times C_C \times n_2) \times (\{S^2\} / \{427.8 \times R\})^2 \quad \text{Equation B}$$

$$R_T = N_T\{ C_R + A_3 - B + (Fe \times 7000 \times n_m) / (4.86 \times C_C \times n_2) \times (\{S^2\} / \{427.8 \times R\})^2 + \{Fe \times Muc \times n_3 \times l_2\} /(2 \times R_C \times n_2)$$

For simplicitity lets express this as:

$$R_T = N_T \times f_q$$

Returning to equation A R_T is not in line with the log load so it is necessary to divide it by $COS(P_3)$

Now write Equation A with all N_T terms on the left hand side.

$$N_T\{X_5 - f_q \times Y_2 / COS(P_3)\} = W_T \times COS(B) \times X_5 + P_L \times COS(B) \times (X_5 - X_4) + P_L \times SIN(B) \times (Y_4 - Y_2)$$

So $$N_T = 1 / \{X_5 - f_q \times Y_2 / COS(P_3)\} \times \{W_T \times COS(B) \times X_5 + P_L \times COS(B) \times (X_5 - X_4) + P_L \times SIN(B) \times (Y_4 - Y_2)\}$$

To get a better estimate of N_T substitute this first estimate of N_T into f_q and then calculate a second value for N_T.

Sufficient forces are now known to calculate T_V and T_H.

$$T_H = 9.81 \times (P_L \times Sin(B) + W_T \times Sin(B) + R_T) \quad kN$$

$$T_V = 9.81 \times (P_L \times Cos(B) + W_T \times Cos(B) - N_T) \quad kN$$

Now the trailer plane has an inclination of B
and the truck plane has an inclination of B_1
so we need to re-align T_H and T_V to the truck plane.

The difference between these planes is $B - B_1 = B_3$

$T_{H1} = T_H \times COS(B_2) + T_V \times SIN(B_2)$

$T_{V1} = T_V \times COS(B_2) + T_H \times SIN(B_2)$

Next by taking moments bout the truck front axle it is possible to calculate the pavement load under the drive axles (N_D).

$$N_D = 9.81\ [(W \times Cos(B_1) \times X_1)+(W \times Sin(B_1) \times Y_1) + (T_{H1} \times Cos(P) \times Y_2)+(T_{V1} \times X_2)] / X_3 \quad kN$$

Next calculate the trucks front axle load (N_F)

$$N_F = W \times COS(B_1) + T_{V1} - N_D$$

Now it is possible to calculate the Tractive Force (T_F) from the equation in section 4

$$T_F = 2 \times 9.81 \times Mu \times (N_D / 2 - N_I - N_E)$$

RESISTANCE CALCULATIONS

Truck rolling resistance (R_{RL}) = $C_R \times (N_D + N_F) \times 9.81$

Truck grade resistance (R_{GL}) = $W \times SIN(B) - N_F \times (B - A_1) + N_D \times (A_2 - B)$

Truck cornering resistances as follows:

Centrifugal resistance (R_{CLC}) = $\{Fe / 4.86 \times C_C \times n\} \times 1000 \times \{([N_F + N_D] \times S^2) / (427.8 \times R)\}^2 \times 9.81$ kN

Scuff Resistance (R_{CLS})= $9.81 \times \{Fe \times Muc \times N_D \times l_1\}/(2 \times R_C)$ kN

Trailer resistance (R_{TL}) = $T_{H1} \times COS(P)$

Air resistance (R_A) = $K \times A \times V^2$ kN   Whole rig

TOTAL RESISTANCE (R) = $R_{RL} + R_{GL} + R_{CLC} + R_{CLS} + R_{TL} + R_A$ kN

The following text develops the various factors used in the above equations.

$A = \mathrm{Atan}[\ G/100\ ]$

$A_2 = \mathrm{Atan}[(\ R/R_3\ ) \times (\ G/100\ )]$

$A_3 = \mathrm{Atan}[(\ R/R_4\ ) \times (\ G/100\ )]$

B = INCLINATION of logs and is the difference in height between the two bolsters divided by the length between them. This is made up of two components; one due to grade and one due to super-elevation.

$B = \mathrm{ASIN}([\ d_{BG} + d_{BE}\ ]/X_5)$

$d_{BG} = C \times Pi \times R \times G\ /\ 18000$ metres

$d_{BE} = (R_3 - R_4) \times E\ /\ 100$ metres

B_1 = Inclination of the truck

$= \mathrm{ASIN}([\ d_{BG1} + d_{BE1}\ ]/X_3)$

$d_{BG1} = C_1 \times Pi \times R \times G\ /\ 18000$ metres

$d_{BE1} = (R - R_3) \times E\ /\ 100$ metres

$C = \mathrm{ASIN}(\ L/R_6\ ) + \mathrm{Asin}(\ X_6/R_6\ ) + \mathrm{Atan}([X_3 - X_2]/R_3)$ degrees

$C_1 = \mathrm{ASIN}(X_3\ /\ R)$

Angle "P" is not readily calculated . It reqires the solution of simultaneous equations.(See spreadsheet)

Using the Sine Rule;

$X_5/\mathrm{SIN}(P_2) = L/\mathrm{SIN}(P)$ ------(Equation C)

Then using the two right angle triangles in fig. 5.2 an expression for P_2 can be written.

$P_2 = \mathrm{ACOS}(\ L/R_6\ ) + \mathrm{ACOS}(\ X_6/R_6\ )$ ------(Equation D)

Combining equations "C" + "D" gives;

$0 = (\ X_5/L\ ) \times \mathrm{SIN}(P) - \mathrm{SIN}(\mathrm{ACOS}\{\ L/R_6\ \} + \mathrm{ACOS}\{\ X_6/R_6\ \}\ )$

Solving this gives angle "P".

Definitions of the various factors used are given below.

$X = X_3 + X_6 - X_2$

$L = (X^2 + X_5^2 - 2 \times X \times X_5 \times Cos(P))^{.5}$

$R_3 = (R^2 - X_3^2)^{.5}$

$R_6 = (R_3^2 + X_6^2)^{.5}$

$R_4 = (R_6^2 - L^2)^{.5}$

$P_3 = ASIN\{[X / L] \times SIN(P)\}$ Using "P" just calculated.

4.4 BAILEY BRIDGE : TRACTION EQUATIONS

The Bailey Bridge Rig is very similar to the Long Log Rig . the following changes are needed in the analysis:

(i) The trailer resistances at the wheels are inline with the logs so the $COS(P_3)$ term can be deleted.

(ii) The cornering geometry changes so that :

$$C = Atan(X_5/R_4)$$

With these changes in place the analysis can proceed as for a Long Log Rig .

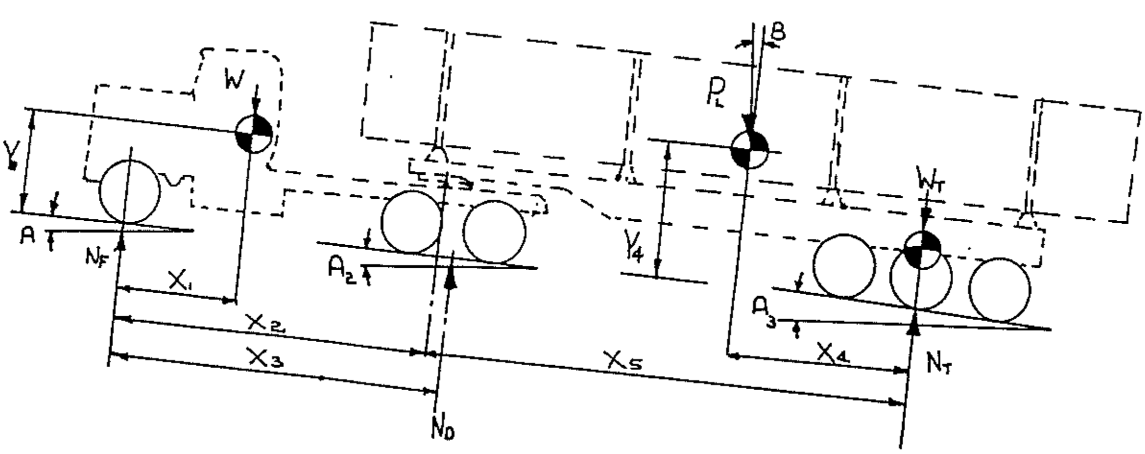


Figure 4.5 : Bailey Bridge Rig

Bailey Bridge (3 axle)

