PRODUCTIVITY AND COST OF THE PONSSE 15-SERIES, CUT-TO-LENGTH HARVESTING SYSTEM IN SOUTHERN PINE PLANTATIONS

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ABSTRACT

Machine productivity data were collected for a Ponsse HS-15 harvester and S-15 forwarder from study sites in central Alabama during a second thinning. Tree size, in terms of diameter at breast height and volume, and the number of pieces processed per tree, were the variables with the greatest impact on harvester productivity. The distance from the machine to the tree was also important. Observed productivity averaged about 34.6 m^3 per productive machine hour (PMH) and ranged from 8.8 to 65.2 m^3 per PMH. For the forwarder, loading and unloading times were affected by the number of pieces per load and load volume. Travel speed was influenced by slope and load volume. Predicted productivity was about 29.2 m^3 per PMH in pulpwood and 33.8 m^3 per PMH in small sawtimber. Machine costs were about $81 per PMH for the harvester and $53 per PMH for the forwarder. The number of trees per hectare harvested, tree size, and the forwarding distance were the most significant factors affecting system productivity.

Cut-to-length timber harvesting systems are beginning to penetrate the market for harvesting southern pine stands. Advantages of these systems include: 1) less damage to the residual stand; 2) the ability to merchandise products in the woods; 3) recovery of higher-valued products; 4) reduced site damage; 5) less visual impact on the residual stand; 6) a smaller, more efficient workforce; and 7) operator safety and comfort (1,2,3-5,10,11,13). The method of operation and a comparison to conventional harvesting systems has been described previously (14).

Although the advantages are numerous, the level of acceptance will depend on productive capacity and the cost of that production. Richardson (7) studied three harvesters operating in eastern Canada. He reported average productivities ranging from 5.3 to 10.2 m^3 per productive machine hour (PMH) (187 to 360 $ft.^3$/PMH) depending on volume per hectare or tree size. He observed that productivity increased with tree size up to a 0.3-m^3 (10.6-$ft.^3$) tree, and then, productivity decreased with increased tree size. In another report (6) productivity was modeled with a stand index (trees/m^3) and average productivities of 5.2 and 7.9 m^3/PMH (184 to 279 $ft.^3$/PMH) were reported.

There are several sizes of cut-to-length systems, typically referred to as 8-, 10-, and 13-ton systems based on the capacity of the forwarder. The productivity for a cut-to-length system with a 10-ton harvester and 8-ton forwarder has been reported (14). The objective of this study was to model the productivity for a 13-ton system. The two-machine system studied consisted of the Ponsse HS-15 harvester and S-15 forwarder. These machines were described in an American Pulpwood Association Technical Release (9).

DATA COLLECTION

The study site was a 19-year old loblolly pine (*Pinus taeda* L.) plantation located in central Alabama that was being thinned for the second time. The machine operators had over a year and a half of experience on smaller machines and a 2-week familiarization period on the study machines. The harvester operator selected the trees to remove based on his judgment, removing the smaller and poorer-quality trees.

Data on the harvester were collected by a three-person team. The first person rode in the cab and read the diameter and length of each cut piece into a microcassette recorder. The second person estimated boom rotation and extension (using tape placed on the boom at known positions) and wheel revolutions during moving (using stripes painted on the wheels). The third person videotaped the operation.

The processing cycle for the harvester was divided into three elements: select and cut, process the stem, and move. The select and cut element started when the top from the previous tree was dropped or when the machine stopped moving and ended when the tree was severed from the stump. The second element, process, started at the end of the select-and-cut element and included the time to

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TABLE 1. — Summary statistics for the 271 observations for the independent and dependent variables for the trees harvested by the HS-15 harvester during second thinning.

Variable	Mean	SD[a]	Minimum	Maximum
DBH (cm)	19.5	2.815	10.1	28.2
Pieces	2.54	0.581	1	4
Volume (m^3)	0.263	0.101	0.037	0.599
Rotation (degrees)	47.3	26.911	0	95
Reach (m)	5.32	1.350	2.85	8.99
Select and cut (sec.)	8.02	2.451	3.57	21.75
Process (sec.)	12.95	5.254	3.46	35.27
Total (sec.)	20.97	6.409	8.95	46.80
Productivity (m^3/PMH)	34.58	9.811	8.78	65.22

[a] SD = standard deviation.

position the tree and process the stem, which included the time to delimb and crosscut each piece from the tree. The last element, move, started when the top of the previously processed tree was dropped and ended when the machine stopped moving.

A computer and video player were used to extract the elemental times and tree measurements from the audio- and videotapes of the harvester operation. A computer program was written that captured a code entered by the person watching the videotape and the current time from the computer's internal clock. The program would calculate the difference in the time of occurrence between the present and past event and record the code and cumulative time for the element in a computer file. This file was "pasted" into a spreadsheet with the tree diameters and lengths. Volumes were calculated from outside-bark diameters and lengths using Smalian's formula. Diameter at breast height (DBH) was predicted from the taper of the first piece.

The time to move between processing locations and the number of trees cut at each location for the harvester were also recorded. The number of trees per hectare before and after harvest were also determined.

Data for the forwarder were collected from two study sites: a second thinning and a clearcut. Cycle time for the forwarder was divided into five elements: travel empty, load, move during loading, travel loaded, and unload.

