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Time Consumption Analysis of the Mechanized Cut-to-length Harvesting System

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The time consumption and productivity of harvesting are dependent on stand conditions, the operators' skills, working techniques and the characteristics of the forestry machinery. Even if the basic methods and machine types of the cut-to-length harvesting system have not changed significantly in 10 to 15 years, improvements in the operators' competence, technical solutions in forest machinery and changes in the working environment have undoubtedly taken place. In this study, the objective was to discover the special characteristics in the time consumption of mechanized cutting and forest haulage in Finnish conditions. The empirical time study was conducted with professional operators and medium-sized single-grip harvesters and forwarders in final fellings and thinnings in easy terrain in central Finland. The models for effective time consumption in the work phases and total productivity were formed. Stem size, tree species and bucking affected the cutting, whereas timber density on the strip road, the average driving distance, load capacity, wood assortment and the bunching result of the harvester operator had an effect on the forest haulage performance. The results may be used in simulations, cost calculations and education.

Keywords cutting, forest haulage, single-grip harvester, forwarder, time study, work phase
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1 Introduction

In the normal Nordic harvesting technique, generally referred to as the cut-to-length (CTL) method, tree stems are processed into smaller logs at the harvesting site. The modern CTL method usually uses two machines: a harvester and a forwarder. Combined harvester-forwarders (harwarders) that are capable of carrying out both tree processing and transportation of logs to the roadside have also recently been introduced and tested (Sirén and Aaltio 2003, Talbot et al. 2003, Wester and Eliasson 2003). Compared to other fully mechanized harvesting methods, the CTL method is generally regarded as a more environmentally friendly, versatile and safe method that provides end products of more consistent and higher quality than mechanized full tree and tree length methods (e.g. Kellogg and Bettinger 1994, Tufts 1997).

The time consumption of CTL harvesting is studied for various reasons. The most typical task is to investigate the main factors affecting work productivity and to establish a base for cost calculations and salaries or payments. Researchers in particular may today have other reasons to conduct time studies. Accurate models may be utilized in different kinds of simulations that aim to find new, more efficient work methods, optimize complete operations or develop more efficient machines.

A time study is usually done either as a comparative study, a correlation study or a combination of the two (Eliasson 1998). The objective of comparative studies is to compare two or several machines, work methods, etc, while the objective of the correlation or relationship study is to describe the relationship between performance and the factors influencing the work (Bergstrand 1991). Time studies can be carried out using continuous time study methods such as continuous or repetitive timing or indirect work sampling (Forest work… 1978, Samset 1990, Harstela 1991). The work sampling technique gives only an approximation of the results obtained by the continuous time study methods, but it has the advantage that longer periods and even multiple processes can be studied at the same time with the same costs (Miyata et al. 1981).

In addition to mere experimental time studies, other methods have also been used to investigate time consumption and productivity. Gullberg (1997a) presented a detailed deductive time consumption model for the loading work phase in forest haulage. Gullberg (1997b) also extended modeling to the whole work cycle of a forwarder by uniting theoretical (deductive) and experimental (inductive) information about the time consumption. In Sweden Brunberg (2004) reported a combination of productivity data for forwarders based on several studies and productivity norms available. Talbot et al. (2003) utilized a simulation technique in deriving time consumption functions for cutting and forest haulage performance.

The productivity of modern single-grip harvesters has been rather intensively studied in the Nordic countries (Brunberg et al. 1989, Brunberg 1991, Kuitto et al. 1994, Brunberg 1997, Lageson 1997, Eliasson 1998, Sirén 1998, Glöde 1999, Hånell et al. 2000, Ryynänen and Rönkkö 2001, Kärhä et al. 2004, Ovaskainen et al. 2004), but also to some extent in North America (Tufts and Brinker 1993, Kellogg and Bettinger 1994, McNeel and Rutherford 1994, Landford and Stokes 1995, 1996, Tufts 1997). The logical result of all these studies reveals that cutting productivity increases with increasing stem size. Modern harvesters are so effective that it takes only slightly more time to process a large tree than a small tree, which leads to increasing productivity with increasing stem size. The relationship is not linear, however. Speculations of McNeel and Rutherford (1994) and recent new studies with small-size harvesters (Ryynänen and Rönkkö 2001, Kärhä et al. 2004) clearly testify that after a certain stem size optimal to the machine in question, the productivity starts to decrease.

In addition to tree size, the operator effect may be regarded as the most important factor related to cutting productivity (Sirén 1998). The productivity of cutting has also been observed to increase with increasing harvesting intensity or the number of removed trees in clear cutting (e.g. Kuitto et al. 1994, Sirén 1998, Eliasson 1999), but also in thinnings (Sirén 1998) and in shelterwood cutting (Hånell et al. 2000). Other properties that affect the productivity are terrain conditions (slope, surface structure, bearing capacity) and machinery.

Due to the marked differences between the productivity of forest workers, forest work scientists have applied several methods to make work study results more comparable. Since the classic method of work sciences, performance rating, is not widely accepted among forest work scientists, Nordic researchers have especially favored the principle of the comparative time study in order to make results more comparable (Harstela 1988, Samset 1990, Harstela 1991). Gullberg (1995) suggests a new variable "adaptation" that could be used in order to reduce the operator's effect in comparative experimental studies. Another approach is to use a simulation technique that links different work phases together and usually takes the variation of work performance into account in the analyses (Aedo-Ortiz et al. 1997, Eliasson 1998, Wang and Greene 1999). There have also been recent studies that focus on observing the productivity differences between harvester and harvester simulator (Ovaskainen 2005) and investigating the effect of the harvester operators' tacit knowledge on the harvesting result (Väätäinen et al. 2005).

Forest haulage seems to have been studied less than cutting. Forwarders are perhaps considered to be a mature technology that needs no extra research. American and European forest scientists seem to have a slightly different approach to work studies of the CTL method. European researchers have seen the harvester and forwarder as separate research tasks while American researchers have investigated complete harvesting systems, i.e. the harvester and forwarder as a united system. Accordingly, there seem to be more research reports on an international level about forwarders' productivity from America (Tufts and Brinker 1993, Kellogg and Bettinger 1994, McNeel and Rutherford 1994, Aedo-Ortiz et al 1997, Tufts 1997) than Europe (Kuitto et al. 1994, Gullberg 1997b, Brunberg 2004). However, the introduction of combined machines has also recently increased the interest in the performance of forest haulage in Europe (Sirén and Aaltio 2003, Talbot et al. 2003, Wester and Eliasson 2003).

The productivity of the forwarder is most strongly correlated with stand type (final felling/thinning), average haulage distance, timber density on the strip road and load volume (the size of wood bunk) (Tufts and Brinker 1993, Kellogg and Bettinger 1994, Kuitto et al. 1994, Tiernan et al. 2004). In addition, the increase of average tree size should, at least in theory, decrease loading time. However, as reported by Tufts and Brinker (1997), Gullberg (1997a,b) and Väätäinen et al. (2005), grapple and pile size may be even more important to the productivity of loading. According to these findings, the effect of the harvesting result of the harvester operator has a significant effect on the efficiency of forest haulage (Väätäinen et al. 2005). The number of wood assortments also has an influence on forwarding productivity since it affects the timber density on the strip road (Kuitto et. al 1994). In certain conditions, for example, it may be wise to haul mixed loads (two or several wood assortments in the load) although it increases the time consumption during the unloading phase (Kellogg and Bettinger 1994).

Since operator, machine type and stand characteristics have a crucial influence on harvesting performance, those studies aiming to give overall productivity values have to be based on large samples. In this sense only the large studies in the 1980s and 1990s carried out in Sweden and Finland (Brunberg et al. 1989, Kuitto et al. 1994, Brunberg et al. 1997) can be assumed to be valid in Nordic conditions. There are, however, many reasons to suspect that these productivity models are no longer valid. In cutting, different features of harvesters have been improved during the last ten to fifteen years. The engines, transmission systems, crane hydraulics and harvester head feeding motors have become more efficient, which in turn means higher speed and longer crane reach. Recent studies indicate that processing speeds (delimbing and cross-cutting) have particularly increased (Ryynänen and Rönkkö 2001, Sirén and Aaltio 2003, Ovaskainen et al. 2004).

In contrast to mechanized cutting, no such clear technical development in forwarder machinery has appeared that would have markedly increased the efficiency of forest haulage. The working environment has, however, become much more complicated than earlier. During the last ten years the number of wood assortments (products) has increased significantly due to more specific product requirements. Transferring from manual cutting to mechanical cutting has also changed the character of harvesters' bunching, leading to a more scattered pile structure. These changes in work conditions have undoubtedly affected the work of the forwarder operator.

The objectives of this study were: 1) to discover special characteristics in the time consumption and productivity of the mechanized cut-to-length harvesting system and 2) to form up-to-date time consumption models for medium sized single-grip harvesters and forwarders from the standpoint of effective work time. The models to be developed should be appropriate for giving accurate productivity estimates in typical Finnish conditions as well as for cost calculations and different kinds of modeling and simulation purposes.

2 Material and Methods

2.1 Study Stands

The time study was conducted in the summer and autumn of 2004 in central Finland. Cutting and forest haulage were observed in the same stands. The study material consisted of sample areas in 8 clear felling stands, 1 seed tree felling stand, 2 first thinning stands and 3 second thinning stands. The only seed-tree felling stand was united by clear fellings and they were handled together as final fellings. First and second thinnings were handled together as thinnings. In final fellings the main tree species were Scots pine (*Pinus sylvestris* L.) and Norway spruce (*Picea abies* (L.) Karst.); but the thinnings were all pine dominated. In both stand types there were also minor numbers of birch (*Betula pendula*) and aspen (*Populus tremula*). However, the number of aspen stems was so small that they were not included in the study. Birch was included in the study only in the final fellings. Tree characteristics of the study stands are presented in Table 1.

The terrain conditions of all 14 stands were measured by using the Finnish classification system during the harvesting (Tavoiteansioon perustuvat puutavaran…1990). The following factors were estimated: bearing capacity; roughness of terrain surface; and steepness of terrain. These factors were put into the most suitable class based on 4 different categories (1 = easy conditions, 4 = very difficult conditions). The terrain was classified only on the plots and trails where the time study was conducted. Terrain conditions were relatively easy and were quite similar in all study stands, so eventually all the study stands were classified into terrain class 1.