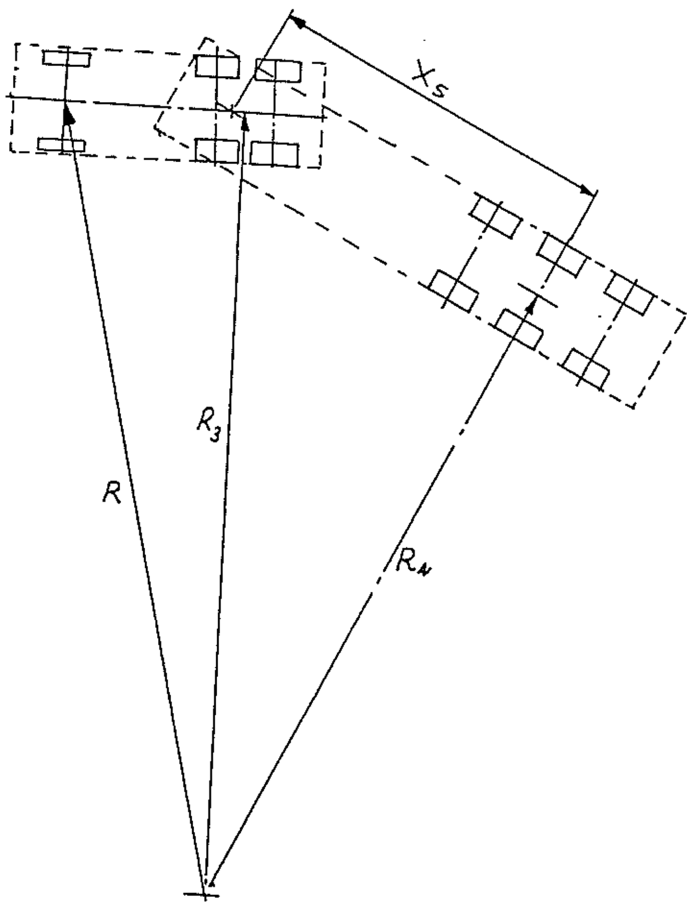


Figure 4.6 - Cornering Geometry Bailey Bridges

4.5 SHORT LOG RIG : TRACTION EQUATIONS

First calculate the pavement loads under each trailer bogie:

$$N_{TR} \times X_5 = W_T \times X_5 + (X_5 - X_4) \times P_L \times Cos(B) + (Y_4 - Y_3) \times P_L \times Sin(B) - R_{TR} \times Y_3 \quad kN$$

This is a similar analysis to that for the Long Log Rig .

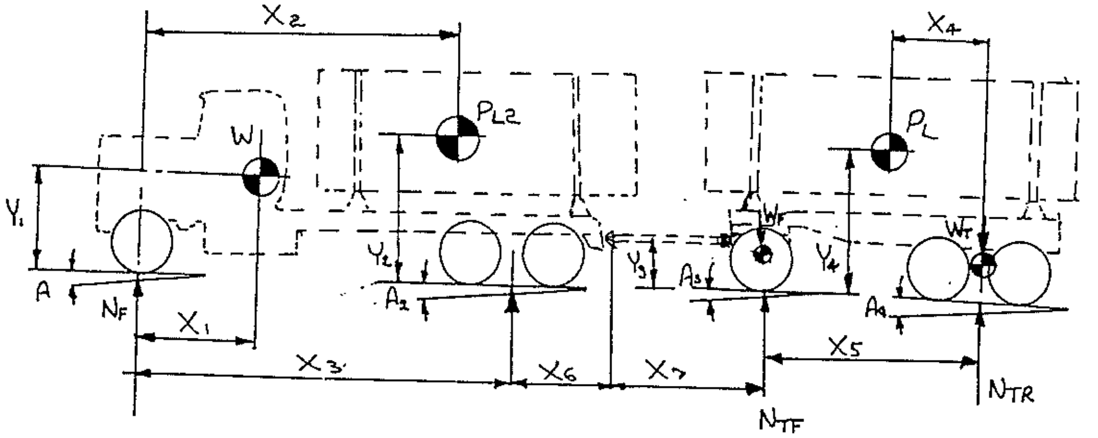
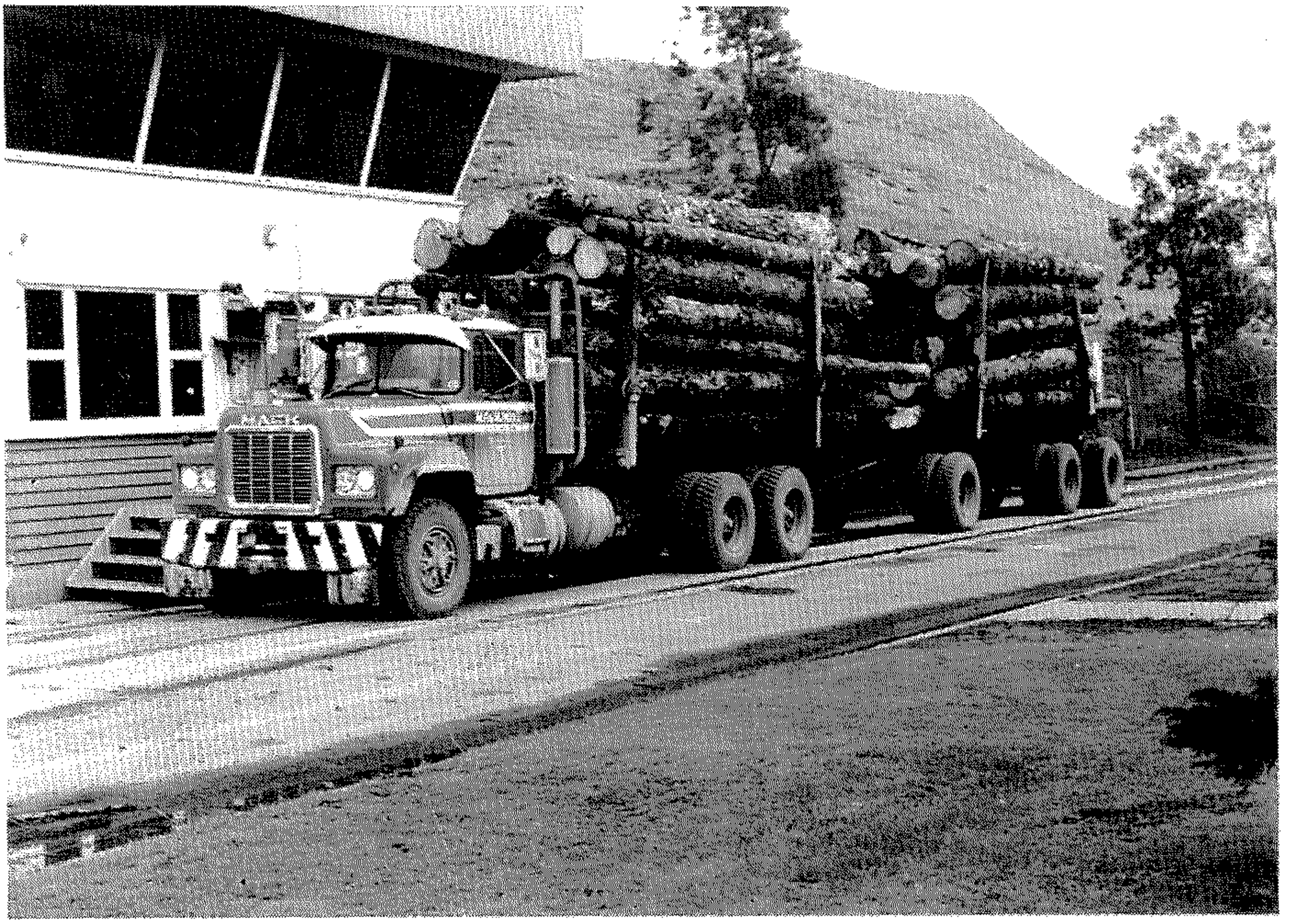