Forwarder data were also collected by a three-person team. A numbered index card was stapled to the end of each piece. Then the bottom and top diameters and length of each piece were measured. In addition, the distance from the center of the piece to the center of the harvester path was measured. As the forwarder operator picked up the pieces, the number of each piece in the grapple was recorded by one of two people standing to either side of the machine. The third person videotaped the operation.

Additional handling during loading was also observed. Index is the process the operator used to align the ends of a grapple load of wood placed on the forwarder. The operator would grapple the wood off-center so that one end leaned toward the ground. He would open the grapple slightly and allow the wood to slide to the ground and align the ends. He would then position the grapple near the center of the load, close the grapple and place the wood on the machine. Regrapple was the term for picking up one bunch or piece of wood, repositioning it on top of another bunch of wood, regrappling both bunches and placing the grapple load on the machine.

The distance moved between piles while loading was determined by painting a stripe on the wheels of the forwarder and counting the number of wheel revolutions to the nearest one-quarter turn. The number of revolutions and wheel circumference were used to calculate the distance.

The forwarder travel path was divided into segments based on slope. A clinometer was used to measure slope and a measuring wheel was used to determine the length of each segment. Travel times were measured with an electronic stopwatch.

DATA ANALYSIS

The objective of the data analysis was to produce models to predict elemental and total times. In addition, the magnitude of the effect of each independent variable was quantified.

The independent variables used to analyze harvester productivity were tree DBH, merchantable volume, the number of pieces cut from each tree, boom rotation from centerline, boom extension, and possible interactions. For example, the interaction between DBH and volume would account for the differences in volumes for trees with the same DBH, and the interaction between volume and boom extension may show a machine effect for larger trees. The average move during harvesting time was calculated by adding the move times and dividing by the number of trees harvested at each processing location.

All statistics were calculated using Statistical Analysis System software (8) on a personal computer. Multiple linear regression analysis was used to develop models for each elemental time.

Costs were developed for each machine based on a discounted, after-tax, cash flow analysis of the expenses of the first 4 years. Costs were not estimated beyond 4 years because of the unknown timing and expense of major maintenance items. The minimum annual equivalent cost divided by the PMHs per year was used to generate a cost per PMH. This cost was used to estimate cost per cord based on predicted productivity. The Equipment Replacement Analysis spreadsheet (12) was used to calculate costs.

Fixed costs were based on a cash purchase, 28 percent marginal tax rate, and 12 percent alternative rate of return. The sum-of-the-years-digits depreciation method for an 8-year life and a 20 percent residual value was used to estimate the salvage value at the end of each year.

Variable costs for fuel, lubrication, maintenance and repair, and machine utilization were based on the manufacturer's estimates. Hazard insurance was calculated at 4 percent of the beginning-of-the-year value of the machine. A labor rate of $10 per scheduled machine hour plus 1.5 times the base rate for overtime plus an extra 30 percent for fringe benefits and worker's compensation insurance was used to calculate annual labor expenses. Fuel and lubrication costs were assumed to escalate at 5 percent per year, maintenance and repair at 15 percent, and labor at 5 percent.

RESULTS

HS-15 HARVESTER

Productivity. — The study site averaged 520 trees per hectare, and approximately 40 percent of these trees were harvested. The harvester felled, delimbed, and crosscut 271 trees during the study. Summary statistics for the independent and dependent variables for the trees harvested are given in **Table 1.**

The merchantable length cut from each tree ranged from 5.4 to 21.2 m. Most pieces were cut as 4.88- or 5.49-m, plus trim allowance, logs. The last piece processed from the stem was usually cut at a random length for pulpwood. Two of the trees with four pieces are shorter than expected because the first cut was to remove a short piece of defect. Since the number of pieces cut from the stem was not a continuous variable, the observed integer values were used in the prediction models.

Merchantable volume by DBH and number of pieces processed from the stem plus predicted values are plotted in **Figure 1.** DBH ranged from 10.1 to 28.2 cm and volume from 0.0374 to 0.599 m^3. The prediction model for merchantable volume was a spline model with a join point at 15.75 cm DBH. The model was:

$$vol = -0.09651 + 0.01084 \times DBH + 0.001916 \times DBH \times pc + 0.004900 \times DBH_2 \times pc \quad [1]$$

$r^2 = 0.956$

where:

vol = the merchantable volume of wood and bark (m^3)
DBH = diameter at breast height (cm)
pc = number of pieces processed from the stem
DBH_2 = maximum of (DBH - 15.75) or 0

The times to select and cut each tree in the second thinning by DBH are depicted in **Figure 2.** The select and cut times ranged from 3.6 to 21.8 seconds. The best model to predict select and cut time was:

$$cut = 3.490 + 0.03870 \times DBH \times reach + 0.002120 \times reach \times rot \quad [2]$$

$r^2 = 0.276$

where:

cut = select and cut time (sec.)
reach = distance from the harvester to the tree (m)
rot = boom rotation from centerline (degrees)

