Performance Standards of Medium- and High-Power Forwarders

Jiří Dvořák
Department of Forest Harvesting, Faculty of Forestry and Wood Sciences
Czech Univerzity of Life Sciences in Prague, Kamycka 129, CZ-165 00 Praguem, Czech Republic
DvorakJ@fld.czu.cz
Farshad Keivan Behjou
Faculty of Agriculture
University of Mohaghegh Ardabili, Ardabil, Iran
fkeivan@uma.ac.ir

Abstract:
Cut-to-length logging volume in the Czech Republic has seen steady growth in recent years. In 2005 – 2008 the ratio of harvester technology increased from 11 % to 30 % of the total annual felling volume (Ministry of Agriculture 2009). The number of medium- and high-powerd forwarders is estimated at 380 machines in the labour market. Considering the fact that this technology is relatively recent, the Department of Forest Harvesting has designed performance standards to enable job scheduling and machine operators' remuneration. Work stages (forwarding) were divided into four work operation segments during experimental measurements. The analysis shows the average ratio of work operation segments - time required for driving without load from a landing to the given stand (t'_{A126}) – 15 % (1 – 19 min), loading time (t'_{A127}) - 43 % (2 – 50 min), time for driving from the stand to a landing (t_{A128}) - 15 % (1 – 21 min), unloading time (t'_{A129}) - 26 % (2 – 25 min). Normal shift time consumption of work operation is 76 % of the total shift time. The forwarder performance ranges from 7.7 m^3/h to 16.7 m^3/h depending on the forwarding distance and the volume of harvested trees with average load volume of 10. m^3, if the slope is up to 33 % and terrain clear and bearable.

Keywords: forwarder, work operation, performance, performance norms, cut-to-length system

1 Introduction

Timber forwarding is typically connected with harvester technology which is highly popular in Scandinavia and widely used in other European countries as well (Lageson, 1997; Kapral, 1999). Assortment method accounts for 90 - 95 % of timber production in Finland, Ireland and Sweden (Karjalainen et al., 2001). In Germany, harvester deployment in clear felling amounts up to 30 % (Gruner, 2001; Jodlowski, 2001). On the other hand, East European countries of EU demonstrate a very low ratio of harvester technology deployment. In the most recently acceded EU member states, e.g. in Bulgaria, we fail to meet harvester technology altogether (Markoff et al., 2008). The Czech Republic forest management has seen an expansive development of harvester technology deployment since the early 1990s. At present, 30 % (4.82 mil m^3) of annual harvesting volume is processed by the assortment method (MZe ČR, 2009).

The relatively rapid and expansive development of harvester technology can be attributed to the increase in labour costs and the consequent necessary cuts in this area, to accurate registration of performance, high work hygiene and work safety, possibility of flexible reaction to customer demands, purity of wood mass, as well as reduced damage to forest tree species and soil surface. On the other hand, the deployment of harvester technology entails certain disadvantages, e.g. demanding work organization, high acquisition costs, and expensive repairs including long waiting times for spare parts as well as long-term and costly training of operators (Bettinger and Kellogg, 1993; Gellerstedt and Dahlin; 1999, Valenta and Neruda, 2003; Dvořák et al., 2008).

Harvester productivity and consequently forwarder performance are conditioned by a number of factors, among them the machine type, volume of the harvested stem, harvesting intensity, number of trees per area unit, forwarding distance (Lageson, 1977; McNeel, 1994; Nimz, 2002; Kärhä, 2003), silvicultural measures (Eliasson et al., 1999; Hanell et al., 2000; Eliasson, 2000; Glöde and Sikström, 2001), the given machine's technical parameters which are usually referred to as its power class (Forbrig, 2001; Heinimann, 2001), as well as the operators' skills (e.g. Kärha et al., 2004; Purfürst, 2007).

Time measurements are conducted in accordance with standard procedures (Klouda et al., 1988; Schlaghamerský, 1994; Dvořák, 2010). Most of the consequent time consumption analyses of forwarder operations are conducted by means of a simple correlation analysis where volume and forwarding distance represent the independent variable.

The aim of the paper was to draw up performance standards for medium and high-power forwarders of engine performance over 60 kW (Lukáč, 2005). The most frequently deployed machines in the Czech Republic include John Deere, Komatsu, Rottne, Ponsse, Logset and other. Their numbers are estimated at 557 (MZe ČR, 2009).

2 Material and Methods

Time studies were conducted in 2007 – 2009 in the Central Bohemia Region of the Czech Republic. Timber felling was done by implementing "complex harvester technology" in accordance with the standard technology (e.g. Malík-Dvořák 2007; Ulrich 2006; Morat et al., 2001). Seven brands or types of forwarders were deployed in harvesting in the course of which the experimental measurements were taken during 14 shifts.

