POTENTIAL USE OF WIDE TIRES FOR STEEP SLOPE SKIDDING

by

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(ABSTRACT)

This study investigated the potential use of wide skidder tires for forest harvesting operations on steep slopes. During the summer of 1984, field tests were conducted to compare the performance characteristics of 24.5-32 and 66-43 rubber tires on a JD-640 grapple skidder loaded with tree length material. The skidder was operated on 20%, 25% and 30% slopes on Piedmont soils near Rome, Georgia.

Video recorders were used to document the field measurements and observations of machine travel time and wheel slip over defined courses. Soil compaction was evaluated by comparing soil cone penetrometer readings taken in the wheel tracks of the test lanes to those taken in undisturbed adjacent areas. Skidder lateral stability was analyzed using the mathematical model developed in this study.

Based on the results of statistical analyses of the data and field observations obtained under the test conditions, the skidder equipped with wide tires generally attained higher average speeds, tended to cause less wheel slip, resulted in smaller increases in soil cone penetrometer readings, and had significantly greater stability on sideslopes than the skidder equipped with the narrow tires. The stability model developed in this study predicted the critical sideways tipping angle for a JD-640 grapple skidder to be approximately 32° when fitted with the 24.5-32 tires, and 44° when fitted with the 66-43 tires.

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INTRODUCTION

Slopes, greater than 30%, have long been a problem in forest harvesting operations. Although wheeled or tracked skidders and crawler tractors can be used for the logging operations on these slopes, they have seen only limited use because of low productivity, high road and trail construction cost, and the environmental impact these operations may pose. While cable logging systems are effective on steep slopes, their use has also been limited in many areas because of high operating costs, irregular slopes, and low volume and value of the product to be harvested. Except in very high value timbers, alternatives, such as helicopters and balloon logging systems, appear to be impractical due to their high operating costs.

During the past two decades, the rubber-tired skidder has become the most commonly used machine in logging operations in the United States due to its relatively low cost and high maneuverability. Current trends indicate that it will probably continue to dominate the logging scene in the predictable future. Considering this popularity, several ways have been proposed to improve operating efficiency, productivity, and to extend its operating range while minimizing disturbance to the site. Among these, the use of wide tires is the most frequently suggested, since they appear to offer the potential of extending the operating range of ground based systems onto slopes previously considered inoperable, with minimum disturbance to the site.

At present, however, there is little definitive information available on the performance of a skidder equipped with wide tires on steep slopes. Therefore, the objectives of this study were:

1. To compare the performance of a wheeled skidder equipped with conventional tires with a skidder equipped with wide tires during the operations on different slopes;
2. To compare the extent of soil compaction from the traffic of a skidder equipped with conventional and wide tires on different slopes;
3. To compare skidder lateral stability on slopes when equipped with different sizes of tires.

LITERATURE REVIEW

Tire Width as a Parameter

The width of a tire has been considered by many researchers to be an important parameter in the evaluation of the performance of a tractive device (Freitag, 1965; Gill and Vanden Berg, 1968; Bekker, 1969; Wismer and Luth, 1972; Dwyer et al., 1976; Zoz and Brixius, 1979; Gee-Clough, 1979, 1980; Dwyer and Heigho, 1984). Freitag (1965) proposed a dimensionless parameter, or wheel numeric, for the prediction of drawbar pull and rolling resistance. This numeric linearly increases as wheel width increases. Bekker (1969) developed a model which also includes the tire width as a parameter for predicting the rolling resistance of a tire although this parameter was shown to be less significant than the tire diameter.

Wismer and Luth (1972) conducted both laboratory and field tests, and derived a traction equation which indicates that the tire width has the same effects as the tire diameter on the wheel towed force and traction force. Since there are two restrictions imposed on the application of the equation, it may not be appropriate to generalize that the towed force and the gross traction force increase with the tire width.

More recently, Zoz and Brixius (1979) developed equations from a test for tires operating on concrete. These equations indicate that pull and efficiency are a linear function of tire width. Gee-Clough (1979, 1980), and Dwyer and Heigho (1984) also related mobility number, which is a predictor of trafficability, on different surfaces to the tire width in their empirical equations for predicting the tractive performance of a tire.

Performance of Singles Versus Duals

Performance comparisons between single and dual configurations have been undertaken by many researchers based on different conditions (Sauve, 1939; Southwell, 1950, 1964; McLeod et al., 1966; Domier and Friesen, 1968; Clark and Liljedahl, 1969; Melzer and Knight, 1973; Domier, 1978; Bailey and Burt, 1981; Hutchings, 1983; Dwyer and Heigho, 1984; Koger et al., 1984). Conclusions were generally in favor of dual configuration. Sauve (1939) compared the performance on an equal unit-cost basis, so the size of the tires was different for singles and duals. With singles of 9:00-36 and duals of 5:00-44 being tested under the same axle load, Sauve reported that the single tires performed better than the dual tires from all aspects.

While McLeod et al. (1966) used the same size of tires for single and dual configurations for their study, the inflation pressure of the dual tires was lower than that of the single tires. The results indicated that the dual system gave generally better tractive performance than the single system. Domier (1978) also reported that the use of dual tires with reduced inflation pressure decreased travel reduction (wheel slip) by 1.4 to 2.5 percent, and increased the maximum tractive efficiency by 1.8 percent as compared to single tires with high inflation pressure. The author attributed this improvement to a combination of reduced load and lower inflation pressure.

Clark and Liljedahl (1969) conducted tests in an artificial soil with the same tires, loads and deflections for both configurations. The conclusion was that the performance of the dual configuration was significantly better than that of the single one in soft soils, but only slightly better in firm soils. They stated that advantages of dual tires could not be fully utilized in firm soils unless the inflation pressure was reduced by 6-12 psi. Melzer and Knight (1973) carried out a similar study in air-dry dune sand. The result was essentially the same as that by Clark and Liljedahl (1969).

Bailey and Burt (1981) conducted a laboratory test to study performance of single and dual systems on a per-tire basis with the same tire size at the same travel reduction, inflation pressure and dynamic load per tire. They found that the single and dual systems developed practically the same net traction force when operated at the same dynamic load and travel reduction. However, they stated that duals had a greater load-carrying capacity than singles, and therefore they could develop greater net traction if this greater load carrying capacity was utilized. This statement was later supported by Dwyer and Heigho (1984). Hutchings' study (1983) in Australia revealed a similar conclusion.

Southwell (1964) compared the relative performance of single versus dual tires in the field with the same tires at the same inflation pressure. He concluded that the overall performance of dual tires was better as compared to single tires. Koger et al. (1984) investigated the relative performance of the two different configurations on a wetland in South Carolina. They found that the biggest advantage of dual-tired skidder is greatly improved trafficability.

Performance of Conventional Tires Versus Wide Tires

Although the relative performance of conventional tires versus wide tires has been investigated by many researchers, the conclusions were quite diverse because of different conditions involved. Dwyer and Heigho (1984) conducted tests with the same load, and reported that the tractive performance of the wide tires was generally inferior to that of the conventional tires. However, they did point out that the main benefit in fitting wider tires is to enable a heavier load to be carried. If wider tires were fitted and a heavier load was applied, the pull capacity would increase.

Gee-Clough (1979) investigated the effect of wheel width on the rolling resistance of rigid wheels in sand, and found that the coefficient of rolling resistance increased strongly as wheel width increased at each sinkage level. He therefore suggested that wheels with a large width/diameter ratio should not be used under a towed condition in sandy soils. One year later, Gee-Clough (1980) carried out another investigation to determine the effect of wheel width on the tractive performance by using pneumatic tires. It was observed in this study that the performance was improved by increasing the tire width within certain limits.

A study undertaken by Reed (1955) indicated that with the same weight on the tires, the use of oversized tires showed no advantage in tractive performance unless the oversizing caused the outside diameter of the tire to increase. He also pointed out that the ability of oversized tires to improve the performance is largely a function of the additional weight that can be safely carried by the larger tires if engine power is not a limiting factor.

Some studies (McAllister, 1983; Burt et al., 1984) showed that tire size had little effect on tractive performance when operating on dry soil conditions. On the other hand, Petrasek (1968) and Semonin (1968) suggested that oversized skidder tires possessed a great potential of extending the operating range into previously inaccessible swamp areas because of additional flotation. McAllister (1983) also investigated the potential of wide tires on wet land, and found that overall performance was greatly improved with the use of wide tires.

Johnson et al. (1963) and Greene et al. (1983) studied the tire size effect on soil compaction. The results showed that the degree of soil compaction was reduced by the use of larger tires. Dwyer (1983) also reported that the use of wide tires caused a significant reduction in soil compaction compared to the use of conventional tires. A study conducted by Koger et al. (1985) at National Tillage Machinery Laboratory at Auburn, Alabama showed that bulk density values of soils were reduced by lowering inflation pressure and increasing tire size. However, in an earlier study, Koger et al. (1984) observed just the opposite. That is, larger tires were found to be associated with higher bulk density of the soils. According to the authors, the increase in bulk density with larger tires was caused by an increase in tire stiffness. Rummer and Sirois (1984) concluded that ability of wider tires to reduce soil compaction due to higher flotation could be obscured by allowing them to carry a larger load.