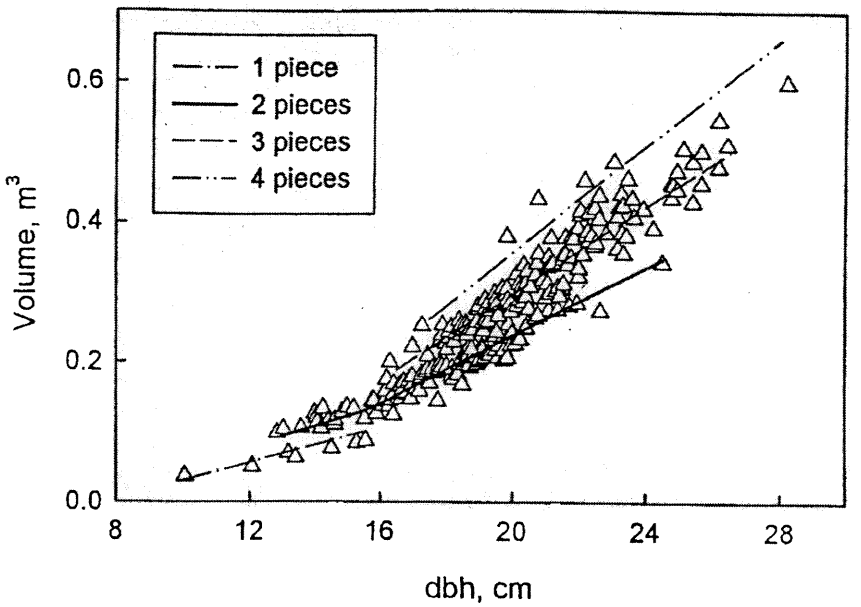

Figure 1. — Merchantable volumes per tree and predicted volumes for the trees harvested in the second thinning.

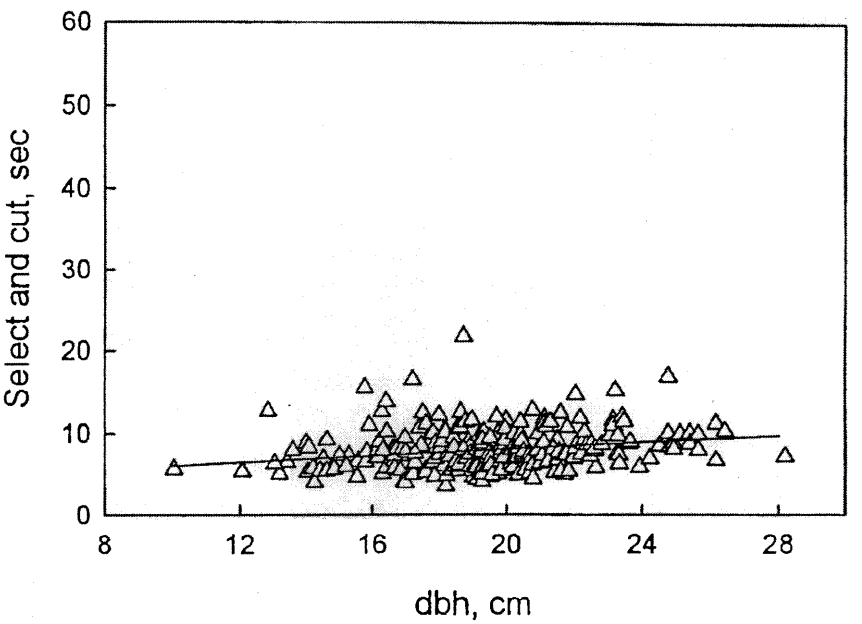

Figure 2. Times to select and cut each tree and predicted times for the harvester.

Select and cut times are primarily a function of 1) the operator's ability to quickly select the next tree to cut; 2) choosing the tree as close to the previous processing location as possible; and 3) the machine's hydraulics, how fast the head can be positioned on the tree to be harvested.

The model indicated that boom movement was more important than tree size in determining select and cut times. DBH explained only 4 percent of the variability in the data. It was not possible to explain much of the variability in select and cut times with the variables measured; therefore, the operator may have a significant impact on these times.

Process times by DBH and number of

pieces processed from the stem and predicted process times are shown in **Figure 3**. These times ranged from 3.5 to 35.3 seconds. The best model to predict process time was:

process = 4.960 + 25.94 × vol × pc + 0.004219 × reach × rot – 3.073 × vol × len [3]

$r^2 = 0.615$

where:

process = processing time (sec.)
len = merchantable length cut from the stem (m)

The model indicated that the following were the most important variables affecting process times, in order of significance: tree size, the number of pieces processed, and the amount of boom movement required. The interaction between volume and length was probably needed because a long, thin stem has fewer and smaller limbs than a shorter, thicker (wolf tree) stem.

