Forest Sci., Vol. 29, No. 3, 1983, pp. 641–652

A Model of Turn-Time Requirements in a Highlead Yarding System

VERNON L. ROBINSON
EDWARD L. FISHER

ABSTRACT. A theoretical model is developed for specifying regression equations for the time requirements of four yarding elements in the highlead yarding system. The equations are estimated from sample data taken from a commercial logging operation in the Southern Appalachians. The hook and unhook equations proved to be the most difficult to specify and estimate. The outhaul and inhaul times were found to be a function of the operating gear, the slope distance to the log, and the work done on the cable and log. FOREST SCI. 29:641–652.

ADDITIONAL KEY WORDS. Logging, timber harvesting.

THE HIGHLEAD CABLE LOGGING SYSTEM is being investigated as an alternative to conventional logging methods because it lessens environmental damage by reducing the amount of road construction needed and by minimizing the amount of soil disturbance during logging. This system has been extensively used in the Pacific Northwest but little is known about its operating costs under Appalachian conditions where volumes per acre are generally much lower. The acceptance of this system in the East is contingent upon it being cost competitive with conventional methods.

Some studies of highlead productivity are reported in the literature. Tennas and others (1955) made an extensive analysis of 1,110 turns. They found the outhaul time to be a function of the slope distance and the inhaul time to be a function of distance, distance squared, and the product of distance times volume per turn, and volume times slope percent. Their hook equation was found to be a function of slope distance and the number of choker setters. The unhook equation was a function of the number of logs per turn. Carow (1959) also made a regression analysis of the elemental times of a highlead system using data from 386 turns. The regression variables used in his analysis were very similar to those described above.

Other studies of highlead productivity are reported, but they do not provide an analysis of the elemental times. For example, Adams (1965) estimated the turn time to be a function of distance, distance squared, the product of distance times volume, and the number of logs per turn. His turn time excluded the time required to unhook the log. Cottell and others (1976) gave average times for each element and Sauder and Nagy (1977) provide a productivity (cunits per 8-hr shift) table as a function of landing quality, deflection, and distance.

This paper provides both a theoretical and empirical analysis of the factors influencing the elemental times required to yard a turn by the highlead system.

Vernon L. Robinson is Principal Economist, Southeastern Forest Experiment Station, USDA Forest Service, Forestry Sciences Laboratory, Athens, GA 30602; and Edward L. Fisher was Research Industrial Engineer, Northeastern Forest Experiment Station, USDA Forest Service, Forestry Sciences Laboratory, Morgantown, WV 26505 when the research for this paper was done. He is currently with the Department of Agricultural Engineering at Purdue University. Manuscript received 25 July 1980.

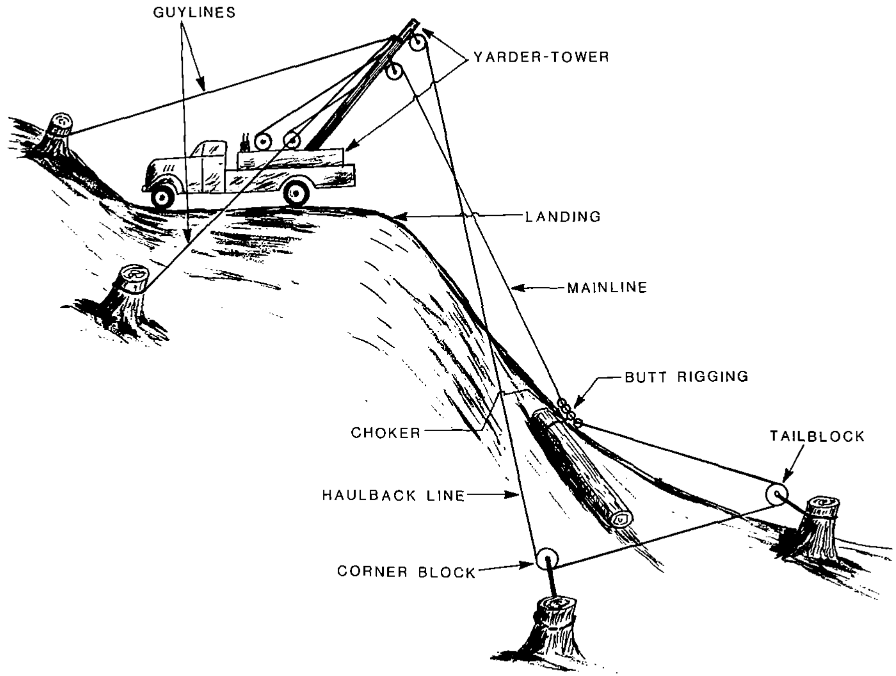

FIGURE 1. Cable configuration in a highlead yarding system.

