

AN ABSTRACT OF THE PAPER OF

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Title: PREDICTING SKIDDER PRODUCTIVITY: A MOBILITY APPROACH

The principles of mobility are applied to the forest setting to simulate the movement of logs with a rubber tired-skidder. A computer program was written to perform the analysis. Vehicle-terrain and log-terrain interactions are the resistances which must be overcome by the available vehicle power. The rate at which these resistances can be overcome is potential vehicle speed. Vehicle speed and turn weight then define productivity.

The "mobility model" is then used to evaluate variable relationships and identify optimum vehicle horsepower, turn weights, and skid trail slopes. A user oriented program is written with documentation for the Hewlett Packard Model 9830 desktop computer.

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PREDICTING SKIDDER PRODUCTIVITY:
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DISCLAIMER

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PREDICTING SKIDDER PRODUCTIVITY: A MOBILITY APPROACH

INTRODUCTION

The forest engineer has for a long time been responsible for making estimates of harvesting and production costs for the ground skidding of a setting. Integral in his decision making process, until fairly recently, has been perhaps the volume measurement of a few trees, a look at the terrain, a few rough calculations, and experience. How good his choice was could probably be correlated with how much he had of the latter.

In the past several years there has been an aid to this decision making process that has come in the form of production prediction tools. By knowing the production of different harvesting options for a given setting, costs can be computed and a proper decision can be made. This is extremely valuable to the individual who does not have much experience, or is working in unfamiliar conditions. The tools used for these predictions have been developed using two entirely different approaches.

By far the most common is regression analysis or simulation models based on regression analysis that are a product of detailed time studies of logging operations. There are, however, some shortcomings to this approach. Although it is possible to obtain a good working prediction equation for the area in which it was produced, there is often uncertainty as to how well it will work when transferred to different operating conditions (i.e., will this equation predict well in an area with steeper average slopes and with new operators?). This

is due largely to the empirical nature of regression analysis, and indicates that a more analytical procedure would be valuable.

Looking at the fundamentals of the log moving problem suggests that mobility (soil-vehicle interaction) would be another way of addressing this problem.

The study of mobility, while used quite extensively for military and agricultural application (Raghavan and McKyes, 1979; Macnab 1976; Freitag, 1965a), has seen limited use in the forest industry. It looks at the ability of the vehicle to impart thrust onto the load-bearing ground surface and the soil's response to this thrust. If the soil is strong, then most of this thrust can be turned into useable work for skidding. In this case, the skidder would be the limiting factor of production. If, however, the soil is weak (low shear strength), then excessive slippage occurs and the soil is limiting for that set of conditions. These are two important factors that can limit productive capacity.

In the Southeast and Pacific Northwestern United States, weak soils due in part to heavy winter precipitation are common. The incentive to extend the harvest season has led companies to increasing operations on wet soils. It is this soil which is least favorable for harvesting that is often most favorable for timber growth. Consequently, the forest manager is often required to carry out harvesting operations in these areas. Also, due to tighter economic constraints, there has been pressure to utilize a skidder to its fullest potential. This means maximum turn weights which would utilize the equipment at or near its power limitations.

It is for these reasons that mobility, which addresses these vehicle power and soil strength limitations directly, is applicable to the forest industry now and will become even more so in the future.

This paper will look at work that has been done in the area of mobility and apply it to ground skidding applications. It should be noted that the study of mobility is still in its infancy and the equations that describe soil-vehicle and soil-log interaction are attempts at quantifying a very complex problem. For this reason, this paper is by no means an attempt to replace the regression equation. It is felt, though, that the application of mobility to the prediction of ground skidding production in the forest is an important step towards improving predictive capabilities. As work progresses in the study of mobility, it is likely that this type of analysis will become commonplace in the tree harvesting industry.

For the purposes of analysis, a program was written for the Hewlett Packard Model 9830 desktop computer, a program that will be referred to as the mobility model. The computational power of a computer is required to make the mobility approach feasible. For the purposes of this paper, two actual programs were written. One was used to generate the graphs in the results section of this paper. The other is a user oriented program which is intended as a tool to aid in the layout and costing of a harvest setting.

The program will output total turn time subsequent to the completion of the computer prompted inputs. The mobility model can analyze both log length and tree length turn loads.

OBJECTIVES

- 1) To develop a skidder production prediction model with emphasis on techniques developed through the study of mobility.
- 2) Expose factors that are most responsible for limiting ground skidding production.
- 3) Generate data on predicted productivity of several skidder horsepower classifications and determine where significant differences exist.

JUSTIFICATION

The use of the mobility approach allows the construction of a comprehensive model that will predict over a wide range of conditions. Considered are such variables as machine geometry and weight distribution, tire size, soil strength, ground slope, and skidding distance. Any or all of these variables can be allowed to vary over the full range of conditions that would be encountered in the field.

A statistically based model rarely contains all of the variables known to have an important affect on production. There are two main reasons for this. The first is that the range of conditions over which they predict is limited to the variables considered and the range over which they were considered. There are many variables which play an important role in describing the production of a ground skidding system. To adequately consider each variable over its full range would require an immense study. For this reason each regression equation will describe a small portion of the total set of harvesting conditions.

Second, for a variable to be statistically significant there must be an adequate range of variation encountered in the field study. If there is not, then the variable will not show up in the model. This does not mean that the variable is not important, only that it did not meet the criteria for acceptance in this case.

It is necessary, then, if one is to look at the whole area of ground skidding, to look at many equations developed under many different sets of conditions. Pieced together, they represent a cumbersome collection of equations that often have no common base for comparison. A model that is largely analytical, however, will allow the development of relationships that are expressly cause and effect. For this reason, the analytical model can predict equally well for several entirely different sets of conditions.

Important also is the consideration specifically of soil strength, as it is known to be an important contributing limitation to ground skidding production. By nature, the strength of this model is defined by the conditions where most other models are weak, when soil conditions are adverse.

It is likely that eventually log skidding models will incorporate both analytical and empirical means for reaching the best production utilizing the strengths of both methods. As for the development of the analytical portion, this is perhaps a start.

SCOPE

Mobility is the study of vehicular motion as it is affected by the conditions of the terrain. Since only a portion of the skidding

cycle involves the actual productive forward movement of the skidder, modeling the travel element of this cycle is valuable only when this element is significant to the overall time. For this reason, the value of this approach increases with the proportion of travel to non-travel time. Long travel elements are characterized by steep adverse slopes, weak soils, long skid distances, and high turn weights. If none of these aspects is present, then the model will be of no value in production prediction. If one or more of these variables does begin to dominate, then the potential value of the model increases.

Also inherent in this model is the assumption that the skidder is the limiting factor in the skidding operation. If operator inexperience or discomfort come into play in the limitation of production, then again its value for prediction is diminished. In this case, the empirical model which by nature considers the effects of human factors on skidder production would likely be a stronger predictor.

LITERATURE SEARCH

The two major components required to build the skidder production program deal with tractive potential of the soil-wheel system and log skid resistance characteristics. In any skidding situation it is necessary for the tractive potential to exceed skid resistance for movement to occur. Once the skidder mobility model is completed, then it will be compared to current regression models of skidder productivity to assess the value of the program as a predictor.

Most theories which describe the interaction between soil and wheel are based on semi-empirical methods. Bekker (1956) used

forced pressure plates to generate sinkage parameters which in turn were used in his formulations of tire rolling resistance and tire sinkage. Bekker's work is based on a generalized form of earlier work done by Bernstein (1913). Efforts of the U.S. Army Corp of Engineers at the Waterways Experiment Station, Vicksburg, Mississippi, over several years has yielded much in the way of quantitative analysis of tires in soil through dimensional analysis. The basis for this work was established through the development of the Freitag Numeric (Freitag 1965a). Combining cone index of the soil, tire width, tire diameter, and weight on tire, the dimensionless parameter has become integral to nearly all work done with tractive pull. Continuing efforts along these lines led to the development by Wismer and Luth (1974) of an equation for tractive pull that has gained acceptance (Fiske and Fridley 1975, Perumperal et al. 1977, Ferguson and Sinclair 1981). Utilizing a common soil strength measurement tool called a cone penetrometer which allows for convenient field data collection, this equation is well suited for field application. The validity of the cone penetrometer test as a parameter for the prediction of drawbar pull is confirmed by Young and Youssef (1977).

Forces required to skid logs were studied first by Herrick (1955). Looking at the pull required to move different loads on level as well as sloped terrain, he determined that skidding resistance coefficients on dry silty and clay loams vary from .84 to .96 depending upon the ground slope. Fiske and Fridley (1975), attempting to relate skidding forces to log weights, determined that a significant factor was the distance of the log's leading end to the ground and developed skidding

force relationships for both ground skidding and arch skidding, one being different enough from the other to warrant separate treatment. Garlicki and Calvert (1969), comparing power requirements for tree length versus whole tree skidding, found that removing the branches reduced power requirements approximately 50 percent. From this work, however, no analytical model was developed. Perumperal (1977) derived such a model for skidding tree length logs. He found the skidding resistance coefficient to be dependent upon normal load, soil moisture content, species, and condition of skidded log (bark or no bark). The result was a model with line pull predictions which compare favorably with measured experimental data.

For the purposes of verification, predictions from the mobility model will be compared statistically with both raw field data (Seifert 1982) and established regression equations (BLM 1977, TVA 1976).

VEHICLE VELOCITY

The principle of the mobility model is simply one of evaluating potential. The maximum speed that the skidder can travel is subject to limitations imposed by available vehicle power and limited soil shear strength, i.e., the soil can accept only so much of this vehicle power before excessive slippage between the tires and the soil reduces travel velocity. There are instances where neither the vehicle power nor the soil strength will limit the maximum vehicle velocity (see Figure 3). When skidding logs downhill or when skidding on level ground with a small log load and a reasonably strong soil, the maximum vehicle velocity would be the maximum speed for which the skidder was

