SILVA FENNICA

Silva Fennica 41(3) research articles

www.metla.fi/silvafennica · ISSN 0037-5330
The Finnish Society of Forest Science · The Finnish Forest Research Institute

Characteristics and Time Consumption of Timber Trucking in Finland

Tuomo Nurminen and Jaakko Heinonen

Nurminen, T. & Heinonen, J. 2007. Characteristics and time consumption of timber trucking in Finland. Silva Fennica 41(3): 471–487.

Cost efficiency and flexibility have become increasingly important in the logistics of cut-to-length harvesting operations. At the same time, the operating conditions for long-distance transportation have become more demanding and variable. Since the number of log products has increased and the size of harvesting sites has decreased, loads of timber must increasingly be collected from several log decks, increasing the time consumption and costs of the trucking operation. The objectives of this study were to formulate time-consumption models for typical timber transportation activities in Finland and introduce a statistical procedure for examining the variation in time consumption during the trucking phases. The study used a combination of time studies and follow-up studies based on empirical data for 368 loads (a total volume of nearly 18 000 m^3) collected from one wood procurement district in central Finland. The model included the following explanatory factors: driving distance, number of log decks, log product and load volume. Since transportation includes several phases and since many factors affect the work performance, significant variation in the total transportation time was observed. This makes planning and cost accounting more difficult. The models developed in this study are a promising initial tool to support route planning and optimization, and cost and profitability calculations for trucking entrepreneurs and the forest industry.

Keywords cut-to-length operations, logistics, time study, work phases, log-normal distribution
Authors' addresses *Nurminen*, University of Joensuu, Faculty of Forest Sciences / Forest Agency Tuomo Nurminen, Joensuuntie 5 B 8, FI-41800 Korpilahti, Finland; *Heinonen*, Finnish Forest Research Institute, Joensuu Research Unit, P.O. Box 68, FI-80101 Joensuu, Finland
E-mail tuomo.nurminen@metsatoimisto.fi
Received 19 June 2006 **Revised** 2 May 2007 **Accepted** 12 July 2007
Available at http://www.metla.fi/silvafennica/full/sf41/sf413471.pdf

1 Introduction

The long-distance transportation of harvested wood is an important part of the forest industry's supply chain. Under Nordic conditions, transportation is carried out by road, railway, water, or a combination of these modes (Uusitalo 2005). Since the demand for an accurate supply of raw material and high quality and flexibility in the logistics upstream of mills have become increasingly emphasized, trucking has become the most important mode of long-distance transportation (Väkevä 1999). In Finland in 2004, 80% of the domestic roundwood was hauled directly to the mill by a fleet of 1280 trucks (Finnish Statistical Yearbook… 2005).

The Nordic cut-to-length (CTL) system provides the primary context for road transportation of wood. In this system, trees are felled and the stems are processed to specified log dimensions (i.e., are cut to length) at the stump, then the logs are moved to roadside decks where they are subsequently loaded and transported by truck to storage yards at mills or at railway and water transfer points. The timber trucks are designed to operate on public roads, but must also work under demanding conditions on narrow and sometimes poorly maintained forest roads. The demand for cost efficiency requires trucks that are light and dependable and able to carry large payloads. Trucks must be equipped with removable timber cranes (self-loaders), since there are no separate loaders at the deck. In Finland, the truck stock is rather uniform. A typical unit consists of a three-axle tractor and a four-axle trailer (Puutavaran kuljetus… 1998, Peltola 2004). The total mass of the vehicle, including payload, is limited by legislation to 60 t (Puutavaran kuljetus… 1998). The total length of these trucks is typically 22 m (Väkevä 1999).

The cost efficiency and flexibility of timber transportation are typically improved by route and resource optimization. To reduce costs and facilitate the planning of wood procurement, Korpilahti (1989) introduced a model for dimensioning the truck fleet based on payload volumes. Simulation techniques have also been used to analyze transportation costs as a function of vehicle and road characteristics (McCormack 1990). Other researchers have suggested reducing unit costs and allocating timber flows more efficiently by minimizing the proportion of empty travel (i.e., driving without payload) by implementing backhauling, a transportation method in which the truck hauls a load to a new mill on its return from another mill instead of traveling without a load (e.g., Carlsson and Rönnqvist 1998, Palander et al. 2002).

Recently, inter-enterprise collaboration in timber logistics has also been considered as a possible way to increase the cost-efficiency of haul operations because this approach provides more opportunities for backhauls (Forsberg 2003, Palander and Väätäinen 2005). In addition to seeking cost savings for the transportation phase, efforts have been made to intensively integrate timber transportation with other wood supply processes, such as in the control of the products produced by in-woods processing (i.e. bucking), with the aim of maximizing net profits (Arce et al. 2002).

The wood supply chain has been adjusted to meet the customer's requirements for increasingly refined log specification and increasing delivery flexibility. At the operational level, this can be seen in the processing phase: the number of log products produced in the woods has increased, while the lot (shipment) size has decreased (Uusitalo 2005). This has affected both time consumption and costs in transportation operations because roundwood must be hauled from an increasing number of log decks (Väkevä et al. 2000). In this respect, both the forest industry and private entrepreneurs who haul roundwood must be able to control their costs so they can run their business profitably. There are also some indications that the responsibility for delivery of roundwood will increasingly be given to transportation entrepreneurs (Palander and Väätäinen 2005). In this situation, effective operational planning and control of costs and revenues become even more important.

Information about the characteristics that affect the performance and time consumption of timber transportation forms a basis for route planning, optimization, and cost calculation. During the last three decades in Finland, several studies of time consumption and fleet performance have been performed. Savolainen (1977) studied the impact of different products (sawlogs, pulpwood) on loading efficiency. Myllyniemi (1980) analyzed the factors affecting time consumption for loading long pulpwood logs. Voipio and Korpilahti (1988) presented the characteristics of roadside decks and their impact on loading conditions. Recently, Väkevä et al. (2000) compared the time consumption for multi-sourced loads (loads that are hauled from several decks) and single-sourced loads (loads hauled from a single deck). Pennanen (1984) and Alve (1988) investigated the breakdown of transportation activities into main work phases as well as introducing time-consumption models for 48-t trucks.

However, current truck fleets and operating conditions differ greatly from those in previous decades, and these differences have rendered older models invalid or inaccurate. Above all, there is a lack of comprehensive time-consumption data and models suitable for trucking activities in the 2000s based on the logistics of the modern Nordic CTL system. Furthermore, from the standpoint of cost calculations and route planning, models must account for more than just the average situation; they must also account for the variation in time consumption.