Unit time consumption per work operation measurements were taken in the course of planned felling on 145 forwarding units (loads). Forwarders were deployed in standard production conditions, which means terrains of slope inclination of up to 20 %, with good bearing capacity and without obstacles, which in the Czech forest management are classified as terrain types 11, 12, 21, 22 (Simanov et al., 1993).

Both training and experience of harvester operators differ. Training was predominantly obtained at polytechnic training institutions. Experience with forwarder operation ranges between 1.5 and 6 years. This type of work was preceded with experience with skidder and haul rig operation. None of the operators obtained training at specialized training institution focusing on harvester operation. They received two to three-week training provided by the machine suppliers either in the Czech Republic or abroad.

2.1 Work Operation and Classification

The time analysis draws on time consumption in the *"forwarding"* work process. The key time is the work time in the course of which the operator performs work operations necessary for reaching the target. Unit time represents the primary time, which corresponds to the length of time at the production stage, i.e. timber forwarding. Another independent component of real work time structure is batch time (*time for preparation and concluding of work* - T'_{B101}, *time for technical servicing of the work place* - T'_{B102}) and shift time (*time for work instructions* - T'_{C103}, *technical maintenance time* - T'_{C104} *and time for repairs* - T'_{C105}). Other normative times include *time for biological and legally required breaks* (T'_2). The analysis also distinguishes necessary and unnecessary (loss) time, i.e. time for *technical-organizational losses* (T'_E) and *personal time losses* (T'_D) which are separated from times necessary for designing the proposed performance standard and as such do not constitute a part of normal shift time balance (Dvořák, 2010).

The time analysis focuses predominantly on analyzing the transport work operation at the production stage. Analysis of transport operation of the work process is conducted together with the time analysis. The work operation starts with the forwarder driving into the respective forest stand and is concluded by unloading at the roadside. The production procedure is divided into the following actions or segments which constitute the work operation – *timber forwarding*, i.e. *time for driving the unloaded machine from the roadside to the extraction site* (t'_{A126}), *time for loading* (t'_{A127}), *time for driving the load from the extraction site to the roadside* (t'_{A128}), *time for unloading at the roadside* (t'_{A129}) (Dvořák, 2010).

2.2 Preparation and Implementation of Time Measurements

Experimental measurements are conducted by taking gradual snapshots of forwarder work in the course of a work shift. These can be within the time study divided into two parts – measurements of time consumption per work operation (or work operation segments) and measurements of other batch times, shift times and time losses during the work day (work shift). For measurements and consequent time analyses, *chronometric analysis method* was deployed (Klouda, 1988).

The workday snapshot, or workday components snapshot, as well as work operations and their segment snapshots are measured in minutes. Check measurements are taken on video recordings of harvester work.

Upon concluding the work stage, the forwarded tree species, produced assortments and their parameters as well as load volume are recorded, the latter being calculated from the metric dimensions of the forwarder's loading area. For the purposes of consequent performance analyses, operating systems of harvesters which carried out felling in forest stands provide measurement protocols listing the volume of harvested timber, processed tree species, number of felled trees, volume of harvested stems, produced assortments from individual tree species, number and volume of the produced assortments.

2.3 Statistical Analysis

Data analysis (time consumption) associated with selected production conditions, machines and operators is conducted in Chapter 3.1. The time study encompasses 14 shifts in the course of which 113 h (6,823 min) of unit time per work operations was consumed. A total of 145 loads were forwarded in this time, the average load volume being 10.1 m^3/load and average forwarding distance amounting to 349 m.

In order to process the obtained data, relevant statistical methods were selected according to the following criteria:

1. Statistical analysis of time consumption per work operation in relation to the forwarders' various engine performance classes.
2. Creating models of *unit time consumption per work operation* based on average volume of harvested trees in the forest stand and on forwarding distance.
3. Total balance of real and normal shift time in planned felling.
4. Creating a model of *total shift time consumption per work operation* based on average volume of harvested trees in the forest stand and on forwarding distance.
5. Drawing up a table of medium and high-power forwarder performance standards.

Statistical methods of regression and correlation analyses as well as methods of statistical hypothesis testing were used for analyses of the obtained data. In the course of hypothesis testing, the multi-selection test in the form of analysis of variance was selected. Since for operation purposes the models are not designed for individual segments of a work operation but rather for a work operation as such, methods of regression and correlation analysis are used for tracing and assessing dependencies between the volume of harvested trees, forwarding distance and unit time consumption necessary for their processing. Their primary task is to describe statistical properties of these variables' relation, to express the behaviour of the dependence and assess changes of the dependent variable based on changes of the independent variable (Hendl, 2009). Unit time is extended to encompass batch and shift times necessary for the harvester's operation in logging. Final time consumption may consequently be transformed into performance. Statistical system Statistica 8.0 was used to process the obtained data.