Figure 4.7 - Short Log Rig



Short Log Rig

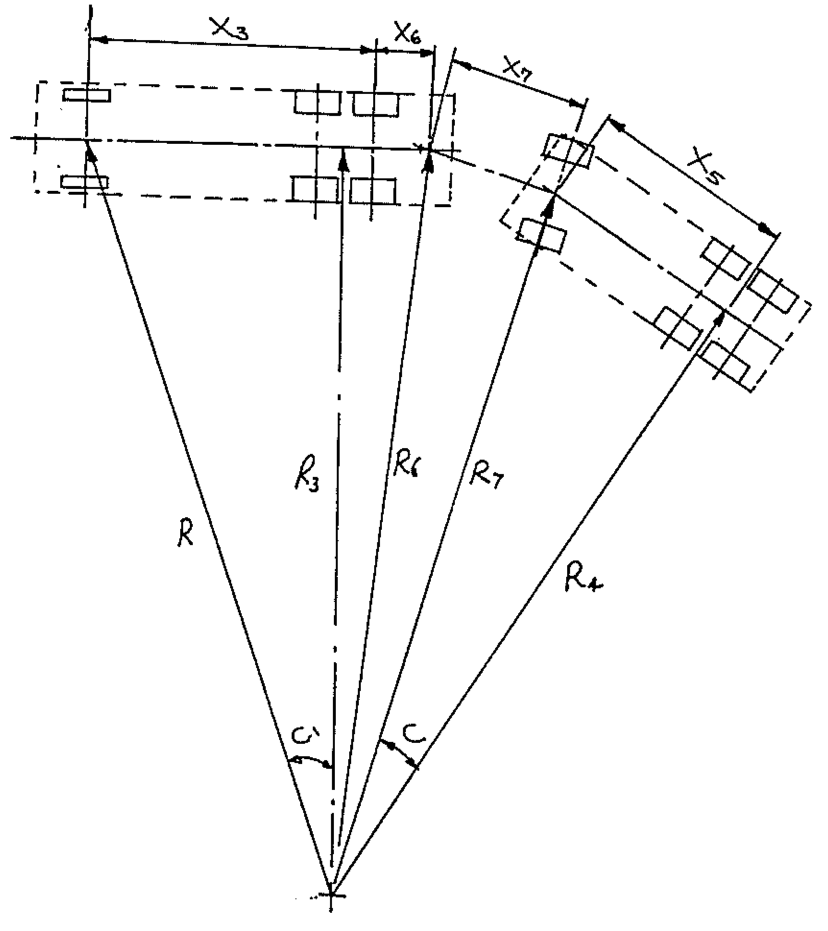


Figure 4.8 - Cornering Geometry for Short Log Rigs

R_{TR} = Trailer Rear Bogie Resistance

= Rolling Resistance of rear bogie (R_{RTR})

+ Grade Resistance Component for rear bogie (R_{GTR})

+ Corner Resistance for rear bogie (R_{CTR})

R_{RTR} = N_{TR} x C_R

R_{GTR} = N_{TR} X (A_4 - B) Note:A_4 & B are small so SIN X approx = X

R_{CTR} = CORNER CENTRIFUGAL RESISTANCE (R_{CTRC})

+ CORNER SCUFF RESISTANCE (R_{CTRS})

R_{CTRC} = {Fe / 4.86 x C_C x n_3} x 1000 x

{(N_{TR} x S^2) / (427.8 x R)}^{2}

R_{CTRS} = {Fe x Muc x N_{TR} x l_2} /(2 x R_C)

R_{CTRC} can be simplified to get rid of the N_{TR}^2 term by assuming that the standard axle weight of 7000 Kg is carried and multiplying by the number of axles on the trailer.

So R_{CTRC} = (Fe x N_{TR}^2) / (4.86 x C_C x n_2) x 1000 x

({S^2} / {427.8 x R})^2

Becomes:

R_{CTRC} ={(Fe x 7000 x n_a x N_{TR}) / (4.86 x C_C x n_3)} x

({S^2} / {427.8 x R})^2

R_{TR} = N_{TR}{ C_R + A_4 - B

+{(Fe x 7000 x n_a) / (4.86 x C_C x n_3)} x ({S^2} / {427.8 x R})^2

+ {Fe x Muc x n_3 x l_2} /(2 x R_C x n_2)

For simplicitity lets express this as:

R_{TR} = N_{TR} x f_{qr}

Now write all N_{TR} terms on the left hand side.

N_{TR}{X_5 - f_{qr} x Y_3 } =

W_T x COS(B) x X_5 + P_L x COS(B) x (X_5 - X_4) +

P_L x SIN(B) x (Y_4 - Y_3)

So $N_{TR} = 1 / \{X_5 - f_{qr} \times Y_3\} \times$
$\{W_T \times COS(B) \times X_5 + P_L \times COS(B) \times (X_5 - X_4) +$
$P_L \times SIN(B) \times (Y_4 - Y_3)\}$

$N_{TF} = P_L \times Cos(B) + W_F \times Cos(B) + W_T \times COS(B) - N_{TR})$ kN

[Assumes the following approximation is true:

$COS(A_3) = COS(B) = COS(A_4)$]

Y_3 is assumed to approximate the trailer axle height .

With the trailer bogie loads determined it is possible to determine the drawbar pull (F_{TD}). This is effectively the trailer's resistance to motion.

F_{TD} = Trailer rear bogie resistances aligned to the drawbar

+ Trailer front axle resistances (R_{TF})

$=(\{R_{TR} + [W_F + W_T + P_L] \times SIN(B)\} \times COS(C_3) + R_{TF}) \times$

9.81 Tonnes

$R_{TF} = R_{CRTF} + R_{GTF} + R_{CTF} \times 9.81$ kN

Rolling resistance (R_{RTF}) = $C_R \times (N_{TF}) \times 9.81$ kN

Grade resistance (R_{GTF}) = $- N_{TF} \times (B - A_3) \times 9.81$ kN

The difference between trailer deck plane and front trailer axle pavement plane causes a negative relative resistance.

Centrifugal resistance (R_{CTFC}) = $\{Fe / 4.86 \times C_c \times n_3\} \times 1000 \times$

$\{(N_{TF} \times S^2) / (427.8 \times R)\}^2 \times 9.81$ kN

Next the drawbar force must be aligned with the truck axis.

F_{TD} is transformed to T_P as follows:

$T_P = \{ F_{TD} \times COS(C_2) \times COS(B - B_2)\} \times 9.81$ kN

Now calculate the truck pavement loads:

$$N_D = (1/X_3)\ \{ W\ Cos(B_2)\ X_1 + W\ Sin(B_2)\ Y_1 + P_{L2}\ Cos(B_2)\ X_2 + P_{L2}\ Sin(B_2)\ Y_2 \}$$

$$N_F = \{ P_{L2} \times Cos(B_2) + W \times Cos(B_2) - N_D)\} \times 9.81 \quad kN$$

Then tractive force is as follows:

$$T_F = 2 \times 9.81 \times Mu \times [N_D / 2 - N_E]$$

The truck resistances are:

Truck rolling resistance (R_{RL}) = $C_R \times (N_D + N_F) \times 9.81$ kN

Truck grade resistance (R_{GL}) $= \{N_F \times TAN(A) + N_D \times TAN(A_2)\} \times 9.81$

Truck cornering resistances as follows:

Centrifugal resistance (R_{CLC}) = $\{Fe / 4.86 \times C_C \times n\} \times 1000 \times \{([N_F + N_D] \times S^2) / (427.8 \times R)\}^2 \times 9.81$ kN

Scuff Resistance (R_{CLS})= $9.81 \times \{Fe \times Muc \times N_D \times l_1\}/(2 \times R_C)$ kN

Trailer resistance $T_P = \{ F_{TD} \times COS(C_2) \times COS(B - B_2)\} \times 9.81$ kN

Air resistance (R_A) = $K \times A \times V^2$ kN Whole rig

TOTAL RESISTANCE (R) = $R_{RL} + R_{GL} + R_{CLC} + R_{CLS} + T_P + R_A$ kN

And the individual factors

$A = Atan(G/100)$

$A_2 = ATAN\{(R/R_3) \times (G/100)\}$

$A_3 = ATAN\{(R/R_T) \times (G/100)\}$

$A_4 = ATAN\{(R/R_4) \times (G/100)\}$

B = INCLINATION OF TRAILER LOGS

$= ASIN\{(d_{BG} + d_{BE})/X_6\}$

$d_{BG} = C \times Pi \times R \times G / 18000$ metres

$d_{BE} = (R_7 - R_4) \times E / 100$

$C = ASIN(X_5/R_7)$

B_2 = INCLINATION OF TRUCK LOGS

$= ASIN\{(d_{BG2} + d_{BE2})/X_2\}$

$d_{BG2} = C_1 \times Pi \times R \times G / 18000$

$d_{BE2} = (R - R_3) \times E / 100$

$C_1 = ASIN(X_3/R)$

$R_3 = (R^2 - X_3^2)^{.5}$ metres

$R_6 = (R_3^2 + X_6^2)^{.5}$ metres

$R_7 = (R_6^2 - X_7^2)^{.5}$ metres

$R_4 = (R_7^2 - X_5^2)^{.5}$ metres

5.0 RESULTS

This section examines the results predicted by the gradeability model TRUCKGRAD. Performance on straight and curved road grades has been analysed for the three common New Zealand logging truck rig types. Curves have been further analysed to assess the effect of super-elevation.

5.1 RIG TYPES

The most important feature of any rig type when considering climbing ability is the proportion of weight on the drive axles(s). In the unladen state there are obvious differences between the rigs and these may significantly affect the ability of a truck to climb out to the skid site. Twin steer trucks, even with a piggyback trailer, have a greater proportion of their weight on non-drive axles. Bailey bridges and trucks towing trailers have even more weight on non-drive axles.

However, laden rigs destined for highway travel all exhibit very similar characteristics. They have a gross weight of approximately 40 tonnes, two drive axles and the weight on the drive axles is approximately 15 tonnes. Suspension and other factors being equal they will have similar climbing ability, as can be seen in Figure 5.1.

From this it can be seen that if slippery conditions exist for laden trucks the only way to significantly improve gradeability is to increase the friction between the tyre and the road. Changing rig type only has a minor effect, assuming that the drive componentry is the same.

