UNIVERSITY OF CANTERBURY

Falcon Forestry Carriage Series 2: A Case Study of Productivity and Operation

A dissertation submitted in partial fulfilment of the requirements for the degree of Bachelor of Forestry Science in the School of Forestry by C. J. Bolitho

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Abstract

The multiple drivers of workplace safety and increasing productivity are resulting in increased mechanisation within the forestry industry. The use of motorised grapples in cable harvesting is an applicable mechanisation method to the large proportion of steep terrain harvesting in New Zealand.

In this dissertation a time study of the Falcon Forestry Carriage Series 2 has been undertaken in order to access its productivity and operation. Mean values of productivity were found to be 54.9m^3/PMH for wood extracted from the ground, 64.6m^3/PMH for bunched wood and 75.6m^3/PMH for excavator fed wood after adjustment for the cycle distance and accumulation type. Longer cycles were found to decrease productivity by 0.15m^3/PMH for each meter of cycle distance.

Utilisation in the study was found to be 56% of total time which was similar to previous studies. 15% of total study time was accounted for by operational delays, 7% by personal delays and 23% by mechanical delays. Mechanical problems with the carriage occurred 6 times and accounted for 171 minutes or 13.4% of total delay time. Mechanical delay breakdown was similar to that found by McFadzean (2012) who recorded that 15% of total delay time was attributable to carriage mechanical delays.

During a study of Operator effect it was found that the inexperienced Operator 3 and Operator 4 had a productivity of 52.2% (not statistically significantly different) and 18.5% (p value <0.05) of that of the experienced Operator 1 on the same site. Large differences in productivity relating to experience were also found in a comparable Norwegian study. An 11.6% difference between experienced operators on different sites was found to be statistically significant (p value <0.05).

The effects of accumulation method and cycle distance upon productivity were found to be similar to the results of previous studies, as was the utilisation of time within the study.

Key words

Motorised grapple carriage, cable harvesting, steep terrain logging, operator effects

CONTENTS

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2. Introduction

The New Zealand forestry industry annual harvest volume is currently at 25 million m^3 and rising. Future harvesting is likely to be difficult harvesting on steep ground; this will necessitate the use of cable harvesting (Raymond, 2012). During cable harvesting felling and breaking out have been identified as the main tasks contributing to serious harm incidents (Labour, 2011). The use of grapple carriages allows cable harvesting without breaking out and is therefore preferable from a health and safety perspective.

With a variety of grapples and other harvesting options available to the New Zealand logger there is value in the knowledge of options and their performance. The Falcon Forestry Carriage is produced by D C Equipment in Brightwater, Nelson for the forestry market. The carriage incorporates a motorised rotating grapple and a camera with live feed to the operator in the hauler cab. These features negate the need for personal breaking out on the hillside during cable extraction. A second version of the carriage labelled the Falcon Forestry Carriage Series 2 (FFCS2) has been recently produced and was the focus of this study. The FFCS2 is 800kg lighter than the Falcon Forestry Carriage Series 1 (FFCS1) and has a slightly smaller grapple. Both carriages attain similar performance in terms of grapple closing time and pressure.

This study investigates the productivity and effectiveness of the carriage under varying accumulation methods, operators and conditions.

3. Literature Review

Cable harvesting in New Zealand involves the extraction of logs utilising a tower or swing yarder. In a survey of 50 New Zealand cable harvesting crews it was found that only 4% of crews used a motorised carriage as a preference and only 28% had used one in the last year (R. Visser, H. Harill, 13-15 Jun 2011). Previous studies by H. Harrill and R. Visser have concluded that the most common type of rigging configuration in New Zealand is the North Bend configuration. The second most common configuration was running skyline, followed by live skyline (R. Visser, H. Harill, 13-15 Jun 2011).

Internal power source, radio controlled grapple carriages have been available for use since at least the 1970's. A 1976 reference provides a detail of this history, stating that the earliest motorised carriage systems enabled the deployment of wire rope rigged with chokers from the carriage clamped to a standing skyline (Christensen, 1978). These carriages were radio controlled and with two models specified, powered by a 95hp diesel engine or 24hp butane engine. It was further stated that increasing labour costs and reducing availability during the 1960's were resultant in the production of a motorised carriage with a grapple attached. Such a carriage enabled the reduction in a crew from five men to two. All the above cable logging systems require the use of a spotter to relay instructions to the yarder operator.