McLeod et al. (1966), and Raghavan and McKyes (1979) studied the relationship between drawbar pull and tire width. Both studies came up with the conclusion that a greater drawbar pull could be developed with the use of wider tires. The authors attributed such improvement mainly to the increase in the contact area with the wider tires, and partly to the higher load applied to the wider tires. Hassan (1977) also suggested that the use of larger and wider tires could improve skidder capability. A recent study by Rummer and Sirois (1984) comfirmed that wider tires exhibited better tractive performance, and had significantly higher productivity than narrower tires.

Most of the previous studies showed that the advantages of using larger tires cannot be displayed unless the weight on the driving wheels is increased. However, an exception can also be found from literature. Dwyer (1978) reported that "fitting larger tire sizes without increasing the weight on the driving wheels can improve a tractor's rate of work by up to 14% depending on the field conditions". The greater improvement was observed in poorer soil conditions. The author attributed the improvement to the increase of mobility number.

Since 1980, an extensive study on the potential applications of wide skidder tires with low inflation pressure has been undertaken in the Forest Engineering Research Institute of Canada (Morley, 1982; Mellgren and Heidersdorf, 1984; Heidersdorf, 1984; Morley, 1984). The results of the study were quite encouraging. With the use of new, wide, high-floatation tires, they reported that the productivity increased by 60 percent, and fuel consumption decreased by 40 percent, as compared to the use of conventional, narrow tires. In addition, reduced ground disturbance on sensitive soils, lower level of soil compaction, smoother ride and improved machine stability associated with the wide tires were also observed.

Performance of Dual Tires Versus Single-Wide Tires

Previous comparisons on relative performance of single configuration versus dual configuration, and narrow tires versus wide tires indicated that dual configuration and single-wide tires possess very similar characteristics. They both have a greater load carrying capability, and generally give better tractive performance than single-narrow tires. Especially when operated on soft soils, or wet land, either dual configuration or wide tires are superior to single and narrow tires in overall performance. The use of dual configuration, or wide tires can reduce soil compaction and ground disturbance. Machine sideslope stability and riding comfort can also be improved by the use of dual configuration, or wide tires.

However, they are more expensive both in installation and services than single-narrow tires. In addition, the use of dual configuration, or wide tires poses an extra stress on the axles, which may shorten machine life, or increase maintenance cost. The machine manoeuverability may also be affected due to the increased dimension.

Some studies (McLeod et al., 1966; Domier, 1978; Gee-Clough, 1979, 1980; Dwyer and Heigho, 1984; Hassan and Sirois, 1984) have discussed relative performance between dual configuration and single-wide tire design. The conclusion remains dependent of studies. A study by McLeod et al. (1966) confirmed that dual tires and Terra-tire (a high flotation tire) gave better tractive performance than single-narrow tires while relative performance between dual tires and Terra-tire remained competitive. Domier (1978) concluded that tire width had no effect on tractive performance, but dual design could improve the performance. Gee-Clough (1979, 1980) and Dwyer and Heigho (1984) demonstrated that dual tires performed better than single-wide tires. Hassan and Sirois (1984) suggested that a dual-tired skidder had an advantage over a wide-tired skidder because the outer tires could be removed when the soil condition permitted single-tire machine operation.

Based on the literature cited, it can be seen that most of the previous studies have dealt only with machine performance on the level surfaces. Since logging contractors are expected to encounter steep slopes during harvesting operations, it is desirable to assess the potential use of wide tires for steep slope skidding.

METHODS AND PROCEDURE

Data Collection

Site Description

The study was conducted at Berry College, north of the city of Rome in Floyd County, Georgia.

Prior to testing, the area was divided into blocks with 50 feet by 25 feet (along slope by across slope), and the ground slope was determined with an Abney level and a compass. The site was clearcut with chainsaws. Most of the cut trees were cleaned by hand. A skidder was used only to clear the large trees, and worked along predefined trails and the boundary so as to keep the test area in a controlled condition.

Field Tests

The field tests were conducted during the summer of 1984. A JD-640 grapple skidder which could be equipped with a set of either 24.5-32 (narrow) or 66-43 (wide) tires was used for the tests (Figure 1, Figure 2 and Table 1). Three plots of approximately 100 feet by 150 feet, with slopes of 20%, 25%

Figure 1. Skidder Used During the Field Study.

Figure 2.   Conventional and Wide Skidder Tires Used for the Tests.

Table 1. Manufacture's Ratings of the Tires.

TIRE SIZE	PLY RATING	INFLATION RATING (psi)	LOAD RATING (pounds)
24.5-32	12	24	9,680
66-43	10	25	9,960

and 30% respectively, were marked off for the tests (Figure 3). Each plot was divided into four travel lanes. For each tire size, two travel lanes were used for the uphill and downhill direction tests. Each lane was designed to be 6 feet wider than the width of the skidder to minimize the influence of skidder traffic in one lane to the neighboring lanes.

Tree length material was used to load the skidder (Figure 4). Each tree was weighed by suspension method, and identified by assigning a distinct number. Therefore, the total weight of a load could be obtained by summing the weight of the individual trees used for the test. During tests, an effort was made to maintain a constant load. However, some variation in the load occurred because of damage to the material during skidding, and because of weight loss due to drying during tests. To minimize the load variation, the trees were reweighed just before tests. Actual weight of the load for each tire-size and slope combination is presented in Table 2.

The narrow tires could not be tested on the 30% slope because the skidder had to be driven on a steeper slope to enter into the test plot. The skidder when equipped with the narrow tires was found to be less stable (sideways) on that slope. The machine equipped with the wide tires, on the other hand, could handle the same load as in the other tests,

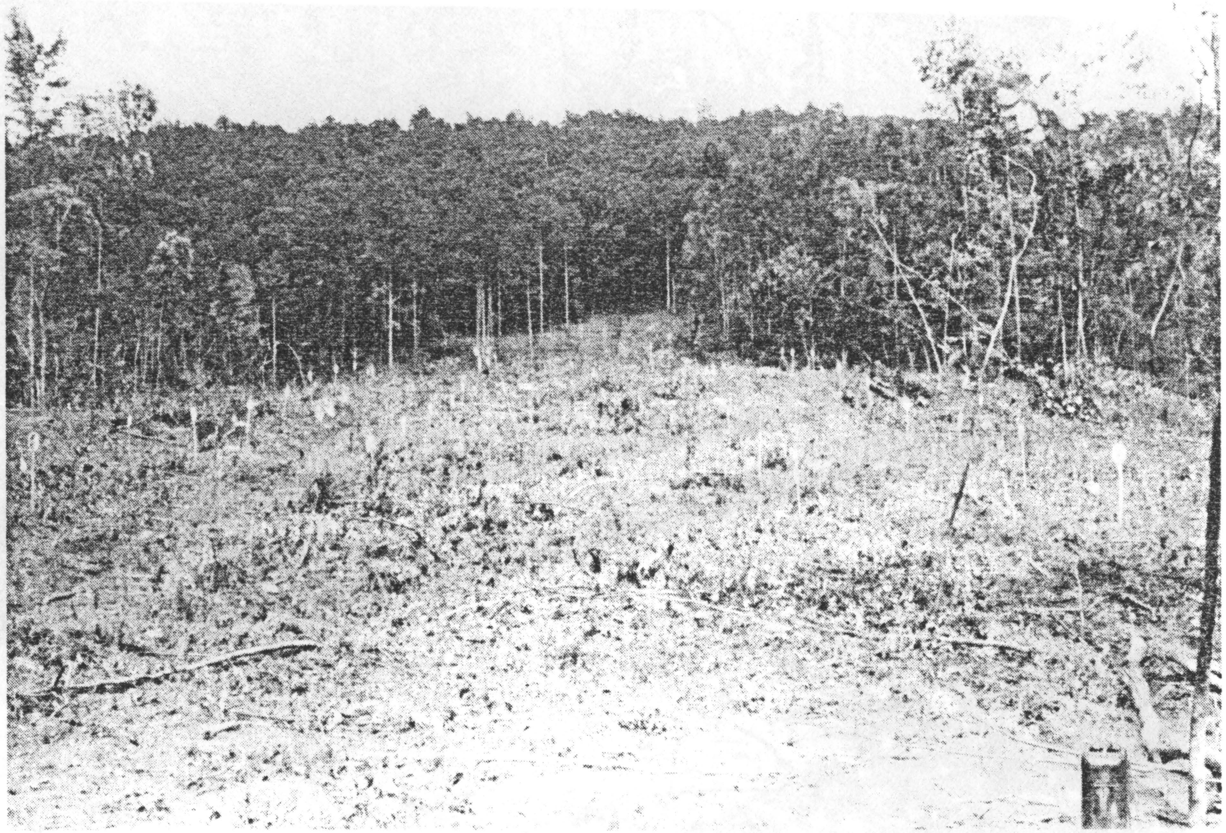

Figure 3. Layout of a Test Plot.