It was used by the authors as the basis for developing an economic analysis of a commercial yarding operation in the Southern Appalachian region (Robinson and Fisher 1982).

PROBLEM DESCRIPTION

In its simplest form, the highlead system consists of a two-drum yarder with a spar. The mainline extends from one of the drums over a block on the spar and down to a log where it connects with a haulback line through a butt rigging. The haulback line extends farther out from the log through a tailblock block, a corner block, then back to the spar, over another block, and onto the other drum (Fig. 1). In outhaul, the haulback line pulls the butt rigging out to the log. In inhaul, the mainline pulls the log into the landing.

Productive time in this system can be divided into two major blocks called yarding and moving time. This paper focuses on the yarding time subset which consists of four phases: outhaul, hook, inhaul, and unhook. Outhaul is the time required to move the empty chokers from the landing to the point of hooking the log. Hooking is the time required to hook a turn of logs to the mainline. Inhaul is the time required to yard the logs into the landing. Unhooking is the time required to unhook the logs at the landing. Various types of operational delays can occur in each of these four elements. The sum of these four elements constitutes a complete yarding cycle, called a turn.

PROBLEM FORMULATION

The variables influencing the time required to yard a turn of logs can be derived from an analysis of the factors affecting the four yarding elements. Let T be the time required to complete the turn. It is the sum of the times required to complete each component:

$$T = t_o + t_h + t_i + t_u \tag{1}$$

where t_o is the time required to outhaul, t_h is the time to hook, t_i is the time to inhaul, and t_u is the time to unhook. Since $t_o = d_o/v_o$ and $t_i = d_i/v_i$, equation (1) can be rewritten as

$$T = t_h + t_u + d_o/v_o + d_i/v_i \tag{2}$$

where d_o and d_i are distances out and in, respectively, and v_o and v_i are the velocities out and in.

Both t_h and t_u are probably affected to some extent by the number of logs in the turn, n, their weight, W_l, and other factors. As a first approximation, let

$$t_h = b_{h_0} + b_{h_1}n + b_{h_2}W_l + \epsilon_h \tag{3}$$

$$t_u = b_{u_0} + b_{u_1}n + b_{u_2}W_l + \epsilon_u \tag{4}$$

where the b_i's are the coefficients in the equation and the ϵ_i's are the error terms.

The next step is to set up power equations to analyze the last two terms in equation (2). Power is the time rate at which work is done in the outhaul or inhaul phase of the turn (Halliday and Resnick 1965). The average power, $\bar{P}$, delivered by the yarder is the total work done by the yarder, W, divided by the time interval t:

$$\bar{P} = W/t. \tag{5}$$

The work done by the yarder is defined as the product of the component of force, F, along the line of motion by the distance, d, the logs and/or cables are moved along that line:

$$W = Fd, \tag{6}$$

therefore,

$$\bar{P} = Fd/t = Fv \tag{7}$$

where v is the velocity of the logs and/or cables.

The power which the yarder can develop is a function of the characteristics of the equipment, K, including the gear in which it is operated, and the forces upon which it reacts. If the inverse of this functional relationship is additive, then it can be approximated by

$$(1/Fv) = b_0(1/F) + b_1(1/K). \tag{8}$$

Hence, $1/v$ from equations (2) and (8) becomes

$$(1/v) = b_0 + b_1(1/K)F. \tag{9}$$

Now F in equation (9) is the tension in the mainline cable at the yarder resulting from the log and a cable component. The magnitude of F needed to just begin movement of a log uphill can be derived from an analysis of a free-body diagram of the forces acting upon the log (Fig. 2). In addition to the force F, the other forces acting on the log are the weight, W_l, of the log segment s, and the reaction of the incline of θ degrees. The latter force is resolved into components N, normal or perpendicular to the incline, and f_l, the frictional drag of the log, which is parallel to the incline but measured horizontally along L. These forces are assumed to be in equilibrium. In this state of impending motion

$$f_l = \mu_l N, \tag{10}$$

where μ_l is the coefficient of static friction between the log and the ground. From Figure 2

