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Time consumption and productivity of a forwarder operating on a slope in a cut-to-length harvest system in a *Pinus radiata* D. Don pine plantation

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Abstract

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Time consumption and productivity of a Valmet 890.3 8 wheel forwarder were evaluated on an Australian radiata pine clearfell site with a slope of 21 to 45% (12 to 24°).
Cycle time was significantly related to extraction distance. Productivity was significantly related to extraction distance and load volume. Slope did not have a significant effect on cycle time or productivity. Productivity was considerably greater than that for many published studies, which was likely to have been the result of many factors at the study site affecting load sizes and cycle times, including the large load capacity of the studied forwarder, larger mean log volumes, larger log volumes per loading stop, fewer log assortments, potentially larger forwarder grapple volume capacity, log lengths suited to efficient loading and higher travel speeds.

Keywords: steep slope; cycle time; elemental time; extraction distance; load volume

The most commonly used harvesting system in Australian ground-based operations is the harvester-forwarder system. Previous studies have shown that the major determinants of forwarder productivity are extraction distance and load size (Spinelli et al. 2004; Tiernan et al. 2004; Ghaffariyan et al. 2012; Walsh, Strandgard 2014). Other factors that have been found to impact forwarder productivity include log size (Kellogg, Bettinger 1994; Plamondon, Pitt 2013), log length (Gingras, Favreau 2005), log pile size (Nurminen et al. 2006; Väätäinen et al. 2006), total wood volume (Nurminen et al. 2006) and assortment wood volume (Manner et al. 2013) per strip road distance, number of assortments per load (Nurminen et al. 2006; Manner et al. 2013) and on the harvesting site (Kuitto et al. 1994), driving speed (Lileng 2007) and slope (Tiernan et al. 2004). Operator experience has also been found to be a significant factor in forwarder productivity (Tervo et al. 2010).

Increased use of ground-based, mechanised harvesting equipment on steep slopes has been seen as a means to reduce harvesting costs (Drews et al. 2001) and increase safety (Bell 2002). Specialised steep slope harvesting machines, such as the Valmet "Snake" (Stampfer, Steinmüller 2001), have been developed to work on steeper slopes both in fully ground-based operations and to perform felling, bunching and processing to increase the productivity of cable extraction systems (Acuna et al. 2011). Remotely-controlled harvesters have also been trialled to increase safety when working on steeper slopes by removing the operator from the cabin (Milne et al. 2013).

The maximum slope that a harvester-forwarder harvesting system can operate on is generally limited by the forwarder's capabilities. Tracked self-levelling harvesters can safely operate on slopes up to 60% (31°) (McEwan et al. 2013) whereas forwarders are restricted to slopes of 45% (24°) due to their high centre of gravity and lower traction (McEwan et al. 2013). The high centre of gravity restricts forwarders to operating up and down slope on steeper slopes (Visser, Stampfer 2015) and the lack of traction restricts the maximum slope a forwarder can operate on. Traction can be increased by using a forwarder with more wheels and through the use of traction aids, such as band tracks (McEwan et al. 2013).

Although operation on steep slopes is known to affect forwarder productivity, there has been little research in this area. The objective of this paper was to examine the productivity and time consumption of a forwarder operating on a site with slopes of 21 to 45% (12 to 24°).

MATERIAL AND METHODS

The study was conducted in a mature clearfell *Pinus radiata* D. Don plantation in south-west Western Australia (Table 1). The trial site was located in a 32-year-old *P. radiata* plantation, near Dwellingup with slopes in the stand of 21 to 45% (12 to 24°), latitude: –32°45'32.4", longitude: 116°4'57". Soil was a deep red loam with good traction and minimal obstructions. Trees were felled and processed infield by a harvester with a Cat541 tracked base (Caterpillar, Japan), equipped with a Rosin RD977 harvesting head (Rosin Developments P/L, Australia). Harvesting residues were left onsite. Logs were extracted to a roadside log landing using an eight-wheel Valmet 890.3 forwarder (Komatsu Forest, Sweden) (> 9,000 engine h) with a maximum payload of 18,000 kg. The forwarder was fitted with band tracks on the rear wheels during the study to improve its traction. The forwarder travelled on a formed track and in the stand for each studied cycle.

The trial was conducted on the 15th and 16th of January 2014 in hot, sunny conditions with dry ground. Slopes were measured in the stand using a clinometer. Extraction in the stand was performed uphill. Harvested log products were laminated veneer lumber (LVL) logs, sawlogs and chip logs. Log characteristics for the trial site were obtained from the harvester StanForD data (Table 2). Twenty-three forwarder cycles were studied: 14 LVL loads (mean load volume 19.5 m^3), 3 sawlog loads (mean load volume 17.1 m^3), 2 chip log loads (mean load volume 11.5 m^3) and 4 mixed loads (mean load volume 16.4 m^3).