At this point in time the coefficient of traction is not readily measured. However it is known that moving to a tighter, more angular surface material will improve traction. Therefore constructing trials in your area can provide the necessary information to develop a road construction strategy for the range of gradients, road materials and traffic volumes to be catered for.

5.2 CORNER RADIUS

At radii below 30 metres there is a significant reduction in truck gradeability, as shown in Figure 5.2. While the coefficient of traction is not readily measured it is reasonable to use the trends shown in Figure 5.2. For a gravel road in good condition the coefficient of traction is assumed to be approximately 0.4. This road would have a straight line gradeability for typical highway rigs of 12.5% but its sharper corners should be relaxed to 10%.

These predictions are based on the TRUCKGRAD MODEL which includes the assumption that diff. locks are not engaged. While this is reasonable for loaded trucks, in most cases it does not apply to empty trucks or loaded trucks in very slippery conditions.

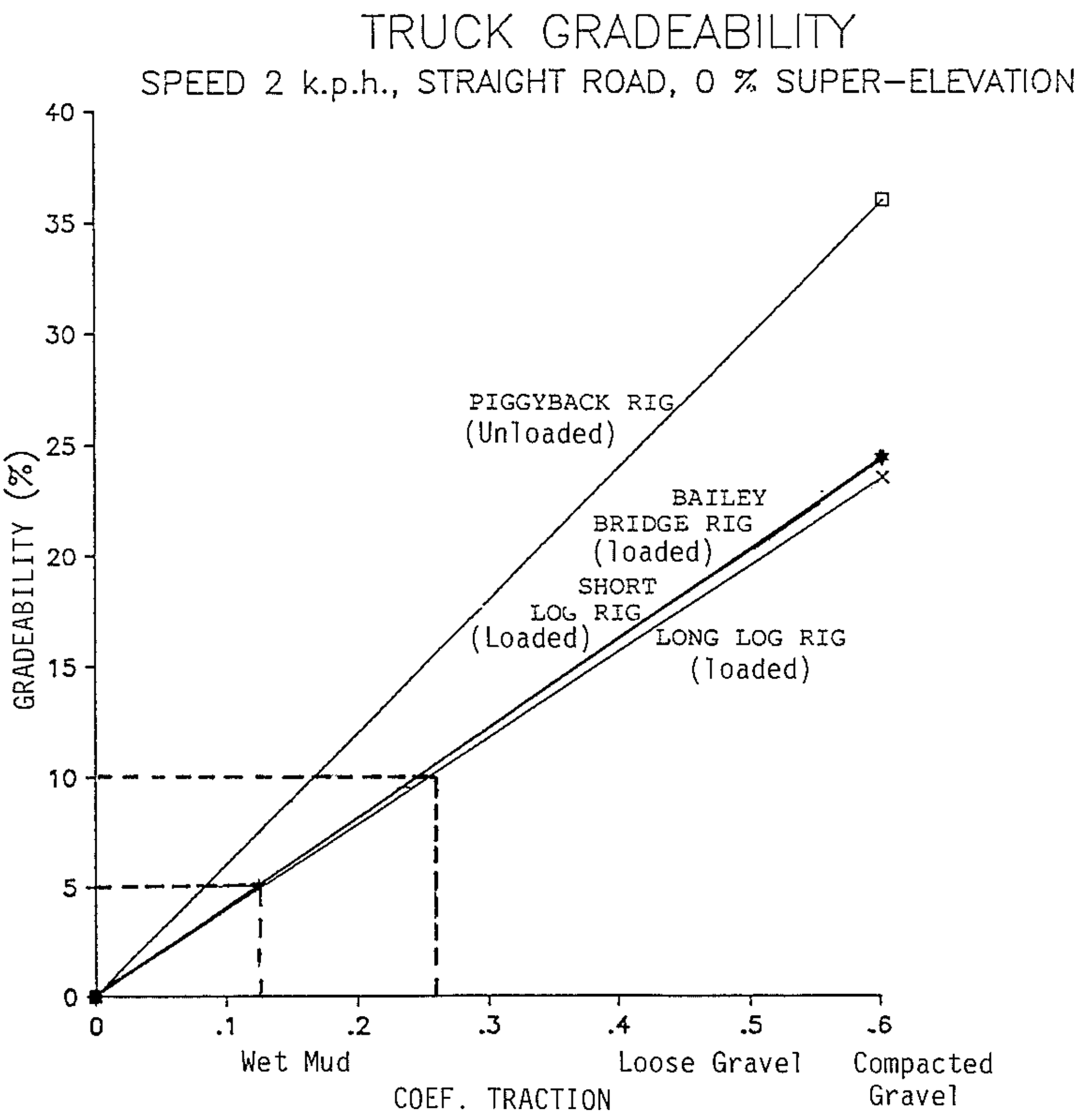


Figure 5.1 - Gradeability vs. Rig Type
(Class 1 Pavement Loads)

Often straight line grades are not pitched to the limit so continuing this grade around the corner may not affect mobility. In the above case the road could be run from bottom to top at 10%. If the road surface then becomes more slippery traction will first be lost on the sharp corners. The effect on road maintenance costs as a result of corners having to "work harder" is not known at this stage.

Another feature which appears in forest roads is the corner which is steeper than the straight line grades. It often arises from upgrading silvicultural access roads, especially when the corner is constrained by terrain, i.e. outside radius is fixed, entry height is fixed and exit height is fixed. The corner must therefore be widened toward the centre thus increasing the grade (shortened centreline distance). Where this occurs on an already steep grade it can result in a loss of traction, requiring assistance for the truck.