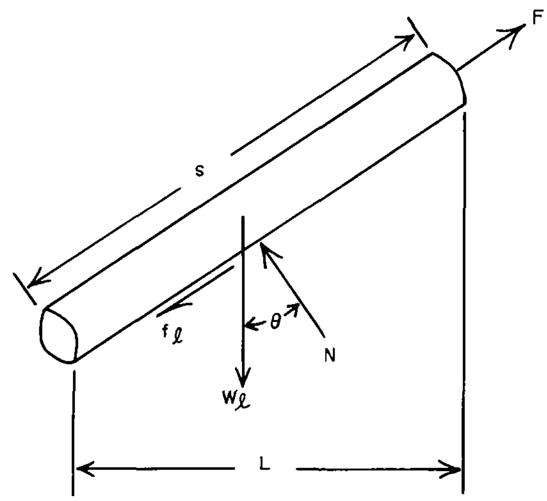

FIGURE 2. Free-body diagram for a segment of a log resting on a slope showing the forces operating upon it. See text for explanation of the forces.

$$N = W_l \cos \theta, \tag{11}$$

therefore,

$$f_l = \mu_l W_l \cos \theta. \tag{12}$$

Since the frictional force on the log is in a direction opposite to its relative motion to the ground, it will always have a positive value regardless of whether yarding is being done uphill or downhill.

In a typical highlead operation, the mainline has a larger diameter than the haulback line. This necessitates breaking the frictional drag of the cable into three components. Let

d_1 = mainline length, slope distance from yarder to log (ft).
d_2 = haulback line length on mainline side of tailblock (ft).
d_3 = haulback line length from tailblock to yarder (ft).
ω_1 = mainline cable weight (lb/ft).
ω_2 = haulback cable weight (lb/ft).
μ_c = cable coefficient of friction (nondimensional).

Since the coefficient of friction is independent of the area of contact, it seems reasonable to assume that only a single coefficient is needed for both sizes of cable. The three components of frictional drag of the cable are now derived in the same manner as shown in equations (10)–(12):

$$f_{c_1} = \mu_c d_1 \omega_1 \cos \theta \tag{13}$$

$$f_{c_2} = \mu_c d_2 \omega_2 \cos \theta \tag{14}$$

$$f_{c_3} = \mu_c d_3 \omega_3 \cos \theta \tag{15}$$

where $d_i\omega_i$ is the weight of the cable. Again, the frictional force on the cable is in a direction opposite to its relative motion to the ground and, hence, always adds to the tension in the mainline. The segment depicted in (15) is, of course, moving in a direction opposite to the other cable segments. These three forces will be operating in both the outhaul and inhaul phases of the turn.

The slope effect of the log is relevant to the inhaul phase only. The component of the weight of the logs yarded uphill, which opposes the yarder, is given by $W_l \sin\theta$, while the component of log weight yarded downhill, which favors the yarder, is given by $-W_l \sin\theta$.

The slope effect of the cable depends upon whether the yarding is being done uphill or downhill and whether it is in the inhaul or outhaul phase of the operation. However, by defining θ as being the angle between the log and the yarder, then in uphill yarding θ will be positive, and in downhill logging θ will be negative. Thus, the slope effect of the cable segments in inhaul yarding will be $d_1\omega_1 \sin\theta$, $d_2\omega_2 \sin\theta$, $-d_3\omega_2 \sin\theta$. For outhaul, the signs will be opposite of those for inhaul.

The tension in the main cable at the yarder can now be expressed as the sum of these component forces. When similar terms are combined, two equations evolve. For the outhaul phase we have

$$F_o = (d_1\omega_1 + d_2\omega_2)(\mu_c \cos\theta - \sin\theta) + d_3\omega_2(\mu_c \cos\theta + \sin\theta), \tag{16}$$

and for the inhaul phase we have

$$F_i = W_l(\mu_l \cos\theta + \sin\theta) + (d_1\omega_1 + d_2\omega_2)(\mu_c \cos\theta + \sin\theta) + d_3\omega_2(\mu_c \cos\theta - \sin\theta). \tag{17}$$

These equations apply to both uphill and downhill yarding when θ is defined as above. Now $t = d/v$, so by combining equations (9) and (16) and (9) and (17) and multiplying both resulting equations by d_1 gives for d_1 $(1/v)$:

$$t_o = b_{o_0}d_1 + b_{o_1}(1/K)\{d_1[(d_1\omega_1 + d_2\omega_2)(\mu_c \cos\theta - \sin\theta) + d_3\omega_2(\mu_c \cos\theta + \sin\theta)]\} \tag{18}$$

and

$$t_i = b_{i_0}d_1 + b_{i_1}(1/K)\{d_1[W_l(\mu_l \cos\theta + \sin\theta) + (d_1\omega_1 + d_2\omega_2) \cdot(\mu_c \cos\theta + \sin\theta) + d_3\omega_2(\mu_c \cos\theta - \sin\theta)]\}. \tag{19}$$

