Excavators as Base Machines in Logging Operations

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ABSTRACT

Time and ergonomic studies were carried out for three excavator-based logging machines. A follow-up study of three excavator-based harvesters was conducted. The studies indicate that productivity was at the same level as that of Nordic specialized forest machines, and with a similar ergonomic level. The ground pressure exerted by the excavator-based harvesters varied from 30 to 52 kPa.

The ability of the machines to operate in the terrain was good, in rough terrain as well as in terrain with soft ground conditions.

These machines can also be used for ditch digging, scarifying, planting, and road building and maintenance. The machines then function more as attachment carriers than custom-built excavators. The relatively low investment cost in comparison with that of custom-built Nordic machines also reduces operating costs.

Keywords: *attachments, base machine, excavator, harvesting.*

INTRODUCTION

Conventional Nordic machines for forest harvesting operations are specialized, have wheels, and can do only one type of work. In the mid-1960s tests were conducted with a tracked logging machine, the Beloit Tree Harvester, based on an excavator chassis [7]. It was large, had poor mobility, and was difficult to transport to the next logging site. Furthermore, the Swedish forestry sector was not adapted to the tree-length system. Specialized forwarders and processors were being developed at the same time.

During the late 1980s some tracked excavators with felling heads attached were introduced in logging operations [14]. Later the felling heads were exchanged for harvester heads. At the same time some of the machines were modified for improved mobility by increasing ground clearance. The tracks on most machines were guarded inside and outside. Machine reach was often increased by an extra dipper with a bucket for preparing the ground to improve mobility (Figure 1). Mass of the excavator-based harvesters was generally 16-25 tons.

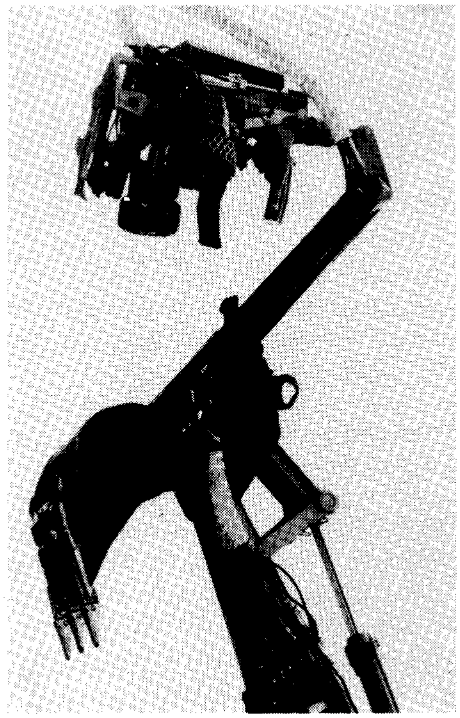

Figure 1. Extra dipper with a bucket. When the end of the dipper (with the harvesting head) is raised, the bucket is free to use.

In the USA, Canada, New Zealand, Australia and Great Britain excavators are common as base machines in forestry with attachments such as feller/bunchers [16], processors [17] or harvesters [8]. They are also used in shovel-logging [12] and as log loaders [15]. The productivity of these machines is good. However, Spencer found that mobility of the excavators is limited by slope [20]. Continuous harvesting could be conducted uphill on slopes of up to 38% as long as ground conditions were reasonable and tree size did not exceed 0.50 m^3. Downhill operation was limited to uniform slopes of 20% or less. Only a few studies on ergonomics have been carried out, but in one study of processors [13], Hope found that the noise level inside the machines was high. Conditions for entering or exiting the machines were also unacceptable.

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OBJECTIVES

The objectives of the studies were to get a general picture of excavator-based logging machines operating in Sweden including:

- fitness for use in logging operations
- productivity
- ergonomics.

MATERIAL AND METHODS

Time studies and ergonomic studies were conducted for three excavator-based logging machines (Table 1, machines 1, 2, and 3). In addition, a follow-up study for three machines was conducted (Table 1, machines 2, 3, and 4). Mean ground pressure was calculated using mass and track contact area from manufacturers specifications. The machines processed/harvested the trees within reach from where they were standing (work place), and then they moved to a new work place.

Table 1. Excavator-based logging machines studied.