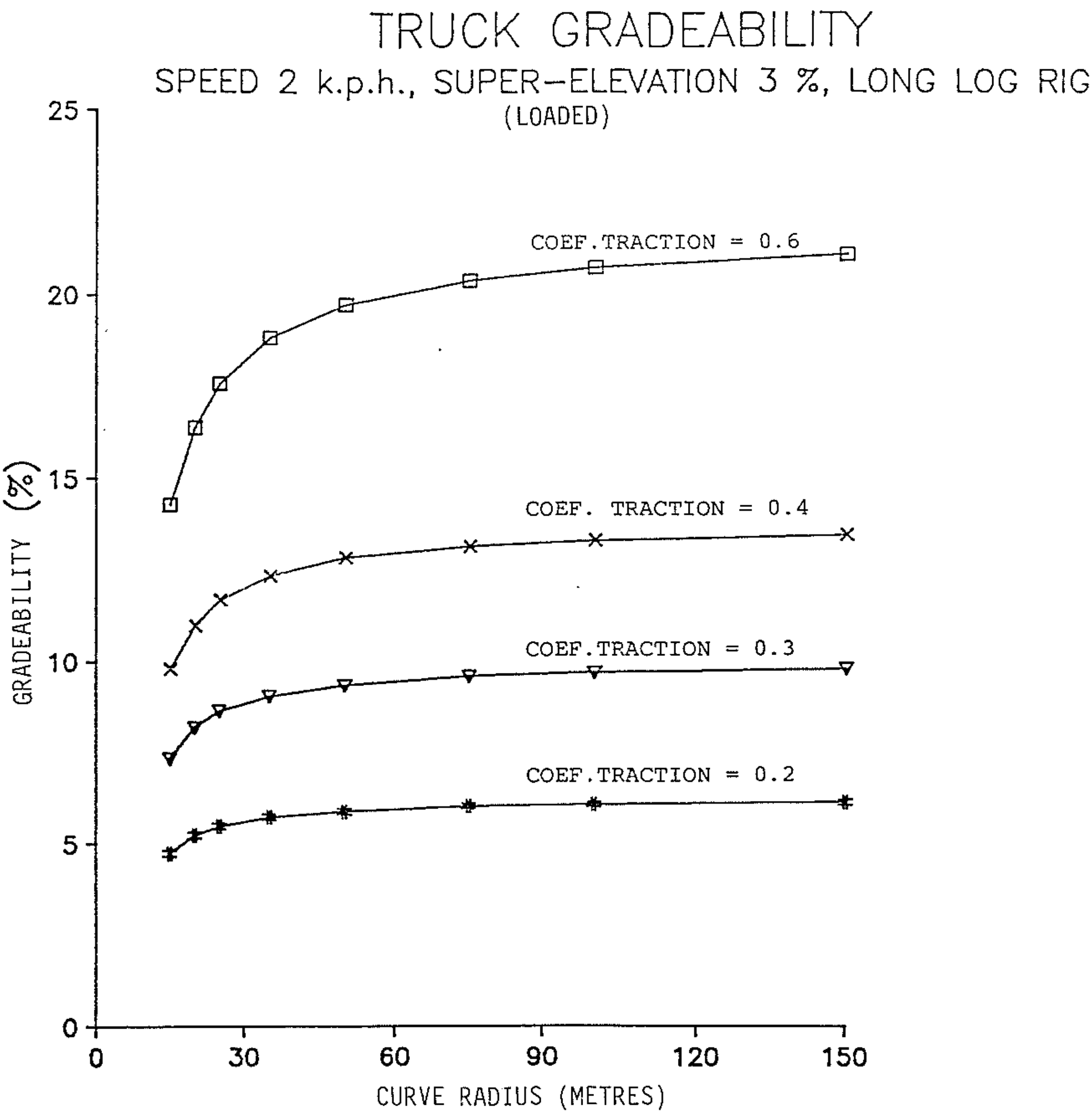
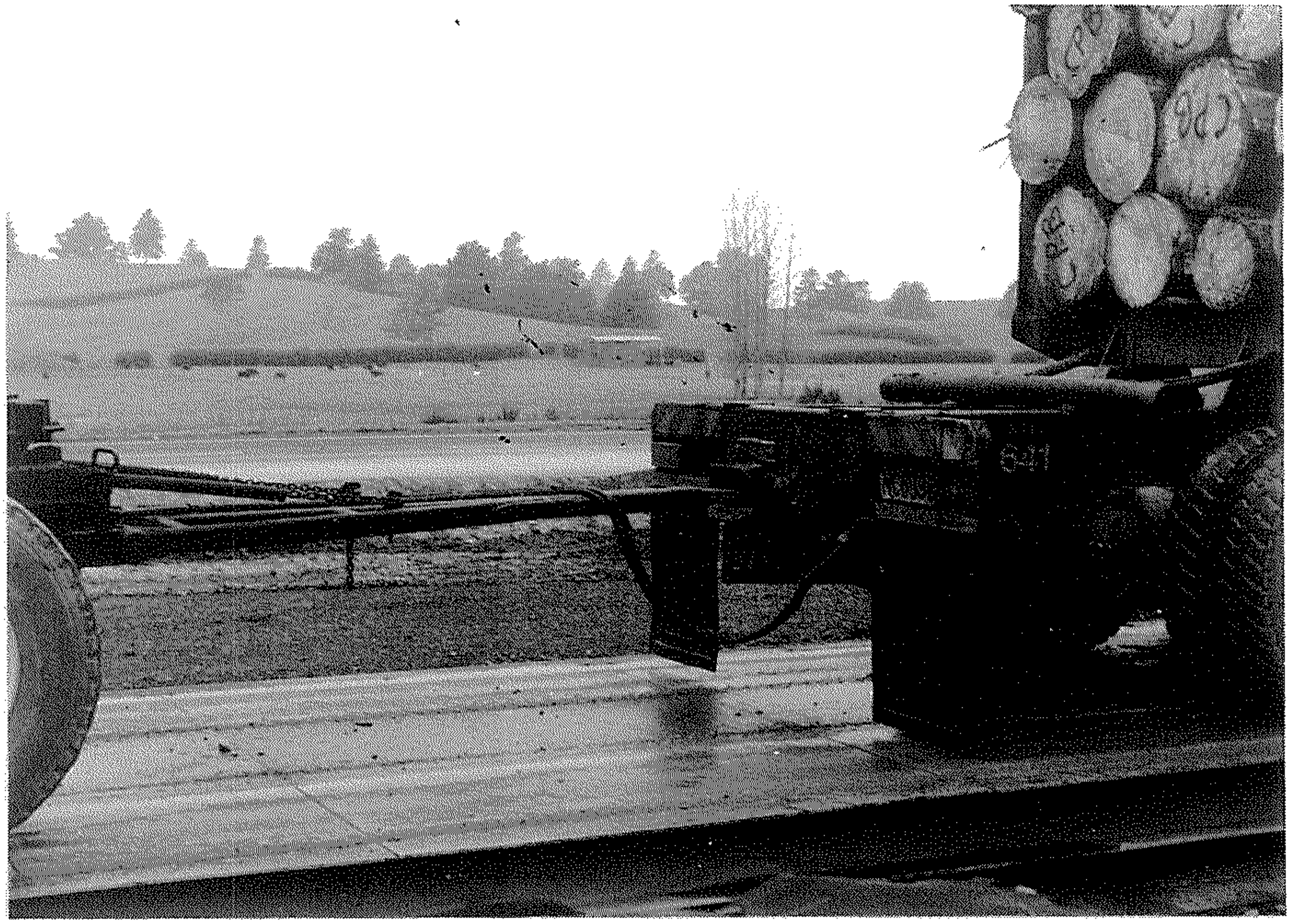


Figure 5.2 - Truck Gradeability vs. Curve Radius

On all steep roads the truck driver can assist in maintaining road condition and hence mobility. He needs to follow the widest possible path on each corner to increase the distance travelled to gain the same height. To achieve this in practice it is necessary to educate the driver in order to change his natural tendency to cut corners. He also needs help from the grader driver who must shape the corner correctly on the path taken by the truck. Light vehicles also influence truck paths as they move loose metal and change the clear path. Truck drivers can not afford to get in the loose metal when on critical adverse grades.



A short log truck has improved gradeability due to the lower trailer attachment height and the small angle between trailer drawbar and truck

6.0 CONCLUSIONS

This gradeability model provides some insight into road shapes needed to get the best out of logging rigs. While it has not been verified by field testing it does coincide with observed operations. Some specific conclusions follow :

6.1 SURFACE CONDITIONS

When roads are slippery (low coefficient of traction) there is little difference in mobility between loaded logging rig types. To get an appreciable improvement it is necessary to improve the road surface by moving to a tighter and more angular material. Each situation should be evaluated separately, taking account of local conditions, costs, and economic returns. In some cases the choice might be to do nothing and leave the area for dry weather access only.

Unloaded vehicles perform differently, with the best performers being those with a high proportion of their weight on the driven axles. Twin steer trucks, bailey bridges and other rigs which tow trailers while empty all have less climbing ability than the 6 x 4 truck with piggyback trailer.

6.2 CURVE RADIUS

Reducing curve radius increases resistance to motion. It also affects weight distribution on the drive axles through trailer in-pull. The nett effect is to reduce gradeability, especially on corners below 30 metres in radius. Corner grades should be less than on the straight-aways to make the truck performance equal in both cases.

6.3 SUPER-ELEVATION

On limiting adverse grades truck speeds are slow and little super-elevation is needed to balance centripetal acceleration. If a higher value of super-elevation is used it tends to lift the outside driving wheels and compound the in-pull of the trailer, thus reducing gradeability further.

6.4 SHORTS TRAILERS

If different rig types of the same gross weight and same drive tandem weight are compared, shorts units can negotiate slightly steeper corners. This occurs principally because of the reduced effect of trailer in-pull.

6.5 GRADEABILITY PERFORMANCE

Use of the spreadsheet described in this report offers an easy way to assess truck grade performance for any particular situation. Despite lack of proof of validity of the absolute values it offers an improvement over guessing and when used in conjunction with knowledge of your area it should provide valuable answers. This means predicting changes rather than absolute values.

7.0 FUTURE RESEARCH DIRECTIONS

7.1 FIELD TESTING

Field verification of this model is necessary to provide confidence in the absolute values predicted. This may be achieved by test or practical experience.

7.2 COEFFICIENT OF TRACTION

Improving this value can be an effective way of improving mobility. At this stage it is not readily measured. A useful project would be to develop a mobile test rig which could measure the coefficient of traction of existing roads and trial sections.

Close up of tyres on road showing importance of coefficient of traction

Its uses would include analysis of pavement construction and provision of values for use in gradeability calculations. A mobile tester would allow local operating conditions to be measured.

7.3 TRUCK SUSPENSIONS

Truck suspensions play a significant role in transferring power to the road. Their effect is to reduce the values predicted in the model although the amount is unknown. From suspension changes made to logging rigs it is suspected that some perform better than others. Current knowledge would suggest that suspensions which have little weight transfer between drive axles under heavy traction load are best.

Two studies are needed to allow selection of optimum drive bogie componentry :

(i) Determine the traction capacities of the various tandem drive suspensions available for logging trucks.

(ii) Determine the transmission and suspension maintenance costs for each suspension/differential combination.

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Wall, B. (1987). Keynote Addresses. In Logging Road and Trucks Seminar, Proceedings, LIRA, June.