Equation (18) suggests that the time required in outhaul is a function of the slope distance from the yarder to the log and the work done on the cable. Similarly, equation (19) suggests that the time required in inhaul is a function of the slope distance from the log to the yarder and the work done on the log and the cable. The term $(1/K)$ is a constant peculiar to the equipment in use and it becomes incorporated into the work coefficients. However, this term also includes the influence of the gear in which the equipment is operated. Since gear[1] is likely to have a significant impact upon the outhaul and inhaul times, it would be best to separate out this variable. Gear is a qualitative rather than a quantative variable so this can be done by defining a 0–1 dummy variable:

$$t_o = b_{o_0}d_1 + b_{o_1}\text{CWORK} + b_{o_2}(D\cdot\text{CWORK}) + \epsilon_o \tag{20}$$

$$t_i = b_{i_0}d_1 + b_{i_1}\text{LWORK} + b_{i_2}(\text{D}\cdot\text{LWORK}) + \epsilon_i \tag{21}$$

where the dummy variable D takes a value of zero in first gear and of unity for second gear, CWORK and LWORK are the terms in the brackets in equations (18) and (19) and where ϵ_o and ϵ_i are the equation error terms. When the yarder is operated in first gear the equations become

$$t_o = b_{o_0}d_1 + b_{o_1}\text{CWORK} + \epsilon_o \tag{22}$$

[1] Many yarders use torque converters where the "gear" varies over a continuous range. On such equipment, the dummy variable would not apply.

$$t_i = b_{i_0}d_1 + d_{i_1}\text{LWORK} + \epsilon_i \quad (23)$$

and in second gear they become

$$t_o = b_{o_0}d_1 + (b_{o_1} + b_{o_2})\text{CWORK} + \epsilon_o \quad (24)$$

$$t_i = b_{i_0}d_1 + (b_{i_1} + b_{i_2})\text{LWORK} + \epsilon_i. \quad (25)$$

The sum of equations (3), (4), (20), and (21) defines total turn time as specified in equation (1). These equations suggest that observations are needed on the number of logs per turn, their weight, the slope and slope distance, the work done on the cable and the log, and the gear in which the yarder is operated in addition to the times for each element of the turn.

Study Methods

The validity of these equations was tested on a highlead yarding operation which was observed at Watershed #7 at the Coweeta Hydrologic Laboratory 9 miles (14 km) south of Franklin, North Carolina. This watershed covers 147 acres (59 ha) on a south-facing slope with elevations ranging from 2,350 to 3,450 feet (716–1,052 m) and slopes up to 80 percent. A timber sale of 469,000 fbm (2,321 m^3) on 101 acres (41 ha) was made to the operator who used a two-drum highlead yarder with a 30-ft boom mounted on a truck. The yarder was powered by a 172-hp Cummins diesel engine with a five-gear Mack transmission, only three of which were used in the yarding operation. Typically, second and third gear were used in outhaul while first and second gear were used in inhaul. The mainline was about 1,050 ft of 1⅛-inch wire cable. The haulback line was about 3,000 ft of ¾-inch cable. Three haulback blocks were used in rigging the cables. Two 30-ft chokers were normally used to hook the logs but at times these chokers were extended by fastening two of them together to reach out 60 ft from the mainline to pick up logs. A rubber-wheeled tractor was used to skid the tree-length logs from the landing to a deck where they were sawed into 16-ft lengths. The crew was generally composed of six persons: a yarder operator, two choker setters, a chaser, a skidder operator, and a bucker. Two fellers worked ahead of the yarding crew to clearcut the setting before the yarder was moved to it.

Most of the sampling effort was devoted to timing the yarding elements and measuring the turn volumes. The turns were timed so that no time was lost as each element ended and a new one began. The times were recorded in minutes and decimal minutes. Delays occurring within any element were also recorded by time and type of delay. A total of 458 turns were observed on 18 of the first 43 days of crew experience with the yarder. The remainder of the operating time was not observed.

In the results that follow, the cable coefficient of friction was assumed to be 0.43 for wet ground and 0.55 for dry ground as reported by Iff (1979). The log skidding resistance was estimated from the equation

$$\mu_l = 0.9008 + 0.001839 \cdot \theta \quad (26)$$

as developed by Herrick (1955), where θ is expressed in slope percent. The mainline cable weighed 2.34 lb/ft and the haulback cable weighed 1.04 lb/ft as found in Studier and Binkley (1974). The log weight for each turn was determined by multiplying the turn volume, as derived by Smalian's formula, by weight-volume ratios for Appalachian hardwood logs as reported by Timson (1975).