Methods of statistical quantification of productivity include the method of detailed time study or shift level study. A detailed time study can be differentiated from a shift level study as it involves the accurate timing of each task undertaken, rather than the timing and results of a whole shift. A report published by Oregon State University on harvesting productivity analysis has found detailed time studies to be an excellent way to compare delay free production between harvesting methods used (Olsen, 1998). A shift level study will include short delays as part of the productive time. In comparison a detailed time study differentiates and records these as separate from productive time to provide greater accuracy (Olsen, 1998). Accuracy in time studies is often attainable to the unit of seconds (Olsen, 1998). Variation for each element of the cycle and for a whole cycle can be predicted by a linear regression equation. Statistical comparison of cycle times and productivity can be used to investigate differences and similarities in harvest operations. Remaining variation that is not explained by the linear regression is equal to ($1-r^2$) and is quantified as all variation that is determined by a variable other than the predictor variables. Unexplained variation can be reported as standard error of the dependant variable and may be used to determine study length. Due to the often limited sample size of time studies (e.g. a few days is often considered sufficient sample size for a harvesting operation) there is a poor representation of long delays within the data. This can be of concern to the accuracy of recording and explaining long delays and therefore limits the utility of the method to explaining these types of delays. Meeting an appropriate representation of the range of conditions, both meteorological and terrain can be a restraint with a sample size of only a few days (Olsen, 1998). In this study the time study method was deemed appropriate due to the accuracy obtainable with limitations deemed acceptable. The time study method allowed comparison with previous study of other harvesting grapples such as the Falcon Forestry Carriage Series 1 (FFCS1), the predecessor of the tested model.

In 2012 Milne provided an overview of the FFCS1 with the functions and principals of the motorised carriage operation explained. Milne (2012) investigated the radio operation of the carriage but did not conduct a time study or assess the productivity of the device.

Also in 2012 a study by S. McFadzean from University of Canterbury was undertaken upon a tower yarder equipped with a FFCS1. A linear regression was performed by McFadzean to predict productivity and cycle time. Productivity was found to be 32.7t/PMH when no bunching was performed but increased to 63.3t/PMH when the wood was bunched or 76t/PMH when the grapple was fed with an excavator. Productivity using chokers was found to be 41.8t/PMH. This shows that the productivity of a grapple is dependent upon the system that it is used within. During this study the heartbeat of hauler operators was measured throughout the day in order to access fatigue and stress. The majority of peaks in heart rate were associated with the operator being required to leave the cab in order to undertake a physical task. Few cases were associated with the normal operations of the grapple and on three out of the four days tested the operator was deemed not to have become fatigued. The study recognises that a small sample and lack of other information limits the conclusions drawn. However the results do indicate that the operation of the Falcon Forestry Carriage does not cause unmanageable ergonomic stress or fatigue.

Further study of the Falcon Forestry Carriage Series 1 (referred to as motorised carriage) was undertaken by S. Nuske (2014) with comparison of the carriage to a mechanical grapple carriage. Productivity of the motorised carriage was found to be 76t/PMH over a range of sites. This was 22t/PMH less than the mechanical grapple that was found to extract 98t/PMH. It was stated that different sites may have accounted for some of this difference in productivity with the mechanical grapple being used on more 'harsh' sites with longer cycle distances, steeper slopes and more often motor-manually felled trees than the motorised grapple. The motorised carriage was found to be also more productive than the mechanical system when extracting motor-manually felled trees. It was stated that the ability of the motorised grapple to rotate presented a clear advantage when extracting trees which were unorganized due to being felled with a motor-manual method. During the study by Nuske (2014) the cycle payload was investigated and it was found that the mechanical grapple attained an average payload of 2.9t; this was greater than that attained by the motorised grapple at 2.6t. It was stated that an increased payload may be attributable to the mechanical system extracting more bunched and handed wood than the motorised system. However it was also stated during payload prediction that when all other variables were equal the motorised grapple appeared to extract smaller payloads and that this may be partially attributable to the greater weight of the motorised grapple at 2.3 tons as compared to the mechanical grapple at 1.3 tons.

During 2014 H. Harill observed 8 different cable harvesting operations New Zealand wide and investigated a range of factors including skyline tension, harvesting method, cycle time and productivity. Three of these sites were at operations utilising the Falcon Forestry Carriage Series 1. Two of these sites were located in Nelson region with one located in Canterbury; all were extracting motor-manually felled stems. Average extraction distance at each site was 184m, 226m and 225m for the sites in Nelson and Canterbury respectively. Productivity was found to be 46.5 m^3, 56.8 m^3 /PMH and 47.7m^3/PMH respectively at these sites.