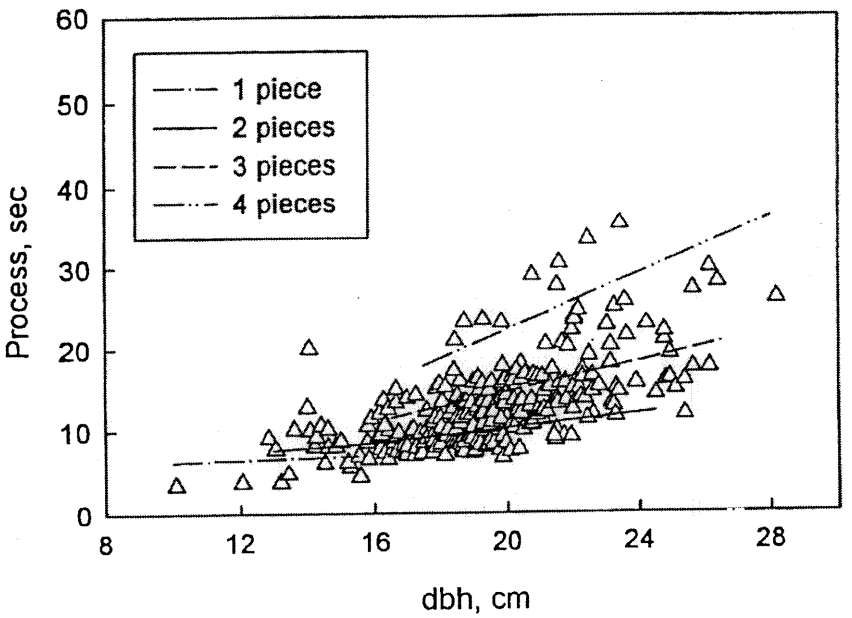

Figure 3. — Times to process individual trees and predicted times for the harvester.

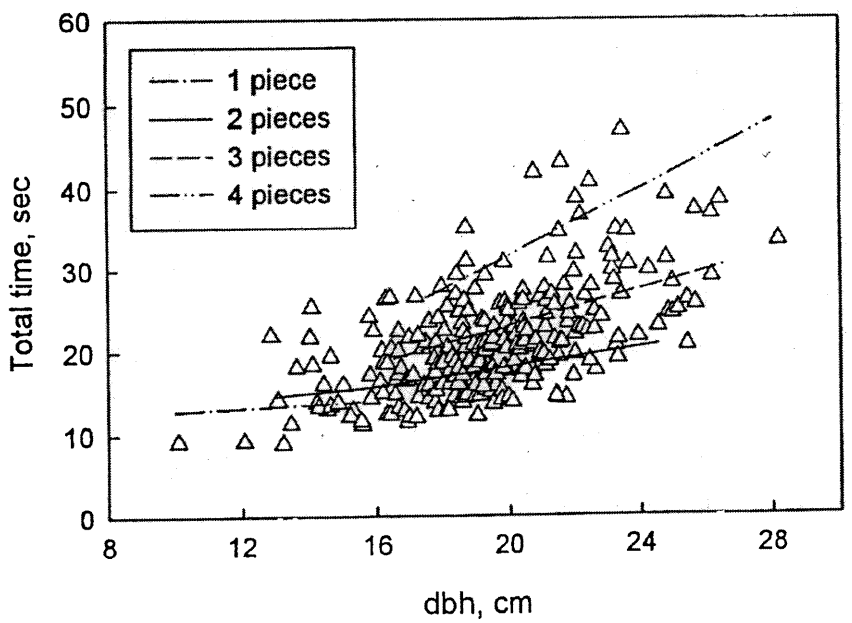

Figure 4. — Total times (select, cut, and process) per tree and predicted times for the harvester.

Processing time was divided into two subelements: processing the first piece, which included positioning the stem, and processing the remaining pieces. As expected, most of the variability was in processing the first piece and the significant variables were the interactions between volume and reach and volume and boom rotation. Processing the remaining pieces was a function of volume and the number of pieces cut. Based on averages, more time was required to process the first piece than to process the remaining pieces.

Total time was the sum of the select and cut time plus the processing time. The total times by DBH are depicted in **Figure 4**. The average time was 21.0 seconds or 2.86 trees per minute, excluding moving time. Total times ranged from 9.0 to 46.8 seconds. The best model to predict the total time per tree was:

total = 6.220 + 30.34 × vol × pc + 1.164 × reach + 0.1334 × vol × rot – 3.900 × vol × len [4]

$r^2 = 0.611$

where:

total = total time to select, cut, and process (sec.)

The model for total time is a combination of the two previous models, and as such, includes the same variables but in a slightly different form. Most of the variables occur as interactions rather than individual variables, indicating that the relationships are not straight-line.

Tree size is the most significant variable affecting the time to harvest a tree. The three variables that indicate tree size, DBH, volume, and merchantable length, were all significantly correlated, but volume explained slightly more of the variability in the data than DBH. The number of pieces cut was more of an indication of the time to crosscut the stem rather than the length of the piece, probably because there was not much variability in the length of pieces cut. The interaction between volume and the number of pieces was important because some trees with

approximately the same volume produced different numbers of pieces.

The interaction between tree size and boom rotation indicated that larger trees take slightly longer to position. The amount of boom extension was the most significant variable affecting the select and cut time and is included in the total time model. Boom extension was slower than boom rotation, and for larger trees, the boom had to be retracted before boom rotation.

Boom rotation and reach were measured to try to maximize the prediction efficiency of the models; or, in other words, to determine the amount of variability that could be predicted. It would not be practical to try to account for these variables when predicting production in other stands. Therefore, a model of total time was developed without these two variables. The resulting model was:

$$total_2 = 12.58 + 11.74 \times vol \times pc \quad [5]$$

$$r^2 = 0.509$$

where:

$total_2$ = total time to select, cut and process (sec.) without considering boom rotation or reach

It is evident that these two variables did account for an additional 10 percent of the variability in the data.