The objectives of the present study were thus to provide sound data that would permit the formulation of time-consumption models for trucking activities in Finland and to introduce a statistical procedure for evaluating the variation in time consumption during the various trucking phases. The study focused on the wood-procurement logistics and transportation of roundwood from decks to mills and transfer yards in the Nordic CTL system.

2 Materials and Methods

2.1 Transportation Environment and General Study Setting

The research was carried out as a combination of time studies and follow-up studies in one wood procurement district in central Finland. The study period lasted from 1 August to 2 September 2005. During this period, 12 sawlog and 9 pulpwood products were transported to 1 paper mill, 1 pulp mill, 5 sawmills, 1 veneer mill, and 1 log cabin manufacturer. The products were allocated into four main groups: 1) mixed lengths (ranging from 3.1 to 6.1 m) of normal, small, and special-length Norway spruce (*Picea abies* (L.) Karst.) and Scots pine (*Pinus sylvestris* L.) sawlogs; 2) 2.6-m spruce veneer logs; 3) long spruce and pine pulpwood, with mixed lengths (ranging from 2.5 to 6.0 m) permitted but a target length of 5.0 m; and 4) 3.0-m birch (*Betula* spp.) and aspen (*Populus tremula* L.) pulpwood.

2.2 Drivers and Trucks

Transportation was carried out by private trucking entrepreneurs. During the 1-month study period, 13 professional drivers participated in the study. Most had significant experience in hauling roundwood, and each had transported roundwood full-time for at least the last 2 years. Nine drivers worked mainly in a two-shift system, but four worked in a single-shift system. The shift arrangements, however, varied during the study period.

Table 1. Technical specifications for the timber trucks in the study.

Make	Model	Year of manufacture	Engine, kW	Trailer	Crane
Scania	R164 GB 6×4	2000	427	Extendable	Foresteri 2010TH
Scania	R164 GB 6×4	2004	427	Extendable	Loglift 96
Scania	R164 GB 6×4	2003	427	Fixed frame	Foresteri 2010T
Volvo	FH12 6×4	2000	338	Extendable	Foresteri 2009TH
Volvo	FH16 6×4 R610	2004	449	Fixed frame	Jonsered 1020
Mercedes-Benz	2648-L 6×4	1999	350	Fixed frame	Loglift 96
Mercedes-Benz	Actros 3350 6×4	2005	370	Fixed frame	Loglift 96
Sisu	E18M 6×4	2004	464	Extendable	Loglift 105

A total of eight trucks were included in the study. The trucks were chosen to permit comprehensive observation of the transportation environment (e.g., driving distances, log products, and mill yards) for the whole district. Each tractor had three axles (a 6×4 axle configuration) and pulled a four-axle trailer. Trucks were equipped with a removable hydraulic timber cranes (Table 1). Trailers were either extendable or fixed-length, with movable load-bunk frames.

2.3 Data Collection

The study covered the regular working hours of the drivers, and we defined a "transportation time" (described in Fig. 1) that was divided into the main work phases shown in Table 2. Loads were divided into two main types: single-sourced loads were hauled from a single log deck, whereas multi-sourced loads were collected from two or more log decks. In this study, a "log deck" was defined based on the wood procurement company's practices, in which a pile or several piles in close vicinity at a single site were considered to be a single deck. All logs of a certain product in a deck area were collectively considered to be as a "timber lot". Each load could thus include one or more lots, either because the load consisted of more than one product or because the wood was collected from several decks. All the timber in each load was, however, always transported to the same mill.

During the time study, work phases were further divided into time elements that were recorded using a Rufco 900 field computer with an accuracy of 1 cmin (0.6 s) as if the observer was using a stopwatch. The time analyst observed the transportation work while sitting in the truck's cabin. Driving distances were measured using the truck's odometer, with an accuracy of 100 m. Roads were divided into three categories: 1) paved asphalt roads, 2) unpaved gravel roads, and 3) forest roads. Volumes (solid m^3 including bark) and masses of the timber lots were based on scaling operations at the mill yards.

During the follow-up study, each work shift during the study period was analyzed (excluding days when the time study was conducted) by asking drivers to independently complete a form

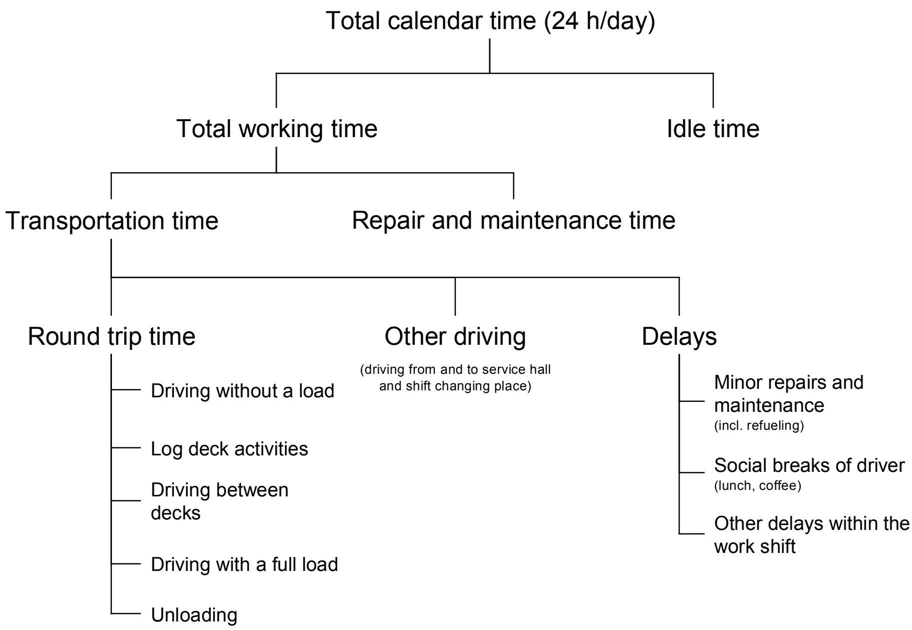

Fig. 1. Division of time in timber trucking operations.

Table 2. Main work phases that make up total transportation time.