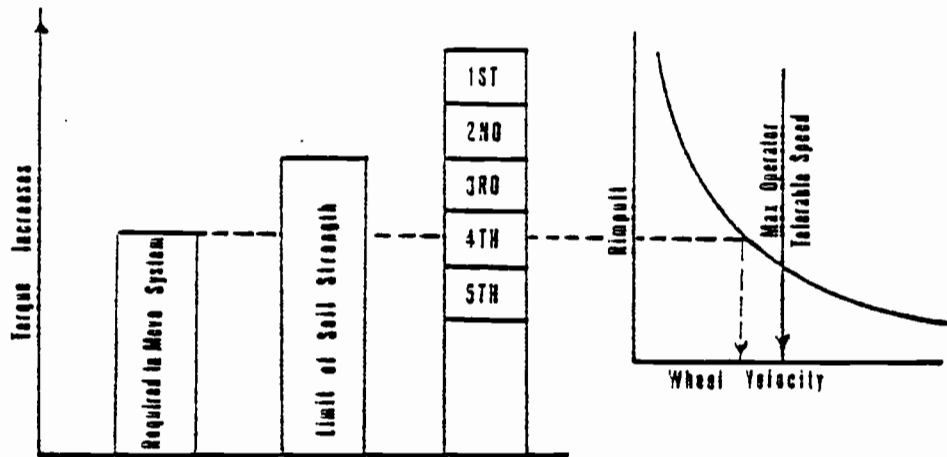


Figure 1. Skidder can sustain movement in 4th gear. Soil strength adequate

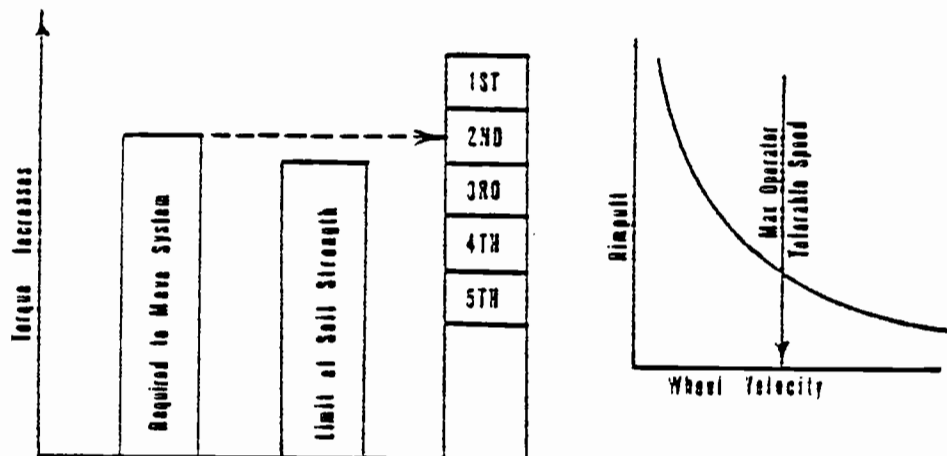


Figure 2. Soil strength inadequate; therefore movement will not occur

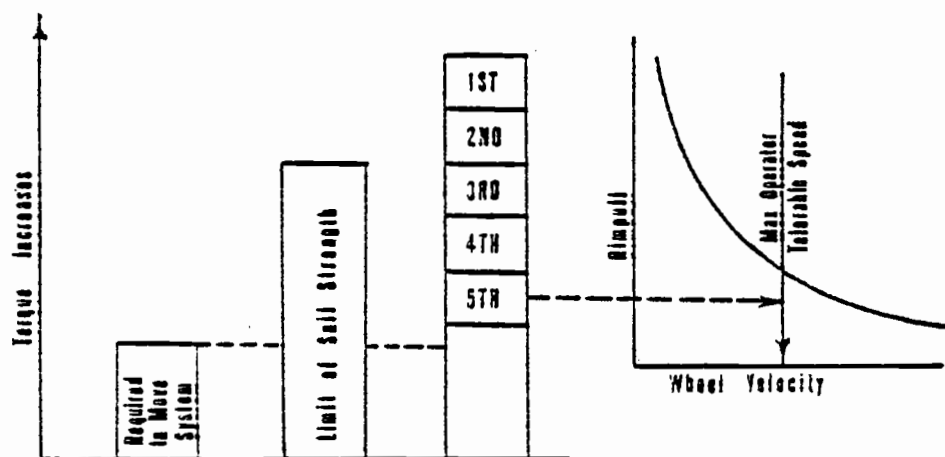


Figure 3. Low system movement requirements allow skidder to travel at maximum operator tolerable speed

designed. This maximum design speed is likely to be between 10 and 20 miles per hour. These speeds are much too high to be realized in off-road conditions. When approaching speeds of six miles per hour the limiting factor becomes driver discomfort (Radforth 1978). For the mobility model to be a realistic predictor, this must be accounted for.

Since the mobility model is one that evaluates potential, it would be consistent to view this maximum speed of six miles per hour as the maximum tolerable operator speed. Since this maximum operator limited speed will vary somewhat, the option will be left in the model for the user to input a different maximum speed, if he so chooses. Therefore, if the model calculates a vehicle velocity that exceeds this maximum tolerable operator speed, the model will default to this speed.

The mobility model does not account for terrain roughness, ground cover, or operator experience. If any or all of these factors combine to create a condition where the maximum tolerable operator speed is significantly different from the six miles per hour assumed, then a new estimate should be input. This estimate should be made by observations of the operator of interest in conditions similar to those of the area for which the productivity predictions are being made.

To further illustrate how soil strength and vehicle power tie together to determine potential velocity of a vehicle, three different aspects are presented in Figures 1, 2, and 3. Figure 1 shows the situation where a given thrust is required to move the system. The horizontal dashed line passes within the limits of the soils' ability to withstand this force. The engine torque required to supply this thrust can be supplied in fourth gear. Continuing the line through to the

wheel thrust-velocity curve yields a wheel velocity. The vehicle velocity is then equal to the wheel velocity minus the relative slip between the wheel and soil (this is discussed further on page 22).

Figure 2 represents the situation where the thrust required to move the system is greater than the thrust which can be supported by the soil. Consequently the tires slip and no forward motion occurs.

Figure 3 indicates a situation whereby the thrust required to move the system is low, as on a downhill skid. The horizontal line passes within the limits of soil strength and below the highest gear. Since the torque requirements are less than for fifth gear, it will be sufficient. Proceeding over to the thrust-velocity curve, the velocity is determined. If, however, this wheel velocity yields a vehicle velocity greater than the maximum tolerable operator speed, then the velocity must drop down to the allowable maximum.

Soil strength, available vehicle power, and downhill slopes define the magnitude of the forces available to cause vehicle motion. Soil strength (rolling resistance), skidding resistance, and uphill slopes define the forces available to resist motion. The role that each of these factors plays in determining potential vehicle velocity is discussed in the following sections.

SOIL STRENGTH

To look at the problem of determining how soil strength could limit vehicle velocity, we must focus on the soil-wheel interface. Much work has been done in an attempt to formulate an analytical solution to describing the relationship between wheel load, soil

strength, and obtainable thrust. Because of the immense complexity of this problem, results have been erratic. In 1973, however, Wismer and Luth (1974) through dimensional analysis found the semi-empirical relationship

$$P = W ((.75 (1 - e^{-.3CnS}) - (1.2/Cn + .04))) \quad (1)$$

where P = tractive pull parallel to ground (lb)
 W = dynamic wheel load normal to the ground (lb)
 e = base of natural logarithm

Cn = Frietag numeric (unitless)

S = wheel slip (ratio)

and

$$Cn = \frac{CIbd}{W} \quad (2)$$

where CI = cone index of soil (psi)
 b = section width of tire (in)
 d = undeflected section height

This equation has been applied with good results (Fiske and Fridley 1975, Raghavan and McKyes 1979) and is a standard tool of the American Society of Agricultural Engineers (ASAE 1981).

P in equation (1) is the net pull available from the wheel after resistance due to sinkage in the soil is accounted for. The first half of the equation represents gross thrust and the second half is rolling resistance. What is left when the rolling resistance is subtracted from gross thrust is known as net thrust or net pull.

The necessity to overcome breakout pull was recognized and incorporated into the mobility model. Breakout pull is the maximum resistance to skidding supplied by the turn, and occurs just before motion is initiated. It is reported to be approximately 110 percent of normal in-motion skid resistance (Ferguson and Sinclair 1981). The model checks to insure that this increased threshold skid resistance can be overcome.

Consideration was also given to including an acceleration subroutine in the model. Trial runs proved this to be unimportant. This is most likely due to the low travel speeds encountered in the forest setting.

Developed by Herrick (1955) with later contributions by Fiske and Fridley (1975), the following equation resulted for determining skidding forces for logs.

$$P_n = n WL \cos \beta \quad (3)$$

$$P_t = (1-n) C_r WL \cos \beta + WL \sin \beta \quad (4)$$

where

P_n = normal force on logs

P_t = tangential force on logs

WL = turn weight

β = ground slope in degrees

n = dynamic weight transfer to skidder

C_r = coefficient of resistance to skidding

The tractive pull equation was developed for cohesive-granular soils, i.e., these soils which have both cohesive and granular elements. Although it is not all inclusive, it does represent a broad spectrum of soils that would be encountered (Wismer and Luth 1974). The equation is not valid for organic soils. This makes the program invalid for soils with very thick organic layers where the tires are not heavily influenced by the mineral soils beneath. With successive passes which are characteristic of most harvest settings or where substantial tire slip occurs, displacement of the organic layer will expose the mineral soil to tire contact (Albright 1980, Froehlich 1980).

Equation 1 along with the Frietag numeric (equation 2) will be used for the determination of wheel thrust which is necessary for the calculation of vehicle speed in the mobility model. Pull (P in equation 1) is a measure of the force the tire can exert parallel to the soil surface limited by the soils' ability to withstand these forces. Frietag (1965a) developed equation (2) in earlier work on mobility.

Available pull is a function of soil strength which is measured as a cone index. The cone index of a soil is obtained with a portable testing device called a cone penetrometer. The cone penetrometer is essentially a rod with compression scale and a small cone on the end. When forced into the soil surface, it measures the resistance of the soil to the penetration of the cone. The cone index is then calculated by dividing the resistance measurement by the area of the base of the cone. The units for cone index are pounds per square inch.

Some factors that will affect the magnitude of the cone index are soil grain size, cohesiveness, void ratio, and moisture content

(Ferguson and Sinclair 1981). Forest soils can have cone indexes ranging from 50 psi for a wet loose soil to well over 300 psi for a dry compacted skid trail. It can be seen by careful inspection of equation (1) that increasing the cone index will increase available pull.

Cone index varies with depth of soil sampled. It is necessary then to establish guidelines to insure that the sample measured is most representative of the soil mass in contact with the skidder tires. The best correlations between real and predicted pulls for equation (1), when sinkage is less than three inches, have been found by taking the average cone index reading between zero and six inches depth for relatively low skidder tire sinkage (strong soils). For tire sinkage greater than three inches, the reading should be averaged over the six inches, three inches above and three inches below maximum sinkage. To be representative, readings should be taken in a pattern distributed over the area of concern to adequately delineate the larger variations in cone index.

LOG DRAG FORCES

Two models were chosen to simulate the log drag forces encountered during skidding. One is for log length logs and the other for tree length. Both models are analytical, predicting skidding force as a function of log geometry, total turn weight, and coefficient of skidding resistance. Both assume implicitly that the logs being skidded act independently, and can thus be represented by a single log with a weight equal to the total turn for simplification of analysis.

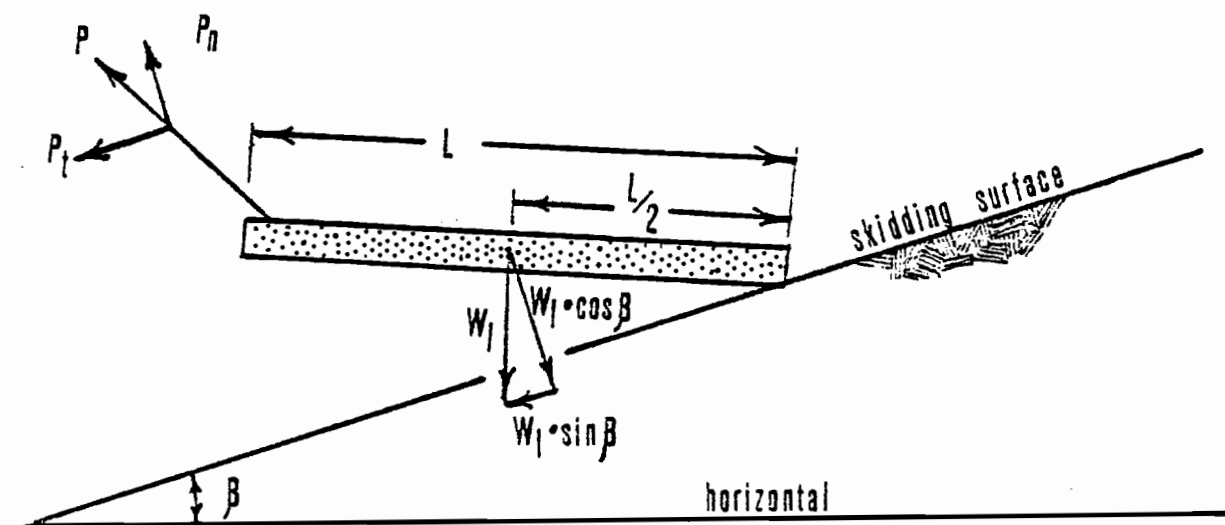


Figure 4. Load geometry for log length skidding for a downhill skid.