3 Results and Discussion

3.1 Mathematical and statistical analysis of the measured time consumption

The assessed quantitative character was shift unit time necessary for forwarding a load of timber. Together with the analyzed dependence of consumption of the abovementioned time, the key factors for forwarders are their engine performance classes, volume of the harvested trees (unified with groups used for harvester standards), forwarding distance and length of the forwarded assortments.

It was possible to assess the impact of all factors individually or jointly. When compared, the results revealed that the joint impact of these factors only improved the qualitative parameters of the analysis but that the primary conclusions remained the same. Consequently, only results of the analysis of variance for each of the above-listed factor separately will be assessed.

Engine performance class represents the first factor. It was monitored only at two levels. In order to determine concord or differences in mean values of unit time, hypothesis test on concord of two mean values was therefore used. As the following Table 1 shows, the difference is not very significant in the category of mean values, while in performance class 1 the values fluctuate more (standard deviation reaches higher values).

Table 1: Average time consumption for individual load classes of forwarder operation

Level engine performance class	**N**	**Unit time (min/load)**	
		Mean value	**Standard deviation**
1 (up to 60 kW incl.)	165	53	32.5
2 (over 60 kW)	145	47	15.1

Based on F-test, variances of these two sets differ, therefore hypothesis test on two mean values concord will be assessed according to the second row of the following Table 2. Comparison of Pr value with the selected significance level 0.05 reveals that mean values of these two sets are different in the basic set, i.e. that engine performance class affects unit time consumption.

Table 2: Two-sample *t*-test of mean unit time consumption in two performance classes

***T*-tests**					
Variable	**Method**	**Variance**	**DF**	***t*-value**	***Pr* > |*t*|**
Unit time	**Pooled**	Equal	308	2.1	0.0362
Unit time	**Satterthwaite**	Unequal	238	2.2	0.0292

In middle and high-power forwarders, the difference in mean unit times upon data classification into groups *according to the logged tree volume* was assessed. There were four groups 4 – 7 (Tab.4) where forwarders of engine performance over 60 kW were deployed. With the help of statistical software we obtained an analysis of variance table, where the last column designated $Pr > F$ (Tab. 3) was significant for assessment. It refers to the calculated significance level which is compared with the selected significance level $\alpha = 0.05$. Since Pr value is lower than α, zero hypotheses is ruled out. To conclude, a statistically significant difference in mean values for individual volume groups was established.

Table 3: Analysis of variance of simple selection *F*-test according to volume groups of logged trees

Source	**DF**	**Sum of squares**	**Mean quadrat**	***F* value**	**Pr > F**
Model	3	1992	664	3.05	0.03
Error	141	30712	218		
Revised sum	144	32704			

Since zero hypothesis was rejected, it is necessary to introduce a more detailed *t*-method assessment. The highest mean time consumption for load forwarding was measured in Class 4 (60 min), while the shortest time is consumed in Class 7 (37 min). When implementing the *t*-method, a statistically conclusive difference between volume groups 5 and 7 and between volume groups 6 and 7 was established. The difference was not established among the remaining volume groups (Tab. 4).

Table 4: Detailed T-method assessment of the analysis of variance, mean time consumption according to volume groups (significance comparisons for 0.05 level are indicated *)**

Level engine performance class	**N**	**Total tree processing time**		**Group difference**
		Mean value	**Standard deviation**	
		(min/load)		
4 (0.20 – 0.29 m^3)	1	60	0	*********
5 (0.30 – 0.49 m^3)	71	49	14.2	***
6 (0.50 – 0.69 m^3)	55	47	16.1	***
7 (0.70 – 1.00 m^3)	18	37	8.3	***

For *forwarding distance*, time consumption was measured only in two variants with regard to the requirements expressed in tenders in the Czech Republic (forwarding distance of up to 300 m and forwarding distance from 301 to 1000 m). Assessment of concord of mean unit times was done with the help of two-sample *t*-test. The basic statistical table reveals a difference in mean values, yet the variability of these two sets is identical (Tab.5).