Work phase	Definition
Driving without a load	Begins when the truck leaves the mill storage area after unloading and ends when the truck stops at a log deck to receive a new load. Preparations, maneuvering the truck in the deck area, and miscellaneous navigation times (e.g., using a GPS map system) are included in this phase.
Log deck activities	Begins when the truck stops at a log deck and the driver starts to prepare for loading and ends when the truck leaves for the mill or for travel to the next deck. Log deck activities activities were divided into: 1) Loading (lifting the logs onto the bunk and sorting the logs within the piles or in the load bunk) 2) Auxiliary activities (preparing the crane, driving between piles, handling the trailer and bunks, binding the load, data communication, etc.) Activities concerning the transloading [a] of logs were also included in the log deck activities.
Driving between decks	Begins when the truck leaves one deck area and ends when the truck stops at the next deck area. Preparations, maneuvering the truck, and miscellaneous activities during driving are are also included. Driving from the first deck to the last one forms a single timber collection route.
Driving with a full load	Begins when the truck leaves a deck area and ends when the truck stops at a mill yard. Miscellaneous times during driving are included in this phase.
Unloading	Begins when the truck arrives at a mill yard and ends when the truck leaves without a load. Unloading activities were divided into: 1) Actual unloading by either a log stacker or wheeled loader or by the truck's own timber crane 2) Auxiliary activities (preparations, scaling, driving while unloading, etc.) 3) Queuing and waiting
Other driving	Driving from and to service stations and shift-change locations within the driver's work shift.
Delays	Delays were divided into: 1) Minor repairs and maintenance (including refueling). 2) Social breaks for the driver. 3) Other delays

[a] Transloading includes reloading and driving between the deck area and the trailer in those cases where the deck cannot be accessed directly with a trailer and the trailer is left, for example, along a main road.

on which they recorded start and end times for the main work phases, with an accuracy of 1 minute, and the odometer readings at the beginning and the end of the driving phases. They also recorded information about the number of log decks, log products, and mill yards, and the volume of each timber lot. Drivers also recorded whether they carried a crane, whether a trip represented back-hauling, and whether the deck activities included transloading. To minimize errors and maximize consistency in the data collection, each driver was taught how to fill in the forms. Drivers were also reviewed to ensure that they were performing this task correctly.

2.4 Characteristics of the Study Loads

In total, 66 loads (3300 m^3) were observed during the time study, and the follow-up study provided data for an additional 302 loads (14 569 m^3) (Table 3).

Single-sourced loads were divided based on the number of log products per load: 84% contained one product, 11% contained two products, 5% contained three products, and <1% contained four products. The corresponding proportions for multi-sourced loads were that 52% contained one product, 32% contained two products, 11% contained three products, 5% contained four products, and <1% contained five products. The number of different product groups (e.g., sawlogs vs. pulpwood) was, however, smaller in both load types. Only 9% of the single-sourced loads included timber from two or more product groups, and the rest of the loads included timber from only one group. In the multi-sourced loads, 70% contained products from one group, versus 28% from two groups and 2% from three groups.

During the study period, 43% of the single-sourced loads and 33% of the multi-sourced loads were backhauled, and the remainder of the trips hauled loads on only one leg of the trip. Transloading had to be used in 8% of the single-sourced loads and 10% of the multi-sourced loads. As is typical in the study area, timber cranes were always carried by the trucks, regardless of the load type or route (single-haul vs. backhaul).

The proportion of multi-sourced loads during the follow-up study was 38%, which is more typical than the value recorded during the time study, in which the load types were selected to provide data for the full range of transportation operations to support model development. Multi-sourced loads originated from two decks in 50% of these loads, versus 23% from three decks, 14% from four decks, 7% from five decks, 4% from six decks, and 1% each from seven and eight decks.

The unloading data were divided into subsets, since the loads were hauled to nine different mill yards. The unloading and scaling methods varied both among and within the mill yards. In addition, information concerning the unloading and scaling methods was not recorded during the follow-up study. The two basic unloading methods were a log stacker or wheeled loader and the truck's own timber crane. In the yards of pulp and paper mills, lots were scaled using the weight fraction or frame scaling methods. Trucks were weighed both loaded and empty, except at some sawmills, where the timber was scaled using a log scanner, and the volume was transformed into mass using green density coefficients (kg/m^3).

2.5 Analyses

Because data from the time study and the follow-up study were complementary, the two sets of data were combined, and are henceforth referred to as the combined data. The time consumption was modeled separately for each main work phase, and the expected total transportation time was computed as the sum of the expected work phase times. Furthermore, an independent-samples *t*-test was employed in the mean comparisons to test the

Table 3. Number of loads observed and total volume of timber that was hauled. Data is divided based on the main product group and wood source for each load.

Product group	Time study						Follow-up study					
	Single-sourced loads		Multi-sourced loads		Total loads		Single-sourced loads		Multi-sourced		Total	
	No.	m^3	No.	m^3	No.	m^3	No.	m^3	No.	m^3	No.	m^3
Sawlog	14	713	12	651	26	1364	45	2188	31	1454	76	3642
Short veneer log	3	170	3	162	6	332	8	430	4	209	12	639
Long pulwood	10	472	11	505	21	977	98	4734	47	2307	145	7042
Short pulwood	2	99	11	529	13	627	37	1726	32	1520	69	3246
Total	29	1454	37	1846	66	3300	188	9079	114	5490	302	14569

null hypothesis (H_0: $\mu_1 = \mu_2$, $p < 0.05$).

For each log product group, and separately for single- and multi-sourced loads, average load volumes (solid m^3 including bark) were calculated based on the combined data. The differences in load volumes between product groups were also analyzed using the independent-samples *t*-test.

Total transportation times were divided into the main work phases described in Table 2 for both single- and multi-sourced loads. The mean driving distances, travel speeds, and proportions of travel on each of the three road classes were also specified. The distances traveled without a load and with a full load were compared between single- and multi-sourced loads using the independent-samples *t*-test.

Nonlinear regression models were fitted to the time-consumption data for the driving phases (without a load, with a load, and traveling between decks). To prevent illogically high driving speeds and underestimation of the time consumption over long driving distances, a two-piece model structure was employed (Eqs. 1 and 2):

$$t_i = a_0 s_i^{b_0} + \varepsilon \quad \text{for} \quad s_i \le x_{v_{\max}} \tag{1}$$

$$t_i = \frac{s_i}{v_{\max}} + \varepsilon \quad \text{for} \quad s_i > x_{v_{\max}} \tag{2}$$

where t_i is the time consumption for driving phase i, a_0 and b_0 are parameters of the nonlinear regression model, s_i is the driving distance during phase i, ε is error term with constant variance, $v_{\max}$ is the maximum driving speed, and $x_{v_{\max}}$ is the corresponding travel distance.