The average move time between harvesting locations would be a function of initial and residual tree spacing; therefore, the denser the initial stand and the more trees cut, the lower the average move time. The average move time per tree was 6.18 seconds and ranged from 2.3 to 25.5 seconds. The average move distance was 6.4 m and varied from 1.8 to 16.8 m. The distance moved and the number of trees harvested were not correlated, i.e., a longer move did not equate to more trees harvested from one location. The average time to move was 13.7 seconds and ranged from 4.3 to 25.5 seconds.

Productivity, volume per time, can be calculated using Equations [1] and [4] plus an average move time. When calculating total time, average values were used for boom reach and rotation. Productivity was calculated on a PMH basis with no allowance for mechanical or non-mechanical delays. The individual and predicted values are plotted in **Figure 5**.

Productivity increased as DBH increased over the range of DBHs for which data were available. As DBH increased, the amount of gain in productivity decreased, indicating that for some, larger tree size productivity may actually decrease. **Figure 5** indicates that predicted productivity is approximately the same for trees with two or three pieces; however, predicted productivity was lower for larger trees with four pieces. An examination of **Figure 4** shows that the steepness of the prediction line increased as the number of pieces processed increased. **Figure 1** indicates the same trend for tree volume; however, the time to harvest increased faster than the volume harvested.

Costs. — The list price for the har-

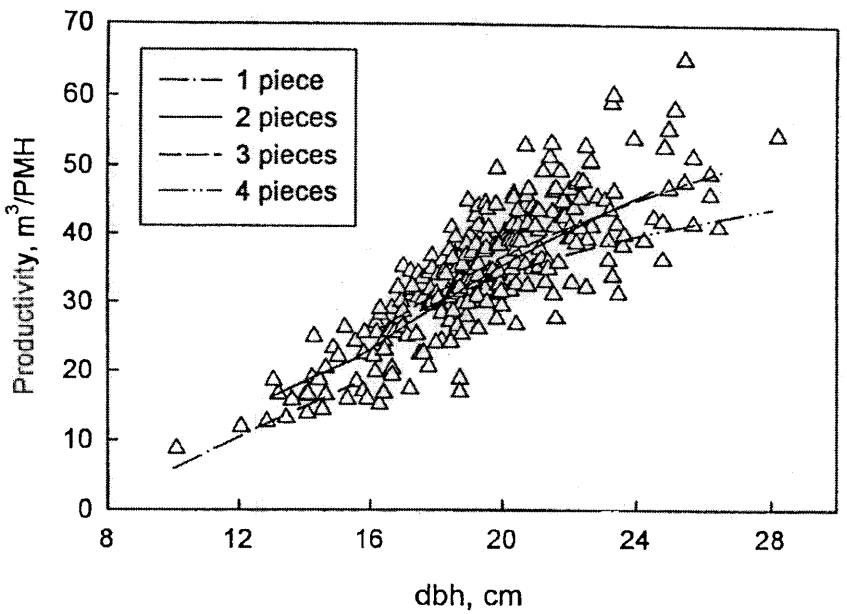

Figure 5. — Productivity (volume/(total time plus average move time)) per tree and predicted values for the harvester.

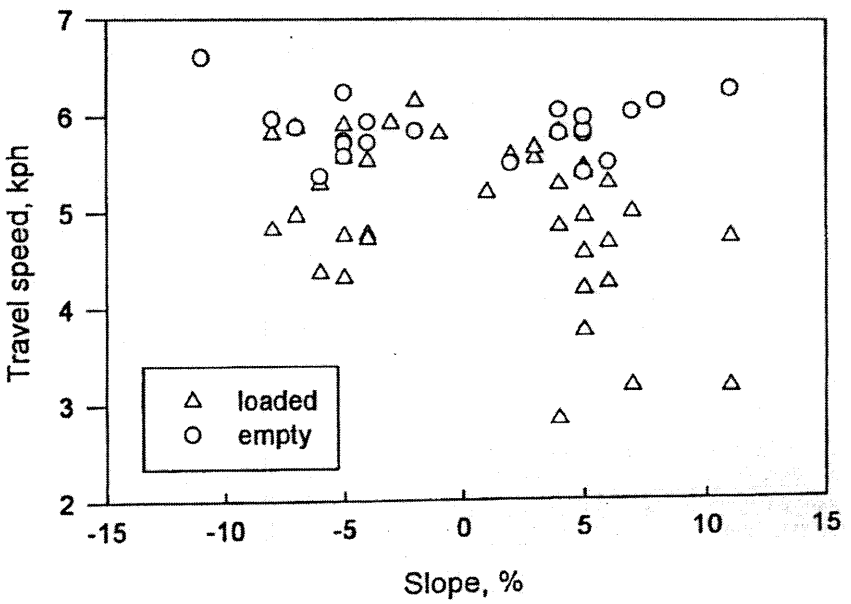

Figure 6. — In-woods travel speeds for the forwarder.