In the 14 stands 22 different wood assortments (products) in all were bucked. The number of wood assortments in a single stand was, how-

Table 1. The average tree and stand characteristics based on sample areas. Harvested merchantable trees.

Stand no	Average DBH, cm				Average stem size, dm^3				Trees/ha				Volume, m^3/ha			
	Pine	Spruce	Birch	Total	Pine	Spruce	Birch	Total	Pine	Spruce	Birch	Total	Pine	Spruce	Birch	Total
Final fellings																
1	28	15	20	28	493	73	141	451	406	25	25	456	200	2	4	206
2	27	13	21	26	604	50	199	414	393	152	88	633	237	8	18	262
3	35	28	32	33	996	309	572	648	127	100	136	362	126	31	78	235
4	27	26	9	26	477	327	13	433	294	104	4	403	140	34	<1	174
5	29	29	20	29	674	644	326	646	96	325	6	427	64	209	2	276
6	27	30	12	28	459	415	63	417	220	220	18	458	101	91	1	193
7	34	34	18	33	854	646	92	506	224	270	280	773	191	175	26	391
8	-	29	-	29	-	472	-	472	-	316	-	316	-	149	-	149
9	-	19	14	18	-	309	433	338	-	553	170	723	-	171	73	244
Thinnings																
1	14	-	-	14	48	-	-	48	665	-	-	665	32	-	-	32
2	17	21	21	18	106	162	226	121	284	59	20	362	30	10	4	44
3	14	-	-	14	75	-	-	75	526	-	-	526	39	-	-	39
4	14	11	-	14	66	24	-	65	478	3	-	481	31	<1	-	32
5	17	-	10	17	86	-	37	85	173	-	1	174	15	-	<1	15

ever, typically smaller. There was only one main pulpwood assortment for pine and spruce. Not all types of saw and veneer logs were bucked in every stand. The number of wood assortments in a single final felling stand could still be as high as 17. In thinnings there were typically 3 different assortments for pine: standard sawlog, small-size sawlog and pulpwood.

2.2 Machines, Operators and Working Methods

For final fellings seven different harvesters and eight different operators were studied. For thinnings there were three different machines and three different operators. For forest haulage, the time study consisted of seven forwarders and seven operators in final fellings and three forwarders and four operators in thinnings. Some operators and machines worked in both stand types (see the Appendix). The operators were professionals and used to working with these types of machines in these types of stands. The harvester operators had 4 to 22 years of experience in working with harvesters (average 14 years) and 1 to 12 years of experience with the studied harvester types in particular (average 8 years). The forwarder operators had 1 to 34 years of experience in working with forwarders (average 14 years) and 1 to 13 years of experience with the studied forwarder types in particular (average 5 years).

Each harvester operator used the same cutting technique for final fellings: trees were felled to one side of the strip road and the logs were bunched on the opposite side, at a 90 degree angle to the strip road. The average width of the felling sector was 13 m (range 10–15 m). Operators sorted each wood assortment either into their own piles or bunched them on different sides of the piles, e.g. when a single stem was bucked into several sawlog assortments. To keep different wood assortments apart for forest haulage, harvester operators used a color-marking device mounted in the harvester head.

The basic method for thinnings was a strip-road method with strip roads 4 m in width and with a minimum spacing of 20 m. In the study stands the average strip road spacing was 21 m (range 19 to 25 m). Strip roads were not marked in advance, but they were planned by the operators during the cutting work. The operators also chose the trees to be removed. In the second thinnings operators also made short spurs from the strip road, because in places the spacing of that road was more than 20 m. Each operator used the same technique whereby the trees were first felled away from the strip road and then from both sides of the machine. Operators did not reverse after opening the strip road, but cut the whole strip at one time. Logs were bunched on both sides of the strip road. Pulpwood and sawlogs were bunched into separate piles, and color-marking was used only in some thinning stands, mostly to sort out standard and small-size sawlogs.

In the forest haulage phase in final fellings timber was loaded from only one side and in thinnings from both sides of the machine. In both stand types, both single and mixed loads were hauled: in single loads the load consisted of only one wood assortment, in mixed loads there were typically two or three different assortments. Depending on the load type, logs were sorted either in the forest (single loads) or at the landing area (mixed loads). Wood assortments were unloaded onto their own piles at the roadside.

2.3 Work Phase Classification

All activities associated with cutting a single tree were considered as a working cycle for cutting and those activities associated with forwarding one load were considered as a working cycle for forest haulage. The cycles were broken down into time elements. In the time study the following work activities were observed:

Cutting

- Moving: Begins when the harvester starts to move and ends when the harvester stops moving to perform some other activity. Moving can be divided into driving forward or reversing either from one working location to another or moving inside the working location.
- Positioning-to-cut: Begins when the boom starts to swing towards a tree and ends when the harvester head is resting on a tree and the felling cut begins.
- Felling: Begins when the felling cut starts and ends

when the feeding rolls start to turn on the stem.
- Processing (delimbing, cross-cutting, bunching and sorting logs): Begins when the feeding rolls start to run and ends when the last bucking cut is made and the last log is dropped onto the pile. Bunching is defined as arranging logs into piles and sorting is defined as keeping similar wood assortments together. For further modeling, the bunching and sorting time were separated from the other processing time.
- Boom-in: Begins when the last bucking cut is made and the boom starts to swing toward the base machine and ends when the harvester head stops in front of the base machine and the moving or positioning-to-cut activity begins.
- Clearing: Clearing of disturbing undergrowth and processing of unmerchantable trees.
- Moving logs, tops and branches: Moving logs, tops and branches to the strip road and away from piles, and bunching and sorting logs and piles (outside the processing phase).
- Miscellaneous times: Other activities involved in the cutting work, e.g. the planning of work and preparations. These times were included in the time elements, in which they were observed.
- Delays: Time that is not related to effective work, e.g. repairing and maintenance, phone calls etc.

Forest haulage
- Driving empty: Begins when the forwarder leaves the landing area and ends when the forwarder stops at the first loading stop and the operator begins to move the grapple loader to start loading.
- Loading: Begins when the operator starts to move the grapple loader from the bunk and ends when the grapple loader is rested on the bunk after the last grapple load of the loading stop is put into the bunk. The loading time was divided into sub elements for more detailed analysis:
  - Reaching the pile
  - Lifting the grapple load into the bunk
  - Sorting and handling the logs on the ground
  - Sorting and handling the logs in the bunk
- Driving while loading (driving between loading stops): Begins when the grapple loader is rested on the bunk after the last grapple load of the loading stop is put into the bunk and the operator prepares to move to the next loading stop. Driving while loading ends when the forwarder stops at the next loading stop and the operator starts to move the grapple loader in order to begin loading.
- Driving loaded: Begins when the grapple loader is rested on the bunk after the last grapple load of the last loading stop and the bunk is full. Driving loaded ends when the forwarder stops at the landing area and the operator starts to move the grapple loader in order to unload.
- Unloading and driving while unloading: Begins when the forwarder stops at the landing area and the operator starts to move the grapple loader. Unloading ends when the last load is lifted onto the pile and the grapple loader is resting on the empty bunk. The unloading time was divided into sub elements for more detailed analysis:
  - Lifting the grapple load onto the landing pile
  - Moving the empty grapple loader back into the bunk
  - Sorting and handling the logs in the bunk
  - Sorting and handling the logs on the landing pile
  - Driving while unloading (moving between the piles at the landing area)
- Miscellaneous times: Other activities included in the effective forwarding work, e.g. planning of work and preparations. These times were included in the time elements in which they were observed.
- Delays: Time that is not related to effective work, e.g. repairing and maintenance, phone calls, etc.

2.4 Organization of the Field Study

Field study material was collected using a digital video camera. Harvesters and forwarders were filmed just as if the operators were in normal working situations without any special experimental arrangements. First the cutting work was observed and filmed for about an hour in each stand. This one-hour sample (the area and trees that were cut during filming) formed one sample area. Stem files (STM) of the trees on the video sample were collected onto a diskette or printed on paper. This data included volume (solid cubic meters including the bark) and dimensional information about each processed tree and log. The STM-files were based on the Nordic standard (Standard for forest… 2003, Standard for forest… 2005). The length of the strip road, width of the cutting sector and the area were also measured.

In the forest haulage phase, depending on the schedule and working situation, one to three sample loads were filmed in each stand. The filming of one load consisted of the whole loading cycle from driving empty to unloading. Before filming, the cut sample area was marked off in the stand. Log piles situated in the sample area were marked with pieces of paper. The following features were measured from the sample piles: wood assortment, number of logs, distance from the midpoint of the pile to the midpoint of the strip road and the distance from the midpoint of the pile to the midpoint of the next pile along the strip road. Filmed loads were chosen so that at least one load or part of a load was loaded in the sample area. With this procedure it was possible to add the STM data and features of the sample piles to the time study data.

The end point of driving empty (the first loading stop) and the starting point of driving loaded (the last loading stop) were marked on the site during filming. Distances between these points and the landing area on the actual paths of the forwarder were measured afterwards with a wire meter device. The following data was also registered during the forest haulage both inside and outside the sample area of harvesting: wood assortment, number of logs in a grapple load and labels of the piles (only in the sample area). The volume of loaded timber was measured at each loading stop. The wood assortment and number of logs in the grapple loads during the unloading phase were also registered at the landing area.

2.5 Data Analysis

Studied machines, operators and the division of data between them and stands are presented in the Appendix. The time study data of cutting consisted of 12.5 hours of effective work on the video tape. In final fellings the average area of one sample was 0.14 ha and in thinnings 0.34 ha. The total harvested area in the time study was 1.30 ha in final fellings and 1.70 ha in thinnings. During the time study, in final fellings 636 stems (296 m^3) were cut in a total of 9 stands. Total removal by tree species was: 272 pine stems (156 m^3), 276 spruce stems (115 m^3) and 88 birch stems (25 m^3).

Table 2. Summary of stems and logs processed in sample areas. The range of values is in brackets.