A limiting value of 75 km h^{-1} (1.25 km min^{-1}) was used for $v_{\max}$ when driving on public roads with or without a load, versus 50 km h^{-1} (0.833 km min^{-1}) for driving between decks. These values represented the maximum speeds that were observed during the study. Furthermore, the limiting distances ($x_{v_{\max}}$) for s_i in Eqs. 1 and 2 were defined according to Eq. 3:

$$v_{\max} = \frac{1}{a_0} s_i^{1-b_0} \tag{3}$$

The time consumption for deck activities was described using mean values. Mean time consumption for loading was calculated for product groups based on the time-study observations. The differences between the product groups were analyzed using the independent-samples *t*-test. Furthermore, total time for actual loading (min $load^{-1}$) was calculated for each product group. Time consumption for auxiliary activities (min $load^{-1}$ and min $deck^{-1}$) was calculated separately for the single-sourced and multi-sourced load types and divided into subphases based on the time-study data.

The time-study data permitted an analysis of the effect of different product groups and load types (single- vs. multi-sourced) on the time consumption for deck activities. The relationship between time consumption and these operating conditions was scaled using a coefficient based on the difference in the time consumption between the time study and the follow-up study; the latter only included information about the loaded log product, load type, and total deck time, and did not divide the recorded times into actual loading versus auxiliary activities.

Total time consumption for unloading was calculated as a mean value based on the combined data. Time consumption for other driving and for delays (min $shift^{-1}$) was allocated to a single round trip (see Fig. 1) based on the number of loads hauled per shift.

For development of the models, a 95% confidence interval was defined for the time consumption during the individual work phases. Since the distribution of the time consumption t for work phase i was a log-normal distribution with expectation m_i and constant variance σ_i^2, the distribution of the natural logarithm of the time consumption was a normal distribution with expectation m_{u_i} and variance $\sigma_{u_i}^2$. These parameters of the normal distribution could be derived from the corresponding parameters of the log-normal distribution (Lindgren 1976). Furthermore, the 2.5% and 97.5% quantiles of the log-normal distribution for the 95% confidence interval were obtained from the expectation m_{u_i} and the variance $\sigma_{u_i}^2$.

Research has shown that there is no closed-form mathematical expression available for the cumulative distribution function of the sum of log-normal distributions. The distribution of the total transportation time can, however, be approximated by a log-normal distribution that has the same mean value and variance as the total time (Fenton 1960). Thereby, the 2.5% and 97.5% quantiles of the total transportation time were computed as described above for the individual work phases.

3 Results

3.1 Load Volume

Sawlogs and long pulpwood were loaded as one bunch on the tractor and as two bunches on the trailer, respectively. Similarly, the loads of short veneer logs and short pulpwood consisted of two bunches on the tractor and three bunches on the trailer. Statistically significant differences ($p < 0.05$) in the mean load volume for all loads (Table 4) were discovered between sawlogs and short pulpwood and between short veneer logs and all other product groups. No significant difference in load volumes were observed between the single- and multi-sourced loads.

3.2 Distribution of Transportation Time among Phases

During the 1-month study period, transportation time was divided into work phases as shown in Fig. 2. For both the single- and multi-source loads, driving with a full load accounted for the single largest proportion of the total time (34 and 26%, respectively), followed by log deck activities (21 and 22%), driving without a load (19 and 16%), and unloading (16 and 15%).

Table 4. Volumes of loads (m^3) for the combined data from the time study and the follow-up study.

	Single-sourced loads			Multi-sourced loads			All loads		
	Mean	Std. dev.	N	Mean	Std. dev.	N	Mean	Std. dev.	N
Saw log	48.9	6.6	59	49.0	7.7	43	48.9	7.1	102
Short veneer log	54.5	3.7	11	53.0	6.2	7	53.9	4.7	18
Long pulwood	48.0	3.5	99	48.6	3.7	55	48.2	3.6	154
Short pulwood	46.8	4.2	38	47.6	2.8	43	47.2	3.5	81
Total	48.4	4.9	207	48.6	5.2	148	48.4	5.0	355

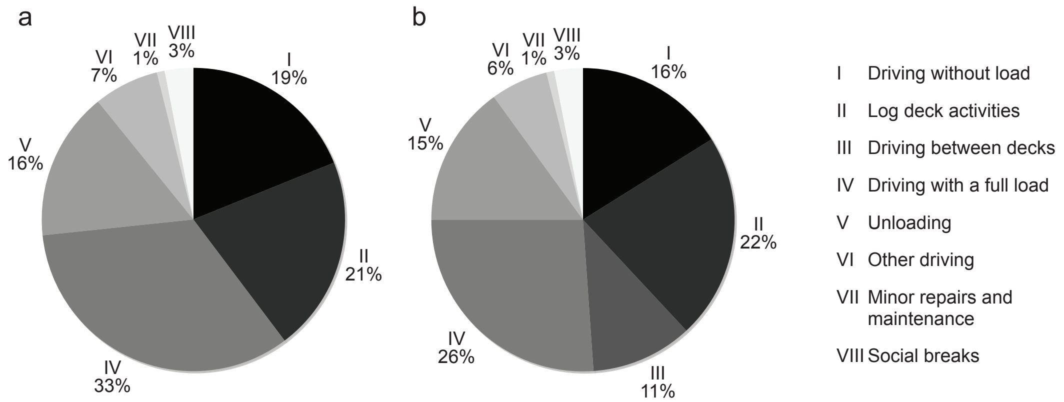

Fig. 2. Division of transportation time during the follow-up study for (a) single-sourced loads and (b) multi-sourced loads.

3.3 Driving Work Phases

The average travel distance was 33 km for driving without a load, versus 67 km for driving with a full load (Table 5). Driving distances did not differ significantly between single- and multi-sourced loads ($p=0.822$ for driving without a load and $p=0.390$ for driving with a full load). The proportion of total driving time spent driving without a load averaged 48% for trips with a single loaded segment and 27% for trips with backhauls.

When timber was hauled from more than one log deck, the driving distances between the decks and the lengths of the timber collection routes varied greatly (Table 6).

On paved asphalt roads, average travel speeds when driving with or without a load did not differ (Table 7). However, the proportion of travel time spent on slower road classes (unpaved gravel roads and forest roads) was larger when driving without a load and was significantly larger when driving between decks than when driving with a full load. The average proportion of total time for auxiliary activities (i.e., subphases in which the truck is not moving) was 14% for driving without a load, 8% for driving with a full load, and 16% for driving between decks.

Average driving speed increased with increasing driving distance for all three types of travel (Fig. 3). Trucks without loads traveled more often on slower road classes (gravel and forest roads) and spent more time on miscellaneous activities than their loaded counterparts, which decreased their driving speeds for shorter routes. However, as the driving distance increased, carrying a full

Table 5. Distances traveled when driving without and with a load (km) for the combined data from the time study and the follow-up study.