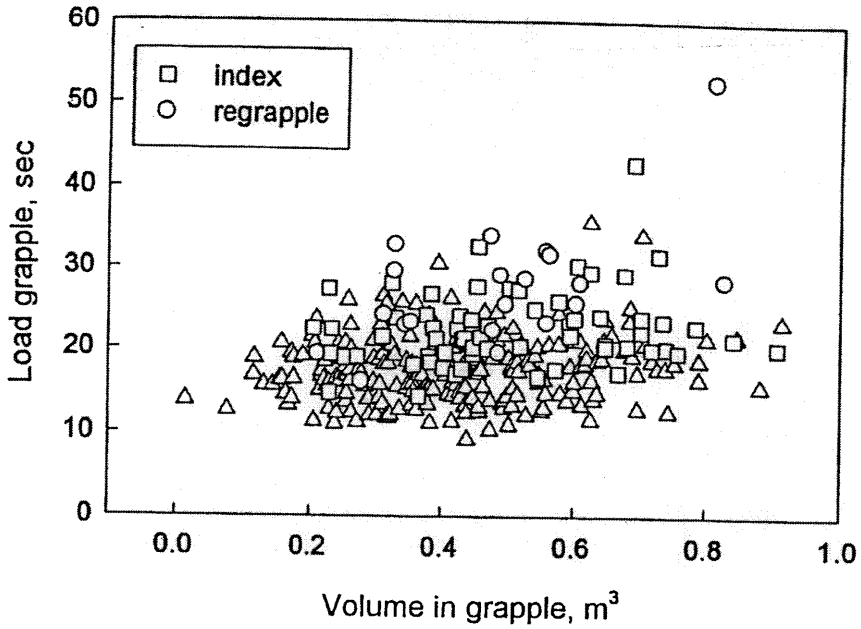

Figure 7. — Times to load a grapple of wood on the forwarder.

TABLE 2. — Summary statistics for the 311 observations of the dependent variable time to load a grapple of wood and the independent variables for loading the S-15 forwarder.

Variable	Mean	SD[a]	Minimum	Maximum
Time (sec.)	19.15	5.050	9.23	43.06
Volume (m^3)	0.440	0.169	0.014	0.915
Pieces	2.27	1.000	1	6
Rotation angle (degrees)	75.77	24.279	20	135
Distance (m)	6.51	0.974	4.27	10.33

[a] SD = standard deviation.

vester was $427,000. Based on the manufacturer's estimates, $3.60 per PMH was used for fuel and lubrication costs, and $9 per PMH was used for repair and maintenance costs. Operating 235 9-hour days per year with a utilization of 82 percent would produce 1,734 PMHs.

The estimated cost for the harvester was $81 per PMH. This cost is an average over a 4-year life, assumes a profitable operation for maximum income tax savings, and does not include overhead, supervision, or profit for the operation.

The cost per cord can be calculated by dividing the $81 per PMH cost by the predicted productivity per PMH. For example, predicted productivity for an 18-cm DBH tree with two pieces was 29.75 m^3 or $2.72 per m^3. The low volume in small trees greatly increased the cost of operation. Predicted costs were as high as $13.80 per m^3 for 10-cm-DBH trees, dropping fast to $3.90 per m^3 for 15-cm DBH trees to a low of $1.47 per m^3 for 28-cm-DBH trees.

S-15 FORWARDER

Productivity. — In-woods travel speeds were recorded for 61 observations, 22 for travel empty and 39 for travel loaded. In-woods refers to the forwarder following the unimproved, harvester path through the woods. These speeds are plotted against slope in **Figure 6**. Speed ranged from 2.84 to 6.61 kph and the maximum slope observed was 11 percent. The best model to predict in-woods travel speed (kph) was:

$$\text{speed} = 5.956 - 0.06885 \times \text{load} - 0.003993 \times \text{load} \times \text{slope} \quad [6]$$

$r^2 = 0.508$

where:

speed = forwarder speed in-woods (kph)
load = load (m^3)
slope = percent slope in the direction of travel

The model and figure indicate that there was no significant difference in travel empty speeds over the range of slopes encountered. The predicted travel empty speed was 5.96 kph compared to the average of 5.88 kph.

Travel loaded speed was affected primarily by load, which explained 41 percent of the variability in the data. Slope was significantly correlated with travel speed, but the correlation was not as strong as that with load or the interaction between slope and load.

Travel speed was also observed along an improved, gravel-surfaced woods road. The maximum slope was 8 percent and load varied from 0 to 18.32 m^3. Correlation coefficients indicated that slope and load each individually explained about 37 percent of the variability in the data with load a slightly stronger term. The interaction between load and slope was significant, but was not as good a predictor of travel speed as either of the variables individually.

The best model to predict travel speed along a woods road (kph) was:

$$\text{speed}_2 = 14.60 - 0.2796 \times \text{load} - 0.6141 \times \text{slope} \quad [7]$$

$r_2 = 0.738$

where:

speed_2 = forwarder speed on the woods road (kph)

The model indicated that at higher speed ranges (Clark 18000 powershift transmission with 2 × 3 speed ranges), slope had a greater impact on machine speed than at the lower speed ranges used for in-woods travel.

Loading time was observed for 311 grapple loads. The loading times per grapple are depicted in **Figure 7**. **Table 2** lists the means, standard deviations, minimums, and maximums for the dependent and independent variables.

Additional handling was needed on 27 percent of the loads, indexing 21 percent and regrappling 6 percent. In addition, 48 percent or 148 grapple loads were small sawlogs and the remaining 52 percent were pulpwood. An indicator variable was used to distinguish between grapple loads of small sawlogs and pulpwood.

Loading time was significantly corre-

lated with all of the independent variables except the distance from the pile to the machine. Although the correlations were significant, none of the variables, including the interaction terms, could account for more than 15 percent of the variability in the data.