	Base machine	Attachment	Mass tons	Reach m	Ground clear cm
1.	Caterpillar 215 BLC	Felling head (Cranab 55)	approx. 21	7.0	46
2.	Åkerman H7c	Harvesting head (AFM Lako 60), extra dipper, bucket	approx. 18	8.5	42
3.	Hitachi EX 220	Harvesting head (AFM Lako 60), extra dipper, bucket	approx. 25	10.7	70
4.	Hitachi EX 150	Harvesting head (AFM Lako 60), extra dipper, bucket	approx. 18	9.2	70

Standard definitions of elements used in Swedish time studies differ from those used in North America. One commonly used term is "Technical degree of utilization," defined as basic time divided by operating time. The following variables used in this study are defined in the Forestry Vocabulary [4]:

Basic time - effective time plus delays of a certain maximum length (here less than 15 minutes)
Delay time - sum of disturbance time, maintenance time, and repair time
Effective time - productive time with no delays
Operating time - basic time plus delay time.

Volume shown in this report (m^3) means solid volume over bark, and diameter (cm) is over bark.

The Stands

Ground conditions in the stands used in the time studies were measured according to the Terrain Classification System for Forestry Work [3] (Table 2). Machine 1 (Caterpillar 215 BLC) was studied in a single stand, on sample plots, 13 by 13 metres. Machine 2 (Åkerman H7[c]) and machine 3 (Hitachi EX 220) were studied in two stands each. Machine 3 was operated by different operators in each stand. The last two machines (Åkerman H7[c] and Hitachi EX 220) were studied when operating along the respective stand boundaries. Additional stand data are shown in Table 3.

Table 2. Ground conditions in the stands for time studies (1=best, 5=poorest).

Machine	Season	Ground factors		
		Bearing capacity	Surface structure	Slope
1. Caterpillar 215 BLC/Cranab 55	Winter with snow and frozen soil	1	1	1
2. Åkerman H7^c/AFM Lako 60	Autumn with			
- stand no. 1	unfrozen peat	4	1	1
- stand no. 2	land	4	1	1
2. Hitachi EX 220/AFM Lako 60	Winter with snow			
- stand no. 1	and frozen soil	1	4	4
- stand no. 2		1	2	1

Table 3. Stand data in the time studies. Standard deviation in brackets.

Machine	Harvest				Total no. of trees/ha
	Species mix., pine, spruce, decid., in tenths	Mean diam. cm	Diameter interval cm	No. of trees studied	
1. Caterpillar 215 BLC/Cranab 55	0,8,2	17.6 (7.4)	6-43	435	1430
2. Åkerman H7^c/AFM Lako 60					
- stand no. 1	2,7,1	18.4 (7.8)	7-45	516	1480
- stand no. 2	0,8,2	18.7 (7.6)	7-41	182	1260
3. Hitachi EX 220/AFM Lako 60					
- stand no. 1	0,8,2	16.6 (6.4)	7-46	263	1200
- stand no. 2	0,9,1	18.6 (6.8)	7-42	795	700

Time Studies

The diameters of the trees to be felled/harvested were measured and marked on the trees. The heights of sample trees in each stand were measured. Field work (time recording) was carried out using a video camera with time-measuring equipment attached. The entire work cycle was recorded. The time studies and the analyses were carried out indoors.

Study of Ergonomics

Ergonomics were studied directly after time recording using An Ergonomic Checklist for Forestry Machinery [2]. The studies were carried out by measuring the machines and interviewing the operators. Vibrations were measured using a Brüel & Kjær 2512 and a Brüel & Kjær 4322 and analyzed (whole body) using SS-ISO 2631 [1]. Noise level was measured using a Brüel & Kjær 2221.

Follow-up Study

Machines 2, 3, and 4 (Hitachi EX 150) were studied. The study periods varied from a little more than one year to a little more than two years. The study was carried out with help of data (productivity, time, and refuelling) from the operators and the forest companies. Factors of special interest were productivity, repair time, maintenance time, and fuel comsumption. Repair time (excl. repairs <15 min.) was divided into two groups depending on what caused the delays, base machine or attachments.

Analysis

Time was analysed with regression analysis. Intercepts and regression coefficients were tested to see if they differed from zero. Time is shown in effective time, commonly used in Swedish time studies, and productivity per effective time unit.

The follow-up study shows productivity per time unit including delays less than 15 minutes, which is commonly used in day-to-day operations.