Table 1. Site description

Site attribute	
Surface area (ha)	2.2
Mean DBH (cm)	35.3
Mean tree height (m)	25.0
Mean merchantable tree volume (m^3)	1.3
Merchantable stocking (No. of trees per hectare)	286
Standing merchantable volume ($m^3 \cdot ha^{-1}$)	360
Slope range (%)	21–45

Forwarder activities during the trial were recorded using a digital video recorder. Forwarder cycle and elemental times (Table 3) were captured from the video recordings using TimerPro software (Version 9.3.15.10, 2010; www.acsco.com). The number of logs per load of each product type was counted during unloading. Load volumes were estimated by multiplying the number of logs per load of each product type by the product type's mean log volume. A Multidat onboard computer (Brown et al. 2002) equipped with a global positioning system receiver was installed in the forwarder to determine travel distances and speeds. Delay times were excluded from cycle times.

Forwarder mean extraction distance was 428 m (range 205–602 m), mean load volume was 17.9 m^3 (range 11.4–23.0 m^3) and mean number of logs per load was 47 logs (range 30–82 logs). Extraction distance was defined as the distance travelled by the forwarder from the first stop to load logs to the first stop to unload logs. This definition was used as it includes the complete distance travelled uphill during extraction.

Table 2. Log characteristics (ranges shown in brackets)

	LVL	Sawlog	Chip log
Mean length (m)	5.48 (5.34–5.5)	3.69 (3.1–5.68)	5.11 (2.74–5.47)
Mean small end diameter (mm)	299 (175–621)	366 (195–728)	163 (56–526)
Mean volume (m^3)	0.46 (0.15–1.67)	0.46 (0.12–1.55)	0.15 (0.014–0.8)
Proportion of total log number (%)	59	18	23

LVL – laminated veneer lumber

Table 3. Forwarder time element definitions

Time element	Description
Travel empty	Starts when forwarder commences travel into the harvest area from the log landing and ends with start of the first crane movement to collect logs.
Loading	Starts with commencement of crane movement to collect logs and ends when the forwarder commences another element. Includes adjustments to the logs on the bunk.
Moving during loading	Movement between log piles with no crane movement. Starts when the wheels begin to rotate and ends when the crane recommences movement. Simultaneous crane and wheel movement is recorded as loading.
Travel loaded	Starts when travel to the log landing with a load and ends when wheels cease to rotate or crane commences to move at the log landing.
Unloading	Starts with commencement of crane movement, with an empty grapple, towards the forwarder's bunk and ends when the forwarder commences another element. Includes adjustments to the log stack.
Moving during unloading	Movement between log stacks at the log landing with no crane movement. Starts when the wheels begin to rotate and ends when the crane recommences movement to the forwarder bunk. Simultaneous crane and wheel movement is recorded as unloading.
Delay	Any interruption causing the forwarder to cease working during a shift.

Forwarder cycle times (cmin), elemental times (cmin·m^{-3}) and productivity [m^3 productive machine hour delay free (PMH$_0$)$^{-1}$] were regressed against extraction distance (m), slope (°), load volume (m^3) and number of logs per load. The statistical significance of the product types making up the studied forwarder loads (LVL, Sawlog, Chip log and Mixed) was tested using dummy variables. Model goodness of fit was assessed using R^2 and root mean square error (RMSE). Speed (m·min^{-1}) empty and loaded, in the stand and on the track were compared using ANOVA. Post hoc comparisons were performed using the Tukey multiple comparison test. All models were checked for compliance with the linear regression and ANOVA assumptions.

All comparisons were made at $P < 0.05$. Multicollinearity was tested using a variance inflation factor (VIF) threshold of 5.

RESULTS

Time consumption

Mean cycle time was 25.4 cmin (standard deviation – SD: 1.2; range: 18.56 to 38.91 cmin). Mean, SD and range (cmin and cmin·m^{-3}) for each time element are shown in Table 4.