	Final fellings	Thinnings
Avg. stem size, dm^3		
Pine	572 [17–1757]	75 [8–420]
Spruce	431 [19–1816]	151 [19–524]
Birch	208 [11–1182]	188 [37–331]
Median number of logs per stem		
Pine	4 [1–7]	2 [1–5]
Spruce	4 [1–7]	2 [1–3]
Birch	3 [1–7]	4 [2–5]
Avg. log volume, dm^3		
Sawlogs	188 [25–999]	100 [49–272]
Pulpwood	51 [4–307]	34 [7–299]
Avg. log length, m		
Sawlogs	4.6 [2.6–7.3]	4.3 [3.2–5.5]
Pulpwood [a)]	3.8 [2.5–6.3]	4.1 [2.3–5.9]

[a)] The volume proportion of short pulpwood logs (log length <3.6 m) from all pulpwood was 49% in final fellings and 19% in thinnings.

In 5 thinnings a total of 569 stems (44 m^3) were cut. The total removal by tree species was: 554 pine stems (42 m^3) and 13 spruce stems (2 m^3). The summary of stems and logs processed in the sample areas is shown in Table 2.

The effective forest haulage work was filmed for 17.5 hours in all. In final fellings a total of 18 loads were observed. Ten loads were single sawlog loads and the other 8 were mixed sawlog loads (2 or 3 sawlog assortments). The total volume of hauled timber in final fellings was 350 m^3. In thinnings a total of 9 loads were observed: 4 single pulpwood loads, 4 mixed loads (pulpwood as the main assortment, sawlog as the marginal assortment) and 1 mixed sawlog load (2 different sawlog assortments). The total volume of hauled timber in the study loads in thinnings was 100 m^3. In both stand types, only softwood (pine and spruce) was hauled. The summary of the study loads is presented in Table 3.

The video material was analyzed according to the stop-watch study principle from the TV screen using the time counter of the video camera. The accuracy of the counter was 1/24 seconds. Time consumption data was checked and adjusted to the right stems and logs from the STM-files or

Table 3. Summary of the study loads and working characteristics of forest haulage.

	Final fellings	Thinnings
Number of loads	18	9
Driving empty, avg. distance, m	147	433
Range, m	[32–392]	[111–659]
Driving while loading, avg. distance, m	111	267
Range, m	[44–218]	[135–489]
Driving loaded, avg. distance, m	118	414
Range, m	[15–264]	[74–662]
Avg. volume/grapple load, m^3	0.47	0.16
Range, m^3	[0.05–1.28]	[0.03–0.63]
Avg. volume/pile, m^3	1.16	0.19
Range, m^3	[0.05–3.73]	[0.03–0.70]
Avg. volume [a)]/loading stop, m^3	1.36	0.28
Range, m^3	[0.05–5.37]	[0.03–1.37]
Avg. timber density [b)] on strip road, m^3/100m	15.4	5.2
Range, m^3	[5.6–34.1]	[1.9–8.4]
Avg. volume/load, m^3	14.0	11.0
Range, m^3	[9.7–19.2]	[8.4–13.9]

[a)] Total volume of logs loaded at one loading stop.
[b)] Total volume of hauled timber per 100 m of strip road.

printouts and a time value was given for each work element. In addition, the information collected from the cut sample areas was utilized in defining the loading stop characteristics, average timber size, wood assortment details and other explanatory factors and measurements relating to the modeling of the time consumption.

For cutting, two different techniques were utilized in forming a model for the total productivity. First, a delay-free time consumption model was formed separately for each of the work phases. Regression analysis with the appropriate transformations of variables was used in those work phases in which the time consumption could be explained with some independent variable, such as stem size. Other work phase models were formed using average time consumption values. Time consumption for bunching and sorting logs was not included in regression processing models, but it was calculated as a mean value according to the number of wood assortments bucked from a stem. If the stem was bucked to only one assortment, there was no bunching and sorting time. The model of total time consumption was formed by combining the work phase models. This technique made it possible to connect time consumption characteristics to a certain work phase and examine them in more detail according to the objectives of the study. Finally, the total time consumption was converted into productivity.

In the other technique, each work phase time which could not be associated with a certain stem (e.g. clearing time) was added up and divided by the total number of observed cutting cycles. This value for average time consumption was attached to the whole list of observed stems and added up with those work phase times that could be associated with a certain stem. Time consumption for bunching and sorting was included in processing. No grouping according to number of wood assortments was made. Values for total time consumption were converted into productivity according to the stem size. With this technique, a regression model was formed to estimate the total productivity of the cutting work cycle directly as a function of stem size.

As in cutting, regression analysis with variable transformations was used for modeling those work phases of forest haulage in which the time consumption could be explained with some independent variable, such as driving distance or timber volume at the loading stop. In the case of loading time, dummy variables were used to express the loading situation, i.e. the type and number of wood assortments at the loading stop. For stand-level calculations, the volume of timber at a loading stop was calculated from the timber density on the strip road [m^3/100m] which was derived from the removal of timber [m^3/ha]. Other work phase models were formed using average values for time consumption. The model for total time consumption was formed by combining the work phase models. This model structure was chosen to be the most suitable and flexible from the standpoint of the study objectives, and also because the work phases of forest haulage differ considerably from each other.

In order to examine the goodness-of-fit of regression models and to test the co-significance of coefficients, an F-test was conducted. Each coefficient of the work phase models was also tested separately in the t-test. For those work phase times of cutting that were based on average values and could be adjusted to stems, an independent samples t-test was conducted to analyze the differences in the time consumption between stand types. The one-way analysis of variance (ANOVA) was used to examine the differences in time consumption for bunching and sorting according to the number of wood assortments bucked from a stem in final fellings (2, 3 or 4 assortments per stem). In the mean comparison tests the null hypotheses were that the average time values do differ between stand types and according to the number of bucked assortments. The null hypotheses were rejected if the test results indicated p-values larger than 0.05 (i.e. there was a probability of more than 5% that the null hypotheses were not true and the differences in the time consumption resulted only from random variation).

The effective productivity models were converted into gross-effective productivity (effective time including < 15 min delays) with the gross-effective coefficients based on the nationwide time consumption and productivity study of harvesters and forwarders (Kuitto et al. 1994). The gross-effective productivity was further converted to correspond to the long term productivity levels of cutting and forest haulage with the follow-up coefficients based on the same study.

3 Results

3.1 Cutting

3.1.1 Breakdown of the Time Consumption

All time proportions presented here are proportions of the observed effective time (excluding delay times). Miscellaneous times were included in the work phase times in which they were observed (Table 4).

3.1.2 Time Consumption for Work Phases

1) Moving
The time consumption for moving was calculated as a mean value in both final fellings and thinnings. Time consumption for moving was independent of tree species. Average moving time (t_1) was 4.6 s/stem (0.077 min/stem) in final fellings and 6.0 s/stem (0.100 min/stem) in thinnings.

2) Positioning-to-cut
The time consumption for positioning-to-cut did not depend on stem size, number of removed trees

Table 4. Average work phase times of cutting as a proportion of total effective time. The range in the time proportions between the sample areas is in brackets.

Work phase	Final fellings %		Thinnings %	
Moving	13	[7–19]	20	[14–26]
Positioning-to-cut	14	[8–18]	20	[15–26]
Felling	17	[15–20]	18	[13–23]
Processing	45	[40–55]	27	[21–30]
Boom-in	6	[4–9]	10	[8–13]
Clearing	3	[1–5]	3	[1–9]
Moving logs, tops and branches	2	[0–6]	1	[0–5]
Total	100		100	

Table 5. Time consumption for bunching and sorting during processing according to the number of wood assortments per stem.

	Number of wood assortments per stem			
	1	2	3	4
Final fellings				
Bunching and sorting time, s/stem	0	1.5	2.3	3.3
Avg. stem size, dm^3	93	439	761	1,142
Range	[19–980]	[108–1517]	[245–1816]	[365–1663]
Proportion of all stems, %	30	42	23	5
Thinnings				
Bunching and sorting time, s/stem	0	0.9	-	-
Stem size, dm^3	65	199	-	-
Range	[8–384]	[93–524]		
Proportion of all stems, %	88	12	-	-

or stand type. The average time consumption (t_2) for both final fellings and thinnings was 6.0 s/stem (0.100 min/stem).

3) Felling
The time consumption for felling (t_3) depended slightly on stem size and was defined in linear regression analysis in final fellings (Eq. 1) and in thinnings (Eq. 2).

Final fellings:

$$t_3 = 0.068 + 0.142x \tag{1}$$

Thinnings:

$$t_3 = 0.093 + 0.101x \tag{2}$$

where
t_3 = time consumption for felling, min/stem
x = stem size, m^3

4) Processing
The time consumption for delimbing and cross-cutting increased as a function of stem size. In thinnings the relationship was linear while in final fellings it was slightly polynomial. Models estimating delimbing and cross-cutting time (t_4) for each studied tree species were formed by means of regression analysis (Eq. 3–6). Models for processing of spruce stems in thinnings are not presented here due to the small number of observations (13 stems).

Final fellings:

$$\text{Pine}: t_4 = 0.206 + 0.054x + 0.308x^2 \tag{3}$$

$$\text{Spruce}: t_4 = 0.071 + 0.616x - 0.180x^2 \tag{4}$$

$$\text{Birch}: t_4 = 0.079 + 0.655x + 0.174x^2 \tag{5}$$

Thinnings:

$$\text{Pine}: t_4 = 0.0359 + 1.1368x \tag{6}$$

where
t_4 = time consumption for delimbing and cross-cutting, min/stem
x = stem size, m^3

When estimating the total time consumption for processing, the bunching and sorting time was added to the delimbing and cross-cutting time according to bucking (Table 5).

The time consumption for processing pine and spruce stems was quite equal in final fellings when stem size varied from 0.2 to 0.9 m^3 (Fig. 1). With larger stems, however, the processing of pine stems took up to 30% more time than the processing of spruce stems. The processing of birch was slower than the processing of softwood; the difference being emphasized with large stems. Within the typical stem size range of final fellings (0.3 to 0.8 m^3) each new wood assortment slowed the processing of pine stems by 3 to 10%, spruce stems 3 to 11% and birch stems 2 to 9%.