RESULTS

Time Per Work Cycle

Feller/Buncher: Variables tested in the regression model were tree species, diameter at breast height (Dbh), tree length, and diameter squared. No significant difference was found between tree species. The following model describes time for an entire work cycle (moving forward excluded) for the Caterpillar 215 BLC/-Cranab 55 feller/buncher:

$$T_{f/b} = 22.20 + 0.011 \times (Dbh)^2 \quad R^2 = 0.38$$

$T_{f/b}$ = time for felling/bunching, cmin/tree
Dbh = diameter at breast height, cm
R^2 = R-square

The intercept and the regression coefficient were significantly different from zero, but R-square was rather poor (Figure 2). The low R-square was probably due to short work cycle times, which make a model sensitive to deviation. However, time was also dependent on factors other than those measured in this study.

The mean time for felling and bunching was 26.4 cmin/tree and the standard deviation was 5.9. Time for moving forward between work places was 5.9 cmin/move or 1.7 cmin/tree. Thus, productivity was in total 214 trees/effective hour. The machine felled and bunched 3.5 trees/work place. Terrain mobility was good.

Harvesters: The variables tested in the regression model were tree species, diameter at breast height (Dbh), tree length, diameter squared, and number of logs per tree. The variables that described time best were tree species and diameter squared. The variable tree species was then expressed as a dummy variable (pine and deciduous). The following model describes time for an entire work cycle (moving forward excluded) for the Åkerman H7ᶜ/Lako 60 harvesting machine:

$$T_{hå} = 25.68 + 0.063 \times (Dbh)^2 - 0.015 \times Dump + 0.012 \times Dumd \quad R^2 = 0.62$$

$T_{hå}$ = time for harvesting (Åkerman, spruce, pine and decid.), cmin/tree
Dbh = diameter at breast height, cm
Dump = dummy variable for pine (Dbh squared)
Dumd = dummy variable for deciduous (Dbh squared)
R^2 = R-square

The following model describes time for the Hitachi EX 220/Lako 60 harvesting machine:

$$T_{hh} = 27.48 + 0.037 \times (Dbh)^2 + 0.015 \times Dumd \quad R^2 = 0.42$$

T_{hh} = time for harvesting (Hitachi, spruce and decid.), cmin/tree
Dbh = diameter at breast height, cm
Dumd = dummy variable for deciduous (Dbh squared)
R^2 = R-square

Intercepts and regression coefficients in both models are significantly different from zero. Time for the Åkerman machine was greater, according to the models, especially for large trees. One reason was probably that the Åkerman stands were located in central Sweden and the trees were harder to delimb than the trees in the Hitachi stands located in the north of Sweden. The Åkerman operator was also less experienced than the Hitachi operators (Figure 3). Note that the models give a generalized picture of real time consumption, and some tree species are not covered at the ends of the diameter interval. The figure does not tell which machine is best, because the conditions during the studies were not the same for both machines.

Mean time for the harvesting operation (moving forward excluded) was 51.8 cmin/tree for the Åkerman machine and 41.8 cmin/tree for the Hitachi machine and standard deviations were 27.2 and 15.9, respectively. Mean time for moving forward was 3.1 and 4.4 cmin/tree for the Åkerman and the Hitachi machines, respectively. Thus, the mean productivity for the two machines was 109 trees/