Unfortunately, the operating gear for each turn was not recorded. As a surrogate, the normal rate of travel while empty in first and in second gear was measured. This information was used to group the time data on the assumption that the rate of travel empty would represent an upper bound for that gear. For example, the empty operating speed for first gear was used to separate the inhaul observations into first and second gear on the basis of the observed rate of travel for each observation. Similarly, the empty operating speed for second gear was used to separate the outhaul observations into second and third gear. In each case, a 0–1 dummy variable was used to represent the gear.

Results and Discussion

Regression equations were estimated for time of each of the four elements of yarding operation (Table 1). In estimating these equations, observations containing a recognizable delay were excluded. In the outhaul equation, the operating gear was treated as a dummy variable. An interaction, DUMO, between gear and the work done on the cable, CWORK, was introduced on the assumption that the work coefficient would be modified by gear. When the yarder is in first gear, the outhaul equation is

$$T_o = -0.041505 + 0.003299 \cdot \text{SDIST} + 0.002611 \cdot \text{CWORK}. \qquad (31)$$

In second gear, the equation becomes

$$T_o = -0.041505 + 0.003299 \cdot \text{SDIST} - 0.000708 \cdot \text{CWORK}. \qquad (32)$$

As can be seen, the operating gear affects the slope coefficient on CWORK. A dummy variable applied to the constant term was not significant at the 5 percent level. In terms of standard partial regression coefficients, DUMO is the most important variable, followed by SDIST and with CWORK a distant third. This is in accordance with a priori expectations since the rate of travel and distance determine the time required to cover that distance. The work done on the cable was not expected to tax the yarder.

The theoretically derived inhaul equation was modified to include a trend variable as a surrogate for crew experience. The observations were taken from the crew's first 43 days of experience with the equipment. As time passed, the crew became more proficient and thus the experience variable, EXP, had a significant impact on inhaul time. Unlike the outhaul equation, yarding distance, SDIST, was the most important variable followed by gear, GEARI. The standard partial coefficients on LWORK and DUMI were relatively smaller, which suggests that an increase in the amount of work done on the log and cable did not substantially increase the time required to haul in a turn of logs.

There are two possible explanations for this result. First, one could reason that for the most part the work done on the log did not tax the equipment. Second, the presence of gear in the equation probably captures much of the effect of work done on the log as there is a direct relationship between the pulling power of a yarder and the gear in which it is operated. This is demonstrated in equations (33) and (34) by the relative size of the constant terms and the coefficients on the work variable. When the yarder is in first gear, the inhaul equation is

$$T_i = 0.706848 + 0.004491 \cdot \text{SDIST} + 0.002008 \cdot \text{LWORK} - 0.005921 \cdot \text{EXP}. \qquad (33)$$

In second gear, the equation becomes

$$T_i = 0.006649 + 0.004491 \cdot \text{SDIST} + 0.000080 \cdot \text{LWORK} - 0.005921 \cdot \text{EXP}. \qquad (34)$$

The coefficient on LWORK in first gear is more than 25 times larger than that in second gear, indicating that an increase in the amount of work done on a log in

TABLE 1. Statistical models for predicting the elemental times required for yarding in a highlead system, excluding delays.

Model yarding elements[a]
(27) TOTO = $-0.041505 + 0.003299\cdot SDIST + 0.002611\cdot CWORK - 0.003319\cdot DUMO, R^2 = 0.85$
(28) TITO = $0.706848 - 0.700200\cdot GEARI + 0.004491\cdot SDIST + 0.002008\cdot LWORK - 0.001927\cdot DUMI - 0.005921\cdot EXP, R^2 = 0.84$
(29) THTO = $4.501768 - 0.607384\cdot WX2 - 0.070476\cdot EXP - 0.064795\cdot THETA + 0.002341\cdot SDIST + 0.673812\cdot CHON + 0.023055\cdot TEMP, R^2 = 0.40$
(30) TUTO = $0.916609 + 0.009332\cdot VOLCF - 0.019372\cdot EXP + 0.535666\cdot CHON - 0.126219\cdot WX1, R^2 = 0.27$

where

CHON—number of chokers.
CWORK—work done on the cables in outhaul, divided by 1,000 (ft/lb).
DUMI—variable GEARI times LWORK, divided by 10,000 (ft/lb).
DUMO—0–1 dummy variable times CWORK, divided by 1,000 (ft/lb).
EXP—days of crew experience (1 . . . 43).
GEARI—0–1 dummy variable for gear used in inhaul.
LWORK—work done on the log(s) and cable in inhaul, divided by 10,000 (ft/lb).
SDIST—slope distance from yarder to the log (ft).
TEMP—average of maximum and minimum daily temperature (°F).
THETA—slope angle (degrees).
THTO—time required to hook (minutes).
TITO—time required for inhaul (minutes).
TOTO—time required for outhaul (minutes).
TUTO—time required to unhook (minutes).
VOLCF—volume of the turn (ft^3).
WX1—amount of 24-hr rainfall (inches).
WX2—amount of 72-hr rainfall (inches).