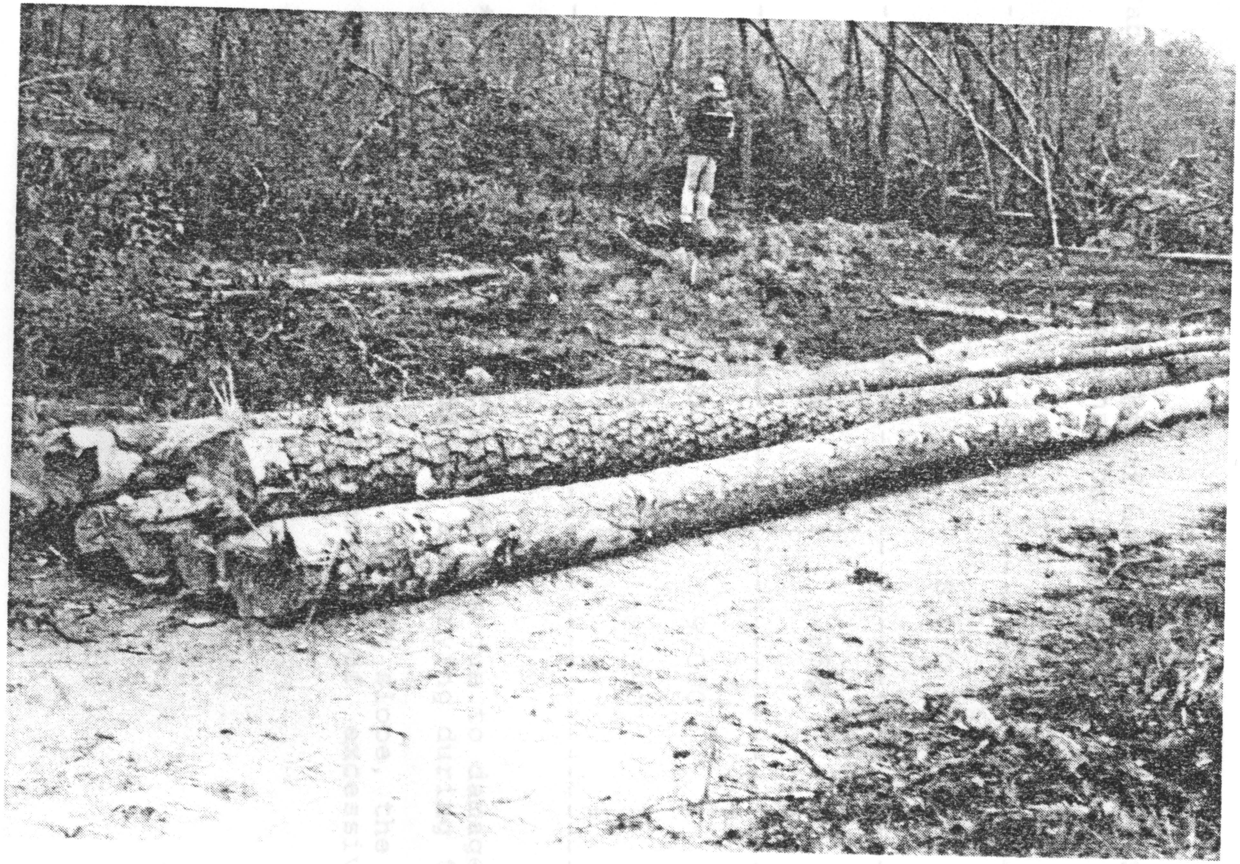

Figure 4. Tree Length Material Used to Load the Skidder.

Table 2. Actual Weight of Load for Each Tire-Size and Slope Combination (pounds).*

	SLOPE		
TIRE SIZE	20%	25%	30%
24.5 - 32	9,000	9,000	-----
66 - 43	7,870	8,080	4,835

* The variation in the load was due to damage to the material during skidding, and drying during the skidding.
For the wide tire test on the 30% slope, the load was intentionally reduced because of excessive wheel sinkage.

but it resulted in a considerable wheel sinkage. The load for this test was therefore reduced to 4,835 pounds.

To facilitate speed and wheel slip measurements, the total length of a lane was divided into several intervals. Each interval was equal to the distance that the wheel covered in one revolution on a level ground with no load on the vehicle. As a consequence, a lane was measured 15 feet by 146 feet and 8 inches for the narrow tire, and 19 feet by 148 feet and 6 inches for the wide tire as shown in Figure 5. The machine travel time and the wheel slip were measured on the basis of the interval length.

Ten passes were made for each tire size and slope combination. Before trials, the sidewall of each wheel was marked with red paint to serve as a visual method of documenting wheel rotations. During each pass, the loaded machine was started at the beginning of a lane, run at maximum sustainable speed for uphill trials (maximum safe speed for downhill trials), and stopped at the end of the lane (Figure 6). Each travel was videotaped from both sides of the machine to record the travel time and the number of wheel revolutions in each pass. The position of the wheel marks at the beginning and the end of each run were recorded on the tapes as well. The video recorders were fixed at the middle of the entire length of the lane and approximately 45 feet away from the outside of the lane.

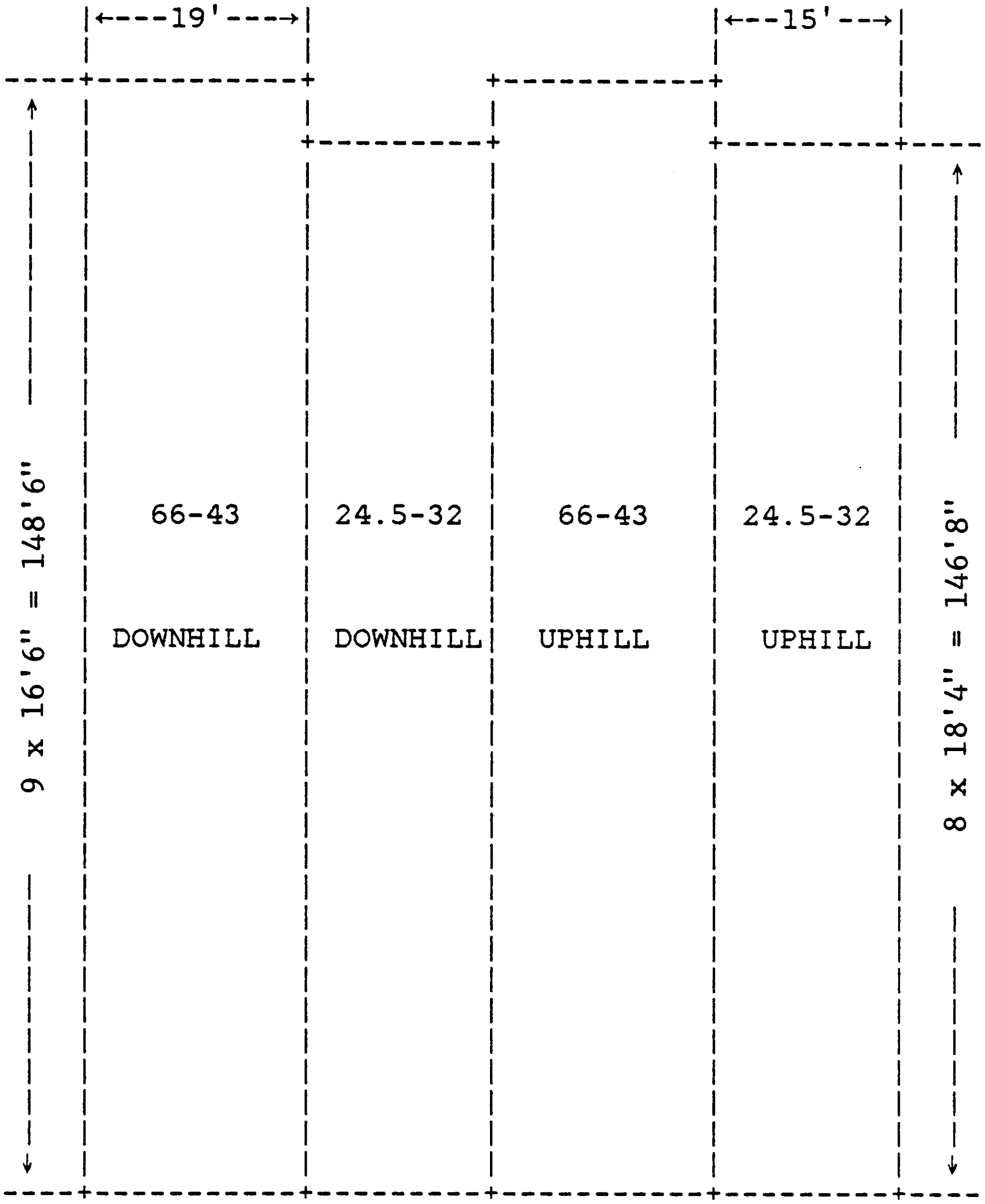

Figure 5. Layout of Travel Lanes in a Test Plot.

Figure 6. Skidder Equipped with the Wide Tires.

After the trials, ten sample points were selected symmetrically from the center of the tracks (experimental sample), and ten from the adjacent undisturbed areas located at the sides of the lanes (control sample) as shown in Figure 7. At each sampling point, soil cone penetrometer readings were taken at six depths (1, 2, 3, 4, 5 and 6 inches in depth respectively).

Four soil samples were removed from two depth ranges (0-6 inches and 6-12 inches) at randomly selected points of each test plot. The field weight of each sample was recorded, and later compared with the oven-dried weight to determine the soil moisture contents during the tests.