Increases in productivity due to bunching are further supported by a report comparing two excavators specially equipped with steep terrain equipment and feller-buncher harvesting heads (D Amishev, T Evanson, 2010). In this study two crews were investigated with both using a grapple to extract stems that had been felled and bunched. A gain in productivity of approximately 33% was seen with bunching the stems (D Amishev, T Evanson, 2010).

In an international literature review of available grapple carriage developments it was found that larger capacity grapples and carriages were available in North America ("International Grapple/Carriage Developments: A review of the Literature," 2011). While carriages were available in Europe none were found to be equipped with grapples. The review concludes that the most innovative grapple carriage found is the Eagle Claw. This carriage is similar to the Falcon Forestry Carriage in the respects that both are diesel powered with remote controlled, camera assisted operation of a hydraulic grapple. Both carriages allow rotation of the grapple. Two versions of the carriage are found to be available with the larger Mega-Claw weighing 1.3 ton and the smaller Yoda-Claw weighting 820kg (Eagle Claw website). No studies of these USA manufactured carriages were available and no other internal power source grapple carriages are identified in this report. In addition to the FFC another notable exception from this review is the Alpine grapple[1]. This battery powered grapple is available in New Zealand and merits similar features as the Eagle claw and Falcon Forestry Carriage with live skyline operation. Other features in common include a rotating and hydraulically powered grapple and a camera providing image to the hauler operator.

[1] Alpine grapple information available from Logpro Website: http://www.logpro.co.nz/alpine-products/

4. Research Question

The aim of this study is to expand upon and provide comparison to current research by measuring the productivity and cycle time of the Falcon Forestry Carriage Series 2. Furthermore, the study will quantify the effects of variables such as felling technique, stem presentation and hauler operator as well as evaluation of the cause of delays. The study aims to provide information that will provide logical assistance for contractors and managers.

5. Methods

Data was collected in the field before being analysed in the lab using freeware R statistical software. R was used for the model creation, graph production and statistical analysis. Linear models were used to evaluate the effects of factors and variables upon productivity of the system and delay free cycle time. A Tukey honest significant differences test was used to determine the differences in productivity and delay free cycle time between factors, this was implemented when comparing differences in operator and method.

5.1 Study Site

Data was collected at two different cable logging operations on the South Island of New Zealand. Both operations were clear felling *Pinus radiata* plantations on steep terrain sites (Table 1). Hauler locations were recorded with a GPS to calculate the average chord slope. In addition a vertex was taken to measure the angle of the hill and approximate chord slope manually for verification.

Table 1: Stand details for forest variable for study sites at Operation 1 and 2

Variable	Operation 1	Operation 2
Site	Eatwell	Mossburn
Year	1986	1987

Mean top height (m)	40.4	29.0
Piece size (t)	1.93	0.91
Stocking (stems/ha)	320	498

Operation 1 was located at Hancock's Forest at Eatwell near Nelson. The operation consisted of a Madill 171 tower yarder located on a ridge and extracting stems to the ridge line and to some extent off to the side of the ridge (Figure 1). The slope was a convex form and chord slope was measured at average of 35% for the setting. A bulldozer tail hold was located on the same ridge and as a result all extraction was done off the front face. Data collection was completed during January at Operation 1. The weather was hot and dry throughout the study period.