[a] All variables are significant at the 1 percent level, except CHON in eq. (29) and WX1 in eq. (30) which are significant at the 5 percent level.

first gear has a substantially greater impact on inhaul time than does a comparable increase in second gear. Similarly, a considerable difference in the level of the constant terms exists as a result of the dummy variable GEARI. One would expect this difference to be explained in terms of the larger size logs yarded in first gear, and hence, more work being done in first gear than in second gear. This expectation is verified by the LWORK means which are 2.1 million ft/lb in first gear and 1.3 million ft/lb in second gear.[2] Hence, the operating gear does capture much of the effect of the amount of work done on the log as previously hypothesized and makes a statistically significant contribution toward explaining the inhaul time.

The first approximation at explaining hook time, as specified in equation (3), was unsuccessful and this equation was respecified on the basis of observing this task at the job site. In their order of relative importance, the time required to hook the logs to the mainline was found to be a function of the cumulative rainfall over a 3-day period, WX2; the number of days of experience, EXP; the ground slope, THETA; the slope distance, SDIST; the number of chokers, CHON; and the temperature, TEMP.

An increase in the cumulative amount of rainfall over a 3-day period decreased the time required to hook a log. It would appear that rainfall softened the ground

[2] The mean volume yarded per turn and the mean yarding distance in first gear, 61.1 ft^3 and 380 ft, were significantly greater statistically than the mean volume and distance yarded in second gear, 42.0 ft^3 and 332 ft.

so the choker would pass under the log easier. The more experience the choker setters acquired, the more quickly they were able to hook a log. For some unexplained reason, an increase in the ground slope decreased the time required to hook a log. A priori reasoning suggested that the steeper the slope, the more difficult it would be to set the chokers. Perhaps the choker setters were wary of the log rolling on steeper slopes and thus put forth greater effort to hook the log as quickly as possible. Adams (1965) also found a negative coefficient on a product variable of volume and slope.

In agreement with Tennas and others (1955) and Carow (1959), an increase in the distance between the log and yarder increased the time required to hook a log. Carow reasoned that distance affects choker setting time because the logs are generally farther from the main line at greater distances from the yarder, and occasionally extra chokers would have to be used near the ends of long yarding roads. Although the latter was not found to be the case in this study, at greater distances, the chaser probably had a more difficult time pulling the butt rigging to reach the choker. CHON is a variable identifying the presence of either one or two chokers attached to the butt rigging. The coefficient on this variable is positive indicating that the presence of the second choker increased the time required to hook the log, as expected.

Finally, an increase in the mean daily temperature increased the time required to hook a log. This result is also not in accord with a priori expectations as observations were begun in February, when the temperature was well below freezing, and ended in April. One would have expected easier hooking conditions as the temperature moderated and thus a negative coefficient. Unlike Carow's study, cubic-foot volume of the turn was not significant at the 5 percent level in explaining the time required to hook a log.

The unhook time as specified in equation (4) was also unsuccessful and was respecified from observing this task. The unhook time was found to be a function of the cubic-foot volume of the turn, VOLCF; experience, EXP; the number of chokers, CHON; and the 24-hr rainfall on the current day, WX1. In terms of standard partial regression coefficients, the variables are listed in the equation in decreasing order of magnitude of their impact upon unhook time.

The coefficient on the rainfall variable appears to be a spurious correlation. It suggests that an increase in the amount of rainfall decreases the time required to unhook a log. But, an analysis of the data shows that rain occurred on 5 of the 9 days with above-average production and on only 2 of the 9 days with below-average production. Hence, the greater efficiency of the crew rather than the rainfall itself probably explains the negative coefficient. Again, experience was a significant variable as it was in the hook and inhaul equations. An increase in the number of chokers used increased the unhook time as expected; but, cubic-foot volume was the most important variable explaining unhook time. The turn volume with two chokers was statistically greater than the turn volume when only one choker was used. In the Tennas study, it was found that it took about as much time to unhook a small log as it did a large one and, hence, volume per turn had no significant impact.