In thinnings, time consumption for processing

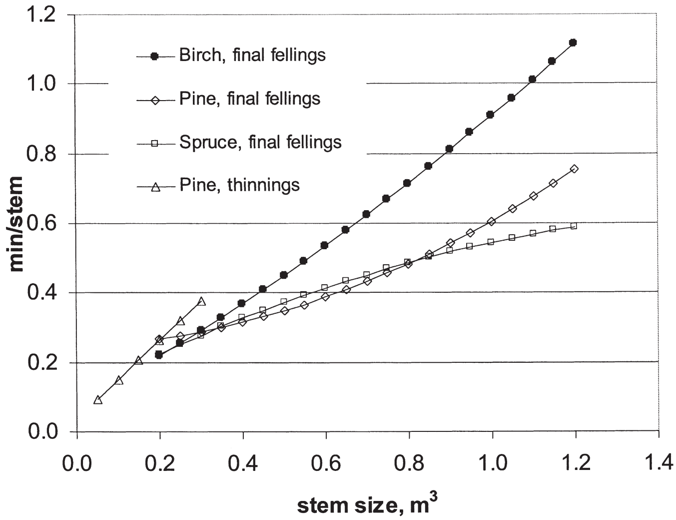

Fig. 1. Time consumption for processing as a function of stem size. The number of wood assortments is 2 for pine, spruce and birch stems in final fellings and 1 for pine stems in thinnings.

pine stems increased linearly as the stem size increased (Fig. 1). Bunching and sorting slowed the processing of pine by 4 to 10% when the stems were bucked into two assortments instead of only one (in the stem size range of 0.1 to 0.3 m^3).

5) Boom-in
The boom-in time was calculated as a mean time consumption value separately for final fellings and thinnings. The average time consumption (t_5) was 2.8 s/stem (0.047 min/stem) in final fellings and 2.9 s/stem (0.049 min/stem) in thinnings.

6) Clearing
The time consumption for clearing (t_6) was calculated as a mean value: 1.3 s/stem (0.022 min/stem) in final fellings and 1.0 s/stem (0.017 min/stem) in thinnings.

7) Moving logs, tops and branches (outside the processing)
Moving logs, tops and branches (t_7) took on average 0.7 s/stem (0.012 min/stem) in final fellings and 0.4 s/stem (0.007 min/stem) in thinnings.

8) Statistical analyses
The characteristics for regression models are presented in Table 6 and the descriptive statistics for mean value based parameters and work phase models in Table 7. According to the independent samples t-test, the time consumption for positioning-to-cut and boom-in did not differ between final fellings and thinnings ($p = 0.785$ for positioning-to-cut and $p = 0.501$ for boom-in), whereas the moving time was clearly affected by stand type ($p = 0.001$). The differences in the mean values of the time consumption for bunching and sorting in final fellings (Table 7) were regarded as statistically significant in the one-way ANOVA ($p < 0.001$ between groups).

3.1.3 *Total Time Consumption and Productivity*

The total time consumption model of a delay free cutting work cycle was defined by adding up the time consumption for work phases:

$$t_{tot} = t_1 + t_2 + t_3 + t_4 + t_5 + t_6 + t_7 \qquad (7)$$

where
t_{tot} = total effective time consumption for cutting, min/stem
t_1 = time consumption for moving, min/stem

Table 6. Statistical characteristics of regression analysis based models (t = time consumption for work phase, min/stem, x = stem size, m^3).

Work phase model	Dependent variable	R^2	F-test F-value	F-test p	N	Term	Constant/Coefficient Estimate	Constant/Coefficient Std. error	t-test t-value	t-test p
Felling; final fellings (Eq. 1)	t_3	0.262	457.225	<0.001	633	Constant	0.068	0.004	16.887	<0.001
						x	0.142	0.007	21.383	<0.001
Felling; thinnings (Eq. 2)	t_3	0.014	52.325	<0.001	554	Constant	0.093	0.001	61.740	<0.001
						x	0.101	0.014	7.234	<0.001
Delimbing and cross-cutting; final fellings, pine (Eq. 3)	t_4	0.546	162.011	<0.001	272	Constant	0.206	0.031	6.679	<0.001
						x	0.054	0.093	0.583	0.561
						x^2	0.308	0.062	5.005	<0.001
Delimbing and cross-cutting; final fellings, spruce (Eq. 4)	t_4	0.602	205.502	<0.001	275	Constant	0.071	0.014	4.978	<0.001
						x	0.616	0.054	11.483	<0.001
						x^2	–0.180	0.038	–4.680	<0.001
Delimbing and cross-cutting; final fellings, birch (Eq. 5)	t_4	0.846	222.172	<0.001	84	Constant	0.079	0.014	5.710	<0.001
						x	0.655	0.101	6.501	<0.001
						x^2	0.174	0.107	1.621	0.109
Delimbing and cross-cutting; thinnings, pine (Eq. 6)	t_4	0.622	902.892	<0.001	551	Constant	0.036	0.004	9.578	<0.001
						x	1.137	0.038	30.048	<0.001

Table 7. Descriptive statistics of mean value based work phase models (t = time consumption for work phase, min/stem).

	Parameter	Mean (s/stem)	Min (s/stem)	Max (s/stem)	Std. Dev.	N
Moving	t_1					
Final fellings		4.6	0	89.4	0.24	638
Thinnings		6.0	0	100.8	0.32	576
Positioning-to-cut	t_2					
Final fellings		6.0	0	23.4	2.53	638
Thinnings		6.0	0	29.4	3.33	572
Boom-in	t_5					
Final fellings		2.8	0	11.4	0.06	638
Thinnings		2.9	0	34.2	0.14	576
Clearing	t_6					
Final fellings		1.3	0	46.8	0.16	638
Thinnings		1.0	0	42.6	0.16	576
Moving logs, tops and branches	t_7					
Final fellings		0.7	0	39.0	0.13	638
Thinnings		0.4	0	90.0	0.18	576
Bunching and sorting						
Final fellings						
1 assortm.		0	0	0	0	108
2 assortm.		1.5	0	11.4	0.09	257
3 assortm.		2.3	0	13.2	0.18	148
4 assortm.		3.3	0	8.4	0.34	34
Thinnings						
1 assortm.		0	0	0	0	499
2 assortm.		0.9	0	3.0	0.11	68

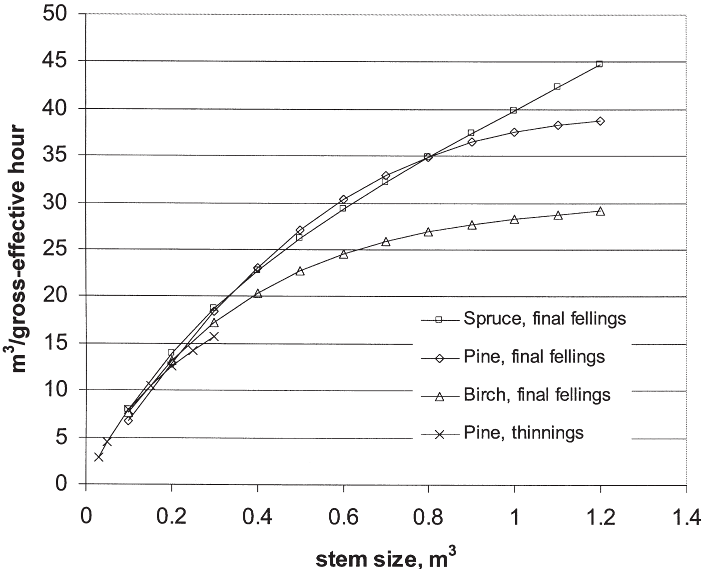

Fig. 2. Productivity of cutting as a function of stem size. The number of wood assortments is 2 for pine, spruce and birch stems in final fellings and 1 for pine stems in thinnings.

t_2 = time consumption for positioning-to-cut, min/stem
t_3 = time consumption for felling, min/stem
t_4 = time consumption for delimbing and cross-cutting, min/stem (For the total time consumption of processing, the bunching and sorting time must be added to the delimbing and cross-cutting time according to bucking.)
t_5 = time consumption for steering the boom in, min/stem
t_6 = time consumption for clearing, min/stem
t_7 = time consumption for moving logs, tops and branches, min/stem

Total effective time consumption was converted into delay-free productivity (Eq. 8) and gross-effective productivity (Eq. 9):

$$p_e = \frac{60x}{t_{\mathrm{tot}}} \tag{8}$$

$$p_{ge} = \frac{p_e}{1.197 \times 1.276} \tag{9}$$

where
p_e = productivity, m^3/effective hour
t_{tot} = total effective time consumption for cutting, min/stem
x = stem size, m^3
p_{ge} = productivity, m^3/gross-effective hour (including < 15 min delays)
1.197 = gross-effective time coefficient for effective time (Kuitto et al. 1994)
1.276 = follow-up coefficient for gross-effective time (Kuitto et al. 1994)

In final fellings the productivity of cutting of pine and spruce was rather similar in the typical stem size range (0.3 to 0.8 m^3) (Fig. 2). When the stem size increased from 0.4 to 0.6 m^3, the productivity of cutting increased by 31% in the case of pine and 29% in the case of spruce. When the stem size increased to over 0.8 m^3, the productivity of cutting pine stems became lower than spruce stems. The productivity of cutting birch stems was clearly lower than cutting softwood: e.g. cutting 0.6 m^3 pine stems was 24% more effective than cutting birch stems of equal size. Each new wood assortment bucked from a stem decreased productivity by 1.5 to 4% with pine and spruce and 1 to 2.5% with birch in the stem size range of 0.3 to 0.8 m^3.

The productivity of cutting pine stems in thinnings varied as a function of stem size parallel to final fellings (Fig. 2). When the stem size increased from 0.04 to 0.06 m^3, productivity increased by 42%. Depending on stem size, productivity decreased 2 to 3% when the pine stems were bucked to 2 assortments instead of 1.

3.1.4 *Overall Productivity Model*

Final fellings:

$$\text{Pine}: p_e = 1.383 + 99.375x - 39.824x^2 \tag{10}$$

$$\text{Spruce}: p_e = 4.067 + 78.623x - 18.507x^2 \tag{11}$$

$$\text{Birch}: p_e = 2.368 + 96.126x - 60.694x^2 \tag{12}$$

Thinnings:

$$\text{Pine}: p_e = 0.383 + 135.896x - 180.065x^2 \tag{13}$$

where
p_e = productivity, m^3/effective hour
x = stem size, m^3

Delay free productivity was converted into gross-effective productivity with the gross-effective and follow-up coefficients presented in the context of Eq. 9. Statistical analysis conducted for each overall productivity model is presented in Table 8.