Both n and Cr from equations (4) and (5) are determined by the configuration of the log load during carry. It has been found that the following relationships approximate the actual log skidding configuration (Fiske and Fridley 1975).

for ground skidding $n = .2$

$$Cr = .9 + 1.667 \tan \beta \quad (5)$$

for arch skidding $n = .5$

$$Cr = 1.2 + .667 \tan \beta \quad (6)$$

The dynamic weight transfer is simply the portion of the total log weight supported by the skidder.

Equations (7), (8), and (9) were developed for predicting the skidding forces for tree length logs (Perumperal 1977).

$$N = \frac{W(CG-L_b) \sqrt{1-(H/x)^2}}{x\sqrt{1-(H/x)^2} + \mu_s H + (L_c/2)} \quad (7)$$

where $x = L - L_b - L_c$ (8)

$$P_n = W - N \quad (9)$$

$$P_t = \mu_s N \quad (10)$$

W = turn weight (lb)

CG = distance from butt to center of gravity (ft) (average for logs)

L_c = average length of contact area between logs and ground (ft)

L_b = distance from butt to choker hook point (ft)

H = distance from ground to hook point (ft)

μ_s = coefficient of skidding resistance

P_n = normal force on logs

P_t = tangential force on logs

L = total length of log (ft)

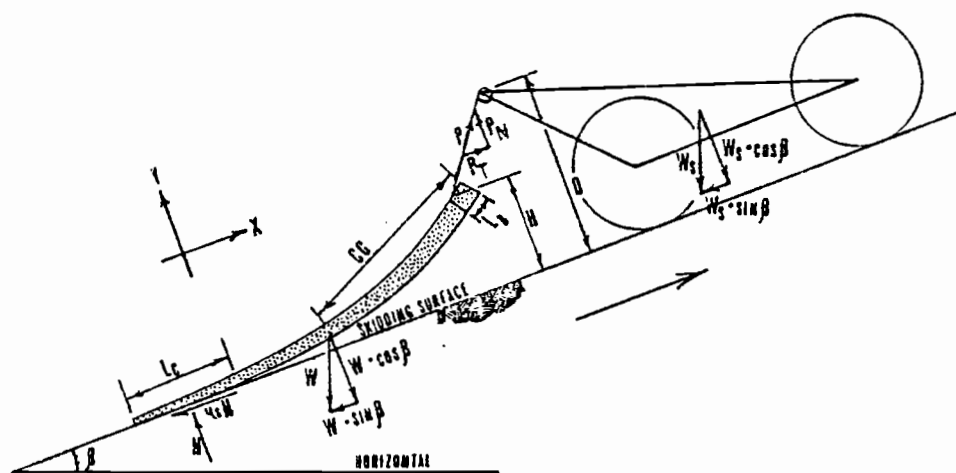


Figure 5. Skidding resistance for tree length logs.
Geometry shown for uphill skid.

For purposes of the mobility model it was necessary to derive the equation again to include ground slope. The result was equation (11).

$$N = W \left[\frac{\cos \beta \left[x + \frac{(L - L_c - CG)H}{\sqrt{1 - (H/x)^2}} + L_c/2 \right] + \sin \beta H \left[1 + \frac{L - L_c - CG}{x} \right]}{\mu_s H + \frac{H}{\sqrt{1 - (H/x)^2}}} \right] \quad (11)$$

where

β = ground slope in degrees

Equation (11) in its present form, however, is still not useful to the mobility model as it requires inputs that would not be readily known to the user. Therefore, the mean values that were given by Perumpral (1977) were substituted to approximate what would otherwise be unknown values. These variables are listed below with their mean and the range over which they could be expected to vary.

The height from the ground to the hook point will be considered to be the height of the winch drum (D) minus some variable distance (see Figure 5).

TABLE 1. Range on Variables to be Assigned Mean Values

Variable	Mean	Range
CG	.40L ft	.35L to .45L ft
H	(D-1.5) ft	(D-.5) to (D-2.5) ft
L_b	1.0 ft	.5 to 1.5 ft
L_c	.20L ft	.10L to .30L ft
μ_s	.80	.60 to 1.0

To determine the effect of the variability in the five variables listed above on the resulting pull (equation 9), the variables were

allowed to vary randomly within the ranges listed above. One hundred points were then plotted about the assumed mean values (Figure 4).

The maximum variability of approximately 10 percent occurred at 30 percent favorable grade (skidder traveling downhill loaded) and decreased to a minimum of about five percent at 30 percent unfavorable.

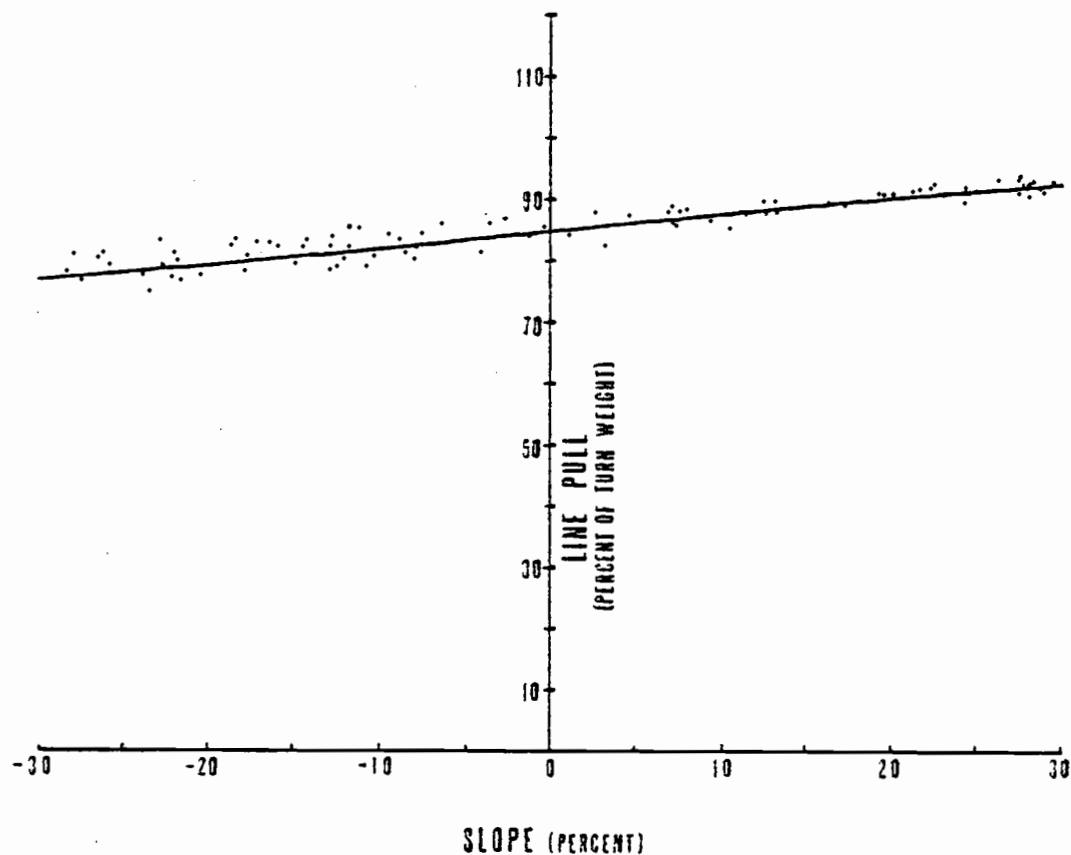


Figure 6. Limits of variability about assumed mean values for tree length skidding resistance equation.

This leaves an average expected error about the mean of less than two percent. It is felt that this error will be insignificant in a model of this type.

It should be noted that assumed mean values are for southern yellow pine. Other softwood species will exhibit slightly different weight distribution characteristics, which will present a small error.

VEHICLE POWER AVAILABLE

Once all the resistances to motion have been determined (rolling, grade, and skidding), then by knowing the power available, the rate at which these resistances will be overcome can be determined. This power in British Units is measured in horsepower. One horsepower equals 33000 foot pounds per minute. The gross horsepower rating for an engine is the power output that could be expected if none of the engine attachments such as air filter, oil-water-fuel pumps, fan and alternator, existed. Since not all of the gross horsepower is available to do work, it is of little use. Ideally the horsepower rating would be given at the tires; then all losses of power in the machine could be ignored. The wheel horsepower is, however, rarely given. Another horsepower rating, termed flywheel horsepower, is the power rating at the output end of the engine. Since this is commonly reported and is the closest to what is needed for the mobility model, it will be what is input into the program. Power losses do occur at the drive train, making corrections necessary. This power loss is usually reported as an efficiency. The drive train efficiency for wheeled vehicles is between .85 and .90 (Radforth 1978). The model will determine wheel horsepower at an efficiency of .875. The drive-train efficiency accounts for drive shaft, transmission or torque converter, and bearing, losses.

One assumption implicit in the mobility model is that the transmission gearing provides a smooth transition from one gear ratio to the next. This is not a bad assumption as the large number of gears

on most skidders approximate a smooth power curve. Figure (7) illustrates a published curve.

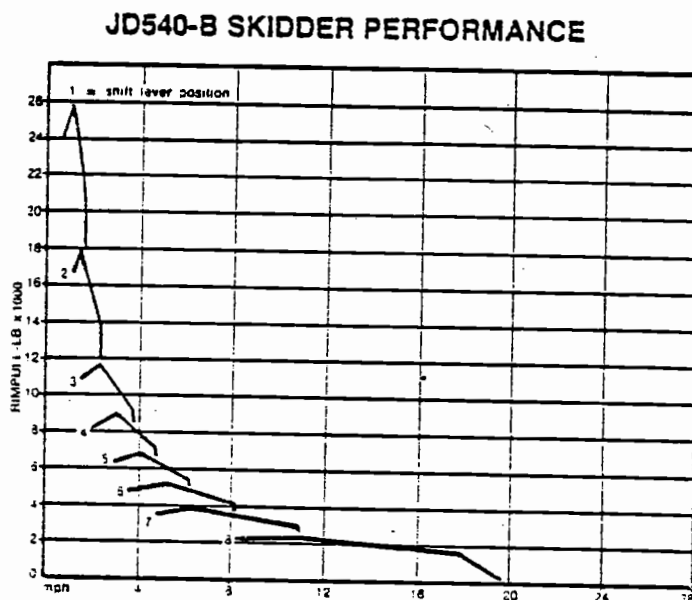


Figure 7. JD540-B skidder performance.
After John Deere Forestry Equipment Purchasing Guide 1980

THE MODEL - A GENERAL DESCRIPTION

The skidder-log-soil system is best understood by looking at the simpler case of an unloaded skidder on level ground and then generalizing to the loaded case on sloped ground. A skidder, in the mobility sense, can be thought of as four wheels each supplied with a torque and each forced to the ground with a portion of the skidder's weight. Each of these wheels in turn transfers the torque to the ground to supply the thrust needed for the skidder to move.

As torque is applied to the wheel, some relative slip between the tire and soil must occur before shear stresses can build to support thrust. Slip is defined as the percent of rotational wheel velocity

that does not contribute to translatory motion. As slippage occurs, the soil beneath the tire deforms to allow sinkage. The energy expended in travel due to this constant sinkage taking place is known as rolling resistance.

Of the several factors which can contribute to the resistance of motion (i.e., rolling resistance, cornering resistance, wind resistance), only rolling resistance is of major concern in primary forest transportation. This is due to the comparatively low speeds and poor surface conditions which exist in the woods.

Travel speed then for the unloaded skidder on level ground is the rate at which the skidder can supply the torque necessary to overcome rolling resistance multiplied by one minus the relative slip which occurs.

If the soil is strong, then the shear stresses will increase until they exceed rolling resistance with only small amounts of slippage between the tire and soil. This will allow for efficient movement. If the soil is relatively weak, then large amounts of slip will occur before rolling resistance is overcome and efficiency is reduced. On very weak soils a point can be reached where slippage becomes 100 percent. At this point the vehicle is immobile.

As gross thrust due to the torque exceeds rolling resistance, an imbalance of forces occur which favor movement. This imbalance is known as useable thrust or pull. Pull is, for a given tire, dependent upon the weight on the tire, allowable slip, and soil strength.