The independent variables in the outhaul and inhaul equations explain 85 and 84 percent of the variation in the time required to accomplish these elements. The explanatory power of the hook and unhook equations, on the other hand, is rather poor; a plight common to other investigations in this area. In the case of the outhaul and inhaul equations, we were dealing mostly with physical relationships which were relatively easy to measure. Such was not the case for hooking and unhooking. Our results suggest that we have failed to include variables which capture the essence of these human activities. Thus, in spite of the fact that the nature of the hook and unhook operations is such that one would expect a large

TABLE 2. Mean values of actual and predicted time by element, downhill yarding.

Element	Observations	Time	
		Actual	Predicted
	Number	*Minutes*	*Minutes*
Outhaul	30	1.46	1.82*
Inhaul	29[a]	2.10	1.98
Hook	30	3.84	4.07
Unhook	29[a]	1.28	2.29**

* Significant difference at the 0.05 percent level.
** Significant difference at the 0.01 percent level.
[a] Volume measurements were missing on one turn.

time variation in these elements, there is some doubt that the coefficients in these two regression equations can be interpreted as structural coefficients.

Model Prediction

An additional validity check consisted of testing the predictive value of the model. During the early stages of the Coweeta yarding operation, a set consisting of 30 turns on two roads was yarded using downhill yarding. These data were excluded from the model-building process in order to confine the observations exclusively to uphill yarding. The equations in Table 1 were applied to the 30 downhill observations to predict the four time elements (Table 2). The predicted mean value of the unhook time was significantly higher than the actual time. It was obviously easier to unhook the log in downhill yarding than in uphill yarding. A possible explanation lies in the fact that in downhill yarding the log hit the landing with considerable impact thus loosening the chokers. Also, in uphill yarding the lay of the log at the landing required the chaser to work above his waist and sometimes above his head to unhook the log while in downhill yarding he worked below his waist.

The predicted mean value of the outhaul time also differed significantly from the actual mean value. But, the predicted values for the outhaul and inhaul elements are biased. This bias arises from the fact that the yarder was placed 290 feet from the landing in downhill yarding but was at the landing in uphill yarding. This greater distance has two impacts on the predicted values. First, the work done on cables is considerably greater in downhill yarding because the yarder is pulling 290 extra feet of mainline and haulback cable. Second, the yarder is operating off a smaller diameter drum in downhill yarding than in uphill yarding. This latter impact meant that it required 34.4 revolutions of the drum to travel the 284 feet of average yarding distance in downhill yarding while it would have required only 31.5 revolutions to travel the same distance in uphill yarding. Hence, for a given drum speed, downhill yarding required about 9 percent more time to travel a given distance than in uphill yarding. After correcting for these biases, the adjusted mean predicted time for outhaul was 1.53 minutes while the adjusted inhaul time was 2.14 minutes. The model thus accurately predicts the time required for outhaul and inhaul in downhill yarding when an adjustment is made for the differences in the position of the yarder relative to the landing.

Model Application

As previously mentioned, the acceptance of the highlead cable yarding system in the East is contingent upon it being cost competitive with conventional yarding

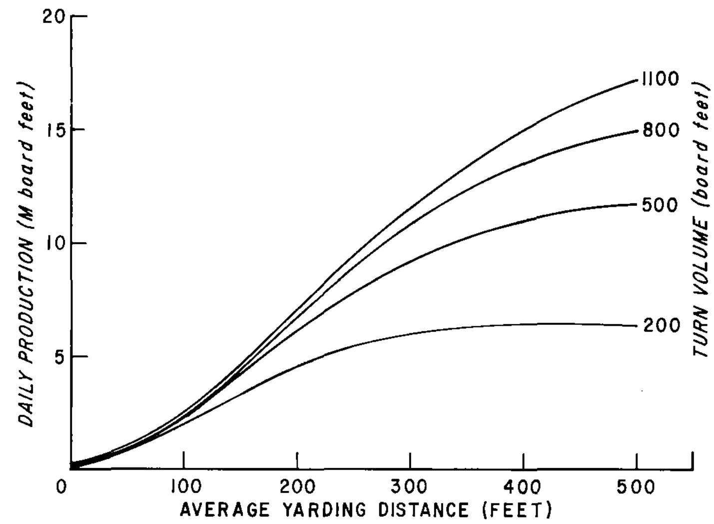

FIGURE 3. Highlead daily production by yarding distance and turn volume. Developed from the equations in Table 1, assuming a slope of 20 degrees, 4,500 fbm/acre uniformly distributed over the area, outhaul in second gear, inhaul in first gear, and the other variables at their sample mean values.