	Driving without a load					Driving with a full load				
	Mean	Std. dev.	Min.	Max.	N	Mean	Std. dev.	Min.	Max.	N
Single-sourced loads	33	22	3	105	182	68	38	4	165	192
Multi-sourced loads	33	24	3	136	147	65	37	8	147	145
All loads	33	23	3	136	333	67	38	4	165	341

Table 6. Distances for driving between decks (km) using the combined data from the time study and the follow-up study.

	Mean	Std. dev.	Min.	Max.	N
Distance between decks	5.9	7.6	0.1	39.2	134
Distance traveled to collect a load	13.9	15.7	0.1	104.0	142

Table 7. Average driving speeds and proportions of time spent driving on each class of road based on the time-study data.

	Paved asphalt roads		Unpaved gravel roads		Forest roads		All roads
	km h^{-1}	%	km h^{-1}	%	km h^{-1}	%	km h^{-1}
Driving without a load	66	78	34	12	13	10	51
Driving with a full load	66	90	27	8	9	2	57
Driving between decks	51	32	27	52	13	16	27

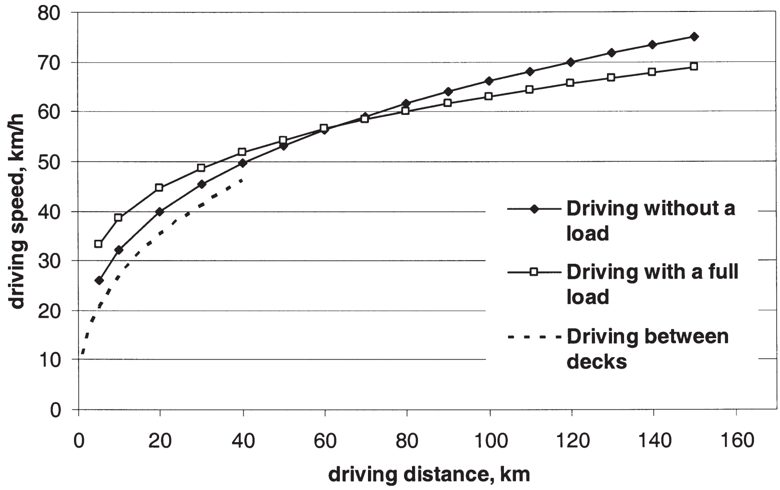

Fig. 3. Average driving speed as a function of driving distance based on the combined data from the time study and the follow-up study.

load decreased acceleration and speed on hilly sections of the road, and increased average speeds for trucks without loads above the speeds for loaded trucks. Driving between decks occurred most often on the slowest road classes, and the proportion of time spent on miscellaneous activities was higher; the combination of these factors kept the driving speeds low.

3.4 Log Deck Activities

Since the scaled time consumption for log deck activities was 25% higher in the follow-up study than in the time study, the values in the time study were multiplied by 1.25 so that data from both studies could be combined. All time consumption values reported here for deck activities thus include this scaling coefficient.

Due to the limited amount of data available on time consumption during the loading of veneer logs, the observations for sawlogs and short veneer logs were combined. The differences in average time consumption for loading long pulpwood and short pulpwood were small and not statistically significant ($p=0.869$). However, the average time consumption for loading sawlogs and veneer logs was significantly shorter than the time required for loading pulpwood ($p<0.001$):

Table 8. Average time consumption for auxiliary activities at the log deck.

Subphase of the work	Single-sourced loads	Multi-sourced loads	
	(min load^{-1})	(min load^{-1})	(min deck^{-1})
Preparing the crane	2.6	6.1	1.9
Completing loading and binding the load	5.2	8.3	2.6
Driving inside the deck	0.1	0.2	0.1
Handling the trailer and bunks	1.6	1.1	0.4
Data communications and paperwork	1.1	2.6	0.8
Other auxiliary activities	0.7	1.9	0.7
Total	11.3	20.2	6.5

0.44 versus 0.84 min m^{-3}, respectively. Sorting the logs in the piles and in the bunk averaged 5.6 s m^{-3} sawlogs, versus 17.6 s m^{-3} for pulpwood. The average grapple load was 1.1 m^3 for sawlogs, versus 0.7 m^3 for pulpwood.

Auxiliary activities averaged 11.3 min $load^{-1}$ for single-sourced loads and 20.2 min $load^{-1}$ and 6.5 min $deck^{-1}$ for multi-sourced loads (Table 8). For the multi-sourced loads, there was no correlation between the average auxiliary time per deck and the number of decks visited to obtain a full load.

3.5 Time-Consumption Models for the Work Phases and for Total Transportation Time

As a result of the abovementioned analyses, time-consumption models were developed for the individual work phases and for total transportation time (Table 9). Since in the model's applications the transportation activities may vary, a relevant combination of work phases and their models is to be chosen for the estimates of total transportation time. The correlations between the observed transportation times and the estimated times produced using the model (including only the relevant phases for each of the observed transportation times) are presented in Fig. 4. The goodness of fit was considerably better for single-sourced loads than for multi-sourced loads.

Time consumption (t_i) falls within the confidence interval $[L_i, U_i]$ with a probability of 95%, where L_i and U_i are the lower (2.5%) and upper (97.5%) quantiles of the log-normal distribution. These quantiles depend on the parameters m_{u_i} and σ_{u_i} according to Eqs. 4 and 5:

$$L_i = e^{m_{u_i} - 1.96\sigma_{u_i}} \tag{4}$$

$$U_i = e^{m_{u_i} + 1.96\sigma_{u_i}} \tag{5}$$

Accordingly, Eqs. 6 and 7 show the relationship between the parameters of the log-normal distribution and the corresponding normal distribution (Lindgren 1976).

$$m_{u_i} = \ln(m_i) - \frac{1}{2}\ln\left(1 + \frac{\sigma_i^2}{m_i^2}\right) \tag{6}$$

$$\sigma_{u_i}^2 = 2\left(\ln(m_i) - m_{u_i}\right) \tag{7}$$

The quantiles L_{tot} and U_{tot} for the total transportation time are computed the same way as described above by replacing the parameters m_i and σ_i^2 with m_{tot} and σ_{tot}^2 (Table 9).