Once the skidder leaves level ground, two major changes take place in the distribution of forces in the skidder-soil system which affect potential skidder velocities. One is that the normal instead of the

total force of skidder weight acts perpendicular to the slope. Also, the component of the weight parallel to the slope assists movement on downhill runs and opposes on uphill travel (Figure 8). The net effect of adverse skidding with a turn of logs is to increase slip and required thrust which reduce velocity and efficiency.

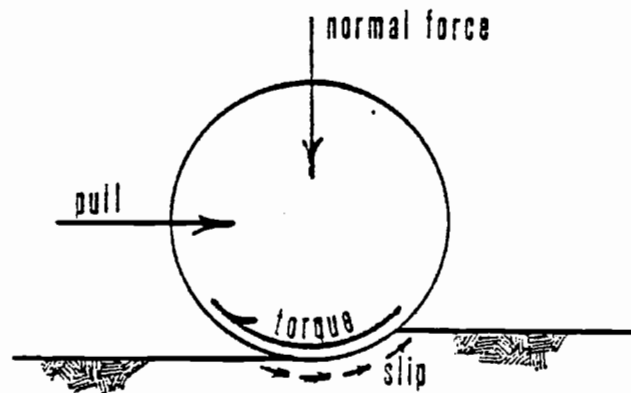


Figure 8. Pull is a function of normal force, allowable slip, and soil strength.

If the skidder is loaded with a turn of logs, skidding resistances due to the normal component of the log weight into the ground are incurred. Not the whole log load, however, is supported by the ground, for some of the weight is transferred to the skidder through the cable on a cable skidder. This weight transfer has the effect of increasing the contact forces between the tire and soil, increasing or reducing available net thrust depending upon soil strength. Since the magnitude of weight transfer is related to the geometry of the turn load, the importance of skidding resistance models for both log length and tree length logs becomes apparent.

A simplified flow chart (Figure 9) shows how the mobility model goes through the process of determining turn time for a single round

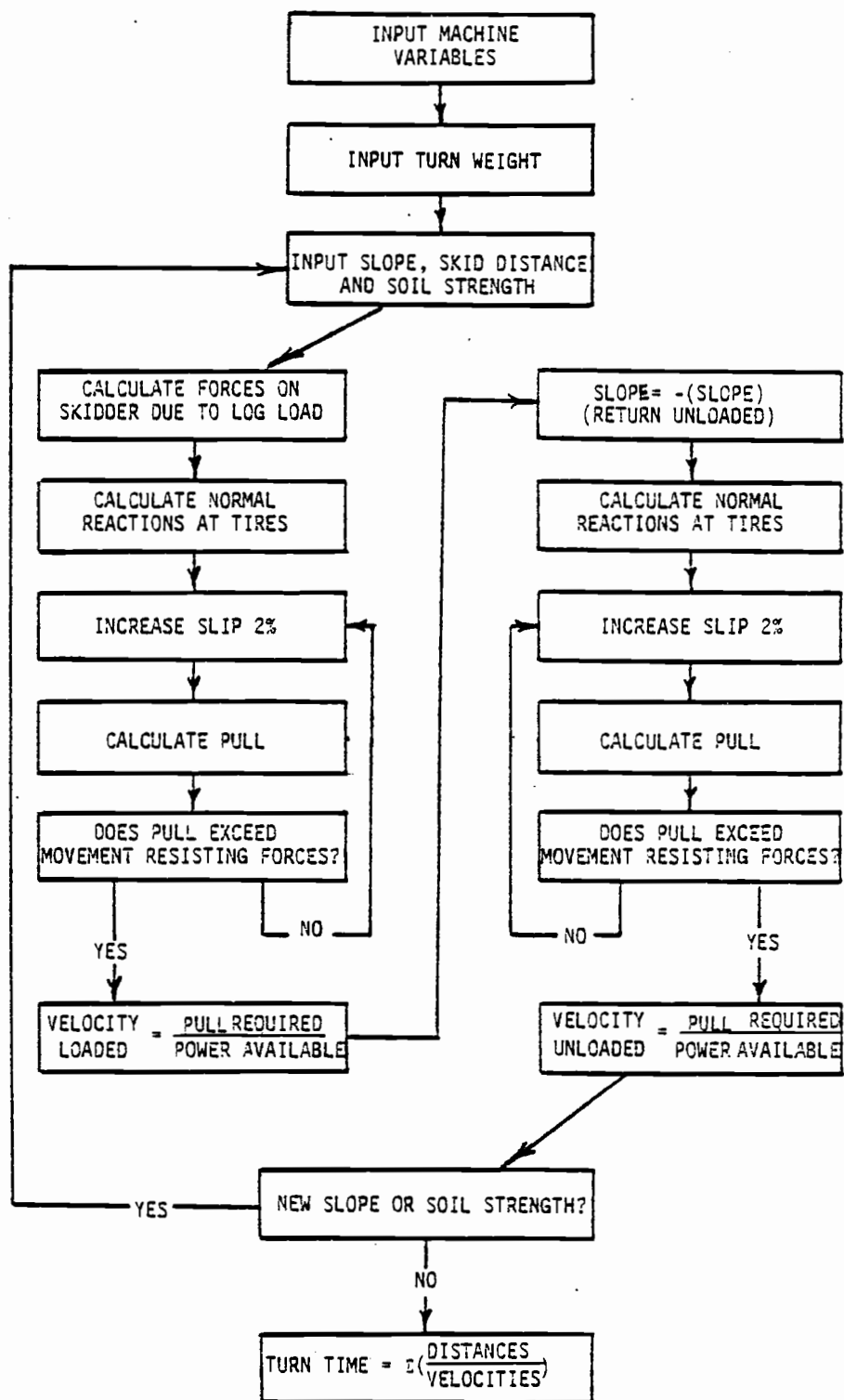


Figure 9. Flow chart showing how mobility model goes through the process of determining turn time for a single round trip skid

trip skid. Note that initial slip is zero and it is increased in two percent increments until resistive forces are overcome. Two percent was the smallest increment that the computer used could accommodate without run time being excessive.

SKIDDING DISTANCE

When skidding in the forest, the driver must always contend with such obstacles as standing trees, stumps, and natural land formations. Obstacles have the effect of increasing the actual skidding distance between two points. The increased travel distance is taken into account by the "weave factor" which is defined as the ratio of travel distance to straight line distance. A high weave factor indicates a path that deviates substantially from the straight line path. Depending on physical site characteristics, stand density, or whether thinning or clearcut, weave factors commonly range from 1.10 to 1.90 (Seifert 1982, TVA 1976). The concept of the weave factor is becoming increasingly important as computerized methods for accurately determining average straight line yarding distances become more available. The actual average yarding distance then is simply the average straight line yarding distance multiplied by the weave factor.

Under normal yarding procedures the choice of the skidding path taken is left up to the operator. Past observation and experience are the only ways a logging manager has of predicting what the weave factor would be for a given operator on a given terrain type. This is important to know because most prediction tools for skidding production require actual average travel distances that are representative

of the area, to be input for predicting average turn time. The mobility model is no exception.

TOTAL TURN TIME

Up to this point no consideration has been given to any of the turn elements other than travel. The non-travel elements include hooking the logs in the woods, unhooking at the landing, and decking. Although the main thrust of the mobility model is to apply the aforementioned analysis to the prediction of travel time, and though statistical comparisons will be done on the basis of travel time only, it is felt that the model would be more functional and valuable to the user if these elements are included. These elements are important as they normally account for between 35 percent and 65 percent of the total turn time (McMorland 1980, Cottel 1971, Ohmstede 1977).

Consideration was given to including one or more regression equations for hook, unhook and decking times in the mobility model. There was, however, little agreement among the several equations considered as to what variables are important as predictors. It was also noted that if an equation was able to describe more than 20 or 30 percent of the variability in these elements, then it contained independent variables that would be difficult to determine as inputs in the model. These are such variables as winch distance, winch slope, number of hook sites and position distance to logs being hooked. This type of equation would be of little benefit to the mobility model. The alternatives are to use either a simple regression equation or to just use a mean "nontravel" time.

The mobility model will contain a published regression equation. To allow for flexibility the mobility model will prompt the user to input the mean nontravel time. If the user instead would prefer to use the regression equation, he/she need only indicate, and the computer will supersede. The regression equation (equation 12) was developed by Ohmstede (1977) from a detailed time study of an FMC Model 210 high-speed skidder. For a mean log size of 293 board feet, the equation explains approximately 20 percent of the variability of the hook, unhook, and decking elements.

$$\text{Nontravel time (min)} = 4.45 + 1.31(\# \text{logs}) \quad (12)$$

VERIFICATION

For the purposes of verification of the mobility model, predicted travel times were compared statistically with both actual field data and with values predicted from established regression equations. The objective of this verification procedure was specifically to answer the following questions:

- 1) Are predicted values from the mobility model significantly different than actual field values?
- 2) Are predicted values from established regression equations significantly different from the same actual field values?

Raw data was obtained from field work done by Seifert (1982) in northern Idaho. The maximum range on the values of skidding distance, slope, and turn weight were 2100 feet, 28 percent, and 10600 pounds.

respectively. From the data base of 170 turns, a 20 percent random sample was removed and the balance used to establish a regression equation (13). Travel time is delay free time, in minutes.

$$\text{Travel Time} = .1097 + .00235(D) + .06025(S) + .0000585(W) \quad (13)$$

where D = one way skidding distance (ft)
 S = slope (%) - favorable is negative
 W = turn weight (lb)

$$\text{Travel Time} = 1.268 + .00323(D) - .000000274(D)^2 + .000178(W) \quad (14)$$

$$\text{Travel Time} = .00267(1-\sin(S))^{2.157} \times D^{1.022} + .000878(W)^{0.1359} \times (1+\sin(S))^{0.6673} \quad (15)$$

The independent variables from the random sample were used to generate travel times from the model and from regression equations (13), (14), and (15). It is these predicted travel times that were compared to the actual field times in the sample.

An attempt was made to choose equations that were both general in application and constructed from a broad base of collected field data. That and the necessity of using equations that predicted travel time specifically led to the choice of the following equations (14) (BLM 1977) and (15) (TVA 1976). Travel time is in minutes.

The bias was evaluated by running a standard paired "T" test on the differences between the actual field collected travel times and these predicted by the mobility model and the regression equations above (Table 2).

TABLE 2. Values of Bias, Mean Absolute Difference, and Standard Deviation in Minutes

	Siefert	BLM	TVA	Mobility Model
$\bar{D}$	.03	-1.34	-1.48	- .15
$ \bar{D} $	.51	1.38	1.73	1.33
S_D	.73	.84	1.63	1.66

$\bar{D}$ = Bias (minutes)

$|\bar{D}|$ = Mean absolute difference (minutes)

S_D = Standard deviation of the differences (minutes)

For the level of significance of $t_{.05} = 1.645$ there was no significant difference between the sample data versus equation (13), or between the data sample and the mobility model. This could not be proved for equations (14) and (15). Two important conclusions can be drawn from this. First is that the regression equations tested did not give similar results even though the data used was within their intended range of predictive capabilities. Second is that the predictive capability of the mobility models is certainly within the range of variability of the chosen regression equations (see Figures 10 and 11).