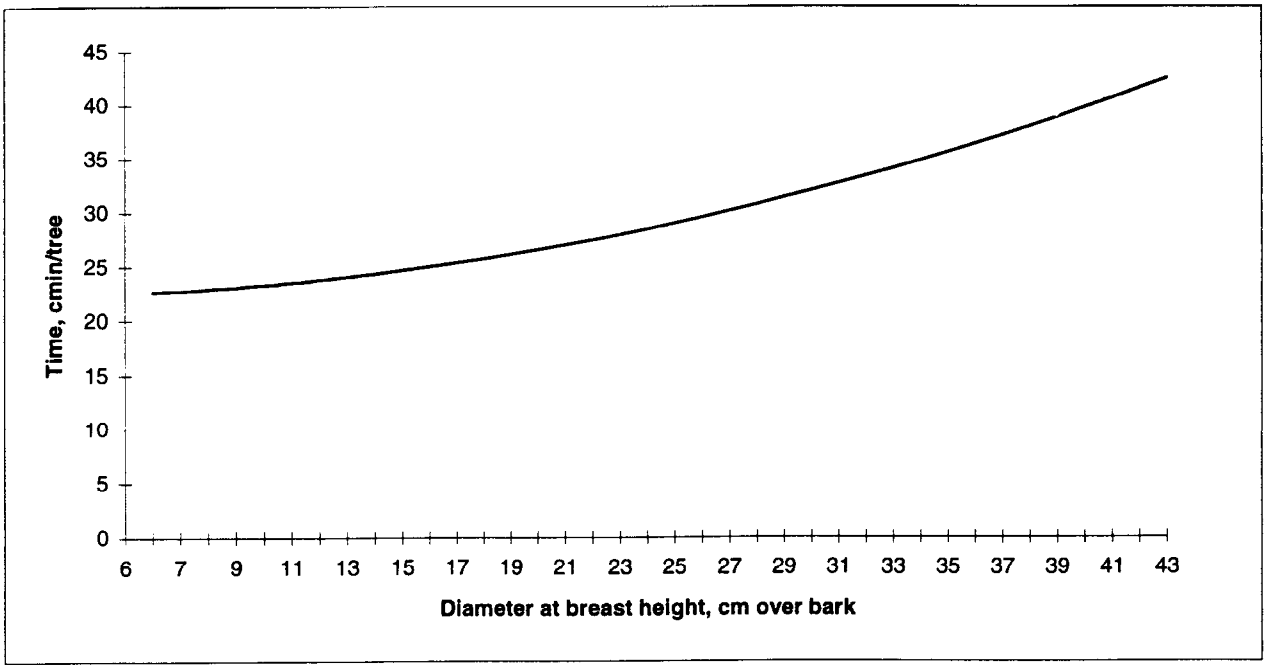

Figure 2. Time per work cycle for the excavator-based feller/buncher, according to the model.

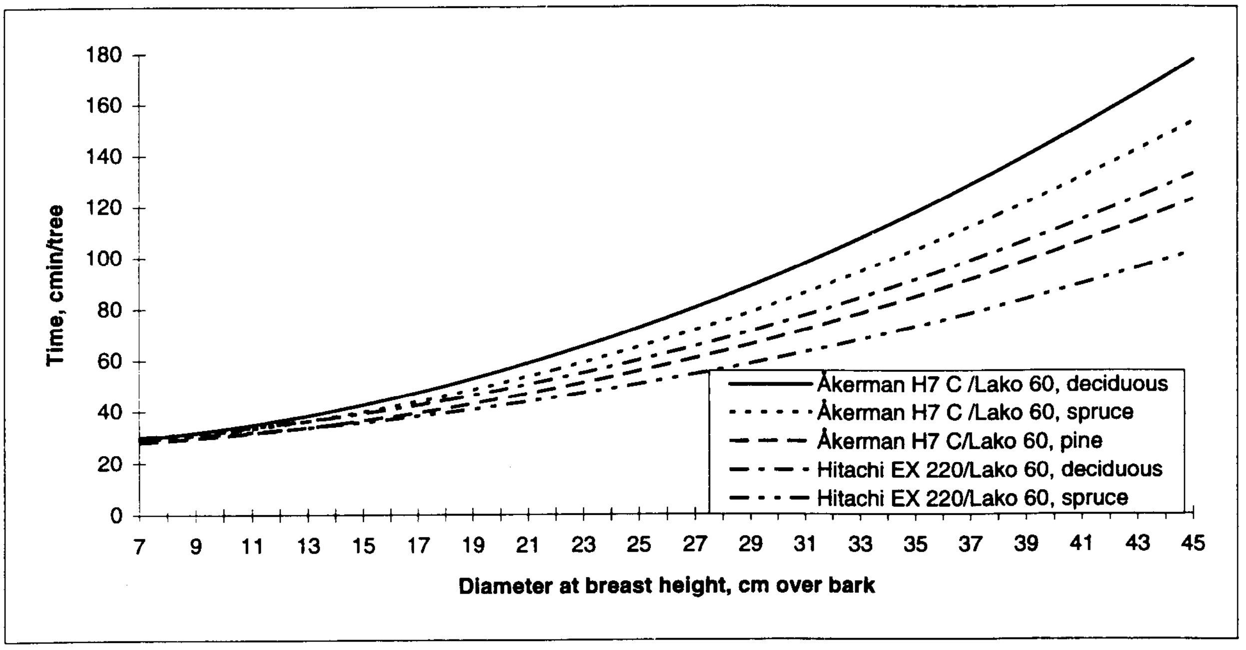

Figure 3. Time per work cycle for the two excavator-based single-grip harvesters, according to the models.

effective hour (Åkerman H7^c/Lako 60) and 130 trees/effective hour (Hitachi EX 220/Lako 60). Mean diameters for each machine were 18.7 and 18.2 cm respectively, and standard deviations were 7.8 and 6.8.