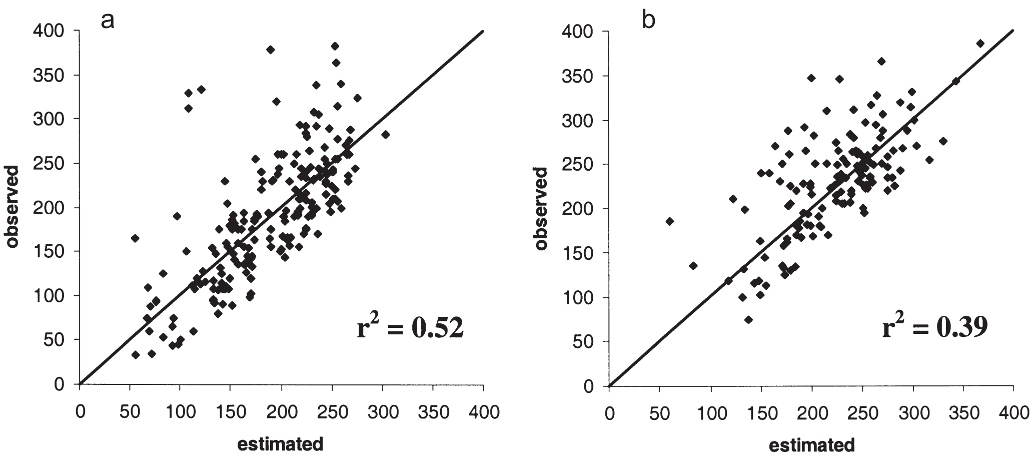

Fig. 4. Observed and estimated total transportation times (min $load^{-1}$) for (a) single-sourced loads and (b) multi-sourced loads.

Table 9. Models of time consumption during the main work phases and of total transportation time, where m_i is the expected time consumption (min load^{-1}) for work phase i, m_{tot} is the expected total transportation time (min load^{-1}) for k work phases, s_i is the driving distance (km) for route i, a is the time consumption for loading (min m^{-3}), b is the time consumption for auxiliary activities (min deck^{-1}), V is the load volume (solid m^3 including bark), S is the number of decks, N is the number of observations, R^2 is the coefficient of determination, σ is the standard error of the residuals, and σ^2 is the variance of the residuals.

Work phase	Model		N	R^2	σ
Driving without a load	$m_1 = 3.820 s_1^{0.688}$ $m_1 = \frac{s_1}{1.250}$	when $s_1 \le 150$ when $s_1 > 150$	332	0.81	9.055
Driving with a full load	$m_2 = 2.561 s_2^{0.785}$ $m_2 = \frac{s_2}{1.250}$	when $s_2 \le 224$ when $s_2 > 224$	339	0.92	9.375
Driving between decks [a)]	$m_{31} = 5.424 s_{31}^{0.613}$ $m_{31} = \frac{s_{31}}{0.833}$ $m_3 = \sum_{i=1}^{n} m_{31}$	when $s_{31} \le 49$ when $s_{31} > 49$	134	0.81	5.528
Log deck activities	$m_4 = a \times V + b \times S$, where $a = 0.44$ for sawlogs and 0.84 for pulpwood $b = 11.25$ for single-sourced loads and 6.52 for multi-source loads		308		20.138
Unloading	$m_5 = 34.93$		342		18.495
Other driving	$m_6 = 12.78$		344		23.839
Delays	$m_7 = 7.83$		368		17.247
Total transportation time	$m_{tot} = m_{i1} + m_{i2} + m_{i3} \ldots + m_{ik}$				
Total variance [b)]	$\sigma_{tot}^2 = \sigma_{i1}^2 + \sigma_{i2}^2 + \sigma_{i3}^2 + \ldots + \sigma_{ik}^2$				

a) m_{31} is the time consumption for driving between two decks separated by distance s_{31}
m_3 is the time consumption for a timber collection route with $n+1$ decks

b) $\sigma_{i3}^2 = \sum_{i=1}^{n} \sigma_{31}^2$

4 Discussion

The transportation environment described in the present paper, including the structure of the road network, the driving distances, the conditions at the log decks and mill yards, and the log products being hauled, can be considered typical for the logistics of Finnish CTL operations. The drivers were all skilled and the trucks were relatively uniform and representative of the current fleet. The number of drivers and trucks, the length of the study period, and the amount of timber that was hauled (nearly 17900 m^3) provided enough data to meet the study objectives. However, this data did not permit an analysis of activities throughout the year. The effect of winter and spring thaw on the driving phases and on the log deck activities is significant, and since the study was carried out during the summer, the results are only applicable to non-winter conditions.

Since no adequate, up-to-date information was available for time consumption during the various phases of timber trucking, an empirical time study was performed to obtain the data. This empirical approach increased the study's value because it provided a good opportunity to closely monitor the transportation work and discuss details with drivers, entrepreneurs, and forest company representatives.

Traditional approaches to time studies of forestry work divide time consumption by machines into effective time, which includes no delays, and gross effective time, which includes delays shorter than 15 minutes (Forest work… 1978, Harstela 1991). Accordingly, the hourly costs of operations have typically been computed and introduced per gross effective hour. However, the concept of gross effective time depends on an artificial limit of 15 minutes for delays and may thus not fit the realities of timber trucking, even though the transportation time (Fig. 1) and the driver's working hours are the most relevant parameters from the standpoint of planning routes and calculating the costs of and returns from transportation operations. Round-trip time represents an iterative combination of work phases, whereas the other driving phases and delays must be assessed for the individual entrepreneurs and their trucks. In the present study, basing the models on the concept of transportation time instead of gross effective time allows computation of the costs of timber trucking per "transportation hour", which provides a more explicit measure of operating time and which can be controlled by the trucking entrepreneur.

In work studies of timber trucking, both time studies (e.g., Pennanen 1984, Väkevä et al. 2000) and follow-up studies (e.g., Alve 1988) have been used. Since in this case, detailed work characteristics and time elements, but also the performance of the transportation work on a larger scale with no emphasizing of data were examined, the combination of time and follow-up studies proved to be efficient way of collecting data.

In the time study, short time elements could be registered accurately using dataloggers and detailed forms, whereas in the follow-up study, the forms had to be designed for ease of use. The drivers were provided with detailed instructions for completing the forms and were monitored during the study period. Because the work phases were defined unambiguously, the data collected using these forms were comparable to the more detailed time-study data and could be combined with these data for analysis. An alternative to completing the forms (i.e., the use of a tachograph) was rejected because the drivers considered the use of this device to be too labor-intensive. In contrast, drivers did not perceive the methods chosen for the present study to affect their normal transportation work.

Methodologically, the study was mainly a relationship study, but also included features of comparative analysis (e.g. the effect of load type on the performance). The main problem with relationship studies is the multiplicity of factors capable of influencing the results (Bergstrand 1991), and this problem was controlled by means of a detailed division of the transportation work into phases and subphases. When analyzing the time consumption for processes that include several different phases, as is the case in timber transportation and harvesting, this modeling technique has been proven to be appropriate (e.g., Bergstrand 1991, Kuitto et al. 1994, Nurminen et al. 2006). Furthermore, the requirement for flexible models with measurable variables capable of being applied in real-world operations (e.g., in cost analyses and route planning) also determined the model structure.