3.2 Forest Haulage

3.2.1 *Time Consumption for Work Phases*

1) Driving empty and driving loaded
The time consumption for driving empty and driving loaded depended on the driving speed, driving distances and timber volume per load. Linear regression analysis was conducted to estimate the time consumption for these phases as a function of driving distance (Eq. 14 and 15). The functions were the same for both final fellings and thinnings.

$$t_1 = \frac{0.7123 + 0.0149x_1}{v} \tag{14}$$

where
t_1 = time consumption for driving empty, min/m^3
x_1 = driving empty distance, m
v = timber volume per load, m^3

$$t_2 = \frac{0.9347 + 0.0185x_2}{v} \tag{15}$$

where
t_2 = time consumption for driving loaded, min/m^3
x_2 = driving loaded distance, m
v = timber volume per load, m^3

Table 8. Statistical characteristics of overall productivity models. (p_e = productivity, m^3/effective hour, x = stem size, m^3).

	Dependent variable	R^2	F-test F-value	F-test p	N	Term	Constant/Coefficient Estimate	Constant/Coefficient Std. error	t-test t-value	t-test p
Pine, final fellings (Eq. 10)	p_e	0.748	398.244	<0.001	272	Constant	1.383	1.761	0.785	0.443
						x	99.375	5.294	18.770	<0.001
						x^2	–39.824	3.512	–11.338	<0.001
Spruce, final fellings (Eq. 11)	p_e	0.901	1236.141	<0.001	275	Constant	4.067	0.816	4.987	<0.001
						x	78.623	3.082	25.509	<0.001
						x^2	–18.507	2.206	–8.388	<0.001
Birch, final fellings (Eq. 12)	p_e	0.809	180.011	<0.001	88	Constant	2.368	0.989	2.394	0.019
						x	96.126	6.898	13.935	<0.001
						x^2	–60.694	7.197	–8.434	<0.001
Pine, thinnings (Eq. 13)	p_e	0.899	2436.279	<0.001	554	Constant	0.383	0.171	2.236	0.026
						x	135.896	3.269	41.576	<0.001
						x^2	–180.065	11.353	–15.861	<0.001

The average speed of the forwarders was 56 m/min when driving empty and 44 m/min when driving loaded. The driving speed was, on average, lower for shorter distances and higher for longer distances.

2) Driving while loading
The time consumption for driving while loading depended on the driving distance and driving speed, whereas the driving distance while loading depended on the timber density on the strip road [m^3/100m]. The time consumption for driving while loading (Eq. 16) was defined according to the average driving speed. The driving distance was calculated as a computational distance according to the volume per load and the timber density on the strip road (Eq. 17). Timber density on the strip road was further measured by removal of timber [m^3/ha] and the total length of the strip road network [m/ha] (Eq. 18).

$$t_3 = \frac{x_3}{av} = \frac{100}{za} \tag{16}$$

$$x_3 = \frac{100v}{z} \tag{17}$$

$$z = \frac{100r}{s} \tag{18}$$

where
t_3 = time consumption for driving while loading, min/m^3
x_3 = driving while loading distance, m
a = average driving speed when driving while loading, m/min
v = timber volume per load, m^3
z = timber density on the strip road for wood assortment/assortments that is/are being loaded, m^3/100m
r = removal of wood assortment/assortments that is/are being loaded, m^3/ha
s = total length of strip road network, m/ha

The average driving speed while loading was 27 m/min. The total length of the strip road network was 769 m/ha in final fellings (based on an average strip road spacing of 13 m) and 500 m/ha in thinnings (based on an average strip road spacing of 20 m).

3) Definitions of the driving distances
The distances of the driving work phases are usually difficult to estimate or specify separately. Driving distances must still be defined in order to describe the general range and distances in the stand. For these purposes, the average forest haulage distance and its relation to other distances were defined in Equations 19 to 22. The average forest haulage distance is the computational distance from the landing area into the stand where the load is half filled with timber. It describes the general distances and area in the respective stand and can be used as an individual variable when, for example, the total productivity is compared between stands with different hauling distances. These definitions for driving distances were also used in the Finnish study for forwarders (Kuitto et al. 1994).

$$x_{\bar{x}} = \frac{x_1 + x_2}{2} \tag{19}$$

$$x_1 = x_{\bar{x}} + \frac{x_3}{2} \tag{20}$$

$$x_2 = x_1 - x_3 \tag{21}$$

$$x_3 = \frac{100v}{z} \tag{22}$$

where
x_x = average forest haulage distance, m
x_1 = driving empty distance, m
x_2 = driving loaded distance, m
x_3 = driving while loading distance, m
v = timber volume per load, m^3
z = timber density on the strip road for wood assortment/assortments that is/are being loaded, m^3/100m

If the average forest haulage distance is short and the timber density is extremely low, the value of the driving loaded distance (x_2) can become negative due to the formulation of Eq. 21. In order to prevent negative values in the calculations, 50 meters was set as a minimum distance in the model for driving loaded.

4) Loading
The time consumption for loading was modeled separately for final fellings (Eq. 23) and thin-

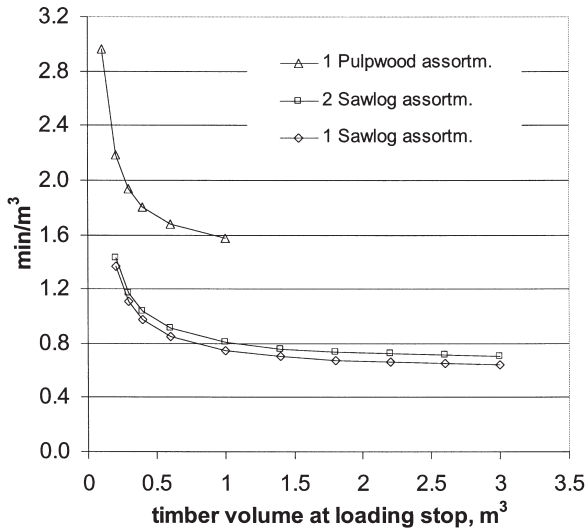

Fig. 3. The time consumption for loading in different loading situations in final fellings as a function of total volume of loaded timber at the loading stop.

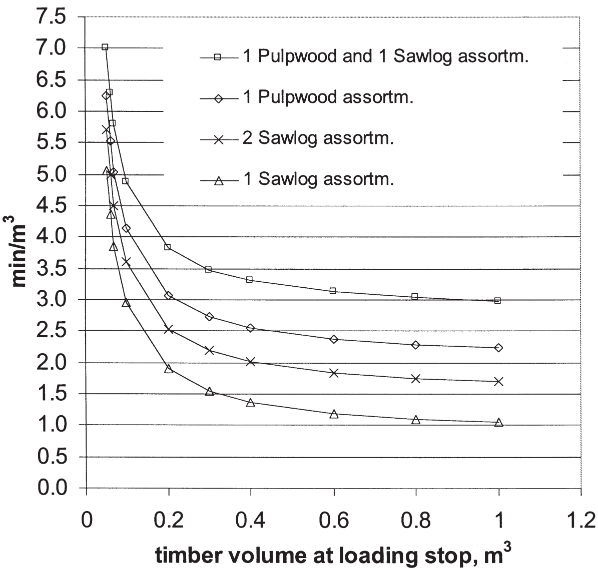

Fig. 4. The time consumption for loading in different loading situations in thinnings as a function of the total volume of loaded timber at the loading stop.

nings (Eq. 24). The time consumption curves in observed loading situations are presented in Fig. 3 for final fellings and in Fig. 4 for thinnings.

Final fellings:

$$t_4 = 0.590 + \frac{0.155}{x_4} + 0.060d_1 + 0.825d_2 \quad (23)$$

where
t_4 = time consumption for loading, min/m^3
x_4 = timber volume at the loading stop, m^3 (loaded wood assortments)
$d_1 = d_2 = 0$ when 1 sawlog assortment is being loaded at the loading stop
$d_1 = 1$, $d_2 = 0$ when 2 sawlog assortments are being loaded at the loading stop
$d_1 = 0$, $d_2 = 1$ when 1 pulpwood assortment is being loaded at the loading stop

Thinnings:

$$t_4 = 2.022 + \frac{0.211}{x_4} + 0.755d_1 - 1.184d_2 - 0.537d_3 \quad (24)$$

where
t_4 = time consumption for loading, min/m^3
x_4 = timber volume at the loading stop, m^3 (loaded wood assortments)
$d_1 = d_2 = d_3 = 0$ when 1 pulpwood assortment is being loaded at the loading stop
$d_1 = 1$, $d_2 = d_3 = 0$ when both 1 pulpwood and 1 sawlog assortment are being loaded at the loading stop (pulpwood is the main assortment)
$d_1 = 0$, $d_2 = 1$, $d_3 = 0$ when 1 sawlog assortment is being loaded at the loading stop
$d_1 = 0$, $d_2 = 0$, $d_3 = 1$ when 2 sawlog assortments are being loaded at the loading stop

5) Timber volume at the loading stop and timber density on the strip road
The relationship between timber volume at the loading stop and the timber density on the strip road was formulated as follows:

$$\ln(x_4) = -0.447 + 0.300\ln(z) - 1.281d \quad (25)$$

where
x_4 = timber volume at the loading stop, m^3 (loaded wood assortments)
z = timber density on the strip road, m^3/100m (loaded wood assortments)
d = 0 in final fellings
d = 1 in thinnings

Table 9. The values of constants u_1, u_2 and u_3 for unloading and driving while unloading function.

Constant	Single loads		Mixed loads	
	Sawlogs	Pulpwood	Sawlogs [a)]	Pulpwood [a)]
	min/m^3			
u_1	0.498	0.522	0.569	0.542
u_2	0.041	0.034	0.061	
u_3	0.008		0.027	
Total	0.547	0.564	0.657	0.630

[a)] According to the main wood assortment in the load.