The Åkerman machine harvested 3.6 trees/work place and the Hitachi machine harvested 5.2 trees/work place. Terrain mobility was good, especially for the Hitachi machine with increased ground clearance. For the Hitachi machine in stand no. 1 there was also time for preparing the ground with the bucket, which took a little more than 22% of total effective time.

Ergonomics

An ergonomic checklist for forestry machinery [2] contains 13 factors to be measured and/or judged (Table 4). Each factor can be measured and/or judged according to a scale of five levels, from very poor to very good. Many of the factors had to be judged subjectively as the checklist is not a precise instrument. In order to get a better overview the scale has been coded from 1 to 5, where 1 is very poor and 5 is very good. Note that the numbers are not measured values.

The factor which was given the lowest rating was entering/exiting the machines. The operators had to climb the tracks, risking slipping.

Work position, cabin, cabin climate, and maintenance were factors that were graded considerably higher. The operators considered work position to be good but the cabins could not be levelled. This could, to some degree, be compensated for by preparing the ground with the buckets (Åkerman H7^c and Hitachi EX 220). The whole machines could to some extent be levelled. According to the checklist the cabins were slightly narrow. The operators did not consider that to be a problem, as the cabins could rotate 360°, although they wanted a little more room for storing personal belongings. Cabin climate was good except for some minor remarks, e.g., one of the machines could not be preheated, and strong sunshine could be annoying in one of the machines. In one of the macines it was difficult to obtain a satisfactory temperature (only two levels on fan), although variable heating in another machine was considered inadequate by the operator. Window fogging was a problem in one machine (rainy weather or due to snow residues in the cabin). Maintenance was also considered to be rather good, although the operators sometimes had to walk on the tracks or the machines.

All other factors were considered to be very good. Although the lighting factor was not measured in the studies the operators seemed satisfied with it. The lighting for Hitachi EX 220 was found to be insufficient in earlier evaluations but was later improved.

Table 4. Ergonomic check-up (5=best, 1=poorest).

Ergonomic factor	Base machine		
	Caterpillar 215 BLC	Åkerman H7^c	Hitachi EX 220
Entering/exiting	2	2	2
Work position	4	4	4
Cabin	4	4	4
Operator's seat	5	5	5
Levers	5	5	5
Instruments	5	5	5
Climate in cabin	4	3	4
View	5	5	5
Lighting	(5)	(5)	(5)
Noise	5	5	5
Exhaust gas and dust	5	5	5
Vibration	-	5	5
Maintenance	4	4	4

Especially high ratings were given for the noise and vibration factors. Furthermore, these factors also are considered to be very important. Hearing impairment is likely if the equivalent noise level during a typical work day exceeds 85 dB(A). The highest noise level inside the cabin (windows closed) when operating was 74 dB(A) and the lowest level was 66.7 dB(A). These levels are far below the level at which hearing impairment may occur. These levels are also below the maximum level of 75 dB(A) recommended in the checklist.

Vibrations were measured in three directions: x (forwards/backwards), y (sideways), and z (up/down). Vibrations were not measured for the Caterpillar 215 BLC. Measured vibration levels show that the operators can be exposed to vibrations for at least one shift without transgressing the limit for fatigue and lowered work capacity (regarding vibrations).

The overall impression was that the ergonomic factors were rather good.

Ground Pressure

When calculating ground pressure it should be noted that ground pressure is dependent on several factors. These factors can vary between machines of the same make, e.g., length of crane, mass of attachments, extra mass due to modification, and tracks. Ground pressures shown are valid for the studied machines and for machines with identical attachments and modifications. Calculated mean ground pressure is mass of the machines divided by contact area between tracks and ground, expressed by the unit Pa. Calculated mean ground pressure for the three machines was approximately:

Caterpillar 215 BLC/Cranab 55	30 kPa
Åkerman $H7^c$/Lako 60	42 kPa
Hitachi EX 220/Lako 60	52 kPa

Damage

The machines were primarily moving on harvesting residues and hence no visible ground damage was observed. When there were areas with no residues, tracks on the ground surface could be noted. Where the machines changed driving direction, there was some evidence of shear strain on the ground.