SYMBOL DEFINITIONS (Also see Figures 5.1 to 5.6 and Sections 3 and 4)

W Weight of truck tractor or piggyback combination (Tonnes)

W_T Weight of trailer or rear bogie of trailer for a shorts rig (Tonnes)

W_F Weight of front bogie of shorts trailer (Tonnes)

P_L Payload or trailer payload for shorts trailer (Tonnes)

P_{L2} Payload on truck of shorts unit (Tonnes)

X_1 Distance from front axle to CofG of truck (Metres)

X_2 Distance from front axle to truck bolster (Metres) or 5th wheel

X_3 Truck wheelbase (Metres)

X_4 Distance from trailer rear axis to payload centre (Metres)

X_5 Distance between bolsters on a longs rig or trailer forward length for shorts and Bailey bridge rigs (Metres)

X_6 Sting length (Metres)

X_7 Drawbar length on shorts rig (Metres)

L Pole length (Metres)

L_1 Tandem spacing on truck (Metres)

L_2 Tandem spacing on trailer (Metres)

Y_1 Truck CofG height (Metres)

Y_2 Truck bolster height (Metres)

Y_3 Drawbar height (Metres)

Y_4 Payload CofG height (Metres)

Y_T Trailer CofG height (Metres)

Y_M Rig CofG height (Metres)

Mu Coefficient of traction

Muc Coefficient of friction for cornering . (Suggested value 0.2 Ref. 5)

$A_{(1)}$ Pavement slope.(Degrees)

B Payload slope for; longs rig, Bailey Bridge rig and the shorts trailer (Degrees)

B_1 Truck slope (Degrees)

B_2 = $(B_1 - B)$ (Degrees)

P Plan angle between truck and trailer (Degrees)

P_2 Obtuse plan angle between truck and longs trailer pole (Degrees)

P_3 Plan angle between trailer and load (Degrees)

C Plan angle (Degrees) subtended at the corner centre by;
Two bolsters of a longs unit
Forward distance of a Bailey bridge or shorts trailer

C_1 Plan angle subtended at the corner centre by the truck wheelbase of a shorts unit (Degrees)

C_2 Plan angle subtended at the corner centre by the trailer drawbar of a shorts unit (Degrees)

C_3 Plan angle subtended at the corner centre by the trailer wheelbase of a shorts unit (Degrees)

R Radius of curve to centre of front axle (Metres)

$R_{(i)}$ Radii 3,4,6&7 see figures 5.1 to 5.6 for corner geometry

T_R Track of drive axle (Metres)

T_H Co-planar load on truck bolster or 5th wheel (Tonnes)

T_V Normal load on truck bolster or 5th wheel (Tonnes)

(T_H and T_V may be qualified , eg. T_{V1} , to show resolution between truck and trailer planes.

T_F Tractive effort (kN)

N_T Pavement load under trailer (Tonnes)(or rear bogie of shorts trailer)

N_D Pavement load under drive bogie (Tonnes)

N_F Pavement load under front axle of shorts trailer (Tonnes)

N_E Weight shift on drive bogie due to super-elevation (Tonnes)

N_I Weight shift on drive bogie due to trailer inswing (Tonnes)

G Grade (%)

E Super-elevation of the road (%)

E_e Neutral super-elevation (%)

V Truck velocity (Metre/sec)

S Truck speed (k.p.h.)

A Truck frontal area ($Metres_2$)

g Gravitational acceleration ($Metre/sec_2$)

Fe Factor in the corner resistance equations to allow for super-elevation of the road . Taken as zero at low speed (0-20 k.p.h.) in this analysis.

n Total number of tyres on the truck.(eg. 10 for a 6 x 4)

n_2 Total number of tyres on the trailer.

n_3 Number of tyres on the trailers' fixed bogie.

n_4 Number of axles on the trailer.

f_q = (R_T / N_T) For long log and Bailey Bridge rigs.

f_{qr} = (R_{TR} / N_{TR}) For short log rigs.

CR = Coefficient of rolling resistance

$= \{ CR_1 + [CR_2 * V^2]\}$

CR_1 Coefficient of rolling resistance No 1

(value from ref. (4) is 7.2)

CR_2 Coefficient of rolling resistance No 2

(value from ref. (4) is 0.01692)

K Drag coefficient

From Ref. (3) K = 0.611 when converted to metric units.

C_c Tyre cornering coefficient — 200 kg / degree loaded; 85 kg / degree unloaded

All Resistances as follows:

$R_{a\,b\,c\,d}$

a=
- L = truck
- T = trailer
- R = rolling
- G = grade
- C = corner
- A = air
- I = inertia
- blank = rig total

b=
- R = rear
- F = front
- L = truck
- T = trailer
- blank = rig total

c=
- R = rear
- F = front
- C = centrigugal
- S = scuff

a=
- C = centrifugal
- S = scuff

eg. R_{CTRS} denotes the scuff component of cornering resistance on the rear of the trailer.

APPENDIX I

SPREADSHEET CALCULATION OF TRUCK GRADEABILITY USING "TRUKGRAD"

While the previous sections provide sufficient information to calculate grade performance, they represent a tedious manual job especially when analysing trends. An easy solution is available in the form of spreadsheet software for PC computers. This section shows and discusses the use of "SUPERCALC 3". A very basic knowledge of using SUPERCALC is needed, but this can be acquired with less than an hours tuition. The program can be easily adapted for other spreadsheets such as LOTUS 123.

Instructions to run TRUKGRAD :

1. Boot up computer.
2. Load SUPERCALC 3.
3. Load TRUKGRAD.

This will display the spreadsheet shown in Figure 6.1. Each rig type is independent so input data must be entered for each separately. To speed use of the programme it should be set to manual calculation thus avoiding recalculation after each entry.

Use /G M to set manual calculation. Then push Shift ! to calculate when desired.

For all three rigs input data is entered as required from the top, down to the "CALCULATIONS" heading. The long log rig has a peculiarity arising from its cornering geometry. At cell "G45" there is an instruction to go to cell "AA45" so that angle "P" can be determined by trial and error. Once this has been done the user returns to cell "G45" and completes as for the other rigs. In doing this sequence some values are automatically transferred between the spreadsheet sections. For this reason it is important to work right from the top of column "G" when changing any inputs. Some exceptions include; grade, super-elevation and coefficient of traction.

In all three cases there is a logical progression through the necessary calculations from the "CALCULATION" heading down. Terminology is identical to the report and easily followed by reference to Figures 5.1 to 5.6.

For those interested in seeing both the input data and the answer, it is worthwhile setting up a window at row "120". Use /W H /W S with the cursor at row 120

Analysing trends is possible by storing the results of consecutive calculations to a row outside the main spreadsheet. Once the desired data is generated use the /V command to graph it. Section 7 covers some pertinent results achieved by this method.

For a full explanation of SUPERCALC 3 commands refer to your manual.

Fig A1 - Supercalc 4 Spreadsheet Printout of TRUKGRAD input section

TRUCK GRADEABILITY INPUT DATA		BAILEY BRIDGE	LONG LOG TRAILER	TRUCK & TRAILER
WEIGHTS (Tonnes)			WORK FULL COLUMN TO AVOID ERRORS	
TRUCK TARE WEIGHT(Truck only OR Truck & Piggyback Trailer)	(W)	9.50	10.50	10.50
TRAILER BOGIE WEIGHT (REAR ON SHORTS)	(WT)	3.50	4.50	3.50
FRONT BOGIE OF SHORTS TRAILER	(WF)	NOT REQ'D	NOT REQ'D	1.50
PAYLOAD	(PL)	26.00	26.00	9.50
PAYLOAD (TRAILER FOR SHORTS ONLY)	(PL2)	NOT REQ'D	NOT REQ'D	16.00
DIMENSIONS A.(Measured in metres from front axle)				
TO CofG OF TRUCK	(X1)	2.65	2.80	2.90
TO TRUCK BOLSTER	(X2)	5.30	5.40	5.40
TO CENTRE OF TRUCK DRIVE TANDEM (Wheelbase)	(X3)	5.60	5.60	5.60
B.(Measured in metres from Trailer R/A)				
TO PAYLOAD CENTRE OF GRAVITY	(X4)	2.80	3.30	1.50
TO TRUCK BOLSTER	(X5)	6.80	8.50	NOT REQ'D
C.(Other dimensions in metres)				
TRUCK C.of G HEIGHT(From Ground)	(Y1)	1.00	1.00	1.00
TRAILER CofG HEIGHT(From Ground)	(YT)	1.00	1.00	1.00
PAYLOAD C.of G. HEIGHT(From Ground)	(Y4)	2.75	2.75	2.75
TOP OF TRUCK BOLSTER(From Ground)	(Y2)	1.50	1.50	NOT REQ'D
DRIVE TANDEM SPACING	(L1)	1.30	1.30	1.30
TRACK OF DRIVE AXLE	(TR)	2.00	2.00	2.00
STING	(X6)	NOT REQ'D	2.50	2.50
TRAILER DRAW/BAR LENGTH	(X7)	NOT REQ'D	NOT REQ'D	2.00
TRAILER DRAW/BAR HEIGHT	(Y3)	NOT REQ'D	NOT REQ'D	.70
TRAILER W/BASE	(X5)	NOT REQ'D	NOT REQ'D	5.50
TRAILER FIXED BOGIE SPACING	(L2)	3.60	1.20 GO TO AA45	1.20
RESISTANCE COEFICIENTS				
TRACTION	(Mu)	.60	.60	.60
ROLLING 1	(CR1)	7.25	7.25	7.25
ROLLING 2	(CR2)	.02	.02	.02
AIR	(K)	.06	.06	.06
CORNERING	(CC)	200.00	200.00	200.00
CORNERING FRICTION	(Muc)	.20	.20	.20
MISC. INFO.				
SPEED (k.p.h.)	(S)	2.00	2.00	2.00
No of Tyres(Truck only eg. 6x4 has 10)	(n)	10	10	10
No of Tyres on Trailer	(n2)	12.00	12	12
No of Tyres on Trailer Fixed Bogie	(n3)	8.00	8.00	8.00
FRONTAL AREA (Metres Sq.)	(A)	10.00	10.00	10.00
VELOCITY (m/sec)	(V)	.56	.56	.56
ROAD DATA				
GRADIENT(%)	(G)	24.30	23.52	24.45
SUPER-ELEVATION(%)	(	.00	.00	.00
CURVE RADIUS (Centreline, Metres)	(R)	9999.00	9999.00	9999.00