RESULTS

In an attempt to expose the factors that are most responsible for limiting skidder production in the travel element, it was found that variable interaction obscured the delineations. It was found that under one set of conditions the vehicle horsepower was most important,

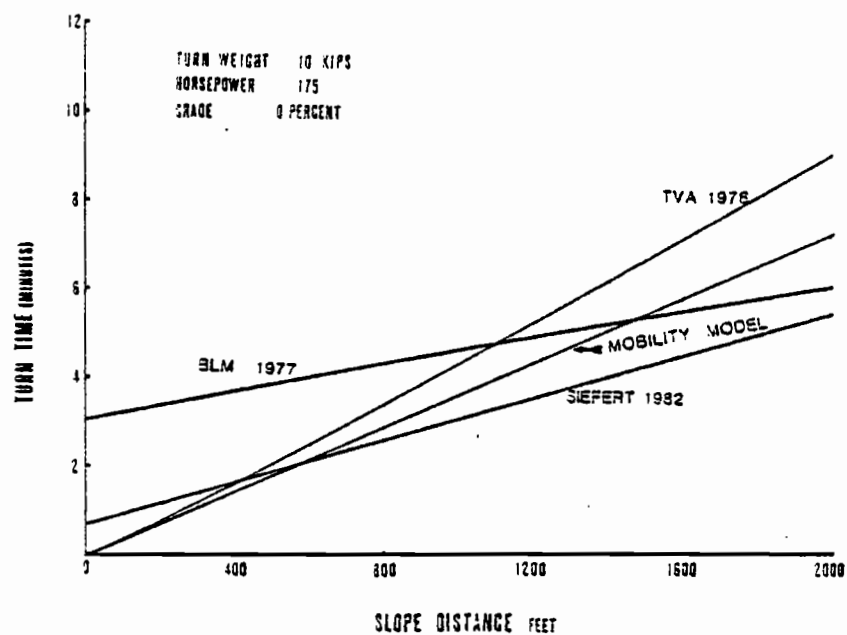


Figure 10. Travel time versus skidding distance, comparison of regression equations and mobility model

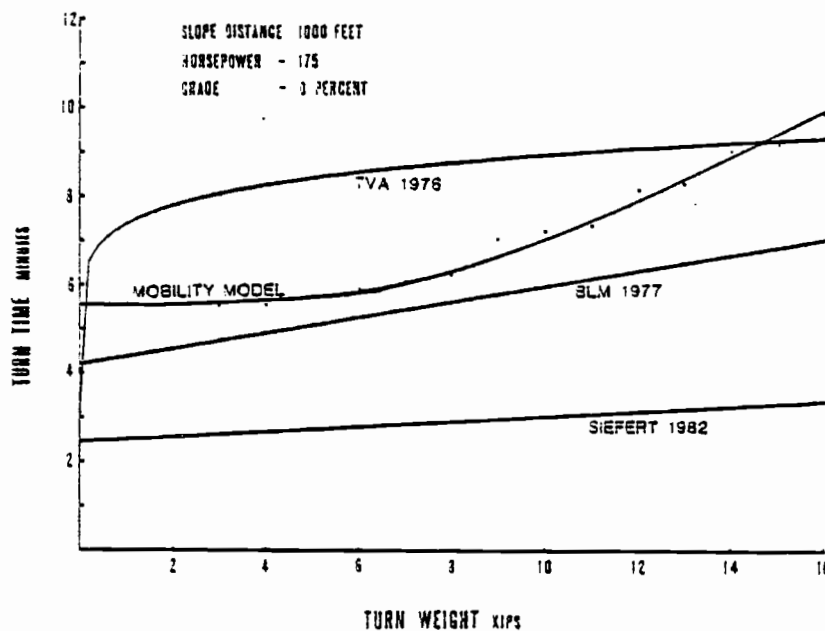


Figure 11. Travel time versus turn weight, comparison of regression equations and mobility model

TABLE 3. Production in Station Pounds Per Minute

Slope	Horsepower	Cone Index = 50 PSI				Cone Index = 300 PSI			
		Turn Weight (lb)				Turn Weight (lb)			
		1000	6000	11000	16000	1000	6000	11000	16000
30% Favorable	60	1090	6520	11960	-	1150	6900	11700	15840
	120	1120	6740	12360	17980	1490	8960	16420	23880
	180	1190	7140	12100	19050	1450	8690	15940	23180
15% Favorable	60	1780	10710	9240	-	1640	7590	11960	13110
	120	1850	11110	14860	15240	2320	13040	20750	21330
	180	1920	11540	20370	23880	2220	13040	21150	28570
0%	60	2770	6000	-	-	1590	5660	7480	-
	120	2940	9380	8460	-	2560	12000	14470	15380
	180	3230	12000	14670	14410	2380	12240	15280	20250
15% Unfavorable	60	1350	-	-	-	1560	780	-	-
	120	1540	4220	-	-	1670	7060	9170	-
	180	1720	6600	6350	-	2130	8330	12090	13910

at another it was slope and still another it was turn weight. Table 3 shows production for different combinations of slope, turn weight, vehicle horsepower and soil strength for the skidding of log length logs. To illustrate how each of these variables independently affects productivity, a series of graphs were generated. It is felt that the concepts exemplified by each graph are important ones. With knowledge of these concepts, a logging manager could optimize production for any given set of conditions.

Figure 12 and 13 show the "coefficient of pull" for both log length and tree length logs, where coefficient of pull is defined as the winch line tension over the total weight of logs during skidding. Figure 12 shows a line tension that is more dependent upon slope than for tree length logs in Figure 13. The absolute average magnitude of the line tension over the range of slopes for log length is not, however, much different than that for tree length. More important to skidding productivity is the effect of angle of pull of the logs on the skidder. Resulting from the fact that a large portion of a tree length log is lying on the ground, the component of this line tension normal to the ground is much less than for log length logs. Conversely, the component parallel to the ground is larger. This has a twofold effect of reducing skidder potential. First, since the component parallel to the ground is larger, the skidder is experiencing more difficulty in moving tree length logs than it would for the same weight of log length logs. Second, since the normal component for tree length logs is smaller and hence there is less of the weight transferred to the real wheels of the skidder, in all but the very soft soils the result

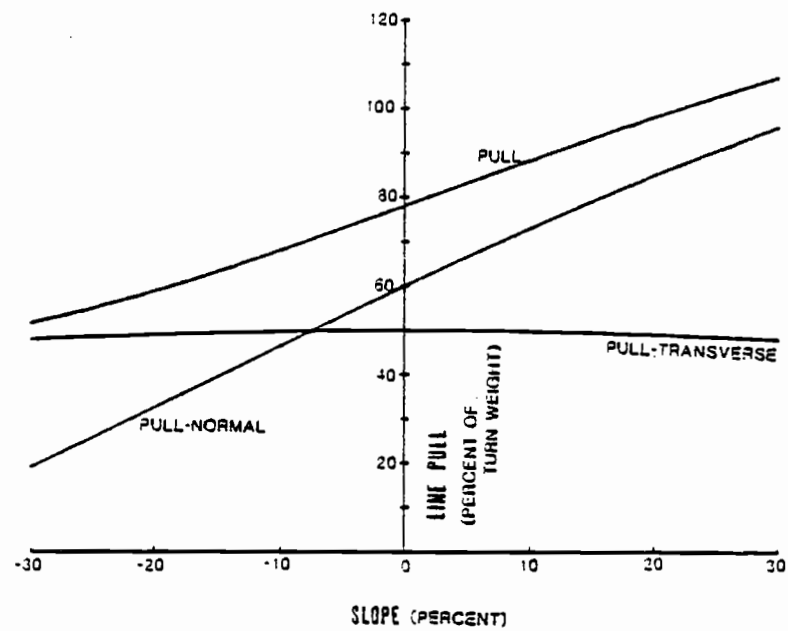


Figure 12. Pull as a percent of turn weight for log length turn

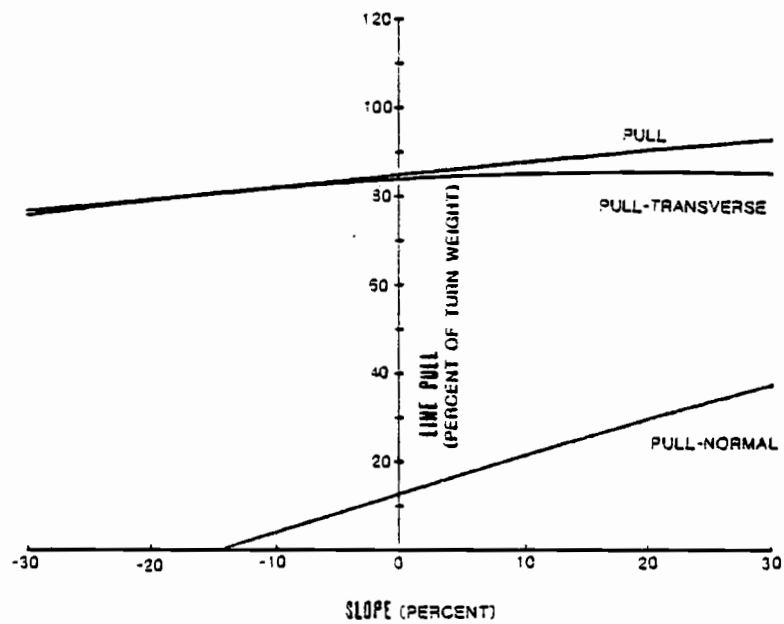


Figure 13. Pull as a percent of turn weight for tree length turn

is an increase of net pull for the skidder overall. The effect is also evident on Figures 14 and 15, which indicate that the optimum turn weight for a skidder is less for tree length logs than for log length.

Figures 14 and 15 illustrate how production is affected by the number of logs hooked for three different categories of average log weights. Including travel elements as well as hook, unhook and decking, production increases for both 500 and 1000 pound average log weights, to the practical limit of about 12 logs per turn. For the 2000 pound average logs there is a peak at seven logs, after which the production starts dropping off. This is due to increased tire slippage and the lower vehicle gearing required to move the excessive loads. The same relationship holds true for tree length logs (Figure 15) but at lower production rates and lower optimum number of logs for the 2000 pound average log size.

Figures 16 through 21 show how slope affects production for three different horsepower categories. Each graph is for a different load size. Figure 16, for a load size of 15000 pounds, indicates that there is a definite best slope for skidder operation given a vehicle horsepower and turn weight. This peak at about 10 percent favorable for the 175 horsepower skidder indicates that large favorable slopes decrease productivity. This is understandable when one considers that the empty skidder must return on an uphill slope. The steeper slopes cause this "return empty" time to become excessive. For this large turn weight the lower horsepower skidders do well at steep favorable slopes. This results from the lower skidder weight experiencing less rolling resistance on the uphill return empty trip. On the steep downhill

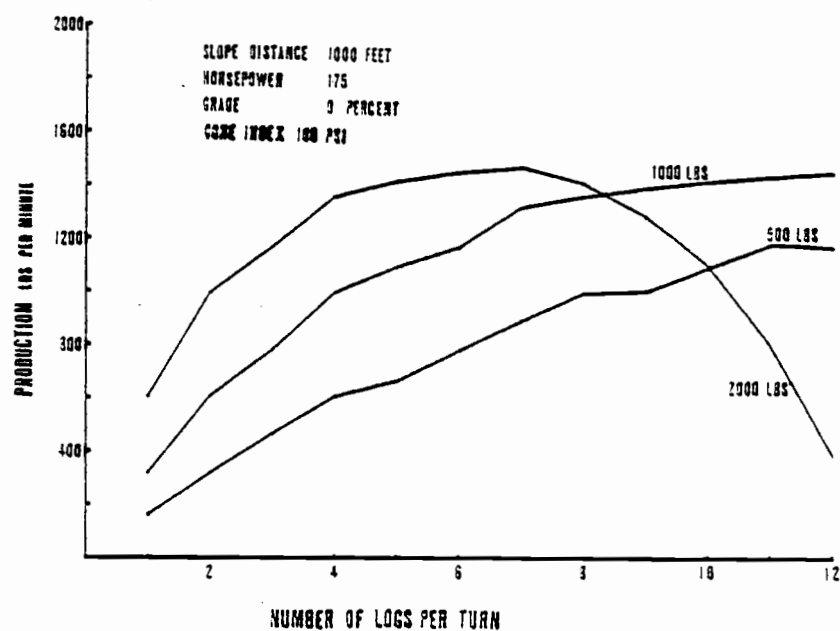


Figure 14. Production versus number of logs per turn, for 3 different average weights per log (log length turn)