Follow-up Study

Productivity during the study period for the excavator-based harvesters Åkerman $H7^c$, Hitachi EX 220, and Hitachi EX 150 was 47, 81 and 91 trees/hour basic time, respectively. Mean stem volume for the Hitachi harvesters was much less than for the Åkerman harvester, which puts volume productivity at about the same level for all machines (Table 5).

Table 6 shows maintenance and repair time. Repair time was mainly due to problems with attachments. Only a small amount of repair time was due to the base machines. Repair time is not only due to the machines, attachments, or modifications. The operator's skill and experience plays a role along with stand conditions. The technical degree of utilization varied from 0.813 to 0.878 (Table 6).

Fuel consumption varied from 13 litres per basic hour to 17 litres per basic hour (Table 7). The machine with the greatest engine power and the smallest mean stem volume had the highest fuel consumption per m^3. The operator's skill and experience and the stand type may be factors that affect fuel consumption as well.

EXCAVATOR-BASED LOGGING MACHINES COMPARED WITH NORDIC CONVENTIONAL WHEELED LOGGING MACHINES

Productivity

Feller/buncher: Productivity in three studies of the Kockum 880 feller/buncher [6], including moving between workplaces, was 267, 236, and 202 trees/effective hour, respectively. Mean diameter was 13, 14.5, and 18 cm, respectively. Productivity in another study [19] of the ÖSA 670 feller/buncher, including moving between work places, was 243 trees/effective hour with a mean diameter of 20.9 cm. Both machines were prototypes. Productivity for the excavator-based feller/buncher was 214 trees/effective hour, including time for moving between work places, with a mean diameter of 17.6 cm.

Table 5. Productivity in the follow-up study.

Machine	Mean stem volume, m^3	Productivity	
		Stems/basic hour	M^3/basic hour
Åkerman H7^c/Lako 60	0.39	47	18.3
Hitachi EX 220/Lako 60	0.21	81	17.0
Hitachi EX 150/Lako 60	0.23	91	21.0

Table 6. Maintenance and repair time in % of operating time, and technical degree of utilizaion in the follow-up study.

Machine	Maintenance time, %	Repair time, %		Technical degree of utilization
		Base machine	Attachment	
Åkerman H7^c/Lako 60	3.3	3.4	9.6	0.837
Hitachi EX 220/Lako 60	4.5	1.7	6.0	0.878
Hitachi EX 150/Lako 60	5.8	1.3	11.6	0.813

Table 7. Fuel consumption for the machines in the follow-up study.

Machine and year-model	Engine power	Fuel consumption	
		litres/hour basic time	litres/m^3
Åkerman H7^c/Lako 60, 1987	Gross 107 kW (1800 rpm)	13	0.71
Hitachi EX 220/Lako 60, 1990	Net flywheel (DIN 6271) 114 kW	17	1.00
Hitachi EX 150/Lako 60, 1990	Net flywheel (DIN 6271) 70 kW	16	0.76

Harvesters: A study of two single-grip harvesters in clear-cutting [18] showed that productivity varied from 118 to 141 trees/effective hour. Mean diameter was 13 cm. If diameter was increased to 20 cm, productivity decreased to 71 to 100 trees/effective hour. Productivity for the two studied excavator-based single-grip harvesters was 109 trees/effective hour (Åkerman H7[c]/Lako 60) and 130 trees/effective hour (Hitachi EX 220/Lako 60). Mean diameters for the excavator-based machines were 18.5 and 18.2 cm respectively.

Times for moving between work places for the Kockum 880 feller/buncher [6] were 13.8, 14.6, and 19.5% of total effective time. The time for the Caterpillar 215 BLC/Cranab 55 was 5.9%. Time for moving between work places in the study of the two single-grip harvesters [18] was 8% of total effective time. Respective times for the excavator-based harvesters Åkerman H7[c]/Lako 60 and Hitachi EX 220/Lako 60 were 5.2 and 9.1%.