Time consumption regression models are shown in Table 5. Extraction distance explained over one half of the variation in "travel empty" time and 22% of the variation in "moving during loading" time. Almost two thirds of the variation in "loading" time were explained by log number and load volume. VIF values for these variables were less than 5. However for the regression of "unloading time", log number was not a significant variable whereas load volume explained over one quarter of the variation. Log

Table 4. Mean (SD) and range for each forwarder time element (cmin and cmin·m^{-3})

Time element	Time (cmin)		Time per m^3 (cmin·m^{-3})	
	mean (SD)	range	mean (SD)	range
Travel empty	4.01 (1.2)	0.94–6.27	0.23 (0.1)	0.05–0.39
Loading	10.58 (2.5)	6.55–15.78	0.62 (0.2)	0.37–1.27
Moving during loading	2.67 (2.2)	0.12–8.8	0.16 (0.1)	0.01–0.47
Travel loaded	3.40 (1.1)	0.59–5.55	0.2 (0.1)	0.04–0.34
Unloading	4.46 (0.9)	3.19–6.56	0.25 (0.1)	0.18–0.36
Moving during unloading	0.28 (0.6)	0–2.48	0.02 (0.05)	0–0.21

SD – standard deviation

Table 5. Regression models for time consumption

Time element	Regression	R^2_{adj} (%)	RMSE
Travel empty (cmin·m^{-3})	−0.0437 + 0.00064 × extraction distance	59	0.05
Loading (cmin·m^{-3})	1.03 – 0.042 × load volume + 0.0072 × log number	64	0.13
Moving during loading (cmin·m^{-3})	−0.125 + 0.00066 × extraction distance	22	0.11
Unloading (cmin·m^{-3})	0.41 – 0.0085 × load volume	27	0.04
Moving during unloading (cmin·m^{-3})	−0.066 + 0.00181 × log number	29	0.04

RMSE – root mean square error

number explained almost one third of the variation in "moving during unloading" time. There was no significant relationship between "travel loaded" time and any of the variables tested.

Extraction distance was the only significant variable in the forwarder cycle time regression model. The best fit forwarder cycle time model is as follows (Eq. 1):

$$\text{Cycle} = 13.62 + 0.0275 \times \text{ED} \tag{1}$$

where:
cycle – cycle time (min),
ED – extraction distance (m),
R^2_{adj} = 29%,
RMSE = 4.0.

Productivity

Mean forwarder productivity was 43.6 m^3 PMH$_0$$^{-1}$. Extraction distance and load volume were significant variables in the forwarder productivity regression model. The best fit forwarder productivity model is as follows (Eq. 2):

$$\text{Productivity} = 44.4 - 0.0614 \times \text{ED} + 1.420 \times \text{LV} \tag{2}$$

where:
LV – load volume (m^3),
R^2_{adj} = 71.1%,
RMSE = 5.9,
VIF < 5 (for the independent variables).

Forwarder speed

Mean forwarder speed was significantly higher when operating on the track (103 m·min^{-1} loaded and 109 m·min^{-1} unloaded) than when operating in the stand (28.5 m·min^{-1} loaded and 44.5 m·min^{-1} unloaded) and significantly slower when operating loaded in the stand compared with operating unloaded in the stand.

DISCUSSION

As has been reported in numerous previous studies (Spinelli et al. 2004; Tiernan et al. 2004; Ghaffariyan et al. 2012; Walsh, Strandgard 2014), extraction distance was the major factor determining forwarder cycle time in the current study, accounting for over one quarter of the variation in cycle time. Slope did not have a significant impact on forwarder cycle time. This was likely to be because the greater proportion of travel time was on the track where slopes were lower than in the stand and travel speeds were significantly greater. In contrast, Hartsough et al. (1994) and Adebayo et al. (2007) found that slope had a significant effect on forwarder cycle times in their studies, where the majority of the cycle took place on the slope, though the effect in the Hartsough et al. (1994) study was relatively minor.

Forwarder travel empty and loaded times depend on travel distance and speed, which is determined by terrain conditions. In the study, travel empty time was significantly dependent on extraction distance whereas travel loaded time had no significant relationships with the tested variables. Nurminen et al. (2006) also found extraction distance (equivalent to travel empty distance in their study) to be significantly related to travel empty time. Variation in travel loaded times was mainly due to the proportion of travel time that occurred in the stand, where travel speeds were significantly slower than on the track. This proportion varied between cycles depending on the point in the stand at which the forwarder had collected a full load.

The finding that loading time increased with increasing log number per load was likely to reflect the fact that loads with larger numbers of logs had greater proportions of chip logs, the smallest logs in the study. This supported the findings of Nurminen et al. (2006) and Danilović et al. (2014), who found that smaller logs took longer to load. Nurminen et al. (2006) also found that products with a lower log volume/ha had increased loading times as fewer logs were available at each loading stop. As chip logs made up less than one quarter of the logs in the study, this factor may also have increased loading times for loads containing more chip logs.