6) Unloading and driving while unloading
The time consumption for unloading and driving while unloading depended on the type and number of wood assortments being unloaded. The unloading constants were defined separately for pulpwood and sawlogs and for single and mixed loads (Table 9). The total time consumption for unloading and driving while unloading was defined by means of Eq. 26.

$$t_5 = u_1 + u_2 + u_3 \quad (26)$$

where
t_5 = total time consumption for unloading and driving while unloading, min/m^3
u_1 = actual unloading time, min/m^3
u_2 = sorting and arranging time, min/m^3
u_3 = driving while unloading, min/m^3

7) Statistical analyses
Statistical analysis was carried out for each regression model (Table 10). Descriptive statistics were calculated for the mean value based work phase models and other mean parameters (Table 11).

3.2.2 *Total time consumption and productivity*

The total time consumption for forest haulage was defined by connecting work phase models

Table 10. Statistical characteristics of the regression analysis (t = time consumption for work phase, min/m^3; x_1 = driving empty distance, m; x_2 = driving loaded distance, m; x_4 = timber volume at the loading stop, m^3; z = timber density on the strip road, m^3/100m; d = dummy variable).

Work phase model	Dependent variable	R^2	F-test F-value	F-test p	N	Term	Constant/Coefficient Estimate	Constant/Coefficient Std. error	t-test t-value	t-test p
Driving empty (Eq. 14)	t_1	0.884	122.330	<0.001	18	Constant	0.7123	0.416	1.712	0.106
						x_1	0.0149	0.001	11.060	<0.001
Driving loaded (Eq. 15)	t_2	0.905	123.543	<0.001	15	Constant	0.9347	0.479	1.950	0.073
						x_2	0.0185	0.002	11.115	<0.001
Loading, final fellings (Eq. 23)	t_4	0.580	85.106	<0.001	a) 189	Constant	0.590	0.041	14.471	<0.001
						$1/x_4$	0.155	0.017	9.002	<0.001
						d_1	0.060	0.071	0.842	0.401
						d_2	0.825	0.128	6.426	<0.001
Loading, thinnings (Eq. 24)	t_4	0.590	124.516	<0.001	b) 351	Constant	2.022	0.093	21.800	<0.001
						$1/x_4$	0.211	0.010	21.368	<0.001
						d_1	0.755	0.350	2.157	0.032
						d_2	–1.184	0.242	–4.902	<0.001
						d_3	–0.537	0.285	–1.885	0.060
Loading stop function (Eq. 25)	$\ln(x_4)$	0.898	105.712	<0.001	27	Constant	–0.447	0.289	–1.545	0.135
						$\ln(z)$	0.300	0.107	2.792	0.010
						d	–1.281	0.165	–7.770	<0.001

a) The number of observations in the different loading situations in final fellings:

1 sawlog assortment	134
2 sawlog assortments	41
Pulpwood	14
Total	189

b) The number of observations in the different loading situations in thinnings:

Pulpwood	299
Pulpwood and sawlog	11
1 sawlog assortment	24
2 sawlog assortments	17
Total	351

Table 11. Descriptive statistics of the mean value based work phase models and other mean values. Parameters and values used in the work phase models are in boldface (a = average driving speed when driving while loading, m/min; u_1 = actual unloading time, min/m^3).

Element	Parameter in model	Mean	Min	Max	Std. dev.	Weighted mean a)	N
			m/min				
Driving speed when empty		51.4	26.3	87.3	14.4	56.0	18
Driving speed when loaded		39.5	14.5	58.7	13.9	43.9	15
Driving speed when driving while loading (Eq. 16)	$\boldsymbol{a}$	33.7	7.6	93.8	19.9	**26.7**	27
			min/m^3				
Actual unloading time (Eq. 26)	$\boldsymbol{u_1}$						
Sawlog, single loads		**0.498**	0.17	1.76	0.308	-	166
Pulpwood, single loads		**0.522**	0.30	1.14	0.148	-	75
Sawlog, mixed loads		**0.569**	0.18	4.00	0.542	-	166
Pulpwood, mixed loads		**0.542**	0.26	5.39	0.640	-	69

a) Observed mean value of sample loads weighted with the time consumption proportion of each load.

together and adding up the time consumed in each work phase (Eq. 27).

$$t_{tot} = t_1 + t_2 + t_3 + t_4 + t_5 \quad (27)$$

where
t_{tot} = total effective time consumption for forest haulage, min/m^3
t_1 = time consumption for driving empty, min/m^3
t_2 = time consumption for driving loaded, min/m^3
t_3 = time consumption for driving while loading, min/m^3
t_4 = time consumption for loading, min/m^3
t_5 = time consumption for unloading and driving while unloading, min/m^3

Total effective time consumption was converted into delay-free productivity (Eq. 28) and gross-effective productivity (Eq. 29):

$$p_e = \frac{60}{t_{tot}} \quad (28)$$

$$p_{ge} = \frac{p_e}{1.084 \times 1.224} \quad (29)$$

where
p_e = productivity, m^3/effective hour
t_{tot} = total effective time consumption for forest haulage, min/m^3
p_{ge} = productivity, m^3/gross effective hour (including <15 min delays)
1.084 = gross effective time coefficient for effective time (Kuitto et al. 1994)
1.224 = follow up coefficient for gross effective time (Kuitto et al. 1994)

Depending on the load type, in final fellings total productivity decreased by 15 to 17% when the average forest haulage distance increased from 200 to 400 m. Hauling single sawlog loads was 42% more efficient than hauling pulpwood and 7% more efficient than hauling mixed sawlog loads when the removal of timber for each load type was, for example, 60 m^3/ha (Fig. 5).

In thinnings, depending on the load type, total productivity decreased by 10 to 13% when the average forest haulage distance increased from 200 to 400 m. Hauling single pulpwood loads was 15 to 19% more productive than hauling both pulpwood and sawlogs in the same load (pulp-

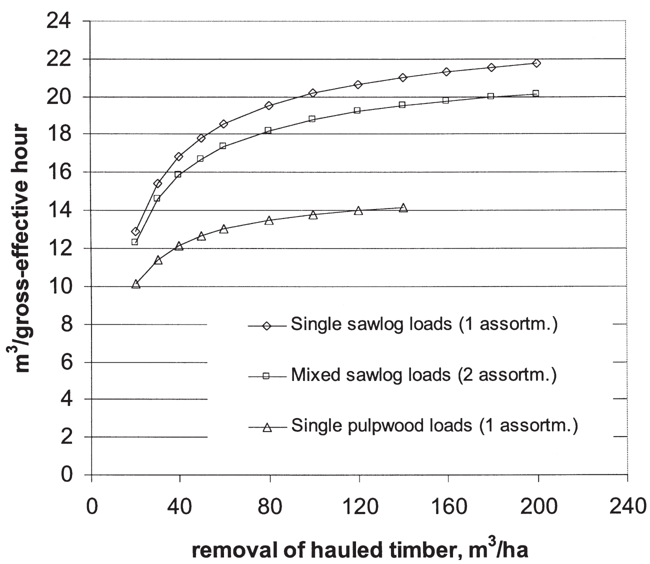

Fig. 5. Productivity of forest haulage in final fellings as a function of removal of hauled timber [m^3/ha]. The average forest haulage distance is 250 m. Volume per load is 14 m^3 for sawlog loads (the 2 upper curves) and 11 m^3 for pulpwood loads (the lower curve).

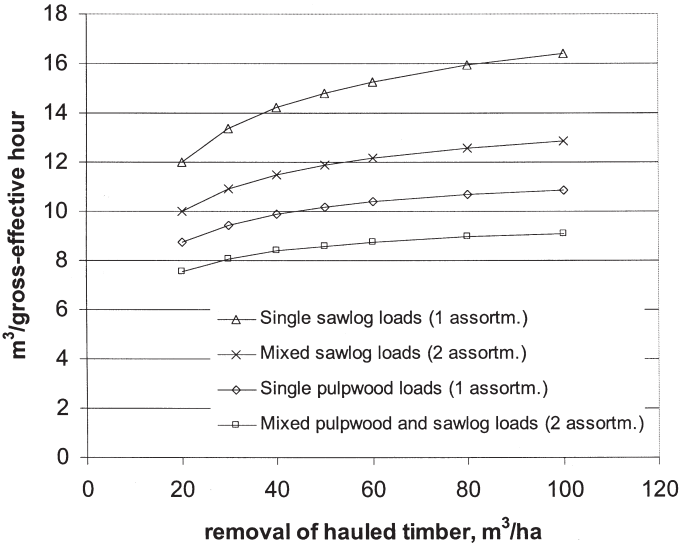

Fig. 6. Productivity of forest haulage in thinnings as a function of removal of hauled timber. The average forest haulage distance is 250 m. Volume per load is 14 m^3 for sawlog loads (2 upper curves) and 11 m^3 for pulpwood and mixed pulpwood and sawlog loads (2 lower curves).

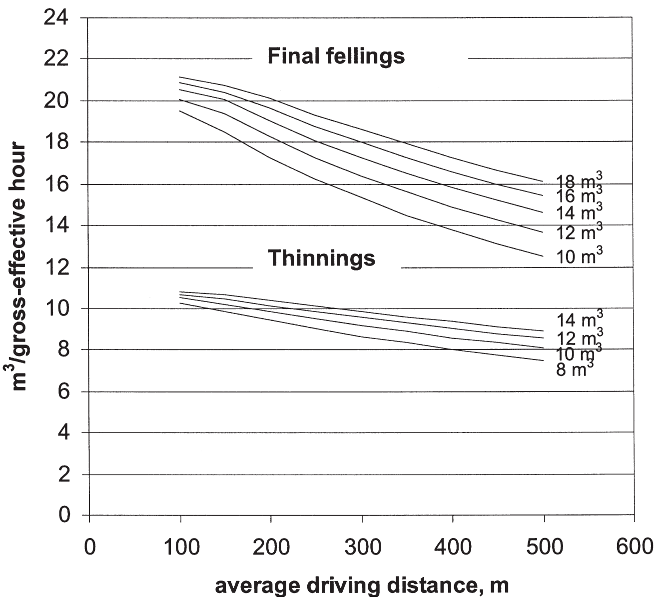

Fig. 7. The effect of load volume on the productivity of forest haulage in final fellings (single sawlog loads) and thinnings (single pulpwood loads). Timber density on the strip road is 7.0 m^3/100m in both stand types.

wood as the main assortment). Hauling single sawlog loads in thinnings was 40 to 43% more productive than hauling pulpwood and 20 to 25% more productive than hauling 2 sawlog assortments in mixed loads (Fig. 6).