Data Analysis

Laboratory Work

In the laboratory, the videotapes were carefully reviewed. The time taken to travel through each interval was determined, and the actual number of wheel revolutions in each pass was counted from the tapes. The time was then transferred to time per unit travel distance, serving as an indirect measurement of speed. Since the length of the intervals was equal for the same tire, the homogeneity of the variances of the data could be retained. This would facilitate later

```
+-----------+         +-----------+
| "       " |         | "       " |
o X       X o-X-----X-o X       X o-X-----X-o
| "       " | "     " | "       " | "     " |
| "       " | "     " | "       " | "     " |
| "       " | "     " | "       " | "     " |
| "       " | "     " | "       " | "     " |
| "       " | "     " | "       " | "     " |
| "       " | "     " | "       " | "     " |
| "       " | "     " | "       " | "     " |
o X       X o X     X o X       X o X     X o
| "       " | "     " | "       " | "     " |
| "       " | "     " | "       " | "     " |
| "       " | "     " | "       " | "     " |
| "       " | "     " | "       " | "     " |
| "       " | "     " | "       " | "     " |
| "       " | "     " | "       " | "     " |
| "       " | "     " | "       " | "     " |
o X       X o X     X o X       X o X     X o
| "       " | "     " | "       " | "     " |
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o X       X o X     X o X       X o X     X o
| "       " | "     " | "       " | "     " |
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| "       " | "     " | "       " | "     " |
| "       " | "     " | "       " | "     " |
| "       " | "     " | "       " | "     " |
| "       " | "     " | "       " | "     " |
| "       " | "     " | "       " | "     " |
o-X-------X-o-X-----X-o-X-------X-o-X-----X-o
```

X ----- experimental sampling points
o ----- control sampling points

Figure 7. Layout of Sampling Points for Taking Soil Penetrometer Readings.

statistical analyses. Knowing the number of wheel revolutions and the total distance travelled, the travel distance per revolution was computed. The wheel slip in each case was then computed using the following formula:

$$S = \{\frac{L_0 - L_1}{L_0}\} 100 \qquad (1)$$

where:

S ---- slip (%);

L_0 ---- travel distance per revolution with no load on a level ground (feet/revolution);

L_1 ---- travel distance per revolution with a load (feet/revolution).

Soil samples taken from each test plot were oven-dried at 105° Celsius to a constant weight, and reweighed. The moisture content was computed on a dry basis using Equation (2):

$$MC = \{\frac{W_w - W_d}{W_d}\} 100 \qquad (2)$$

where:

MC ---- soil moisture content (%);
W_w ---- field (wet) weight of soil sample (ounces);
W_d ---- oven dried weight of soil sample (ounces).

Data Analysis

The data was analyzed statistically using a computer software package of the Statistical Analysis System (SAS Institute Inc., 1982a, b). Duncan's multiple range test was used to test at .05 significance level for differences in travel time through a unit distance due to the effects of tire size and slope. The same method was also used to study the effects of tire size and slope on wheel slip.

To allow examination of the effects of tire size and slope on soil compaction, the differences in soil cone penetrometer readings between the experimental and control samples were computed. The differences were then submitted to statistical analyses.

Since the skidder was run at either maximum sustainable speed for uphill trials, or maximum safe speed for downhill trials, some adjustment in the gear settings had to be made during the tests. However, because such adjustment was inconsistent throughout the tests under different machine performance conditions and environments, it was impossible to split the data based on the different gear settings. Consequently, the statistical analyses for the data were carried out regardless of the difference in gear settings.

A Mathematical Model for Skidder Lateral Stability Analysis

Model Development

One of the problems using a wheeled skidder for steep slope operations is its instability. As the slope increases, the potential of overturning increases. This can also lower productivity because the travel speed of an off-road vehicle is affected by the operator's feeling of safety (Radforth, 1978).

Some studies (Mellgren and Heidersdorf, 1984; Rummer and Sirois, 1984) have shown that the use of wide tires for a wheeled skidder can improve its sideslope stability because of the increased wheel tread. To provide a quantitative comparison of skidder sideslope stability with different sizes of tires, a mathematical model containing the parameter of wheel tread (or tire width for the same machine) is developed and discussed in this section. The discussion involves the derivation of the mathematical model as well as its application in predicting the maximum slope a wheel skidder can negotiate safely across a slope.

As noted by several researchers (Gibson et al., 1971; Smith et al., 1974; Davis and Rehkugler, 1974; Liljedahl et al., 1979), a wheeled skidder with pinned front axle may tip sideways about two axes. The first tipping motion can take place around the axis connecting the pin point of the front axle to the contact point directly beneath the center of the rear wheel on the lower hillside. The entire machine except the front axle assembly rotates about this axis until the frame contacts the front axle assembly. Then, the entire machine may tip around a second axis connecting the contact points of the front and rear wheels on the lower hillside (Figure 8). However, Gibson et al. (1971) concluded that a machine having proceeded through the first tipping motion will have sufficient momentum to tip over the second axis. For this reason, a slope which can cause tipping about the first axis is considered as a critical slope.

In addition, the following assumptions are made for the development of the model:

1. The skidder is driven straight across the slope;
2. The ground surface is planar;
3. The effect of fluid shifts in the skidder, and operator size and his position is negligible;
4. The effect of tire and ground surface deformation is also negligible.

For a skidder with known dimensional parameters shown in Figure 9, a three dimensional coordinate system is set as illustrated in Figure 10, where:

x ---- parallel to the major slope profile line;
y ---- parallel to a contour slope line;
z ---- perpendicular to the ground surface.

For convenience, the dimensional parameters B, D and H can be reexpressed as angles:

$$\beta = \arctan \frac{\sqrt{D^2 + H^2}}{B} \tag{3}$$

and

$$\gamma = \arctan \frac{H}{D} \tag{4}$$

where:

B ---- half of the rear wheel tread;
D ---- horizontal distance from the pin to the rear axle;
H ---- height of the pin location.

As stated above, the skidder rotation initially will be about the line PQ when the critical slope is reached. For convenience, the coordinate system XYZ is transformed into a

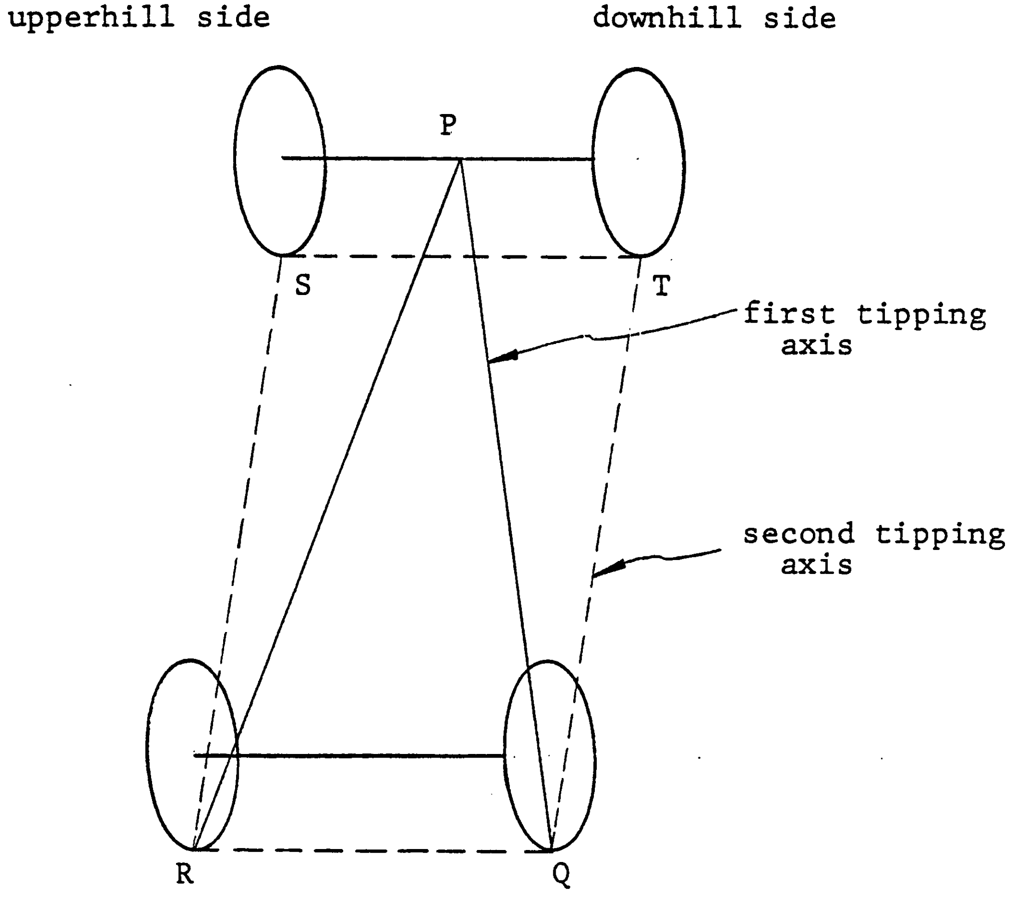

Figure 8. Diagram Illustrating the Two Tipping Axes.