Fig A2 - Supercalc 4 Spreadsheet printout of TRUKGRAD calculation section

CALCULATIONS
****

RADIUS 3 (Metres)	9999.00	9999.00	9999.00
RADIUS 4 (Metres)	9999.00	9999.00	9999.00
RADIUS 6 (Metres)	NOT REQ'D	9999.00	9999.00
RADIUS 7 (Metres)	NOT REQ'D	NOT REQ'D	9999.00
ANGLE A (Radians)	.24	.23	.24
ANGLE A2 (Radians)	.24	.23	.24
ANGLE A3 (Radians)	.24	.23	.24
ANGLE A4 (Radians)	NOT REQ'D	NOT REQ'D	.24
ANGLE C (Radians)	6.501e-4	8.500852e-4	.00
ANGLE C1 (Radians)	.00	.00	.00
ANGLE C2 (Radians)	NOT REQ'D	NOT REQ'D	.00
ANGLE C3 (Radians)	NOT REQ'D	NOT REQ'D	.00
ANGLE P (Radians)	.00	.00	NOT REQ'D
ANGLE P3 (Radians)	NOT REQ'D	.00	NOT REQ'D
DELTA B/E (Metres)	.00	.00	.00
DELTA B/G (Metres)	1.58	2.00	1.34
DELTA B/E1 (Metres)	.00	0	.00
DELTA B/G1 (Metres)	1.36	1.32	1.37
SIN ANGLE B	.23	.24	.24
INCLINATION OF LOAD (B) (Radians)	.23	2.374244e-1	.25
SIN ANGLE B1	.24	.24	.24
INCLINATION B1 (Radians)	.25	2.374243e-1	.25
ANGLE B2 (Radians)	-.01	4.603836e-8	.00
NEUTRAL SUPER-ELEVATION (%) (Ec)	.00	.00	.00
RIG CofG HEIGHT (Metres) (Ym)	2.17	2.11	1.83
COMBINED ROLLING RESISTANCE COEF. (Cr)	7.26	7.26	7.26
CORNER SUPER ELEV FACTOR(Now Set 1.0)	1.00	1.00	1.00
TRAILER RESIST FACTOR(1st Est.) (Fq)	.01	.00	.00
TRAILER PAVEMENT LOAD(1st Est.)(Tonnes)(NT)	19.44	20.74	16.14
TRAILER RESIST FACTOR(Final Est.) (Fq)	.01	.00	.00
TRAILER PAVEMENT LOAD (Tonnes)(NT)	19.44	20.74	16.14
FRONT AXLE OF SHORTS TRAILER (Tonnes)(NTF)	NOT REQ'D	NOT REQ'D	4.23
HORIZONTAL LOAD ON FRONT BOLSTER (T's)(TH)	7.07	7.19	NOT REQ'D
VERTICAL LOAD ON FRONT BOLSTER (Tonnes)(TV)	9.25	8.91	NOT REQ'D
REALIGN TH (TH1)	6.97	7.19	NOT REQ'D
REALIGN TV (TV1)	9.18	8.91	NOT REQ'D
DRAWBAR LOAD (Tonnes)(FTD)	NOT REQ'D	NOT REQ'D	5.14
WEIGHT ON DRIVERS (Tonnes)(ND)	15.40	16.06	16.40
TRUCK FRONT AXLE LOAD (Tonnes)(NF)	2.99	3.05	3.00
LOAD SHIFT THRU' TR'LER INSWING (T's) (NI)	.00	.00	.00
LOAD SHIFT THRU' SUPER-ELEV (Tonnes)(NE)	.00	.00	.00
TRAILER RESISTANCE (kN) (RT)	68.36	70.54	50.38
GRADE RESISTANCE (Truck only) (kN) (RLG)	21.37	23.02	46.60
ROLLING RESISTANCE (Truck only) (kN) (RLR)	1.31	1.36	1.38
CORNERING RESISTANCE (Truck only) (kN)(RLC)	.00	.00	.00
AIR RESISTANCE (Whole rig) (kN) (RA)	.00	.00	.00
INERTIA RESISTANCE (Whole rig) (kN) (RI)	.00	.00	.00
TOTAL RESISTANCE (kN) (R)	91.04	94.93	98.36
RIMPULL (kN) (TF)	91.06	94.98	98.38
	.02	.05	.01
	1.00	1.00	1.00
	GRADE-OK	GRADE-OK	GRADE-OK
SURPLUS RIMPULL (OK IF LESS THAN 2)	.02	.05	.01
(TEST)	1.00	1.00	1.00
MAX. DESIGN GRADE (%)	24.30	23.52	24.45
********************	********************		**********

Fig A3 - Supercalc 4 Spreadsheet cell contents listing for TRUKGRAD calculations (3 pages)

```
F73          = SQRT(F67^2-F23^2)
F74          = SQRT(F73^2-F29^2+((F23-F22)^2))
F75          = "NOT REQ'D
F76          = "NOT REQ'D
F77          = "
F78          = ATAN(F65/100)
F79          = ATAN((F67/F73)*(F65/100))
F80          = ATAN((F67/F74)*(F65/100))
F81          = "NOT REQ'D
F82     E    = ATAN(F29/F74)-ATAN((F23-F22)/F73)
F83          = ASIN(F23/F67)
F84          = "NOT REQ'D
F85          = "NOT REQ'D
F86          = F82
F87          = "NOT REQ'D
F88          = (F73-F74)*F66/100
F89          = F82*F67*F65/100
F90          = (F67-F73)*F66/100
F91          = F83*F67*F65/100
F92          = (F88+F89)/F29
F93          = ASIN(F92)
F94          = (F90+F91)/F23
F95          = ASIN(F94)
F96          = F93-F95
F97          = (F61^2*100/(F67*9.81))
F98          = (F11*F33+F15*F35+F13*F34)/(F11+F13+F15)
F99          = F47+(F48*(F61^2))
F100         = 1
F101    $    = (F99/1000)+F80-F93+(F100*1750/(4.86*F50))*((F55^2)/(427.8*F74
               ))^2+(F100*F51*F58*F43)/(2*F74*F57)


F102         = (1/(F29-(F101*F36)))*1*(F13*COS(F93)*F29+(F29-F28)*F15*COS(F9
               3)+(F35-F36)*F15*F92)
F103    $    = (F99/1000)+F80-F93+(F100*F102*1000/(4.86*F57*F50))*((F55^2)/(
               427.8*F74))^2+(F100*F51*F58*F43)/(2*F74*F57)
F104         = (1/(F29-(F103*F36)))*1*(F13*COS(F93)*F29+(F29-F28)*F15*COS(F9
               3)+(F35-F36)*F15*F92)
F105         = "NOT REQ'D
F106         = F15*F92+F13*F92+F104*F103
F107         = F15*COS(F93)+F13*COS(F93)-F104
F108         = F106*COS(F96)+F107*SIN(F96)
F109         = F107*COS(F96)+F106*SIN(F96)
F110         = "NOT REQ'D
F111         = ((F11*COS(F95)*F21)+(F11*F94*F33)+(F108*COS(F86)*F36)+(F107*F
               22))/F23
F112         = F11*COS(F95)+F109-F111
F113         = (F108*SIN(F86)*F36)/F38
F114         = F111*F98*(F66-F97)/(F38*100)
F115         = F108*COS(F86)*9.81
F116         = (F11*F94-F112*(F95-F78)+F111*(F79-F95))*9.81
F117         = (F111+F112)*F99*9..81/1000
F118         = (9.81*F100)*((1000/(4.86*F50*F56))*((((F111+F112)*(F55^2))/(4
               27.8*F67))^2)+F111*F37*F51/(2*F67))
F119         = F49*F60*(F61^2)/101.9
F120         = 0
F124         = SUM(F115:F120)
F125         = 19.72*F46*((F111/2)-ABS(F113+F114))
F126         = F125-F124
F127         = IF(F126>=0,1,0)
F128         = IF(F127=1,"GRADE-OK","TOO-STEEP")
F129         = IF(F126>=0,F126,2.5)
F130         = IF(F129<2,1,0)
F131         = IF(F130=1,F65,"TRY-AGAIN")
F132         = "*********
```