Table 5: Mean time consumption for individual forwarding distances in middle and high-power forwarder operation

Level forwarding distance	**N**	**Unit time (min/load)**	
		Mean value	**Standard deviation**
1 (up to 300 m)	67	38	12.6
2 (301 – 1000 m)	78	55	12.1

This concord as well as the initial assumption about a difference between mean values of the consumed unit time can be established also for standard deviations of the basic set. *Pr* value is lower than significance level of 0.05 and therefore the zero hypothesis on concord of two mean values can be rejected (Tab.6). Forwarding distance in engine performance class 2 affects the mean unit time (difference between the mean values is statistically conclusive in the basic set).

Table 6: Two-sample *t*-test of mean unit time consumption according to load type

***T*-tests**					
Variable	**Method**	**Variance**	**DF**	***t* value**	***Pr* > |*t*|**
Unit time	**Pooled**	Equal	143	-8.5	< 0.0001
Unit time	**Satterthwaite**	Unequal	138	-8.5	< 0.0001

The last factor, load type, was monitored only at two levels according to the length of the forwarded assortments (assortments of up to 4 m and over 4 m incl.). In order to verify concord in mean values, a two-sample test was used. Basic statistical Table 7 reveals that both mean values and variability show only a slight difference.

Table 7: Mean time consumption for individual loads in middle and high-power forwarder operation

Level Load type	**N**	**Unit time (min/load)**	
		Mean value	**Standard deviation**
1 (assortments of up to 4 m)	22	49	15.8
2 (assortments over 4 m incl.)	123	47	15.0

Hypothesis test on two variance concord as well as hypothesis test on two mean unit time concord leads to conclusion that zero hypothesis should be rejected. This means that both variability and mean values of the two sets are equal in the basic set and a statistically significant difference cannot be proved (Tab.8).

Table 8: Two-sample *t*-test of mean unit time consumption in two load types

T-tests					
Variable	**Method**	**Variance**	**DF**	***t*-value**	***Pr* > |*t*|**
Unit time	**Pooled**	Equal	143	0.67	0.5031
Unit time	**Satterthwaite**	Unequal	28.2	0.65	0.5227

3.2 Unit time consumption per work operation

For forwarders it is possible to independently assess the dependence of load forwarding unit time (dependent variable) on stem volume and forwarding distance (independent variables). Both these variables are numerical and therefore methods of regression and correlation analyses were used together with the analysis of variance. The objective was to determine the most suitable regression function based on values of correlation and determination indexes. Selected functions then can be used to estimate unit times for given stem volume and forwarding distance values.

In terms of the multiple regression model it can be stated that both variables (stem volume, forwarding distance) are statistically significant for unit time determination, i.e. that both stem volume and forwarding distance affect the resulting unit time.

The total dependence assessed by the determination index of 42.13 % can be described as medium-strong dependence. The regression function is defined by the following relation (1).

$$t_{A1} = 47{,}4164 - 21{,}5832 \cdot h + 0{,}031605 \cdot L \quad \text{(min/load)} \tag{1}$$

$p = < 0.001, I = 0.65, I^2 = 0.42$

where

t_{A1} unit time consumption per work operation in timber forwarding (min)

h volume of logged trees in operation unit (m^3/stem)

L forwarding distance (m)

The relation between stem volume and forwarding distance may be described as weak, i.e. the presence of multi-correlativity cannot be proved in this case.

3.3 Working day snapshots of a forwarder

Working day observation focuses on the entire duration of a work shift, from its start (operator's arrival at workplace) to its conclusion (carried out maintenance and operator's departure from workplace). These limits do not necessarily have to be binding, should the operators engage in other maintenance work required for ensuing shifts prior to or after the actual work shift. This includes cases when the operators leave the workplace to go to collect pre-ordered spare parts from the storehouse or may engage in purchasing required materials themselves after leaving the workplace (new spare parts, fuel, oil, etc.). The objective is to assess the time and percentage share of individual actions which take place in the course of a work shift. Components of the shift time are listed in chapter 2.1.

In forwarder operation, *real time consumption balance* per a work shift accounted for 10.58 h (Tab.9). Work snapshots confirm the highest total time consumption falling to operative time which takes up 73 % of the total shift time. The second most used time within the working day snapshot were 1.2 h of time required for repairs (11 %), followed by time for technical maintenance accounting for 0.53 h (5 %). Other times fall below the 5 % share of the total shift time.