A common problem in comparative analyses, the existence of irrelevant and disturbing factors ("noise"; Bergstrand 1991), was leveled out as a result of studying equally skilful drivers and relatively uniform trucks during the same period, working under similar conditions. Almost all drivers hauled, for example, both single- and multi-sourced loads and hauled both sawlogs and pulpwood. On the whole, the effect of human factors on the modeling of trucking performance can be considered less significant and easier to control than in the case of harvesting operations, where it can be substantial (e.g., Sirén 1998, Ovaskainen et al. 2004, Väätäinen et al. 2005).

From the standpoint of modeling and statistical analyses, the study provided sufficient relevant data. Regression models proved to fit the data well and reliably estimated the time consumption for individual work phases. The residuals of the regression models were symmetrical and were normally distributed, and the coefficients of determination were high (ranging from 0.81 to 0.92 for the driving components; Table 9). Even if the regressions for individual work phases worked very well for the driving phases, the variation in the time consumption of log deck activities and unloading was great. As a result, the overall model for transportation time worked less well than we hoped. Additional research to refine the submodels with the poorest performance may improve the estimation of total transportation time, but it is also possible that the inherent variability in operating conditions in the forest will make it impossible to produce a model with highly accurate predictions without further research to parameterize the problematic components of the models.

In the computation method for ranges in time consumption, the models did not account for the possibility that the driving distances exceeded the limits for the maximum speeds (see Eqs. 2 and 3 and Table 9). However, since the nonlinear regression models were valid for the most typical ranges of driving distances, the method for computing the quantiles can be generalized for most of the transportation situations in Finland.

Even though the estimated total transportation times were positively correlated with the observed times, a high amount of random variation was observed in the times (Fig. 4). In the example shown in Table 10, the ranges of total transportation time for a single-sourced load and a multi-sourced load are presented for driving distances of 60 km both with and without a load, for transportation of sawlogs, and for a load volume of 48 m^3. The timber from the multi-source load was hauled from three log decks, with a distance of 9 km between decks. In both cases, the variation in travel times between the lowest and highest estimates was roughly 200%.

The variation in time consumption must be taken into account when, for example, planning routes and schedules for trucks using optimization procedures. In addition, trucking entrepreneurs should understand this variation and incorporate it in their cost accounting and their pricing of shipments: the data from the present study clearly indicate that mean values do not always reflect the whole truth.

From the standpoint of transportation times, load volume is not a particularly significant factor, since the load volumes did not vary greatly in the present study (Table 4) and since loading times are only a small part of the log deck activities, which accounted for a total of only about 22% of the total transportation time (Fig. 2). However, load volume has a large financial effect on transportation (Väkevä et al. 2000), since in Finland, transportation charges are typically based on the mass or volume of the load. The time consumption (min $load^{-1}$, min m^{-3}) measured in this study can be expressed in mass units based on the green density of timber (kg m^{-3}), which varies among regions, seasons, tree species, and product assortments (e.g., Kainulainen and Lindblad 2005). Timber cranes, which typically weigh 3000 kg (Peltola 2004), reduce the available payload. In this study, however, the nature of the operating environment, including the organization of the consecutive driving routes and the high proportion of backhauls, made it impossible to detach the crane before driving with a full load.

Table 10. Expected total transportation times for two sample loads and the corresponding ranges of transportation times (95% confidence interval).

	Expectation, min	Range, min
Single-sourced load	215	145–309
Multi-sourced load	266	192–359

Since the division of total transportation time among work phases is greatly affected by the driving distances and the distributions of load and route types, the proportions introduced in Fig. 2 cannot be generalized at the national scale. If there were, for example, fewer potential backhaul routes in certain districts, the proportion of driving without a load would be considerably higher. Furthermore, the time consumption for the “other driving” phase depends on the location of the service facilities and work shift arrangements. As a result, it may be necessary to parameterize these components of the total work cycle by adding a weighting factor that accounts for their actual proportion of total transportation time under different operating conditions.

The proportion of the total transportation time accounted for by delays (only 4%) was smaller than that reported by Alve (1988), who reported values ranging between 9 and 11% under summer conditions. The difference may result from improvements in trucks that have occurred in the nearly 20 years since Alve's study, as well as in the increasingly tight schedules and requirements for cost efficiency that have developed during this period.

The time consumption for different driving phases generally depends on the speed limits and other relevant legislation, the proportions of the different road classes, and the condition of the roads. These phases also include fixed or auxiliary activities such as maneuvering the truck, data communication, and waiting at the log deck, all of which increase the variation in the time consumption

The log deck activities account for a large share of the variation in the total time consumption (accounting for roughly 21% of the total time) as a result of variation in the shape of the road; the driver's loading efficiency; the power and reach of the crane; the size, location, and shape of the piles; and the length and size of the logs (Pennanen 1984, Voipio and Korpilahti 1988, Väkevä et al. 2000), among other factors. In the present study, only the log products and load type (number of decks) could be included as variables in the model. Future research should investigate the impacts of other factors on the model's predictive ability.

The data from the follow-up study was included to account for the effects of occasional trans-loading, of waiting times, and of other elements capable of introducing variation into the analysis. Furthermore, this data provided an indication of the effects of the operating conditions on the driver's loading efficiency (i.e. the possibility that the drivers loaded logs faster during the stop-watch study, when they were being directly observed, than under normal working conditions).

The data did not enable detailed analysis of unloading activities, which accounted for roughly 15% of total transportation time. However, the data on average time consumption during unloading and its high variation described the general situation that exists under typical conditions at a mill yard. From the standpoint of total transportation time and cost, the organization of the unloading phase may be more important than, for example, the unloading method. In this respect, the driver's impact on the time consumption is limited. However, delays during the unloading phase disturb the schedules of subsequent trips and can cause financial losses to entrepreneurs.

The higher time consumption for multi-sourced loads than for single-sourced loads resulted from repetition of auxiliary activities at each log deck and travel between decks. Furthermore, the timber collection route was not observed to shorten the distances for driving without a load and loaded. In addition, the time consumption for loading might be somewhat higher for smaller decks where the logs are loaded from smaller piles (Väkevä et al. 2000). Väkevä et al. (2000) also suggested that since multi-sourced loads typically include several timber lots, unloading might be slower than in the case of loads with fewer lots. However, the data in the present study do not make it possible to confirm either of these suggestions. The improved fit of the model for single-sourced loads compared with the model for multi-sourced loads (Fig. 4) indicates that additional work must be done to quantify the impact of travel between decks and the additional maneuvering required as a result of this travel and the increased number of loading phases.