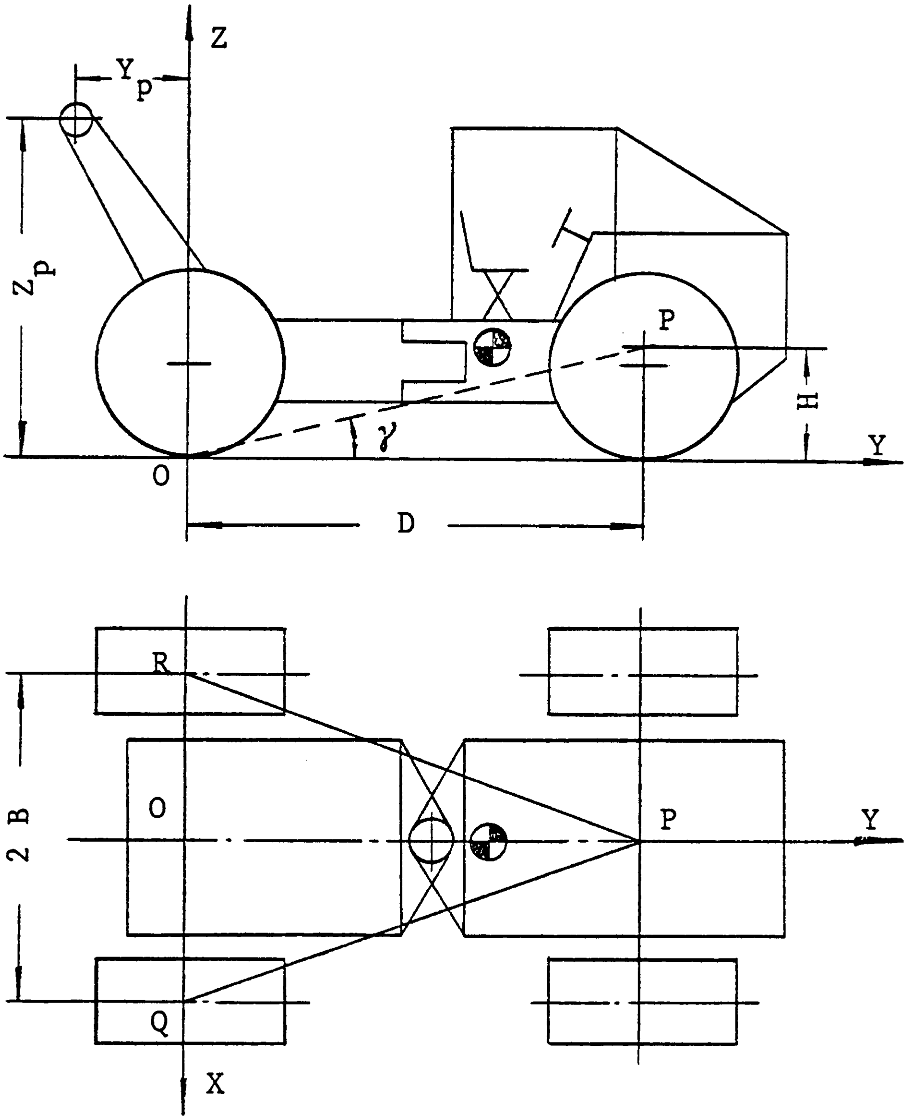

Figure 9. Schematic of a Skidder Illustrating Dimensions, and Locations of the Center of Gravity of the Tipping Weight and Pull.

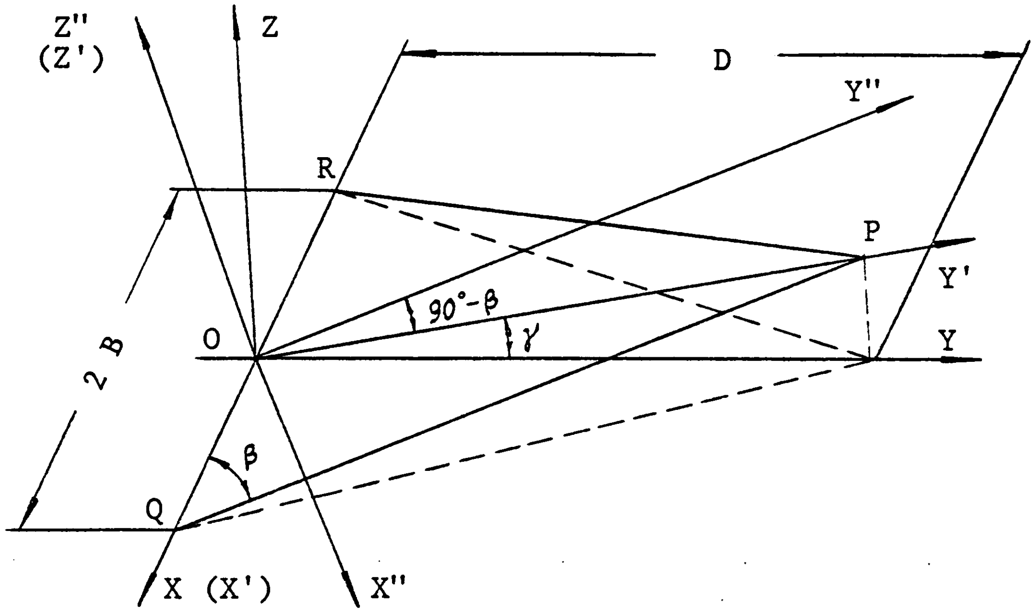

Figure 10. The Coordinate Systems Used for the Development of Model.

new system X"Y"Z" with Y" axis parallel to the line PQ (Figure 10). According to the principle of transformation, the two systems have general relationships as follows:

$$x'' = x \sin\beta + y \cos\beta \cos\gamma + z \cos\beta \sin\gamma \qquad (5)$$

$$y'' = - x \cos\beta + y \sin\beta \cos\gamma + z \sin\beta \sin\gamma \qquad (6)$$

$$z'' = - y \sin\gamma + z \cos\gamma \qquad (7)$$

where (x, y, z) is a coordinate, or vector, in the initial system, and (x", y", z") in the new system.

With the help of the above general relationships, the location of the center of gravity of the tipping weight[1] with respect to the new coordinate system can be determined by:

$$x''_{cg} = x_{cg} \sin\beta + y_{cg} \cos\beta \cos\gamma + z_{cg} \cos\beta \sin\gamma \qquad (8)$$

$$y''_{cg} = - x_{cg} \cos\beta + y_{cg} \sin\beta \cos\gamma + z_{cg} \sin\beta \sin\gamma \qquad (9)$$

$$z''_{cg} = - y_{cg} \sin\gamma + z_{cg} \cos\gamma \qquad (10)$$

where (x_{cg}, y_{cg}, z_{cg}) is the location of the center of gravity of the tipping weight in the initial coordinate system.

Similarly, the coordinates of the point on which the pull acts become:

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[1] This is referred the portion of skidder weight that does not include the front wheel assembly. The same hereafter.

$$x''_p = x_p \sin\beta + y_p \cos\beta \cos\gamma + z_p \cos\beta \sin\gamma \tag{11}$$

$$y''_p = - x_p \cos\beta + y_p \sin\beta \cos\gamma + z_p \sin\beta \sin\gamma \tag{12}$$

$$z''_p = - y_p \sin\gamma + z_p \cos\gamma \tag{13}$$

where (x_p, y_p, z_p) is the pull acting position in the initial coordinate system.

Consider X Y Z (or X" Y" Z") as forces, then, the components of the tipping weight in the new coordinate system can be determined in the same way as above. That is,

$$W''_x = W_x \sin\beta + W_y \cos\beta \cos\gamma + W_z \cos\beta \sin\gamma \tag{14}$$

$$W''_y = - W_x \cos\beta + W_y \sin\beta \cos\gamma + W_z \sin\beta \sin\gamma \tag{15}$$

$$W''_z = - W_y \sin\gamma + W_z \cos\gamma \tag{16}$$

Assuming that the slope angle is α, and that the tipping weight of the skidder is W, then, from Figure 11 the weight components, W_x, W_y, W_z, in the initial coordinate system can be determined as follows:[2]

$$W_x = W \sin\alpha \tag{17}$$

$$W_y = 0 \tag{18}$$

$$W_z = - W \cos\alpha \tag{19}$$

---

[2] The negative sign on the right hand side of the equations indicates that the force is in the negative direction with respect to the selected coordinate system.

Substituting Equations (17), (18), and (19) into Equations (14), (15) and (16) gives:

$$W''_x = \quad W\,(\sin\alpha\,\sin\beta - \cos\alpha\,\cos\beta\,\sin\gamma) \tag{20}$$

$$W''_y = -\,W\,(\sin\alpha\,\cos\beta + \cos\alpha\,\sin\beta\,\sin\gamma) \tag{21}$$

$$W''_z = -\,W\,\cos\alpha\,\cos\gamma \tag{22}$$

Similar to the transformation of the tipping weight components, the skidder pull components in the new coordinate become:

$$P''_x = \quad P_x\,\sin\beta + P_y\,\cos\beta\,\cos\gamma + P_z\,\cos\beta\,\sin\gamma \tag{23}$$

$$P''_y = -\,P_x\,\cos\beta + P_y\,\sin\beta\,\cos\gamma + P_z\,\sin\beta\,\sin\gamma \tag{24}$$

$$P''_z = \quad -\,P_y\,\sin\gamma + P_z\,\cos\gamma \tag{25}$$

A number of studies have dealt with a skidder pull required to skid a tree length load (Fiske and Fridley, 1975; Perumpral et al., 1976; Hassan, 1977; Hassan and Gustafson, 1983; Lysne and Burditt, 1983). Although they are all useful, the models developed by the previous researchers are not appropriate for the situation referred in this study because they are limited to two dimensions. To determine the pull with three components (P_x, P_y, P_z), the same coordinate system XYZ is selected except for its origin location (Figure 12). In Figure 12, θ is the angle that the log tail would slip downhill from the skidder moving direction. λ is

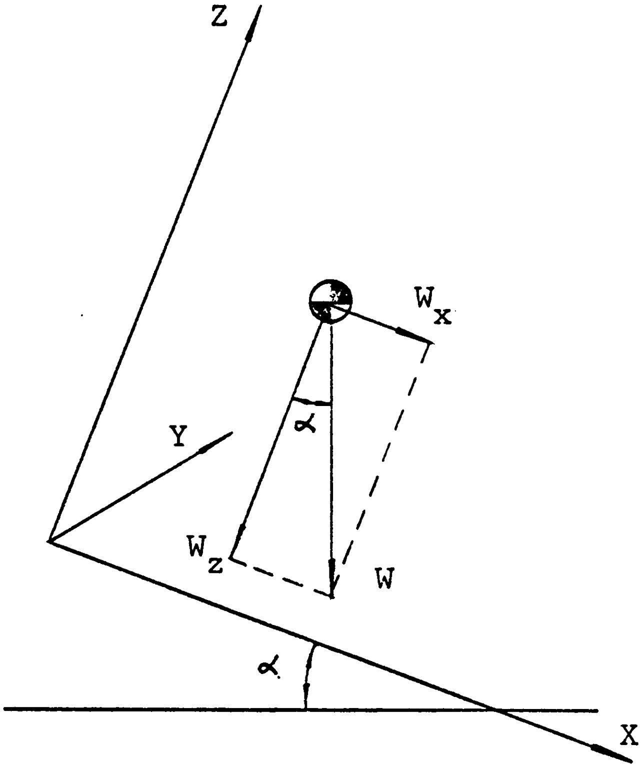

Figure 11. Diagram Illustrating the Determination of the Tipping Weight Components.