The best model to predict the loading time per grapple (sec.) was:

$$load = 13.74 + 2.137 \times pc \times vol + 0.003899 \times rot \times reach + 8.777 \times regrapple + 3.735 \times index \quad [8]$$

$r^2 = 0.377$

where:

load = time to load a grapple of wood (sec.)
regrapple = 1 if regrappled; otherwise 0
index = 1 if indexed; otherwise 0

The equation indicated that the amount of wood in the grapple (pieces and volume) and boom movement (rotation and distance) could be used to predict the time to load a grapple of wood, but there is quite a bit of variability not explained by these variables. Regrappling added about 9 seconds to the time to load a grapple of wood and indexing added 4 seconds.

Indexing was more common for loads with more pieces, greater volume, and pulpwood. Regrappling was not correlated with the number of pieces in the grapple. This could indicate that regrappling usually consisted of placing one piece (leftover from a pile too large to load with one grapple or a single small sawlog) with another pile for loading.

To help predict cycle time, the total loading times for each of the nine loads observed were also analyzed. Excluding one partial load of large sawlogs, there were four loads of small sawlogs and four loads of pulpwood. The average load of small sawlogs required 34 grapple loads (31 to 38) to pick up 56 pieces (54 to 59) in 10.37 minutes (8.75 to 12.63). The average load of pulpwood required 41 grapple loads (34 to 44) to pick up 118 pieces (105 to 132) in 13.62 minutes (11.33 to 15.34). The best model to predict the total time to load the forwarder as a function of the volume and number of pieces on the machine was:

$$load_2 = 5.915 + 0.004251 \times pc \times vol \quad [9]$$

$r^2 = 0.785$

where:

$load_2$ = time to load the forwarder (min.)

Move time during loading was recorded for 76 observations. The average move time between loading locations was 18.05 seconds and ranged from 5.6 to 102.9 seconds. The move distance averaged 10.4 m and ranged from 2.93 to 84.86 m.

The best model to predict the move time during loading (sec.) was:

$$move = 5.817 + 1.181 \times distance \quad [10]$$

$r^2 = 0.920$

where:

move = time to move from one loading point to the next (sec.)
distance = distance from one loading point to the next (m)

The model indicated a fixed time of 5.8 seconds plus 1.18 seconds per meter. Some of the variability in the move time was due to the driver planning his subsequent operation during moving.

The number of times moved and the distance moved depends on the density and size of the harvested timber. For the clearcut and forwarding small sawlogs, the forwarder moved an average of 9 times during loading (8 to 11). The average distance moved was 12 m and the total distance moved during loading was 108 m. For the second thinning and forwarding pulpwood, the forwarder moved an average of 12.5 times during loading (9 to 14). The average distance moved was 8 m and the total distance moved during loading was 99 m.

Unloading was observed for nine forwarder loads, five sawlog and four pulpwood. Excluding one partial load of large sawlogs, the time to unload the forwarder averaged 5.67 minutes with a narrow range from 5.12 to 6.34 minutes. Load volume averaged 16.15 m^3 and varied from 15.07 to 18.32 m^3. The average load of small sawlogs contained 56 pieces (54 to 59) and required 26.25 grapple loads (26 to 27) to unload. Forwarder loads of pulpwood contained 118 pieces (105 to 132) and required 22.25 grapple loads (22 to 23) to unload.

Unloading time was significantly correlated with the volume of the load, but not the number of pieces on the load. The best model to predict unloading time (min.) was:

$$unload = 0.3517 \times vol \quad [11]$$

$r^2 = 0.748$

where:

unload = time to unload the forwarder (min.)

The predicted productivity for the S-15 forwarder would be the sum of the predicted times for travel empty, load, move during loading, travel loaded, and unload. Assuming a 500-m travel distance and a -5 percent slope in the travel empty direction and using the averages for pulpwood previously given, the forwarder productivity would be 29.17 m^3 per PMH. Using the same analysis for the small sawlogs, the predicted productivity would have been 33.79 m^3 per PMH.

An hourly cost was calculated for the forwarder by dividing the minimum annual equivalent cost by the PMHs. Again, only 4 years were considered because of the uncertainty of timing and expense of major maintenance items.

The list price for the forwarder was $255,000. Based on the manufacturer's estimates, $2.20 per PMH was used for fuel and lubrication costs, and $5 per PMH was used for repair and maintenance costs. Operating 235 9-hour days per year with a utilization of 84 percent would produce 1,777 PMHs per year.

The estimated cost for the forwarder was $53.24 per PMH. As for the harvester, this cost is an average over a 4-year life, assumes a profitable operation for maximum income tax savings, and does not include supervision or profit for the operation.

Costs per m^3 were based on the predicted productivity for pulpwood and small sawtimber and one- and two-shift operation. For pulpwood, the costs were $1.83 and $1.41 per m^3, respectively. For small sawtimber, the costs were $1.58 and $1.22 per m^3, respectively.

CONCLUSIONS

Tree size, in terms of DBH or volume, and the number of pieces processed from the tree were the most important factors affecting the productivity of the HS-15 harvester. However, the increase in productivity was not linearly related to tree size; as tree size increased, the amount of increase in productivity decreased. This trend would suggest that at some larger tree size, productivity would decrease.

Another factor affecting the productivity of the system was the average move time per tree. Since the average move time accounted for almost a quarter of the total time per tree, boom reach is an important harvester characteristic. The number of trees harvested per hectare would also impact the average move time.