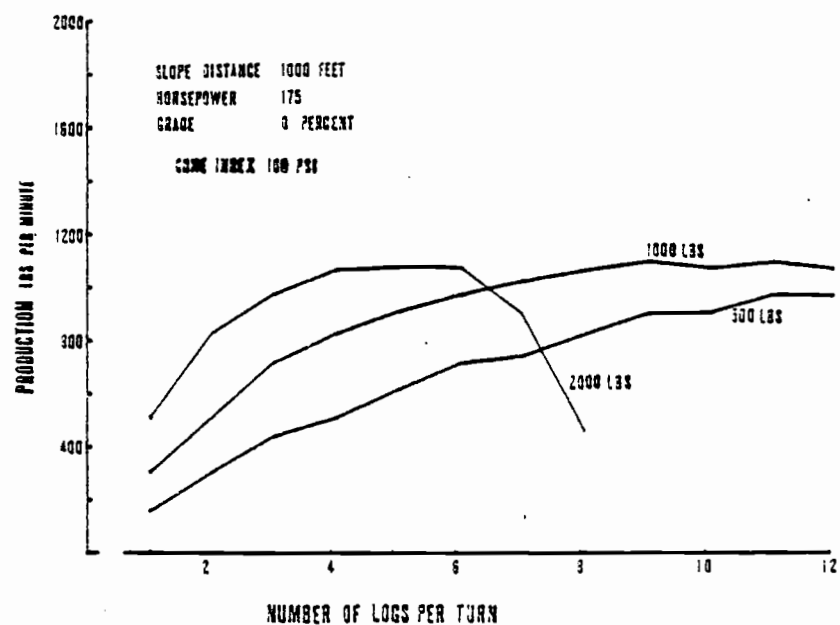


Figure 15. Production versus number of logs per turn, for 3 different average weights per log (tree length turn)

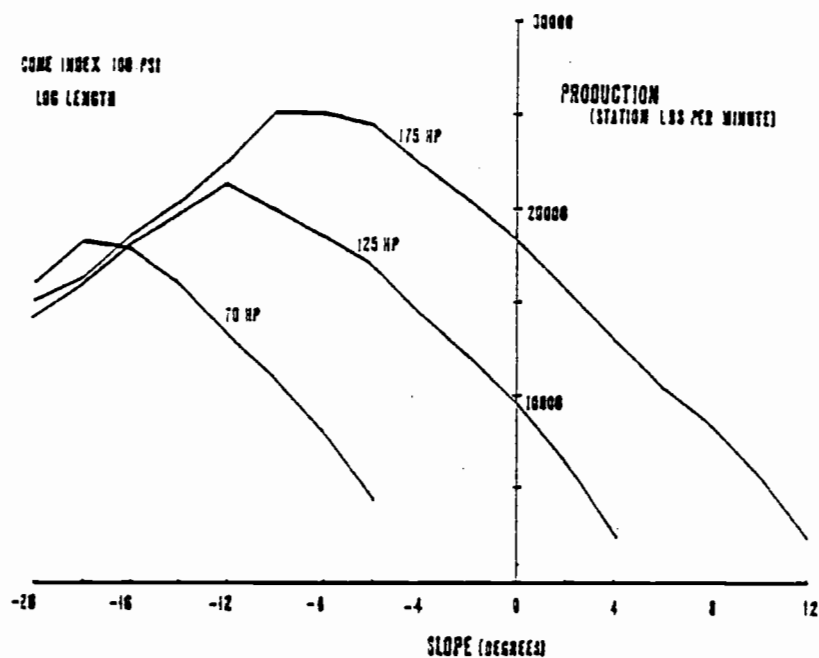


Figure 16. Production versus slope for 3 different vehicle horse-powers and a turn weight of 15000 pounds

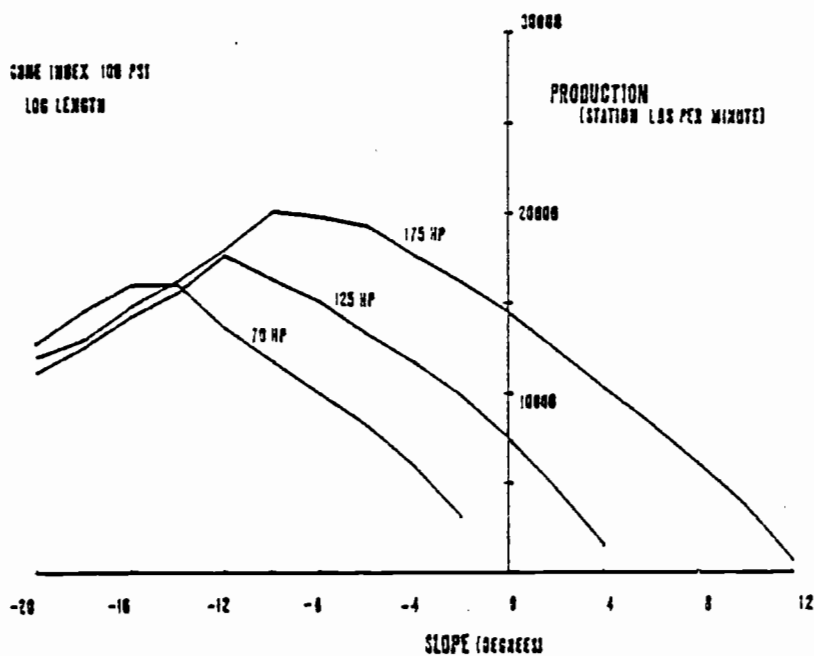


Figure 17. Production versus slope for 3 different vehicle horse-powers and a turn weight of 12000 pounds

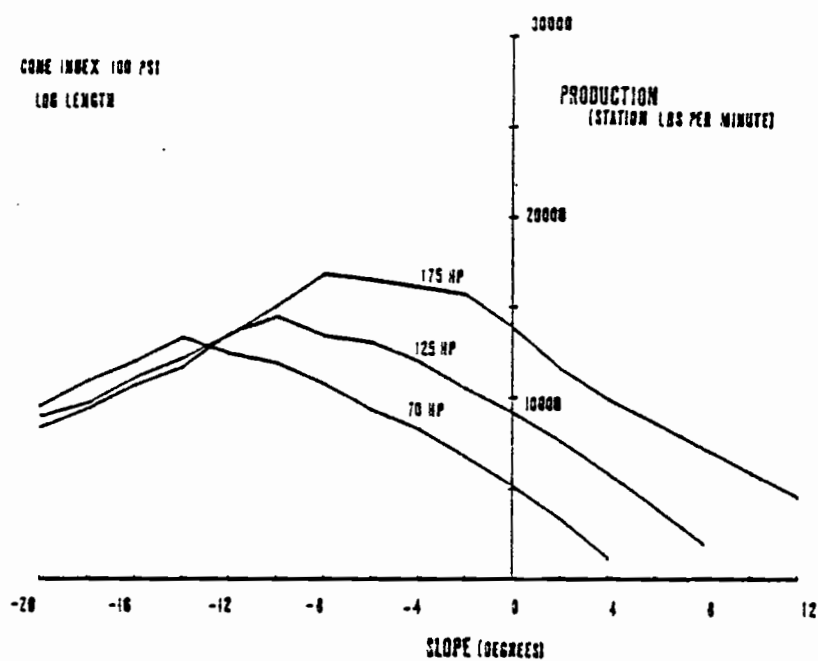


Figure 18. Production versus slope for 3 different vehicle horse-powers and a turn weight of 9000 pounds

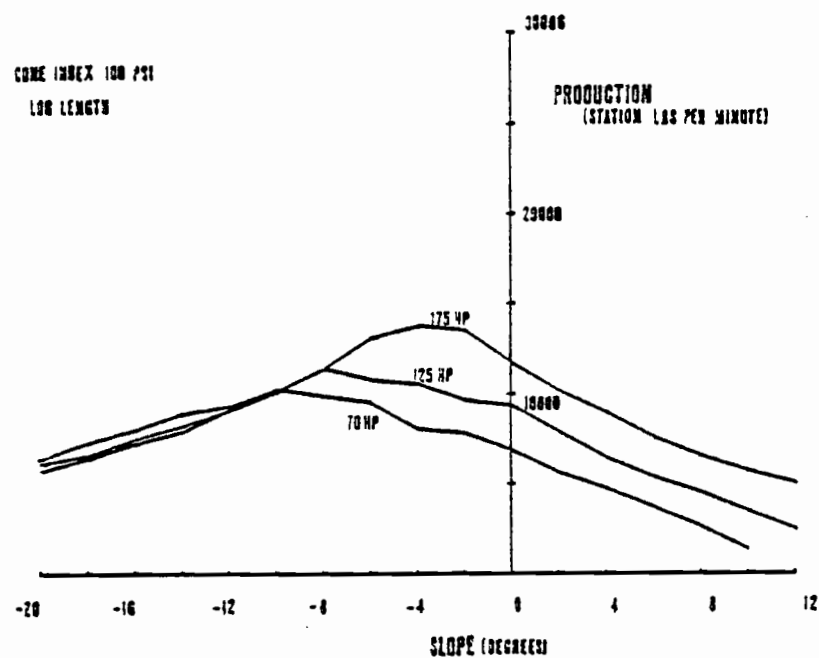


Figure 19. Production versus slope for 3 different vehicle horse-powers and a turn weight for 6000 pounds

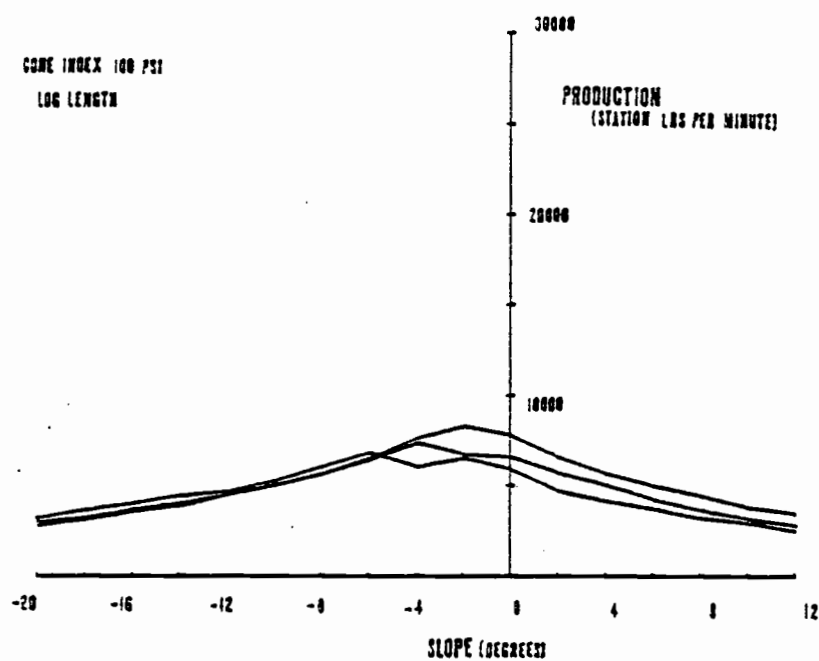


Figure 20. Production versus slope for 3 different vehicle horse-powers and a turn weight of 3000 pounds

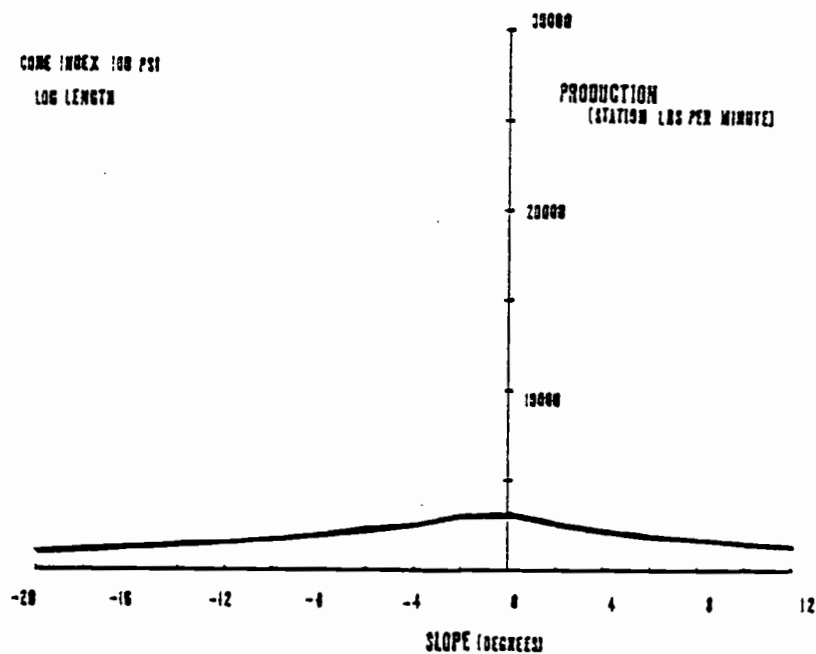


Figure 21. Production versus slope for 3 different vehicle horse-powers and a turn weight of 1000 pounds

skids very little power is needed to move the logs. If a logging manager were skidding a unit which averages between 12 and 20 percent favorable skids, he would be wise to choose a medium skidder even at these high turn weights as production would be high and operating costs would be lower than for the large machine.