methods. Such an analysis rests upon the relationship among production per day, average yarding distance, and volume per turn (Fig. 3). To derive this figure, a computer model was written to solve the equations in Table 1 for various combinations of turn volume and distance assuming the sample mean values for the other variables and with outhaul in second gear and inhaul in first gear. It was further assumed that a volume of 4,500 fbm/acre was uniformly distributed over the area. The road length related to the average yarding distance was calculated from the formula derived by Greulick (1980). The number of roads required per set was calculated from the formula for the length of a chord, using 8.5 degrees between roads. All of these assumptions were derived from the sample data. The resulting computer model predicts the actual average daily production of 8,600 fbm per day with an error of less than 7 percent.

Figure 3 clearly illustrates that both average yarding distance and turn volume have a significant impact upon daily production. For example, daily production increases by 4,870 fbm with 500 fbm turns when the average yarding distance increases from 200 to 400 ft. This result is achieved because there is more volume available from a given road and, hence, the proportion of time devoted to yarding increases relative to the time devoted to road and set changes. Similarly, daily production increases by 3,275 fbm at an average yarding distance of 300 ft when turn volume increases from 200 to 500 fbm. Here the increase in daily production occurs because the decrease in number of turns per road resulting from the increase in turn volume offsets the increase in time per turn and, hence, more roads are yarded per day.

The figure also shows that daily production increases at a decreasing rate as average yarding distance increases and as turn volume increases. For example, at a given turn volume, the curve of daily production first increases rapidly then flattens out as average yarding distance increases; and, at a given average yarding distance, the distance between the daily production curves decreases as turn volume increases. The shape of these relationships suggests that an increase in either average yarding distance or turn volume will decrease the cost of yarding 1,000 fbm of logs; but, there is a limit to this increasing production efficiency. This limit is reached at about 400 feet with 200 board-foot turns and at about 600 feet with 500 board-foot turns. While the production limit is not included in the figure for larger turns, Studier and Binkley (1974) suggest that the maximum yarding distance for the highlead system is 1,000 feet for uphill yarding and 600 feet for downhill yarding. In this study, the maximum yarding distance was 770 feet uphill and 450 feet downhill. The optimum efficiency of the system depends, of course, upon the relative cost of substituting greater turn volume for yarding distance as well as upon their respective production possibilities.

Literature Cited

Adams, T. C. 1965. High-lead logging costs as related to log size and other variables. USDA Forest Serv Res Pap PNW-23, 38 p. Pac Northwest Forest and Range Exp Stn, Portland, Oreg.

Carow, J. 1959. Yarding and logging costs for salvaging in old-growth Douglas-fir with a mobile high-lead yarder. USDA Forest Serv Res Pap PNW-32, 26 p. Pac Northwest Forest and Range Exp Stn, Portland, Oreg.

Cottell, P. L., B. A. McMorland, and G. V. Wellburn. 1976. Evaluation of cable logging systems in interior B. C. and Alberta. Forest Eng Res Inst of Canada, Tech Rep TR-8, 33 p.

Greulick, F. E. 1980. Average yarding slope and distance on settings of simple geometric shape. Forest Sci 26(2):195–202.

Halliday, D., and R. Resnick. 1965. Physics for students of science and engineering. John Wiley and Sons, New York. 1122 p.

Herrick, D. E. 1955. Tractive effort required to skid hardwood logs. Forest Prod J 5(4):250–255.

Iff, R. H. 1979. Analyzing slack-pulling forces in manually operated skyline logging systems. Forest Sci 25(3):475–484.

Robinson, V. L., and E. L. Fisher. 1982. High-lead yarding costs in the Southern Appalachians. South J Appl For 6(3):172–176.

Sauder, B. J., and M. M. Nagy. 1977. Coast logging: highlead versus long-reach alternatives. Forest Eng Res Inst of Canada, Tech Rep TR-19, 51 p.

Studier, D. D., and V. W. Binkley. 1974. Cable logging systems. USDA Forest Serv, Pac Northwest Region. 205 p.

Tennas, M. E., R. H. Ruth, and C. M Berntsen. 1955. An analysis of production and costs in high-lead yarding. USDA Forest Serv Res Pap, PNW-11, 37 p. Pac Northwest Forest and Range Exp Stn, Portland, Oreg.

Timson, F. G. 1975. Weight/volume ratios for Appalachian hardwoods. USDA Forest Serv Res Note NE-202, 2 p. Northeast Forest Exp Stn, Broomall, Pa.