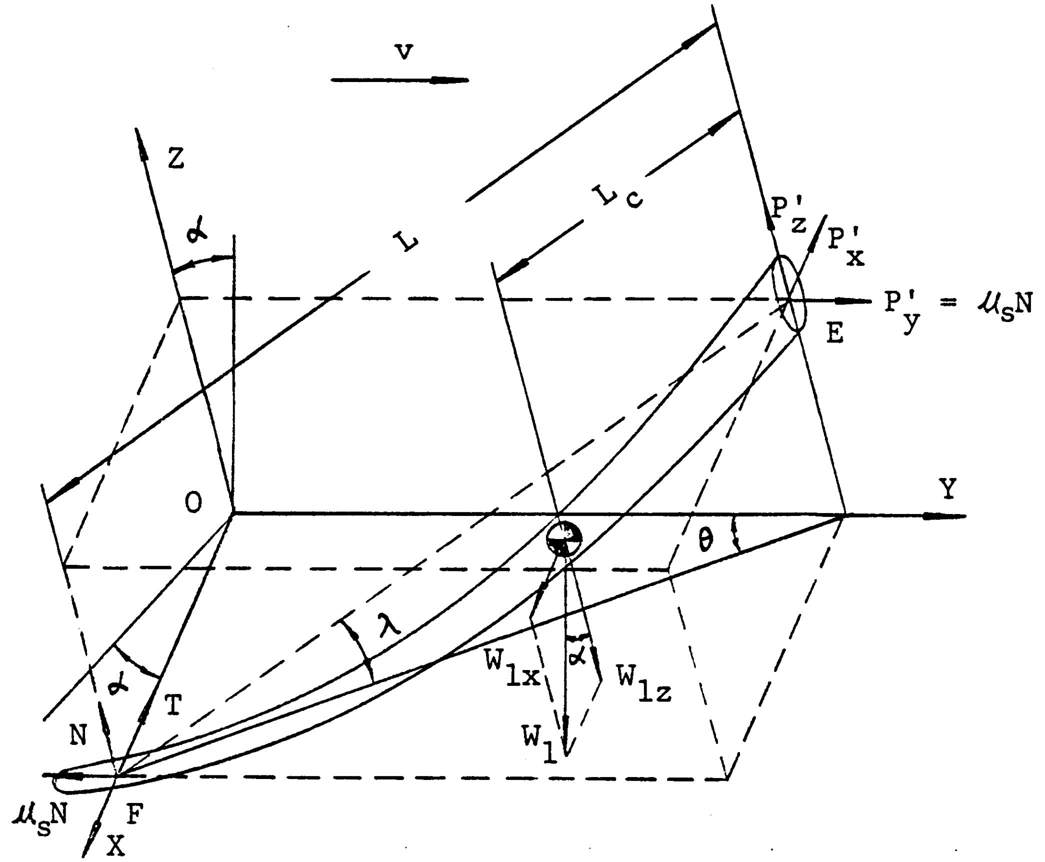

Figure 12. Diagram Illustrating the Free Body of the Log and a Coordinate System Setup.

the angle between the log and the ground surface, and can be determined by:

$$\lambda = \arcsin \frac{Z_p}{L} \tag{26}$$

where:

Z_p ---- height of grapple hange;
L ---- average log length.

L_c is the distance from the center of gravity of the logs to its butt end. Then, the total weight of logs (W_L) can be decomposed in the same way as the skidder turning weight:

$$W_{Lx} = W_L \sin\alpha \tag{27}$$

$$W_{Ly} = 0 \tag{28}$$

$$W_{Lz} = - W_L \cos\alpha \tag{29}$$

To find P_x, P_y and P_z, it is assumed that the logs are in equilibrium. Then, it follows:

$$P'_y = \mu_s N \tag{30}$$

$$P'_z = - W_{Lz} - N \tag{31}$$

and the sum of moments about axis X must be zero. Therefore,

$$L \cos\lambda \cos\theta P'_z + (L - L_c) \cos\lambda \cos\theta W_{Lz} - L \sin\lambda P'_y = 0 \tag{32}$$

where:

μ_s ---- skidding coefficient.

Substituting Equations (29), (30) and (31) into Equation (32) yields:

$$N = K \cos\alpha \cos\theta W_L \tag{33}$$

where:

$$K = \frac{L_c}{L (\cos\theta + \mu_s \tan\lambda)} \tag{34}$$

Substituting N into Equations (30) and (31) gives:

$$P'_y = K \mu_s \cos\alpha \cos\theta W_L \tag{35}$$

$$P'_z = \cos\alpha (1 - K \cos\theta) W_L \tag{36}$$

Similarly, the sum of moments about axis Z through point F must also be zero. Therefore,

$$- L \cos\lambda \cos\theta P'_x - (L - L_c) \cos\lambda \cos\theta W_{Lx}$$
$$- L \cos\lambda \sin\theta P'_y = 0 \qquad (37)$$

Equation (37) together with Equations (27) and (33) gives:

$$P'_x = - (K \mu_s \cos\alpha \sin\theta + \frac{L - L_c}{L} \sin\alpha) W_L \qquad (38)$$

Each component of the pull acting on the skidder by the logs is equal in magnitude to that acting on the logs by the skidder, and opposite in direction. Therefore,

$$P_x = (K \mu_s \cos\alpha \sin\theta + \frac{L - L_c}{L} \sin\alpha) W_L \qquad (39)$$

$$P_y = - K \mu_s \cos\alpha \cos\theta W_L \qquad (40)$$

$$P_z = - \cos\alpha (1 - K \cos\theta) W_L \qquad (41)$$

When the rear wheel on the upper hillside just lost a contact with the ground, the skidder becomes unstable. In this case, the sum of the moments about line AB follows:

$$z''_{cg} W''_x + (B \sin\beta - x''_{cg}) W''_z + z''_p P''_x$$
$$+ (B \sin\beta - x''_p) P''_z = 0 \qquad (42)$$

Substituting Equations (20), (22), (23), (25), (39), (40) and (41) into Equation (42) gives the following:

$$
\begin{aligned}
& z''_{cg}\, W\, (\sin\alpha\ \sin\beta - \cos\alpha\ \cos\beta\ \sin\gamma) \\
& \quad - (B \sin\beta - x''_{cg})\, W \cos\alpha\ \cos\gamma \\
& \quad + z''_{p}\, \{(K\, \mu_{s} \cos\alpha\ \sin\theta + \frac{L - L_{c}}{L} \sin\alpha) \sin\beta\ W_{L} \\
& \qquad\qquad - K\, \mu_{s} \cos\alpha\ \cos\beta\ \cos\gamma\ \cos\theta\ W_{L} \\
& \qquad\qquad - \cos\alpha\ \cos\beta\ \cos\gamma\ (1 - K \cos\theta)\ W_{L}\} \\
& \quad + (B \sin\beta - x''_{p})\, \{K\, \mu_{s} \cos\alpha\ \sin\gamma\ \cos\theta\ W_{L} \\
& \qquad\qquad\qquad - \cos\alpha\ \cos\gamma\ (1 - K \cos\theta)\ W_{L}\} \\
& = 0
\end{aligned}
\tag{43}
$$

Let:

$$
K_1 = z''_{cg} \cos\beta\ \sin\gamma + (B \sin\beta - x''_{cg}) \cos\gamma \tag{44}
$$

$$
\begin{aligned}
K_2 = z''_{p}\, \{K\, \mu_{s}\, (\sin\beta\ \sin\theta - \cos\beta\ \cos\gamma\ \cos\theta) \\
- \cos\beta\ \sin\gamma\ (1 - K \cos\theta)\}
\end{aligned}
\tag{45}
$$

$$
\begin{aligned}
K_3 = (B \sin\beta - x''_{p})\, \{K\, \mu_{s} \sin\gamma\ \cos\theta \\
- \cos\gamma\ (1 - K \cos\theta)\}
\end{aligned}
\tag{46}
$$

Then, the critical slope can be determined by:

$$
\tan\alpha = \frac{K_1\, W - (K_2 + K_3)\, W_{L}}{(z''_{cg}\, W + z''_{p} \dfrac{L - L_{c}}{L} W_{L}) \sin\beta} \tag{47}
$$

Although the model looks highly complex, it can be analyzed easily with the help of a computer. Given machine tipping weight, load, dimensional parameters of the stability triangle PQR, locations of the center of gravity of the weight and pull, and pull direction, the critical sideways tipping can be found with a small program incorporating Equations (3), (4), (8), (10), (11), (13), (26), (34), (44), (45), (46) and (47) as presented in Appendix A.