The distance from the machine to the tree, in terms of boom rotation and extension were also significant. They were measured primarily to try to improve the prediction models. However, it would not be practical to measure these variables in a production setting, and it would not be necessary since the average in each case is approximately the midpoint of the range.

Productivity for the harvester was significantly higher than for harvesters reported in the Canadian studies mentioned in the literature review. However, the productivity was similar to the productivity reported in a previous study (14). Possible reasons could be the differences in tree species and terrain.

Forwarder productivity was determined by the number of pieces and volume per load and the travel distance and slope. The loading element required the most time, and was affected by piece size and location relative to the forwarder. However, for a given stand, with similar tree size and distribution, loading time would not vary greatly and the forwarding distance could become the variable with the greatest impact on productivity. Since pieces are accumulated into a pile for the forwarder, its productivity is much less sensitive to tree size than that of the harvester.

The estimated costs per m^3 are based on one set of assumptions. Since operating expenses accounted for only 43 percent of the total cost of the forwarder and 35 percent of the total cost for the harvester, it would require a large change in one category, such as maintenance and repair costs, to significantly change the cost per m^3. However, a change in utilization could have a much greater impact.

An important aspect of utilizing this type of harvesting system is balancing harvester and forwarder productivity. The productivities reported represent the unconstrained capability of the machines. Since the harvester is more expensive than the forwarder, generally, system productivity should be determined by the harvester.

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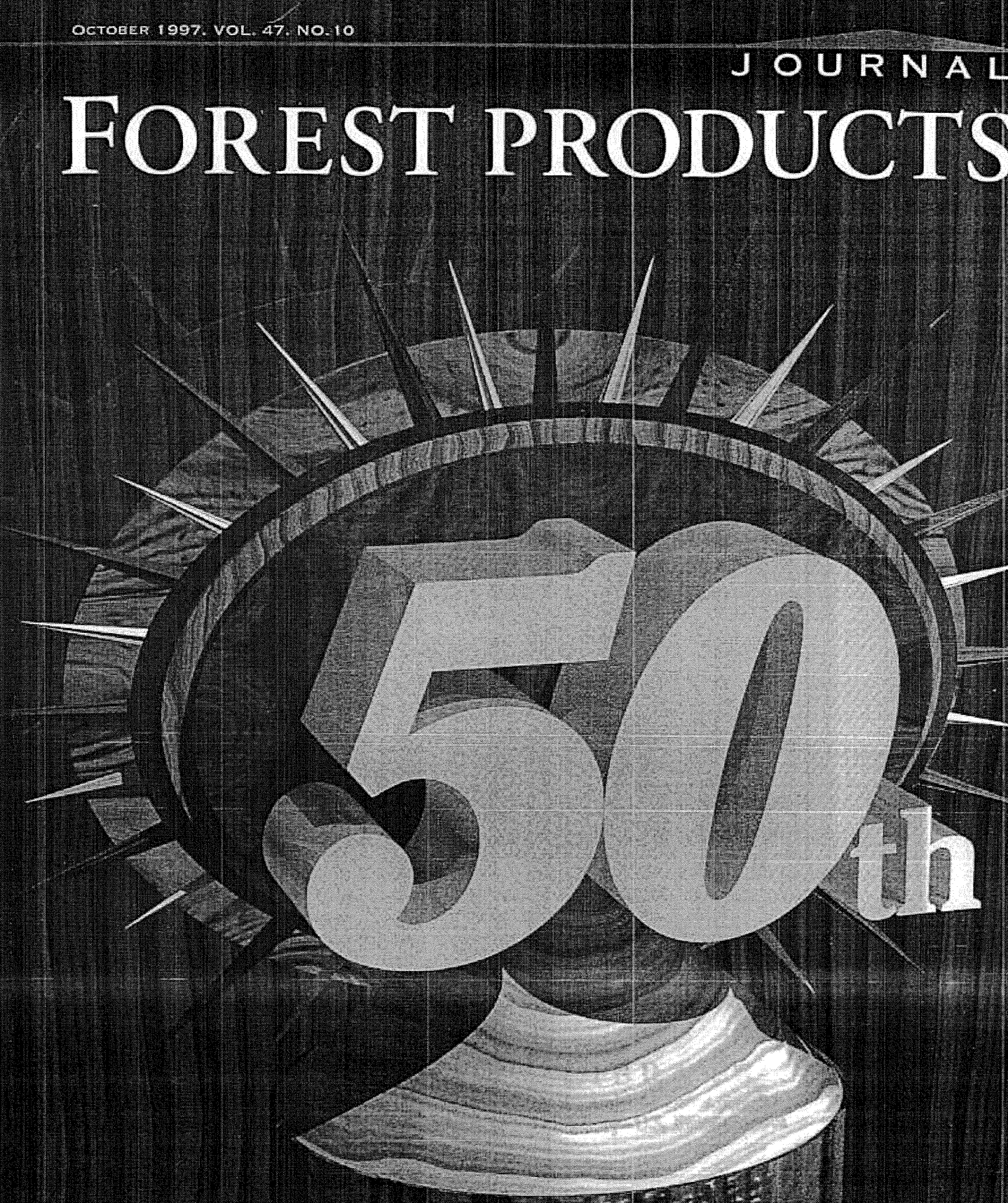

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