As the turn weights decrease, the differences in productivity decrease, and the optimum slope moves toward zero percent. For low turn weights the effect of the logs is decreasing, diminishing the benefit of the favorable skid and favoring a less steep return empty trip. As the load size keeps decreasing, the lines degenerate to one solid line (Figure 21) which indicates that skidder size has no effect on productivity.

Realizing that a skidder operator will sometimes be required to skid logs uphill, an important question becomes evident. Given the choice, would it be better to go straight up a 20 percent slope, or to travel laterally along the slope a longer distance to reduce the slope of his path? By allowing slope to vary inversely with skidding distance such that the change in elevation of the skid remains constant, Figure 22 was generated. Three different load sizes are indicated as a percentage of vehicle weight. Although this graph was plotted for a single vehicle size, the relationship is very nearly the same for other vehicle sizes, and therefore was normalized.

Figure 22 indicates that if a load is only 10 percent of the vehicle weight, it is best to go straight up a 30 percent slope. At 30 percent of the vehicle weight, a 24 percent path would be optimum. For a large log load of 50 percent of the vehicle weight, a 16 percent

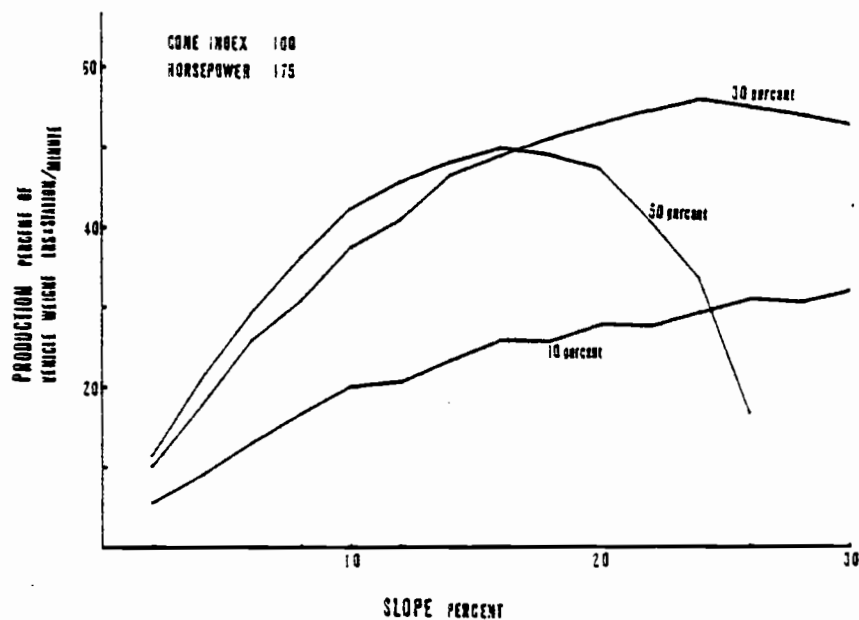


Figure 22. Production as a percent of vehicle weight versus slope for three different turn weights. Turn weight also as a percent vehicle weight (log length logs)

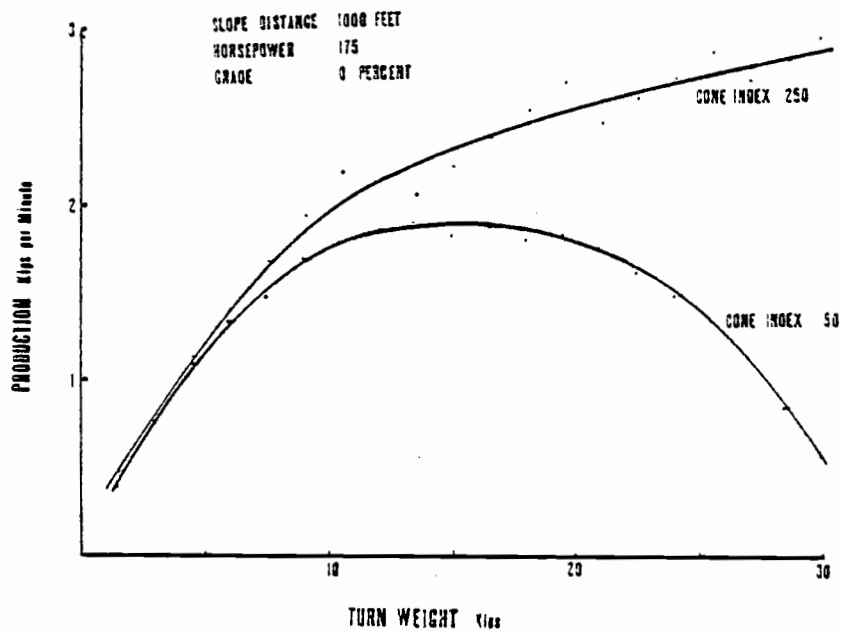


Figure 23. Production versus turn weight for two different soil strengths

slope resulting in a path about twice as long as the straight line distance between the stump and landing would optimize productivity. As the slopes become less, the increase in vehicle speed is more than offset by the extremely long skidding distances, decreasing productivity.

Figure 23 illustrates how turn weight will affect productivity for two extreme soil strengths. On a strong soil, production increases at a decreasing rate even as the turn weight approaches the vehicle weight. On a weaker soil, a point is reached where the slip at the tires increases to the point that the effective vehicle velocity is rapidly decreasing. This offsets the increasing turn weight to have the net affect of reducing productivity.

SUMMARY

The use of developed mobility principles is a viable way of approaching the skidder productivity prediction problem. The approach not only gives reasonable estimations of productivity, but also gives valuable insight into the effects of the independent variables on productivity. The most important of these independent variables are skidding distance, vehicle horsepower, ground slope, turn weight, soil strength, and load geometry. The mobility model was used to generate graphs which will allow a logging manager to better understand how vehicle horsepower, load size, and skid trail steepness affect productivity. These graphs will aid in choosing among such alternatives as buying a skidder, loading a turn, or building a skid trail. All work in this paper was done using delay free time.

RECOMMENDATIONS FOR FUTURE STUDY

This study is viewed as the initial step towards a more analytical approach to predicting skidder potential. It is hoped that through refinement, expansion, and verification that this model will lead to a widely accepted alternative to regression analysis for modeling log skidding. The model could be fairly easily expanded to include tracked vehicles, as the fundamentals of track-soil interaction are well established. It would also benefit from the inclusion of a whole tree skidding resistance model, for then it would handle all possible load geometrics. Finally, and perhaps most importantly, would be a detailed comparison of the model with actual field testing.

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APPENDICES

APPENDIX A

Visual prompter on display	Sample keyboard response	Explanation
Skidder Dimen? A,B,C,D,L	43.6, 43.3 19,80,114	Input Dimensions in <u>Inches</u> (See Program)
Input Tire Diameter, Width	61,18.4	Input total <u>Outside</u> tire Diameter and Section Width
Input Skidder Wt.-LBS	20500	Gross Vehicle Weight
Input Flywheel HP	125	Flywheel Horsepower
Hook-Unhook User Estimate (Y/N)	Y	If Y is input, then user is asked to estimate total (Hook, unhook & decking) time and input If N is input, regression equation will estimate this time (requires average number of pieces per turn to be input)
Input Ave. (Hook & Unhook & Deck) Time	6.2	(Minutes)
Input 1-Tree Length, 2-Log Length	1	Indicates that user is interested in yarding tree length logs
Input Average Stem Length (Ft)	70	Note: If log length was chosen the question follow- ing is "skidding with arch? Y or N" referring to skid- der arch attachment

Visual prompter on display	Sample Keyboard response	Explanation
Input No. of segments in Skid	3	A skid is broken into segments when either slope or soil strength changes significantly
Input turn + Wt. in lbs	8000	Average turn weight
Input slope, dist, Cone Index Section 1	10,250,200	Input slope in percent (Favorable is positive), distance in feet, and cone index in PSI for Section I.
Input slope, Dist, Cone Index Section 2	6,100,200	
Input slope, Dist, Cone Index Section 3	4,500,100	Note: At this point turn time will be calculated (minutes)
Calculate Productivity (Y or N)	Y	
Input Availability in Percent	75	Note: Productivity is calculated (lbs/min) and program is finished.

APPENDIX B

TABLE 4. Sample Inputs for Mobility Model

Name & Model	A	B	C	D	L	Tire Diam/Tire Width	Skidder Weight	Flywheel Horsepower
Clark 664 C	42*	43.1	19	76	104	61/18.4	17000	91
Clark 667 C	44*	48.1	18.8	77	112.5	68/23.1	20500	126
Clark 880	53.8	69.4	46	121.7	178	84/30	61000	267
CAT 518	43.6	43.3	19	80	114	61/18.4	20500	120
CAT 528	46.1	49.9	19.5	91	128	77/24.5	30700	175
John Deere 440	40	29.4	15	74	89	61/18.4	12400	70
John Deere 540	42*	32.8	17.9	77	106	68/23.1	16700	90
John Deere 640	43*	36.2	19.8	79.6	113	77/24.5	19900	110