Model Application

To illustrate an application of the model, the critical sideways tipping angle was calculated for a JD-640 grapple skidder with a tree length load of 9,000 pounds as well as with no load. The input parameter values regarding the skidder were estimated with the help of Deere and Company (1980). The values regarding the load were estimated considering the load used for this study.

Table 3 lists the input and output parameter values for the two different sizes of tires. The increase in the value of the critical tipping angle α indicates an increase in the static lateral stability of the skidder.

Table 3. Typical Parameter Values for the Analysis of Skidder Lateral Stability.

PARAMETER	NUMERICAL VALUE *	
	24.5-32	66-43
2B	86.7	128.2
D	120.0	120.0
H	35.0	31.5
W	21,321.0	21,321.0
x_{cg}	0.0	0.0
y_{cg}	57.0	57.0
z_{cg}	52.3	52.3
x_p	0.0	0.0
y_p	-83.0	-83.0
z_p	100.0	100.0
L	720.0	720.0
L_c	288.0	288.0
μ_s	0.6	0.6
θ	10.0	10.0
α with $W_1 = 9{,}000$	32.3	44.7
α with $W_1 = 0$	32.5	44.8

* Values are in inches for length, pounds for weight, and degrees for angle.

RESULTS AND DISCUSSION

Soil Moisture Content

The average soil moisture content varied from 16.17% to 21.62% during the tests (Table 4). The average moisture content in the surface layer (0-6 inches) was greater than that in the subsurface layer (6-12 inches) in most cases. This is mainly because some of the tests were run soon after rain, and adequate time for the water to permeate into the subsurface was not available prior to the tests.

Effects of Tire Size and Slope on Speed

The results of statistical analyses illustrating the effect of tire size on speed are summarized in Table 5. The results indicate that on the 20% slope, there was a significant difference in the travel time for both the uphill and downhill trials. In either direction, the skidder equipped with the narrow tires moved slower than that with the wide tires. On the 25% slope, however, a significant difference in the travel time is found only during downhill skidding.

During the downhill travel, the maximum speed at which the

Table 4. Soil Moisture Content During Each Test (%).

SAMPLING DEPTH	TIRE SIZE					
	24.5 - 32			66 - 43		
	GROUND SLOPE			GROUND SLOPE		
	20% 1st-3rd passes	20% 4-10th passes	25%	20%	25%	30%
0-6"	18.75	24.00	19.30	18.52	23.08	22.22
6-12"	14.29	19.23	13.04	18.52	17.95	17.86
AVERAGE	16.52	21.62	16.17	18.52	20.52	20.04

Table 5. Effect of Tire Size on Time Taken for Skidder to Travel Through a Unit Distance (seconds/10 feet).

SLOPE	DIRECTION	TIRE SIZE	N	TIME	DUNCAN'S TEST *
20%	UPHILL	24.5-32	95	3.3669	B
		66-43	110	2.6755	A
	DOWNHILL	24.5-32	100	1.9576	B
		66-43	110	1.5295	A
25%	UPHILL	24.5-32	83	2.9842	A
		66-43	90	3.0182	A
	DOWNHILL	24.5-32	80	1.4959	B
		66-43	88	1.2658	A

* Duncan's multiple range test at .05 significance level.
Means of time with the same letter are not significantly different.

skidder could be driven is greatly limited by the safety considerations. The operator found that the wide tires offerred smoother rideability and better stability. Therefore, the skidder with the wide tires could be driven at a faster speed.

It should be noticed that during the tests, the machine equipped with the wide tires pulled approximately 1,000 pounds less load than the machine with the narrow tires because of the variation in loads. This may make the actual difference less significant.

The results of the statistical analyses on the data of travel time per unit distance on the different slopes do not show consistent tendency of the effect of slope on the travel time (Table 6).

Since the load for the test with the wide tires on the 30% slope was substantially different from those in the other tests (Table 2), the results from this test can not be compared with the results from the other tests.

It would be expected that the skidder would move slower on steeper slopes if other conditions remain the same. However, such speed-slope relationship cannot be found from the results. This is probably because there was not enough difference between the slopes for the tests to be affected.

Table 6. Effect of Slope on Time Taken for Skidder to Travel Through a Unit Distance (seconds/10 feet).

TIRE SIZE	DIRECTION	SLOPE	N	TIME	DUNCAN'S TEST *
24.5-32	UPHILL	20%	95	3.3669	B
		25%	83	2.9842	A
	DOWNHILL	20%	100	1.9576	B
		25%	80	1.4959	A
66-43	UPHILL	20%	110	2.6755	A
		25%	90	3.0182	B
		30%	63	2.9437	B
	DOWNHILL	20%	110	1.5295	B
		25%	88	1.2658	A
		30%	81	2.1003	C

* Duncan's multiple range test at .05 significance level.
Means of time with the same letter are not significantly different.

Effects of Tire Size and Slope on Wheel Slip

The results of statistical analyses conducted to determine the effect of tire size on wheel slip are summarized in Table 7. The results indicate a reduction in wheel slip for the wide tires in 50% measurements made. Since the wide tires provide larger contact area than the narrow tires, its tractive performance should be better. As a result, for the same load, a lower slip level with the wide tires is reasonable.

Table 8 shows the results from the statistical tests conducted to determine the effect of different slopes on wheel slip.

Based on the traction theory, since the resistance that the vehicle has to overcome increases with slope, a higher slip level would be expected on steeper slopes. However, the results do not illustrate the expected relationship between wheel slip and slope. This may be attributed to the fact that the difference between slopes tested was too small so that slope effect could be overwhelmed by other undetermined factors.

During the operation, it was observed that rim slip occurred with the wide tires. The rim slip was observed to be more with the rear wheels than with the front wheels. The actual inflation pressure for the wide tires in this study was 20 psi, which is 5 psi lower than the manufacture's rat-

Table 7. Effect of Tire Size on Wheel Slip.

SLOPE	DIRECTION	WHEEL	TIRE SIZE	N	SLIP (%)	DUNCAN'S TEST *
20%	UPHILL	FRONT	24.5-32	10	11.58	B
			66-43	10	8.25	A
		REAR	24.5-32	10	13.11	B
			66-43	10	7.21	A
	DOWNHILL	FRONT	24.5-32	10	-3.44	A
			66-43	10	-3.61	A
		REAR	24.5-32	10	-3.23	B
			66-43	10	-2.10	A
25%	UPHILL	FRONT	24.5-32	11	10.76	A
			66-43	10	9.39	A
		REAR	24.5-32	11	11.71	B
			66-43	10	9.05	A
	DOWNHILL	FRONT	24.5-32	10	-4.13	A
			66-43	10	-4.63	A
		REAR	24.5-32	10	-5.09	A
			66-43	10	-5.20	A

* Duncan's multiple range test at .05 significance level.
Means of slip levels with the same letter are not significantly different.

Table 8. Effect of Slope on Wheel Slip.

TIRE SIZE	DIRECTION	WHEEL	SLOPE	N	SLIP (%)	DUNCAN'S TEST *	
24.5-32	UPHILL	FRONT	20%	10	11.58	A	
			25%	11	10.76	A	
		REAR	20%	10	13.11	A	
			25%	11	11.71	A	
	DONWHILL	FRONT	20%	10	-3.44	A	
			25%	10	-4.13	A	
		REAR	20%	10	-3.23	A	
			25%	10	-5.09	A	
66-43	UPHILL	FRONT	20%	10	8.24	A	B
			25%	10	9.39		B
			30%	9	7.04	A	
		REAR	20%	10	7.21	A	B
			25%	10	9.05		B
			30%	9	6.85	A	
	DOWNHILL	FRONT	20%	10	-3.61	A	
			25%	10	-4.63	A	
			30%	9	-4.96	A	
		REAR	20%	10	-2.10	A	
			25%	10	-5.20		B
			30%	9	-4.62		B

* Duncan's multiple range test at .05 significance level.
Means of slip levels with the same letter are not significantly different.

ing (Table 3). This may be the cause for the rim slip. Because of the load transfer, or weight shift during the opertions on slopes, the rear wheels are expected to carry more load than the front wheels. This probably is the reason for more rim slip in the rear tires.

Effects of Tire Size and Slope on Soil Compaction

Effects of tire size and slope on soil compaction were evaluated by testing the difference in the average increase of the soil cone penetrometer readings measured before and after skidder traffic treatment in each case. A summary of the results is presented in Table 9 and Table 10.

From Table 9, it can be seen that except in one test, the wide tires resulted in a smaller increase in the soil cone penetrometer readings due to the treatment than the narrow tires. This is expected because of comparatively lower contact presure from the larger contact area provided by the wide tires.

The dynamic load on the wheels and thus the contact presure decrease with an increase in ground slope. As a result of this, one would expect a reduction in soil compaction on steeper slopes. However, the results of this study as shown in Table 10 do not display such a trend. Too small a difference between the slopes tested might be the reason for that.