The apparently contradictory finding that loading and unloading times increased with decreasing load volume was likely to be the result of the inverse relationship between load volume and the number of logs per load (Kellogg, Bettinger 1994) which resulted in smaller load volumes being associated with loads with greater proportions of chip logs. As with loading times, smaller logs have also been associated with longer unloading times (Nurminen et al. 2006). Increasing numbers of assortments per load have also been found to increase unloading times (Nurminen et al. 2006; Manner et al. 2013). The number of assortments per load did not significantly affect unloading times in the study as each product was kept separate on the bunk. However, it did affect moving during unloading time which only occurred when mixed loads were unloaded. The significant relationship between moving during unloading time and log number reflected the greater distance between the chip log pile and the other product piles than that between these piles and that mixed loads with chip logs tended to have higher total log numbers.

Moving during loading time has been found in previous studies to be related to the loading distance which in turn is dependent on the log concentration along the strip road (Nurminen et al. 2006; Manner et al. 2013). Log concentration was not measured in the study and hence could not be used in the analysis. The significant relationship between moving during loading time and extraction distance in the current study may have resulted from extraction distance including the distance travelled during loading.

Mean forwarder productivity at the study site was almost double that reported in many previous forwarder studies at similar mean extraction distances (Tiernan et al. 2004; Gingras, Favreau 2005; Nurminen et al. 2006; Eriksson, Lindroos 2014). Forwarder productivity is a function of load size and cycle time (Gingras, Favreau 2005). The forwarder in the current study had an 18 t nominal load capacity whereas most forwarders in the previous studies had nominal load capacities of ≤ 14 t. Mean log volumes reported in the previous studies were also smaller than those in the current study (in many cases substantially less) which was likely to have limited the forwarder operators' ability to achieve loads at or above the nominal load size given the inverse relationship between load volume and log size noted above. In the current study, approximately half of the loads exceeded the forwarder's nominal load capacity. Cycle times for the previous studies (calculated from models and mean productivity figures) exceeded 30 min (extraction distance = 400 m), which was considerably greater than that for the current study. There were a number of potential reasons for the lower mean cycle time in the current study. A number of previous studies (Gullberg 1997; Nurminen et al. 2006; Väätäinen et al. 2006) found that when log concentrations were less than approximately 0.1–0.2 m^3 per loading stop, loading time ($min \cdot m^{-3}$) increased significantly. Although log concentrations were not measured in the study, individual log volumes of the majority of logs exceeded this value. The number of assortments was also much lower than that in modern Finnish harvesting operations (Manner et al. 2013) with most loads consisting of a single product, and the log volume per hectare was high. The latter two factors were also likely to have minimised moving during loading time. Grapple volume was reported by Gullberg (1997) as having a significant effect on loading times. Although grapple volume was not measured in the study, a large forwarder, such as used in this study, would be expected to have a grapple with a larger volume capacity than the smaller forwarders used in most previous trials. Gingras and Favreau (2005) reported that minimum loading times were achieved for log lengths of 5 m, which was close to the length of the majority of the logs in the current study. The relative time element proportions in the current study (loading time 42%, travel empty and travel loaded times 29%, unloading and moving during unloading time 19%, moving during loading time 10%) were similar to those modelled by Manner et al. (2013) at an extraction distance of 400 m. Given the lower mean cycle time in the current study, this implies that forwarder travel speeds were greater than those in the previous studies. Travel empty and loaded speeds on the track in the current study were almost double those reported in previous studies while travel unloaded speed in the stand was comparable (Nordfjell et al. 2003; Tiernan et al. 2004; Gingras, Favreau 2005; Nurminen et al. 2006). Travel loaded speed in the stand was comparable to that reported by Gingras and Favreau (2005) for travel loaded on a slope of greater gradient than 30%.

CONCLUSIONS

As found in many previous studies, forwarder cycle time was significantly related to extraction distance, which accounted for over one quarter of the variation in forwarder times. Slope did not have a significant effect on forwarder cycle time which was likely to be because the greater proportion of travel time was on the track where slopes were lower and travel speeds were greater than in the stand.

Forwarder travel empty time in the study was significantly dependent on extraction distance whereas travel loaded time was not significantly dependent on any of the tested variables. The significant relationship between loading time and the number of logs per load and the load volume and between unloading time and load volume was likely to reflect the greater time required to load and unload forwarder loads with greater proportions of chip logs, which had the lowest mean log volume in the study.

Forwarder productivity in the current study was greater than that reported in many previous studies, which was likely to have been the result of many factors at the study site affecting load sizes and cycle times, including the large load capacity of the studied forwarder, larger mean log volumes, larger log volumes per loading stop, fewer log assortments, potentially larger forwarder grapple volume capacity, log lengths suited to efficient loading and higher travel speeds.

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