The total volume of the load affected the productivity of forest haulage especially for the longer haulage distances. In final fellings the productivity increased 10% when the volume per load increased from 10 to 14 m^3 in an average driving distance of 200 m. The increase in productivity was 15% when the average driving distance was 400 m. The same increase in load volume in thinnings increased the productivity by 5% for an average driving distance of 200 m and 9% for an average driving distance of 400 m (Fig. 7).

4 Discussion

Due to the limited number of study stands, operators and work cycles, the results do not represent the nationwide time consumption and productivity level of mechanized cutting and forest haulage, but give trends and estimates for the work performance of the modern cut-to-length harvesting system operating in unfrozen and snowless stands in relatively easy Finnish terrain. In final fellings there were both spruce and pine dominated stands, whereas the study material in thinnings consisted of pine stands due to the risk of silvicultural damage in spruce dominated areas in summer. The removal of timber in the studied thinnings was also relatively low, average 33 m^3/ha. Second thinnings with relatively high removal and working conditions more similar to final fellings than first thinnings were not studied.

The models for effective time introduced in this paper are valid and accurate in analyzing the factors affecting the time consumption for work phases and finding comparable differences, for example, between tree species, wood assortments and driving distances. The variation caused by the human factor was leveled out by studying several professional operators who used the same working technique and were familiar to the studied forest machines. Since the operators were observed for rather short periods, there is, however, a risk that their performance was affected by the study situation, even if they were asked to work as normally as possible. Many large studies have revealed that the productivity of the operators may rise to a higher level during the time study than in normal working periods (e.g. Kuitto et al. 1994, Ryynänen and Rönkkö 2001). In this respect, taking into account the limitations of the data and utilizing the gross-effective and follow-up coefficients (e.g. Kuitto et al. 1994), the functions should also give rather accurate estimates for the present productivity level of the CTL operations.

The video camera as a data collecting tool proved to be appropriate and enabled the separation and analysis of very short time elements, for example, inside the work phases of processing and loading. The dimensional information of tree stems and logs based on the stem files of the harvesters' measuring computers was detailed and suitable for the study purposes. The exploitation of stem files was seen as a more efficient and accurate way than, for example, the pre-harvest measurements of the sample trees.

The arguments that suggest analyzing the cutting and forest haulage closely together as a complete system (e.g. Tufts and Brinker 1993, Kellogg and Bettinger 1994, McNeel and Rutherford 1994, Tufts 1997), were further supported during the data collection and analysis. Since the cutting phase defined the working environment of the forest haulage, for example, in the case of loading by means of the volume of timber to be loaded and characteristics of the pile size and structure, the findings that the harvesting result of the harvester operator has a significant effect on the efficiency of forest haulage (Väätäinen et al. 2005) were strongly verified. In this respect, a very demanding, but also a very informative way of study might be the combined analysis of the CTL-harvesting system that includes the harvesting result as an independent variable or group of variables in the modeling of forest haulage performance.

The time consumption modeling of cutting and forest haulage differ from each other especially from the standpoint of an observation unit: a single stem forms one observation and a rather solid work cycle for cutting, whereas for the forest haulage work cycle, the time consumption of the whole load must be observed. The loading phase makes an exception to this as the loading stop may be handled as an observation unit (see Eqs. 23 and 24). Due to the small number of work cycles observed in forest haulage, no breakdown of the time consumption was presented in the results.

Both parts of the CTL system share difficulties, when comparing the absolute level of the time consumption for a single work phase and especially the total productivity between studies. Differences may be found in, for example, stand conditions, working techniques, machinery and the operators' experience. Even if several basic concepts and standards for time studies are introduced (e.g. Björheden 1991), the methodological aspects, like the work phase classification, variable definitions and measurement systems also often vary. In the Swedish productivity norms for forwarders (Brunberg 2004), for example, timber volume was measured without the bark and the average hauling distance was defined as the distance between the landing area and the timber volume weighted at the midpoint of the stand area. Brunberg (2004) also used a different kind of work phase classification: loading, driving while loading and unloading were combined and considered together as terminal time. In some respects though, the comparisons are valid and informative.

The moving work phase for cutting was modeled as an average moving time by stand type, whereas in the study of Kuitto et al. (1994) the moving time in final fellings was observed to be highly dependent on stem size. Due to the limited number of observations (only 1 per sample area) in this study, no significant dependence of moving time on the number of removed stems per hectare or stem size was observed. This kind of analysis would have required both time consumption and distance information from every single working location. These measurements would have adversely affected the operators' work. However, the time consumption for moving was observed to be 29% greater in thinnings than in final fellings. Also the t-test clearly indicated the difference between stand types. This was mainly due to the fact that the operators watched the remaining trees and placed the harvester more carefully in the working location in thinnings than in final fellings.

In thinnings the time consumption for moving has been proved to decrease when the number of removed stems increases (Kuitto et al. 1994, Sirén 1998) or the stem size decreases (Ryynänen and Rönkkö 2001). The average time consumption for moving was proved to be at rather a similar level in this study compared to other studies in the most typical stand conditions of thinnings. For example in the range of 300 to 600 removed stems per hectare, the time consumption for moving was 0 to 14% higher in this study than in the study of Sirén (1998) and 0 to 10% lower than in the study of Ryynänen and Rönkkö (2001) in the stem size range of 0.05 to 0.1 m^3.

The time consumption for positioning-to-cut was not observed to depend on stem size or differ between stand types, while the time consumption for felling was slightly dependent on stem size. This resulted from the fact that the felling cut and the actual felling of the tree took longer in the case of large stems. In thinnings, however, the relationship was very weak. Even if the regression model fitted to the data and the residuals were symmetrical, the share of unpredictable variation in the model was high. This was mainly due to the fact that all stems felled in thinnings were rather small and that the time consumption for transferring the stem after felling varied a lot and was not dependent on stem size. Also Sirén (1998) and Ryynänen and Rönkkö (2001) reported rather weak coefficients of determination for this work phase model in thinnings.

The time consumption for felling took 2 to 3% less time in thinnings than in final fellings when the stem size was the same. This may be due to the difference in tree species: in thinnings practically all the harvested trees were pines whereas in final fellings the stems equal in size to those in thinnings were typically spruce or birch trees. According to Kuitto et al. (1994) the felling of pine stems in thinnings is less time consuming than the felling of the other tree species.

Because no separate models of the time consumption for positioning-to-cut and felling in final fellings was presented in the other studies, the time consumption comparisons were only made in the circumstances of thinnings. In the stem size range of 0.03 to 0.3 m^3, the combined time consumption for positioning-to-cut and felling was 6 to 8% lower than in the study by Ryynänen and Rönkkö (2001) and 16 to 29% lower than in the study by Sirén (1998). The rather clear difference compared to Sirén's model may be due to the harvested tree species: the study stands in that research were spruce dominated.

When modeling the most important and time-consuming work phase of cutting, delimbing and cross-cutting, the observations were not distributed evenly: the number of stems larger than 1.0 m^3 in final fellings, and 0.3 m^3 in thinnings, was rather small. In addition, the variation in the time consumption increased as the stem size increased. Different transformations and curve types were tested to get the residuals of the regression models as symmetrical as possible and to achieve the best values for the coefficients of determination. The functions for delimbing and cross-cutting were considered reliable up to 1.2 m^3 for final fellings and 0.3 m^3 for thinnings.

In addition to these statistical indicators, the choices for curve types were made according to the characteristics of the harvester machinery. In final fellings, the time consumption for processing pine and birch stems was slightly exponential due to the limitations of the harvester head and crane: when the stems were a certain size, the transferring, feeding and delimbing of the stem started to become difficult. No such exponential growth was observed in the case of spruce. The processing of pine stems larger in size than 0.9 m^3 and birch stems larger in size than 0.4 m^3 was slower than processing spruce stems due to the fact that, from the standpoint of delimbing, the branches of pine and birch were thicker and the branch angles were less favorable than in the case of spruce. Glöde (1999) also observed that delimbing became markedly more difficult when the average thickness of branches exceeded 7 to 8 cm.

The bunching and sorting time in different bucking situations was based on the operators' working technique where the logs were piled either onto their own piles or at least onto the different sides of the piles. When adding the average time consumption for bunching and sorting to the processing time, it was to some extent possible to take into account the bucking control of the stand and its effect on the productivity. The time consumption for the operators' manual bucking decisions and quality observations was, however, impossible to measure. In this respect, the results concerning the effect of bucking on the processing time were slightly underestimated.

As with the positioning-to-cut, the boom-in time was observed to be rather constant and not dependent on stand type, but on the location of the processing, which was typically a few meters from the base machine. The deviation in time consumption was, however, small (see Table 7). The study stands contained rather small amounts of unmerchantable trees to be cleared. In stands containing a dense undergrowth, the proportion of clearing time would have been significantly larger. The undergrowth would probably also slow, for example, positioning-to-cut and bunching. Moving logs, tops and branches took 64% more time per stem in final fellings than in thinnings. This was due to the fact that the piles were larger in size and included several wood assortments.

The differences in productivity between the two techniques presented in this paper, the work phase based model and the overall productivity model, varied from –2 to 4% with pine, –9 to 4% with spruce and –2 to 2% with birch in the stem size range of 0.3 to 0.8 m^3. The variation in productivity in the case of large stems was due to the quadratic formulation of the overall productivity model. However, both techniques proved to fit well with the observations and to reliably predict the productivity. The advantage of the work phase based model was, above all, the possibility to observe the harvesting work more carefully, as the overall productivity model gave the same results concerning the total cutting work in a simpler form. This modeling of overall productivity with quadratic formulation has been used in several studies dealing with the productivity of cutting (e.g. Sirén 1998, Ryynänen and Rönkkö 2001, Kärhä et al. 2004).

Depending on stem size, in this study the productivity of cutting in final fellings was 14 to 35% higher with pine, 12 to 34% higher with spruce and 5 to 21% higher with birch compared to the study of Kuitto et al. (1994). The differences were always greater with large stems. In thinnings no such difference was observed, but the productivity was practically at the same level. Even if these two studies are based on data of very unequal size, the findings presented in this article may reveal that changes in factors affecting cutting work have taken place.