Table 9. Average Increase in Penetrometer Resistance due to Skidder Traffic with Different Sizes of Tires.

SLOPE	DIRECTION	TIRE SIZE	N	INCREASE (psi)	DUNCAN'S TEST *	
20%	UPHILL	24.5-32	60	6.83	A	
		66-43	60	8.33	A	
	DOWNHILL	24.5-32	60	50.00		B
		66-43	60	17.17	A	
25%	UPHILL	24.5-32	60	37.00		B
		66-43	60	3.50	A	
	DOWNHILL	24.5-32	60	39.33		B
		66-43	60	3.67	A	

* Duncan's multiple range test at .05 significance level.
Means of the increases in the penetrometer readings with the same letter are not significantly different.

Table 10. Average Increase in Penetrometer Resistance due to Skidder Traffic on Different Slopes.

TIRE SIZE	DIRECTION	SLOPE	N	INCREASE (psi)	DUNCAN'S TEST *
24.5-32	UPHILL	20%	60	6.83	A
		25%	60	37.00	B
	DOWNHILL	20%	60	50.00	A
		25%	60	39.33	A
66-43	UPHILL	20%	60	8.33	A
		25%	60	3.50	A
	DOWNHILL	20%	60	17.17	A
		25%	60	3.67	A

* Duncan's multiple range test at .05 significance level.
Means of the increases in the penetrometer readings with the same letter are not significantly different.

Table 11 presents the results of the statistical analyses for testing significant increase in the readings of the cone penetrometer measured before and after the traffic treatment within each tire-size and slope combination. The significant increase, if any, is used to indicate significant compaction. This inference is valid under the assumption that the soil moisture content and soil type at the sampling locations were the same. Therefore, any change in the cone penetrometer readings was due only to the skidder traffic.

From the results, it can be seen that the skidder traffic with the narrow tires generally caused a significant increase in the soil cone penetrometer readings. This implies that the treatment with the narrow tires caused significant soil compaction. However, it is also interesting to note that in most cases, the traffic treatment did not cause a significant change in the penetrometer readings even with the narrow tires. Since the site was thinned with a ground based system just a few years prior to the tests, it is likely that the soils in the test areas were still compacted.

Effect of Tire Size on Skidder Lateral Stability

The stability model developed in this study predicted that the critical sideways tipping angle for a JD-640 grapple skidder to be approximately 32° when fitted with the 24.5-32 tires, and 44° when fitted with the 66-43 tires (Table 3).

For the same skidder, increasing the tire width increases the wheel tread, which in turn causes the tipping axis further away from the center of gravity of the tipping weight. Therefore, the moment against the tipping motion increases. Practically, this indicates an increase in the stability on sideslopes.

Table 11. Difference in Penetrometer Readings Measured Before and After treatment in Each Tire-Size and Slope Combination.

SLOPE	DIRECTION	TIRE SIZE	N	BEFORE (psi)	AFTER (psi)	DUNCAN'S TEST *
20%	UPHILL	24.5-32	60	153.17	160.00	N
		66-43	60	140.50	148.00	N
	DOWNHILL	24.5-32	60	118.00	168.00	S
		66-43	60	180.67	163.50	N
25%	UPHILL	24.5-32	60	148.17	185.17	S
		66-43	60	147.67	151.17	N
	DOWNHILL	24.5-32	60	144.83	184.17	S
		66-43	60	136.00	139.69	N

* Duncan's multiple range test at .05 significance level.

N ---- Difference in the penetrometer readings between before and after the treatment is not significant.

S ---- Difference in the penetrometer readings between before and after the treatment is significant.

SUMMARY AND CONCLUSIONS

Steep slopes have long been a problem in forest harvesting operations. They either cause conventional systems to be inoperable, or operating costs to increase tremendously. Presently, the rubber-tired skidder is commonly used on slopes up to 30%. On steeper slopes, special trails have to be constructed before the introduction of the ground based systems. The purpose of constructing these trails is merely to reduce the magnitude of the slopes such that the ground based systems can operate, and a sufficient pulling capacity can be developed. However, the layout design, the cost and the environmental impact associated with these trails pose a significant problem.

To investigate potential applications of wide skidder tires for steep slope operations, a study was conducted at Berry College, north of the city of Rome in Floyd County, Georgia during the summer of 1984. Two different sizes of skidder tire: 24.5-32 and 66-43 were used in the field tests to allow examination of the effects of tire size on skidder performance on various slopes. Video recorders were used to document machine travel time and wheel revolutions when running on a test lane. The data were then extracted from the video tapes in a laboratory.

To compare machine lateral stability on slopes when equipped with different sizes of tires, a mathematical model containing the parameter of wheel tread (or tire width for the same machine) was developed. This model indicated that increasing wheel tread will increase machine lateral stability on slopes.

Based on the results of data analyses and field observations, the following conclusions were drawn:

1. An analysis of the average travel time per unit distance (seconds per 10 feet) including the effects of acceleration, maximum sustainable (or safe) speed and deceleration showed that the skidder equipped with the wide tires attained higher average travel speeds than that with the narrow tires with one exception.
2. An analysis of wheel slip in the narrow and wide tires indicated that in 50% of the measurements made, there was less wheel slip in the wide tires.
3. An analysis of soil cone penetrometer readings showed that except in one test, the traffic of the skidder equipped with the wide tires caused smaller increases in soil cone penetrometer readings than that with the narrow tires.
4. Due to the small difference of the average slopes in the test lanes, no conclusions can be drawn regarding the

effect of slope on machine performance with either tire size.

5. The field trials indicated that the skidder equipped with the wide tires had greater stability on sideslopes than when fitted with the narrow tires. Prediction for a JD-640 grapple skidder using the stability model developed in this study indicated the critical sideways tipping angle to be approximately 32° when fitted with the 24.5-32 tires, and 44° when fitted with the 66-43 tires.
6. The use of a video recorder for documenting the field measurements and observations was found to be very helpful, especially in saving the field test time. However, care should be taken in positioning the video camera to minimize the parallelism problem.

The reader should be cautioned that the above results and conclusions were based on the trials made in the physiographic region of Piedmont, Georgia, and should not be extrapolated to other soil types and physiographic regions.

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APPENDIX A.

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10 REM *****************************************************************
20 REM *                                                               *
30 REM *             ANALYSIS OF SKIDDER LATERAL STABILITY             *
40 REM *                                                               *
50 REM *****************************************************************
60 CLS
70 INPUT "WHEEL TREAD (IN.) ";B
80 INPUT "HORIZONTAL DISTANCE FROM PIN TO REAR AXLE (IN.) ";D
90 INPUT "HEIGHT OF PIN (IN.) ";H
100 INPUT "WEIGHT OF SKIDDER EXCEPT FRONT AXLE ASSEMBLY (LBS.) ";W
110 PRINT "COORDINATE OF THE CENTER OF GRAVITY OF THE WEIGHT (IN.)"
115 INPUT "XCG=";XCG
120 INPUT "YCG=";YCG
130 INPUT "ZCG=";ZCG
140 INPUT "COORDINATE OF THE POINT WHERE PULL ACTS (IN.) XP=";XP
150 INPUT "                                              YP=";YP
160 INPUT "                                              ZP=";ZP
170 INPUT "TOTAL WEIGHT OF LOGS (LBS.) ";WL
180 INPUT "AVERAGE LOG LENGTH (IN.) ";L
190 INPUT "AVERAGE DISTANCE FROM CENTER OF GRAVITY TO BUTT END (IN.)";LC
200 INPUT "SKIDDING COEFFICIENT ";MU
210 INPUT "LOG SLIP ANGLE (DEGREES) ";THETA
220 B=B/2
230 BETA=ATN(SQR(H*H+D*D)/B)
240 GAMMA=ATN(H/D)
250 LAMBDA=ATN(ZP/L/SQR(1-(ZP/L)^2))
260 THETA=THETA*3.141592/180
270 K=LC/((COS(THETA)+MU*TAN(LAMBDA))*L)
280 XCG2= XCG*SIN(BETA)+(YCG*COS(GAMMA)+ZCG*SIN(GAMMA))*COS(BETA)
290 ZCG2=-YCG*SIN(GAMMA)+ZCG*COS(GAMMA)
300 XP2= XP*SIN(BETA)+(YP*COS(GAMMA)+ZP*SIN(GAMMA))*COS(BETA)
310 ZP2=-YP*SIN(GAMMA)+ZP*COS(GAMMA)
320 K1=ZCG2*COS(BETA)*SIN(GAMMA)+(B*SIN(BETA)-XCG2)*COS(GAMMA)
330 K2=ZP2*(K*MU*(SIN(BETA)*SIN(THETA)-COS(BETA)*COS(GAMMA)*COS(THETA))
       -COS(BETA)*SIN(GAMMA)*(1-K*COS(THETA)))
340 K3=(B*SIN(BETA)-XP2)*(K*MU*SIN(GAMMA)*COS(THETA)
       -COS(GAMMA)*(1-K*COS(THETA)))
350 NUM=K1*W-(K2+K3)*WL
360 DEN=(ZCG2*W+(L-LC)/L*ZP2*WL)*SIN(BETA)
370 SLOPE=ATN(NUM/DEN)*180/3.141592
380 SLOPE=CINT(SLOPE*100)/100
390 CLS : PRINT "THE CRITICAL SLOPE FOR THE PARTIAL TIPPING WEIGHT IS ";
                 SLOPE; "DEGREES."
400 END
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