* Estimated


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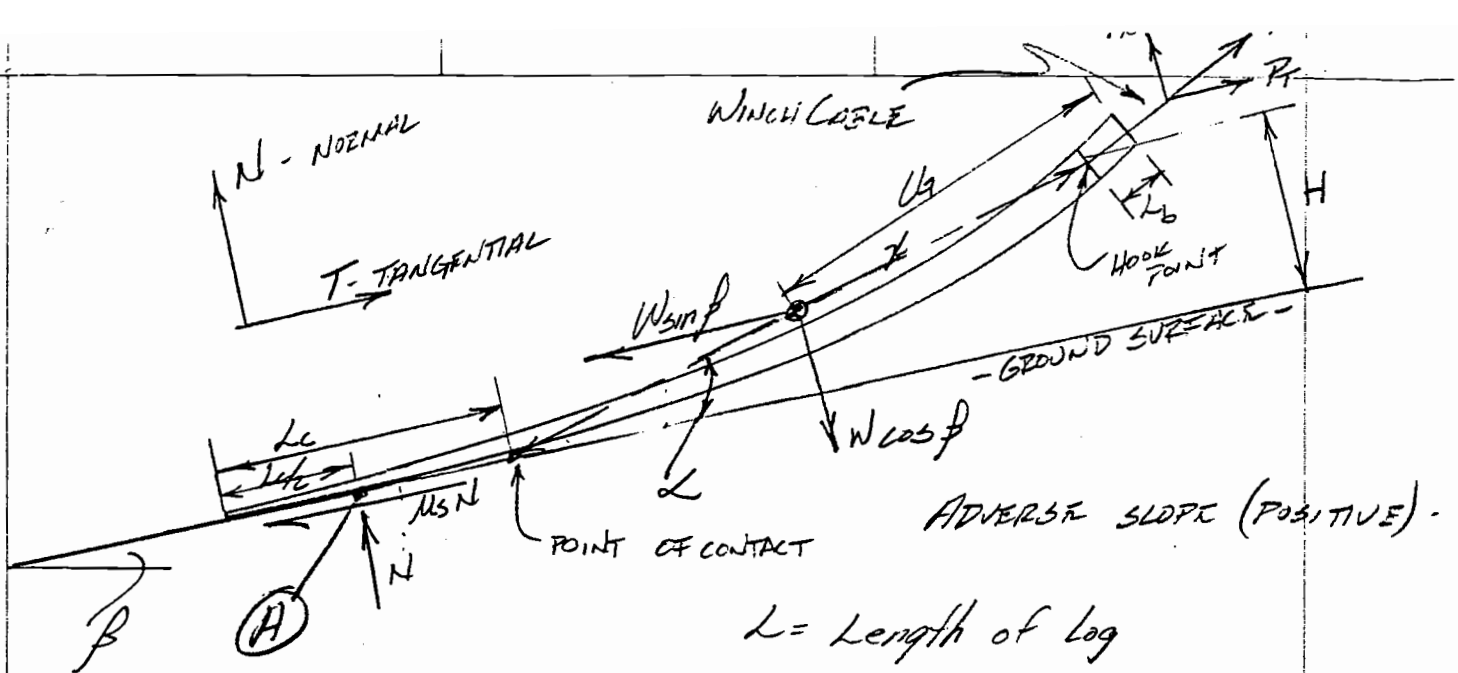
1490 F=P-1.1*P1-W*SIN(T)
1500 IF F>0 THEN 1700
1510 GOTO 1380
1520 REM CALCULATE AMOUNT CAPACITY IS EXCEEDED BY
1530 C4=((P2+W*SIN(T)-P)/(P2+W*SIN(T)))*100
1540 PRINT
1550 PRINT "LOAD EXCEEDS SKIDDER CAPACITY BY "C4"PERCENT"
1560 PRINT
1570 DISP "TRY NEW TURN WTCY/N":
1580 INPUT N$
1590 IF N$="N" THEN 1650
1600 DISP "INPUT NEW TURN LOAD":
1610 INPUT W1
1620 PRINT "NEW TURN WEIGHT = "W1"LBS"
1630 PRINT
1640 GOTO 760
1650 DISP "TRY NEW SKIDDER?(Y/N)":
1660 INPUT Y$
1670 IF Y$="Y" THEN 1670
1680 END
1690 REM CALCULATE SKIDDER VELOCITY LOADED
1700 V2=((1-S)*(H1+33000)/((N1*P5+N2-P6)+P2+W*SIN(T)))
1710 N5=(W*(L-B)*COS(T)-W*A*SIN(T))/L
1720 N6=W*COS(T)-N5
1730 C5=((C1*B1+D1)/(N5*0.5)
1740 C6=((C1*B1+D1)/(N6*0.5)
1750 S1=0
1760 S1=S1+0.02
1770 IF S1>0.95 THEN 1860
1780 P7=0.75*(1-EXP(-0.3*C5*S1))
1790 P8=0.75*(1-EXP(-0.3*C6*S1))
1800 R7=1.2/C5+0.04
1810 R8=1.2/C6+0.04
1820 P4=N5*(P7-R7)+N6*(P8-R8)
1830 F1=P4-W*SIN(-T)
1840 IF F1>0 THEN 1890
1850 GOTO 1760
1860 PRINT "ADVERSE SLOPE CANNOT BE CLIMBED"
1870 END
1880 REM CALCULATE SKIDDER VELOCITY UNLOADED
1890 V3=((1-S1)*(H1+33000)/((N5+P7-N6+P8)-W*SIN(-T)))
1900 IF V2<0 THEN 1980
1910 IF V2>93 THEN 1980
1920 IF V3<0 THEN 2000
1930 IF V3>93 THEN 2000
1940 V1=(V2+V3)/2
1950 REM IF SKIDDER SPEEDS EXCEED MAX ALLOWABLE, DEFAULT TO MAX ALLOWABLE
1960 V=(V1+90)/3360
1970 GOTO 2020
1980 V2=93
1990 GOTO 1920
2000 V3=93
2010 GOTO 1940
2020 T2=R2/V2+R2/V3+T2
2030 NEXT J
2040 T2=T2+T3
2050 PRINT
2060 PRINT
2070 PRINT
2080 FIXED 1
2090 PRINT "TOTAL ROUND TRIP TURN TIME = "T2"MINUTES"
2100 FIXED 0
2110 DISP "CALCULATE PRODUCTIVITY?(Y OR N)":
2120 INPUT N$
2130 IF N$="N" THEN 2210
2140 DISP "INPUT AVAILABILITY IN PERCENT":
2150 INPUT E
2160 S1=(W1/T2)*E
2170 PRINT
2180 PRINT
2190 PRINT
2200 PRINT "FOR AVAILABILITY= "E"PERCENT, PRODUCTIVITY= "S1"POUNDS PER MINUTE"
2210 END

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750 GOTO 840
760 DISP "SKIDDER DIMENSA-B-C-D-L":
770 INPUT A-B-C-D-L
780 PRINT "A="A;"B="B;"C="C;"D="D;"L="L
790 PRINT
800 DISP "INPUT TIRE DIAMETER,WIDTH":
810 INPUT D1-W
820 DISP "INPUT SKIDDER WT-LBS":
830 INPUT W
840 DISP "INPUT FLYWHEEL HP":
850 INPUT H2
860 FIXED 1
870 PRINT
880 PRINT "      TIRE      TIRE      SKIDDER      FLYWHEEL      TURN"
890 PRINT "      WIDTH      DIAMETER  WEIGHT      HORSEPOWER  WEIGHT"
900 PRINT
910 PRINT "      "B1"      "D1"      "W"      "H2"      "W1"      "
920 PRINT
930 PRINT
940 PRINT
950 FOR J=1 TO I
960 DISP "INPUT SLOPE,DIST,CONE IND-SECT":
970 INPUT ACJJ-BCJJ-CCJJ
980 FIXED 0
990 PRINT "SKIDDING SEGMENT"J"SLOPE="ACJJ"DISTANCE="BCJJ"CONE INDEX="CCJJ
1000 NEXT J
1010 FOR J=1 TO I
1020 T1=ACJJ
1030 A2=BCJJ
1040 C1=CCJJ
1050 T=ATN(T1/100)
1060 REM LIMIT SPEED TO 5 MPH
1070 S3=5-1.47+50
1080 IF K=2 THEN 1230
1090 REM SKID RESISTANCE TREELENGTH
1100 H=(D/12)-1
1110 L1=1
1120 L2=0.2*L
1130 C1=0.4*L
1140 U=0.3
1150 X=L-L1-L2
1160 Q1=COS(T)+(C1-L1)*H/(X*(1-(H/X)+2)+0.5)
1170 Q2=H*SIN(T)+(L3-L2-C1)/X-1)
1180 Q=W1*(Q1+Q2)/(H*(1-(H/X)+2)+0.5)+0.1*L3+U*H
1190 P1=W1+COS(T)*Q
1200 P2=W1+SIN(T)*U*Q
1210 GOTO 1320
1220 REM SKID RESISTANCE LOG-LENGTH
1230 IF N5="N" THEN 1270
1240 N6=0.5
1250 C6=1.2+0.667*TAN(T)
1260 GOTO 1290
1270 N6=0.3
1280 C6=0.9+1.667*TAN(T)
1290 P1=N6*W1+COS(T)
1300 P2=(1-N6)*C6*W1+COS(T)*W1+SIN(T)
1310 REM MECHANICAL EFFICIENCY=.875
1320 H1=0.875*H2
1330 REM CALCULATE NET THRUST SKIDDER LOADED
1340 N1=(W*(L-B)*COS(T)-W*A*SIN(T)-P1*C-P2*D)/L
1350 N2=W*COS(T)+P1-H1
1360 C2=(C1*B1+D1)/(N1*0.5)
1370 S=0
1380 S=S+0.02
1390 IF S>0.95 THEN 1530
1400 C3=(C1*B1+D1)/(N2*0.5)
1410 P5=0.75*(1-EXP(-0.3*C2*S))
1420 P6=0.75*(1-EXP(-0.3*C3*S))
1430 FIXED 5
1440 DISP P5
1450 R5=1.2/C2+0.04
1460 R6=1.2/C3+0.04
1470 P=N1*(P5-R5)+N2*(P6-R6)
1480 REM BREAKOUT FORCE = 110 PERCENT OF SKID RESISTANCE

```



$$\sum F_T = 0 \quad P_T - \mu_s N - W \sin \beta = 0$$

$$P_T = \mu_s N + W \sin \beta \quad (1)$$

$$\sum F_N = 0 \quad P_N + N - W \cos \beta = 0$$

$$P_N = W \cos \beta - N \quad (2)$$

$$\text{Let } x = L - L_c - L_g \quad (3)$$

Summing moments about point (A) and substituting Eq (1) (2) & (3) in for P_T , P_N , and $L - L_c - L_g$ respectively

$$-W \sin \beta ((L - L_c - L_g) \sin \alpha) + W \cos \beta ((L - L_c - L_g) \cos \alpha + \frac{L_g}{2}) - (W \cos \beta - N)(x \cos \alpha) + (\mu_s N + W \sin \beta)(x \sin \alpha) = 0 \quad (4)$$

$$(\mu_s N + W \sin \beta)(x \sin \alpha) - (W \cos \beta - N)(x \cos \alpha) = W \sin \beta ((L - L_c - L_g) \sin \alpha) + W \cos \beta ((L - L_c - L_g) \cos \alpha + \frac{L_g}{2}) \quad (5)$$

$$N(\mu_s x \sin \alpha) + N(x \cos \alpha) = W \cos \beta (x \cos \alpha) - W \sin \beta x \sin \alpha + W \sin \beta ((L - L_c - L_g) \sin \alpha) + W \cos \beta ((L - L_c - L_g) \cos \alpha + \frac{L_g}{2}) \quad (6)$$

$$N =$$

$$N \left[\frac{\cos \beta x \cos \alpha - \sin \beta x \sin \alpha + \sin \beta (L - L_c - L_g) \sin \alpha + \cos \beta (L - L_c - L_g) \cos \alpha + \frac{L_g}{x}}{\mu_s x \sin \alpha + x \cos \alpha} \right] \quad (D)$$

From the diagram

$$\sin \alpha = \frac{H}{x} \quad (4)$$

$$\cos \alpha = \frac{H}{\sqrt{x^2 - H^2}} = \frac{H}{x \sqrt{1 - (H/x)^2}} \quad (5)$$

substituting (4) & (5) into (D)

$$N = W \left[\frac{\cos \beta \left((x + (L - L_c - L_g)) \left(\frac{H}{\sqrt{1 - (H/x)^2}} \right) + \frac{L_g}{x} \right) + \sin \beta H + \sin \beta (L - L_c - L_g) \frac{H}{x}}{\mu_s H + \frac{H}{\sqrt{1 - (H/x)^2}}} \right] \quad (E)$$

$$N = W \left[\frac{\cos \beta \left(x + \frac{(L - L_c - L_g)H}{\sqrt{1 - (H/x)^2}} + \frac{L_g}{x} \right) + \sin \beta H \left(1 + \frac{L - L_c - L_g}{x} \right)}{\mu_s H + \frac{H}{\sqrt{1 - (H/x)^2}}} \right] \quad (F)$$

↗ FINAL