The machine development, for example, may be seen especially in final fellings with large stems. The power of diesel engines and hydraulics has increased. Technical features in the harvester head such as feeding motors and rolls, delimbing knives and the sawing motor have been developed. The lifting capacity and maximum reach of cranes have also improved. Furthermore, the measuring and bucking computer and automatics of the harvester are much more advanced than, for example, 10 to 15 years ago.

In thinnings, however, the cutting performance is a more complex combination of different factors. The stem size, for example, explains only part of the efficiency. The role of the operator is more important when choosing the trees that will be removed, planning the strip roads and moving the crane and the harvester head. This kind of tacit knowledge has been proved to be a significant factor in the efficiency of cutting and also to vary markedly between operators (Ovaskainen et al. 2004, Väätäinen et al. 2005).

The work cycle of forest haulage consists of very different types of work phases that depend on several factors in time consumption. The time consumption for, for example, driving empty and driving loaded was largely dependent on driving speed, driving distance, but also timber volume per load. The number of observations for the driving regression models (Eqs. 14 and 15, see also Table 10) was small, but the observations were distributed evenly in relation to the driving distance. The terrain conditions were also quite similar between the study stands. Statistically, the standardized residuals of the models were rather symmetrical and normally distributed. According to the high levels of the coefficients of determination and the result of the F-test, both models proved to fit the observations (Table 10). Also the numerical coefficients of dependent variables proved to be statistically significant in the t-test ($p<0.05$).

According to Kuitto et al. 1994, the stand type (final felling/thinning) has not been observed to affect the time consumption for these work phases. Brunberg (2004), however, has reported that the driving speed is 10 to 20% slower in thinnings than in final fellings. In this study, neither of these conclusions could been confirmed due to the limited amount of material.

The time consumption level of driving empty and driving loaded observed in this study was quite similar to that found by Kuitto et al. (1994). The average driving speed when empty, for example, was 56 m/min in both studies. Since the proportion of acceleration and stopping time is higher with shorter distances, the driving speed was observed to be lower for shorter distances than for longer ones in both studies.

In the Swedish forest haulage study by Gullberg (1997b), time consumptions for driving empty and driving loaded were handled together as driving. Also unlike the Finnish studies, Gullberg (1997b) divided driving into two categories: driving on the strip road and driving on the main haulage road, in which driving speeds may differ significantly. A precise comparison to Gullberg's model would have required the classification of the off-road type; no proportions of driving on the main haulage road and strip road were examined in this study.

The time consumption for driving while loading decreased due to the shortening of driving distance as the timber density on the strip road (and the removal of timber) increased (Eq. 16). The difference in time consumption between stand types during the same removal of timber was due to the differences in strip road spacing. Since the total length of the strip road network was 769 m/ha in final fellings and 500 m/ha in thinnings, the same removal of timber was more spread out on the longer distance of the strip road in final fellings than in thinnings.

The average driving speed while loading in this study was 27 m/min. Kuitto et al. (1994) reported only a slightly higher value, 29 m/min. In Gullberg's study (1997b), depending on timber density on the strip road, the driving speed varied from 25 to 30 m/min in final fellings and 23 to 30 m/min in thinnings.

From the modeling standpoint, loading has been considered the most complex and difficult work phase of forest haulage, because the unexplained variation in loading efficiency is great and only a few significant variables can be used in regression analysis for the time consumption (Gullberg 1997a, b). In this study, timber volume at the loading stop was used as an independent variable, since it describes both work conditions at the loading stop level, but also enables the time consumption analysis at the stand-level, as a function of timber density on the strip road.

Statistically, the regression models for the loading phase fit rather well to the data in general. In both stand types, timber volume at the loading stop explained nearly 60% of the variation in the time consumption (see table 10). However, observations of loading in different loading situations were not distributed evenly. Only the results concerning the most typical situations, where 1 sawlog assortment in final fellings and pulpwood in thinnings were being loaded, can be considered reliable, whereas the results concerning the other loading situations are only indicative.

Loading was most effective with high timber volumes and from the large piles, because it made it possible for the operator to load full or almost full grapple loads of timber. When the timber volume at the loading stop increased enough, the loading conditions became rather optimal as the whole capacity of the grapple was utilized (Fig. 3 and 4). This relationship between loading efficiency and pile and grapple volume has been reported also by Gullberg (1997a,b) and Väätäinen et al. (2005). In this study, the average grapple volume was 0.16 m^3 and the average pile size was 0.19 m^3 for pulpwood in thinnings. In other words, operators occasionally needed two loading cycles in order to remove the whole pile into the bunk. The importance of pile and grapple volume to loading was emphasized in thinnings where removal of timber was typically small and piles were scattered onto the strip road. In addition to removal of timber, pile volume is also a result of the method of bunching and the working habits of the harvester operator (Väätäinen et al. 2005). The bunching result was, however, rather similar among the studied operators according to visual observations.

The time consumption for loading was also significantly affected by the type of wood assortment (sawlog/pulpwood) at the loading stop. Kuitto et al. (1994) also observed this relationship. The average length of pulpwood has also proved to have an effect on the loading performance: according to Kuitto et al. (1994) loading of short pulpwood (logs shorter than 3.6 m) takes significantly more time than long pulpwood (logs longer than 3.6 m). In this study loading was not modeled separately for short and long pulpwood, because the pulpwood logs were bucked according to minimum small-end diameter without any fixed log lengths.

In final fellings, differences in the loading efficiency between sawlogs and pulpwood were mostly due to the fact that the pile and grapple volume of pulpwood was typically smaller than that of sawlogs. Since the pulpwood piles were also typically more scattered and their shape was more uneven than sawlog piles, arranging the piles on the ground and the logs in the bunk took considerably more time with pulpwood than sawlogs. The great variation in the log length (2.3 to 5.9 m) also made it difficult for operators to handle pulpwood. At those loading stops where 2 different assortments were loaded, the sorting and handling of logs took more time than in the case of only one assortment.

The maximum grapple volume has proved to be a significant factor affecting unloading (Gullberg 1997a, b). In this study, however, grapples were rather similar in the studied forwarders, representing a typical grapple for a medium-sized forwarder. Grapple volumes in different unloading situations were also rather similar. The sorting and arranging of logs took 50 to 80% more time in mixed loads than in single ones. Gathering the grapple load from the bunk was very much slower especially in the case of mixed sawlog loads than for single ones. This explained the difference in the actual unloading time between single and mixed sawlog loads. The time consumption for driving while unloading was over three times higher in mixed loads than in single loads. Driving between landing piles is though greatly dependent on conditions at the landing area: if piles are situated on both sides of the forest road, for example, there may be no driving at the landing area at all, even if the load consists of 2 to 3 assortments. The results presented in this paper concerning unloading can not be generalized to apply to every possible unloading situation, but give a general perspective on factors affecting this work phase.

The main factors that have been shown to affect the work performance of forest haulage in large time studies (e.g Kuitto et al. 1994): stand type, timber density on the strip road, average driving distance, load capacity and the type of wood assortment, were also clearly recognized in this study. In final fellings for an average driving distance range of 100 to 500m, the productivity of hauling single sawlog loads was only 3 to 10% higher in this study than the productivity of hauling sawlogs in general in the study of Kuitto et al. (1994). In thinnings, however, the productivity of hauling pulpwood in this study was on average 15 to 20% lower than in the study of Kuitto et al. (1994). The comparisons were made by standardizing the load volume to 14 m^3 for sawlog loads and 11 m^3 for pulpwood loads.

Even if improvements in the forwarder machinery, for example in cranes, have taken place, the working environment of forwarder operators has changed: during the past 10 to 15 years the number of wood assortments has increased and the piles are bunched in a more scattered way, at least in thinnings. In other words, the conditions of loading and unloading have became more demanding.

This study focused on the effective time which is only a part of the total work. Development in the durability of the machinery, operative planning and the operators' skills have a crucial effect on long-term productivity and on the technical and operative grade of machine utilization. The CTL-harvesting system is still widely operated and controlled from the standpoint of the most expensive and capital-binding part of the system: the cutting and the single-grip harvester. The interesting questions is, how to optimize the total performance of the harvesting so that the negative impacts of the unbalanced productivity between the two parts of the system can be reduced. Furthermore, quality requirements and environmental issues have affected forest work and influenced productivity, and also the profitability of harvesting as a business activity. These issues set requirements for versatile research, in which the models for time consumption form a reliable basis. The results may also be used in simulations, cost calculations and education.

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Appendix. Studied machines, harvester operators (A–J), forwarder operators (K–S) and the division of data between stands, operators and machines.

Stand no	Harvester	Model	Harvester head	Operator	Number of stems	Observed effective time, min	Forwarder	Model	Operator	Number of loads	Observed effective time, min
Final fellings											
1	Timberjack 1270 B	2000	Ösa 746 C	B	73	57	Valmet 860	1998	K	2	51
2	Ponsse HS 16 Ergo	2003	H 73	C	79	47	Ponsse S16 Buffalo	1998	L	2	66
3	Valmet 911.1	2004	960	D	40	53	Valmet 860	1998	M	3	59
4	Timberjack 1270 B	1998	755 B	E	93	61	Timberjack 1110	1998	N	3	43
5	Timberjack 1270 C	2001	758	F	67	56	Timberjack 1110	1998	O	1	39
6	Logman 801	1997	Keto 150	G	77	59	Valmet 840	1997	P	2	80
7	Timberjack 1270 C	2001	758	H	83	54	Timberjack 1110	1998	O	2	53
8	Timberjack 870 B	1997	745	I	26	24	Timberjack 1110	1995	Q	2	52
9	Ponsse HS 16 Ergo	2003	H 73	C	98	61	Ponsse S16 Buffalo	1998	L	1	35
Thinnings											
1	Timberjack 1270 B	2000	Ösa 746 C	A	69	35	Valmet 860	1998	K	1	82
2	Timberjack 1270 B	2000	Ösa 746 C	A	74	58	Valmet 860	1998	K	2	132
3	Timberjack 1070	2000	745	J	138	57	Lokomo 910	1991	R	2	113
4	Timberjack 1070	2000	745	J	149	57	Lokomo 910	1991	S	2	113
5	Timberjack 870 B	1997	745	I	139	72	Timberjack 1110	1995	Q	2	127