Ergonomics

Ergonomic factors for the excavator-based machines were judged to be equivalent to those for the two wheeled machines FMG 250 E [9] and Skogsjan/LL 487 [10], although conditions for entering and exiting the machines were much poorer for the excavator-based machines. Work position, operator's seat, levers, view, and vibrations were judged to be a little better than for the wheeled machines. Lighting was measured for only one tracked machine. Overall, ergonomic factors for the excavator-based machines were subjectively judged to be equivalent to those for the wheeled machines.

Follow-up

Productivity for single-grip harvesters in large-scale forestry in Sweden in 1990 [11] was approximately 70 m^3 total volume over bark (from stump to top) per 8-hour shift in final felling. If the technical degree of utilization was 0.85 and the volume of tops was 5%, productivity was 9.8 m^3 per hour basic time, which was far below productivity for the excavator-based harvesters studied. The follow-up cited [11] does not tell anything about size of trees or harvesters.

In a study of fuel consumption [5] for three types of two-grip harvesters (a total of 9 machines), fuel consumption was 20.9, 16.1, and 15.3 litres/hour effective time. Fuel consumption for the excavator-based harvesting machines in the follow-up study varied from 13 to 17 litres/hour basic time, or from 15.5 to 19.7 litres/hour effective time. Fuel consumption cannot be compared further because productivity [5] was not shown by volume.

DISCUSSION

Field work in the time studies was carried out with a video camera with time-measuring equipment attached, making it possible to rewind the tape afterwards to refreshen one's memory and make corrections if necessary.

Diameter at breast height squared, and in most cases tree species, proved the best descriptors of cycle time. The models shown are simple but easy to use and understand. R-square was sometimes low, but can probably be higher with help of some other variables. It is rather common for a disturbance during some part of the work cycle in time studies of harvesting operations to lead to a large deviation from expected time when production is not disturbed. This variability from exogenous factors including stand conditions may overwhelm the predictor.

The differences between excavator-based and wheeled harvesters are a function of the possibilities and problems that occur when using excavators as base machines. The combination of high lift capacity and a long reach can increase the concentration of logs, making forwarding easier and cheaper. The lift capacity and reach also make it possible to put the logs where the forwarders can easily reach them in rough terrain. Delimbing of trees can also be done rather easily with the cranes at full reach.

Terrain mobility was good. Some of the machines were modified by increasing the ground clearance and some of them could make their own way. But tracked machines have a rigid undercarriage which does not always adapt to the terrain very well. Wheeled machines are built to adapt to the terrain. Tracked machines should therefore not be driven over large stones or rocky outcrops as the operator's comfort suffers and the machines could slide and finally turn over. The problems with a rigid undercarriage can be offset by the longer crane length, which makes it easier to choose the way and to reach the trees in rough terrain. Gathering residues in front of the machines can also improve the comfort factor.

The studies also indicate that mobility of tracked harvesters on wet land is good, especially when considering the possibility of increasing bearing capacity by harvesting residues.

Transportation costs for tracked logging machines to the next logging site are often considered high due to high trailer costs. That is denied by forestry staff employing tracked logging machines. They state that wheeled harvesting machines are commonly transported by a trailer. If the wheeled machines are not transported by trailer, anti-skid devices must be removed prior to driving the machines to the new site and travel speed for wheeled logging machines is slow. They also point out the possibility of using excavators as base machines for other types of work such as ditching, scarifying, and preparation of landing sites. These base machines then function as carriers instead of specialized machines.

Productivity for the machines studied proved to be at the same level as that of wheeled, Nordic specialized logging machines. High productivity was also confirmed in the follow-up study, and the technical degree of utilization was high. Ergonomics were at the same level as those of wheeled machines. Some factors were better and some factors were poorer. Especially high ratings were judged for important factors such as noise and vibrations. Conditions for entering/exiting the machines were poor. Mobility was good on land with high bearing capacity and with low bearing capacity. Large stones and rocky outcrops should not be driven on. No ground damage was noticed. Advantages resulting from long reach and high lift capacity improved conditions for the forwarders. The investment level is also low. The price for a Hitachi FH 200/Lako 60 is 1.8 million SEK. The price for a large, wheeled single-grip harvester is approximately 2.5 million SEK, and the price for a wheeled two-grip harvester is approximately 3.5 million SEK. The machines studied were productive and reliable, had rather good ergonomics, and a low cost level. Furthermore, a forest company can reduce costs by realizing high annual utilization using the right planning.

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