Table 9: Forwarder shift time consumption balance

Shift time	**time symbol**	**real time consumption**			**normal time consumption**		
		(min)	(h)	(%)	(min)	(h)	(%)
work operation	T_{A1}	463	7.72	73	463	7.72	76
preparation and concluding of work	T_{B101}	23	0.38	4	23	0.38	4
technical servicing of workplace	T_{B102}	12	0.20	2	12	0.20	2
work instructions	T_{C103}	3	0.05	0	3	0.05	0
technical maintenance	T_{C104}	32	0.53	5	32	0.53	5
Repairs	T_{C105}	72	1.20	11	30	0.50	5
other work times	T_{BC106}	14	0.23	2	14	0.23	2
biological and legally required breaks	T_2	10	0.17	2	30	0.50	5
technical-organizational losses	T_E	6	0.10	1	0	0.00	0
personal time losses	T_D	0	0.00	0	0	0.00	0
Total	$\boldsymbol{T}$	635	10.58	100	607	10.12	100

Time losses, whether caused by staff in charge of organizing the machines' long-distance transport to new workplaces and providing servicing in cases of unexpected breakdowns or those who caused idle periods by giving work instructions, as well as time losses caused by the operators themselves (primarily by making personal phone calls) accounted for 1 % of the total shift time (0.10 h) – Tab.9.

Under the existing standards, *normal time consumption balance* allows for the same time consumption for common breakdowns as for harvesters (Dvořák, 2010), with a maximum 5 % ratio of shift time allowed for repairs (30 min). It also includes 30 min of legally required break per a work shift in accordance with the Labour Code (Act No. 262/2006 Coll.) and excludes all time losses. The total summary accounts for 10.12 h of normal time per work shift for the operation of a harvester (Tab.9), out of which 76 % represents work operation time (7.72 h).

3.4 Total time per forwarding work operation

Unit time which is defined by the previous function (1) is extended to include normal batch and shift time as well as normal time for required breaks. The coefficient of including batch and shift time norms (k_{BC})

into unit time is 1.25 for forwarders, while the coefficient of including break time norm into unit time (k_2) is 1.06.

After mathematical adjustments, the function for medium and high-power forwarders can be expressed by the following relation (2):

$$t_C = 56{,}426 - 25{,}684 \cdot h + 0{,}038 \cdot L \quad \text{(min/load)} \tag{2}$$

where:

t_C total time consumption per work operation, including batch and shift times for timber forwarding (min/load)

h volume of logged trees in operation unit (m^3/stem)

L forwarding distance (m)

Table 10: Performance standards listed according to selected production factors for medium and high-power forwarders

Work field: Harvesting **Type of work:** Timber forwarding			**Means of work:** Forwarders of performance class over 60 kW		
Number of workers: 1					
Tree species:		Coniferous and deciduous– fresh and dry			
Forwarded timber:		Assortments 2 – 6 m			
Type of felling:		Advance			
		Principal			
Mean-tree volume (m^3)		0.20 – 0.29	0.30 – 0.49	0.50 – 0.69	0.70 – 1.00
Forwarding distance (m)	**Number of standard**	4	5	6	7
		Time consumption (Nh/m^3)			
up to 100	5001	0.08	0.07	0.06	0.06
100 – 200	5002	0.08	0.08	0.07	0.06
201 – 300	5003	0.09	0.08	0.08	0.07
301 – 400	5004	0.10	0.09	0.08	0.07
401 – 500	5005	0.10	0.10	0.09	0.08
501 – 600	5006	0.11	0.10	0.09	0.08
601 – 700	5007	0.11	0.11	0.10	0.09

701 – 800	5008	0.12	0.11	0.10	0.09
801 – 900	5009	0.12	0.12	0.11	0.10
901 – 1000	5010	0.13	0.12	0.12	0.11
for further 100 m	5011	0.005	0.005	0.005	0.005

Average load size – N = 10.1 m^3

Time norms for the operation of medium and high-power machines derive from function (2) (Tab.10).

4 Conclusion

Assortment harvesting method, which at present is associated with harvester technology, is the second most frequently used technology in the Czech Republic with respect to its extent and volume of processed timber. Owing to the high performance of both harvesters and forwarders during a shift, operation of the machinery is highly demanding in terms of technical and organizational planning in order to maximize its work capacity and minimize idle periods. Performance standards are designed predominantly for the purposes of work planning.

Performance standards for medium and high-power forwarders were designed in relation to stem volume and forwarding distance. They do not define tree species from which the assortments of 2 – 6 metre length are produced. In forwarder performance class over 60 kW, performance ranges from 7.7 to 16.7 m^3/h and is conditioned by the above mentioned factors. Work performance encompasses unit and batch times as well as time for necessary breaks (batch and shift time coefficient for forwarder operation is 1.25 and the coefficient for including time necessary for biological breaks is 1.06).

Performance standards divided according to selected production factors can be adjusted by respective percentages with regard to other production factors or can be extended to encompass complementary norms (Dvořák, 2010).

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