Fig A3 Cont.

```
G73             = SQRT(G67^2-G23^2)
G74             = SQRT(G73^2+G39^2-AE56^2)
G75             = SQRT(G73^2+G39^2)
G76             = "   NOT REQ'D
G77             = "
G78             = ATAN(G65/100)
G79             = ATAN((G67/G73)*(G65/100))
G80      $      = ATAN((G67/G74)*(G65/100))
G81             = "   NOT REQ'D
G82      E      = (ASIN(AE56/AE55))+(ASIN(AE50/AE55))+(ATAN((G23-G22)/SQRT(G67^
                  2-G23^2)))
G83             = ASIN(G23/G67)
G84             = "   NOT REQ'D
G85             = "   NOT REQ'D
G86             = AE63*PI/180
G87             = ASIN(((G23+G39-G22)/AE56)*SIN(G86))
G88             = (G73-G74)*G66/100
G89             = G82*G67*G65/100
G90      E      = (G67-G73)*G66/100
G91             = G83*G67*G65/100
G92             = (G88+G89)/G29
G93      E      = ASIN(G92)
G94             = (G90+G91)/G23
G95      E      = ASIN(G94)
G96      E      = G93-G95
G97             = (G61^2*100/(G67*9.81))
G98             = (G11*G33+G15*G35+G13*G34)/(G11+G13+G15)
G99             = G47+(G48*(G61^2))
G100            = 1


G101     $      = (G99/1000)+G80-G93+(G100*1750/(4.86*G50))*((G55^2)/(427.8*G74
                  ))^2+(G100*G51*G58*G43)/(2*G74*G57)
G102            = (1/(G29-(G101*G36/COS(G87))))*1*(G13*COS(G93)*G29+(G29-G28)*G
                  15*COS(G93)+(G35-G36)*G15*G92)
G103     $      = (G99/1000)+G80-G93+(G100*G102*1000/(4.86*G57*G50))*((G55^2)/(
                  427.8*G74))^2+(G100*G51*G58*G43)/(2*G74*G57)
G104            = (1/(G29-(G103*G36/COS(G87))))*1*(G13*COS(G93)*G29+(G29-G28)*G
                  15*COS(G93)+(G35-G36)*G15*G92)
G105            = "   NOT REQ'D
G106            = G15*G92+G13*G92+G104*G103
G107            = G15*COS(G93)+G13*COS(G93)-G104
G108            = G106*COS(G96)+G107*SIN(G96)
G109            = G107*COS(G96)+G106*SIN(G96)
G110            = "   NOT REQ'D
G111            = ((G11*COS(G95)*G21)+(G11*G94*G33)+(G108*COS(G86)*G36)+(G107*G
                  22))/G23
G112            = G11*COS(G95)+G109-G111
G113            = (G108*SIN(G86)*G36)/G38
G114            = G111*G98*(G66-G97)/(G38*100)
G115            = G108*COS(G86)*9.81
G116            = (G11*G94-G112*(G95-G78)+G111*(G79-G95))*9.81
G117            = (G111+G112)*G99*9.81/1000
G118            = (9.81*G100)*((1000/(4.86*G50*G56))*((((G111+G112)*(G55^2))/(4
                  27.8*G67))^2)+G111*G37*G51/(2*G67))
G119            = G49*G60*(G61^2)/101.9
G120            = 0
G124            = SUM(G115:G120)
G125            = 19.72*G46*((G111/2)-ABS(G113+G114))
G126            = G125-G124
G127            = IF(G126>=0,1,0)
G128            = IF(G127=1,"GRADE-OK","TOO-STEEP")
G129            = IF(G126>=0,G126,2.5)
G130            = IF(G129<2,1,0)
G131            = IF(G130=1,G65,"TRY-AGAIN")
G132            = "************
```

Fig A3 Cont.

```
I73          = SQRT(I67^2-I23^2)
I74          = SQRT(I73^2+I39^2-I40^2-I42^2)
I75          = SQRT(I73^2+I39^2)
I76          = SQRT(I75^2-I40^2)
I77          = "
I78          = ATAN(I65/100)
I79          = ATAN(I67*I65/(I73*100))
I80          = ATAN(I67*I65/(I76*100))
I81          = ATAN(I67*I65/(I74*100))
I82     $    = ATAN(I42/I74)
I83          = ASIN(I23/I67)
I84          = ATAN(I40/I76)
I85          = I83
I86          = "   NOT REQ'D
I87          = "   NOT REQ'D
I88          = (I76-I74)*I66/100
I89          = I82*I67*I65/100
I90          = (I67-I73)*I66/100
I91          = I83*I67*I65/100
I92          = (I88+I89)/I42
I93          = ASIN(I92)
I94          = (I90+I91)/I23
I95          = ASIN(I94)
I96          = I93-I95
I97          = (I61^2*100/(I67*9.81))
I98          = (I11*I33+I15*I35)/(I11+I15)
I99          = I47+(I48*(I61^2))


I100         = 1
I101    $    = (I99/1000)+I81-I93+(I100*1750/(4.86*I50))*((I55^2)/(427.8*I74
               ))^2+(I100*I51*I58*I43)/(2*I74*I57)
I102         = (1/(I42-(I101*I41)))*1*(I13*COS(I93)*I42+(I42-I28)*I16*COS(I9
               3)+(I35-I41)*I16*I92)
I103    $    = (I99/1000)+I81-I93+(I100*I102*1000/(4.86*I57*I50))*((I55^2)/(
               427.8*I74))^2+(I100*I51*I58*I43)/(2*I74*I57)
I104         = (1/(I42-(I103*I41)))*1*(I13*COS(I93)*I42+(I42-I28)*I16*COS(I9
               3)+(I35-I41)*I16*I92)
I105         = I16*COS(I93)+I13*COS(I93)+I14*COS(I93)-I104
I106         = "   NOT REQ'D
I107         = "   NOT REQ'D
I108         = "NOT REQ'D
I109         = "NOT REQ'D
I110         = ((I103*I104)+(I13+I14+I16)*I92)*COS(I85)+I105*I99/1000+I105*(
               I80-I93)+(I100*1000/(4.86*I50*(I57-I58)))*(I105*(I55^2)/(427.
               8*I76))^2
I111         = (1/I23)*(I11*COS(I95)*I21+I11*I94*I33+I15*COS(I95)*I22+I15*I9
               4*I35+I110*COS(I84)*COS(I96)*I41)
I112         = I11*COS(I95)+I15*COS(I95)-I111
I113         = I110*COS(I96)*SIN(I84)*I41/I38
I114         = I111*I98*(I66-I97)/(I38*100)
I115         = I110*COS(I84)*COS(I96)*9.81
I116         = ((I11+I15)*I94-I112*(I95-I78)+I111*(I79-I95))*9.81
I117         = (I111+I112)*I99*9.81/1000
I118         = (9.81*I100)*((1000/(4.86*I50*I56))*((((I111+I112)*(I55^2))/(4
               27.8*I67))^2)+I111*I37*I51/(2*I67))
I119         = I49*I60*(I61^2)/101.9
I120         = 0
I124         = SUM(I115:I120)
I125         = 20*I46*(I111/2-ABS(I114))
I126         = I125-I124
I127         = IF(I126>=0,1,0)
I128         = IF(I127=1,"GRADE-OK","TOO-STEEP")
I129         = IF(I126>=0,I126,2.5)
I130         = IF(I129<2,1,0)
I131         = IF(I130=1,I65,"TRY-AGAIN")
I132         = "**********
```

Fig A4 - Supercalc 4 Spreadsheet printout for calculation of Long Log Rig corner geometry

```
CALCULATE "P"  Only enter data at (E) positions

ENTER GUESS "P" IN AD47 (E)                    .0325
FRONT AXLE TO BOLSTER DIST. (C)                  5.4
WHEELBASE (C)                                    5.6
STING (C)                                        2.5

BOLSTER TO BOLSTER DIST. (C)                     8.5
BOLSTER TO TOW PT. DIST. (C)                     2.7
RADIUS OF CURVE. (E)                            9999
RADIUS TO TOW PT. (C)                       9998.999
POLE LENGTH (C)                                 5.80


CHECK GUESS                                 -.000001
                                                   0

   P OK =                                      .0325GO TO A45
```

```
AE47          = .0325
AE48          = G22
AE49          = G23
AE50          = G39
AE52          = G29
AE53          = AE49+AE50-AE48
AE54          = 9999
AE55          = ((AE54^2);-(AE49^2)+(AE50^2))^.5
AE56     $    = SQRT((AE53^2)+(AE52^2)-(AE53*AE52*2*COS(AE47*PI/180)))
AE60          = SIN(ACOS(AE56/AE55)+ACOS(AE50/AE55))-((AE52/AE56)*SIN(AE47*PI
                /180))
AE61          = IF(ABS(AE60)>.0005,1,0)
AE63          = IF(AE61=0,AE47,"*****")
```