The effect of obtaining a full load on the total transportation time varies among situations and depends on the number of log decks visited and the length of the route traveled to obtain the full load. The effect can be considerable, for example, with many small lots of special products that must be collected from a wide area. Total transportation time for the multi-sourced load in Table 10 averaged 24% higher than that for a corresponding single-sourced load. Careful organization of the routes and optimization of pile size is thus crucial to minimize the impact of loading from multiple decks.

The results of this study will support tactical and operational route planning and the calculation of costs and profitability. They also provide background information on the overall wood supply process that can help managers to improve the allocation of logistics costs among timber lots and log products and to improve decisions related to processing of trees into a range of products. The models will also be useful in the development of simulations and in training of students and drivers.

References

Alve, M. 1988. Puutavara-autojen ajankäyttö. Metsäteho Hand-out 1.9.1988. Metsäteho, Helsinki, Finland. (In Finnish).

Arce, J.E., Carnieri, C., Sanquetta, C.R. & Filho, A.F. 2002. A forest-level bucking optimization system that considers customer's demand and transportation costs. Forest Science 48(3): 492–503.

Bergstrand, K.-G. 1991. Planning and analysis of forestry operations studies. Skogsarbeten, Bulletin 17. The Forest Operations Institute of Sweden.

Carlsson, D. & Rönnqvist, M. 1998. Tactical planning of forestry transportation with respect to backhauling. LiTH-Mat-R-1998-13. Linköping University, Sweden.

Fenton, L.F. 1960. The sum of lognormal probability distributions in scatter transmission systems. IRE Trans. Commun. Syst. 4(CS-8): 57–67.

Finnish Statistical Yearbook of Forestry. 2005. Finnish Forest Research Institute, Vantaa.

Forsberg, M. 2003. Inter-enterprise collaboration for cost-effective roundwood haulage. Skogforsk Resultat 12. SkogForsk, Sweden. (In Swedish, English summary).

Harstela, P. 1991. Work studies in forestry. Silva Carelica 18. 41 p.

Kainulainen, J. & Lindblad, J. 2005. Puutavaralajien tuoretiheyden alueellinen vaihtelu mittausasemien vastaanottomittauksessa. Metlan työraportteja / Working Papers of the Finnish Forest Research Institute 19. 29 p. ISBN 951-40-1981-4 (PDF). Available at: http://www.metla.fi/julkaisut/workingpapers/2005/mwp019.htm. (In Finnish).

Korpilahti, A. 1989. A system for analysing truck haulage of timber. Metsäteho Review 12/1989. Metsäteho, Helsinki, Finland. (In Finnish, English summary).

Kuitto, P.J., Keskinen, S., Lindroos, J., Oijala, T., Rajamäki, J., Räsänen, T. & Terävä, J. 1994. Mechanized cutting and forest haulage. Metsäteho Report 410. Metsäteho, Helsinki, Finland. (In Finnish, English summary).

Lindgren, B.W. 1976. Statistical theory. Third edition. MacMillan, New York. 614 p.

McCormack, R.J. 1990. TRUCKSIM – a log truck performance simulator. Journal of Forest Engineering 2(1): 31–37.

Myllyniemi, A. 1980. Loading onto truck of long pulpwood bucked by eye. Metsäteho Review 3/1980. Metsäteho, Helsinki, Finland. (In Finnish, English summary).

Forest work study nomenclature. 1978. The Nordic Forest Work Council (NSR), Norwegian Forest Research Institute, Ås, Norway.

Nurminen, T., Korpunen, H. & Uusitalo, J. 2006. Time consumption analysis of the mechanized cut-to-length harvesting system. Silva Fennica 40(2): 335–363.

Ovaskainen, H., Uusitalo, J. & Väätäinen, K. 2004. Characteristics and significance of a harvester operators' working technique in thinnings. International Journal of Forest Engineering 15(2): 67–77

Palander, T. & Väätäinen, J. 2005. Impacts of inter-enterprise collaboration and backhauling on wood procurement in Finland. Scandinavian Journal of Forest Research 20: 177–183.

— , Väätäinen, J., Laukkanen, S. & Harstela, P. 2002. Back-hauling optimization model for Finnish wood procurement. In: de Carvalho, J.C. (ed.). Conference proceedings of Fourth International Meeting for Research in Logistics. Lisbon, Portugal. p. 595–607.

Peltola, J. 2004. Puutavara-autojen rakenteen vaikutus omamassaan. Metsäteho Report 176. Metsäteho Oy, Helsinki, Finland. (In Finnish).

Pennanen, O. 1984. The effect of timber truck development on the time expenditure on timber transport. Metsäteho Report 387. Metsäteho, Helsinki, Finland. (In Finnish, English summary).

Puutavaran kuljetus yleisillä teillä. 1998. Tielaitos, Liikenteen palvelut. (In Finnish).

Savolainen, R. 1977. Output ratios of truck loading of logs and pulpwood. Metsäteho Review 2/1977. Metsäteho, Helsinki, Finland. (In Finnish, English summary).

Sirén, M. 1998. One-grip harvester operation, its silvicultural result and possibilities to predict tree damage. Doctoral thesis. Finnish Forest Research Institute, Research Papers 694. 179 p. (In Finnish, English summary).

Uusitalo, J. 2005. A framework for CTL method-based wood procurement logistics. International Journal of Forest Engineering 16(2): 37–46.

Väätäinen, K., Ovaskainen, H. Ranta, P. & Ala-Fossi, A. 2005. Hakkuukoneen kuljettajan hiljaisen tiedon merkitys hakkuutulokseen työpistetasolla. Finnish Forest Research Institute, Research Papers 937. 90 p. (In Finnish).

Väkevä, J. 1999. Long-distance transportation in 1990–

98. TTS-Institute Forestry Bulletin 10/1999. TTS-Institute, Helsinki, Finland. (In Finnish, English summary).
— , Lindroos, J, Rajamäki, J. & Uusi-Pantti, K. 2000. Puutavaran keräilyajon ajanmenekki. Metsäteho Report 96. Available at: http://www.metsateho.fi. [Cited 3 Mar 2006]. (In Finnish).
Voipio, V. & Korpilahti, A. 1988. Characteristics of road-side landings of timber. Metsäteho Report 400. Metsäteho, Helsinki, Finland. (In Finnish, English summary).

Total of 29 references