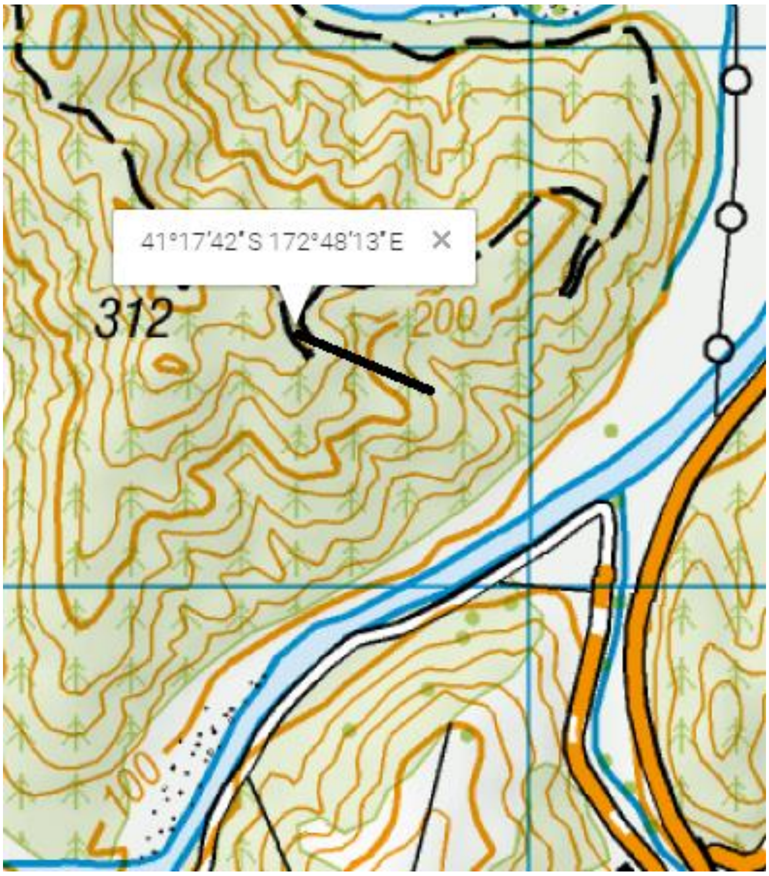

Figure 1: Topographic map showing coordinates of Operation 1 hauler location and haul corridor.

Operation 2 was located in Rayonier's Forest at Mossburn, Southland. The operation consisted of a BE 60 tower yarder located on a large ridge with a haul corridor off the side of the ridge to a tail spar tree, with a chord slope of 38%. The corridor did not cross the gully or stream in the bottom of the gully, therefore all extraction was from the front face (Figure 2). The terrain over the corridor was described as undulating and slightly concave. Data collection was completed during July at Operation 2. The weather was cold with precipitation on all days, mostly in the form of snow. Some problems were encountered with water running down the haul corridor; having the potential to cause sediment runoff.

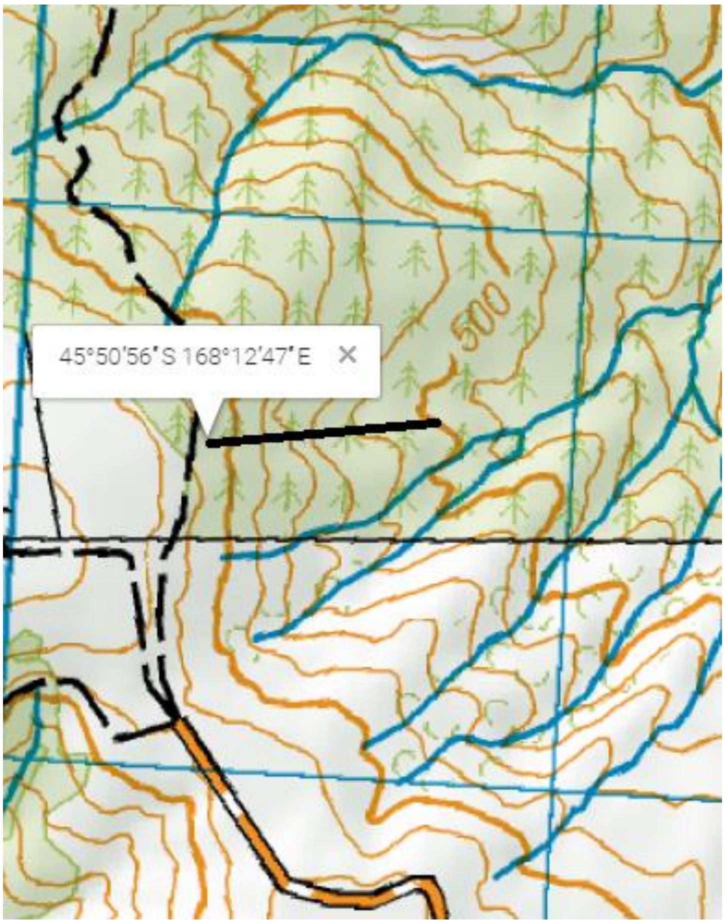

Figure 2: Topographic map showing coordinates of hauler at Operation 2 and haul corridor.

5.2 Operational Description

Both logging operations were fully mechanised operations. They used an excavator with a felling head to fell the trees and an excavator with a processing head to remove logs from the chute for processing. Comparison of operation details by process are shown below in Table 2.

Table 2: A description of Operation 1 and 2 showing processes and other operation factors.

Process	Operation 1	Operation 2
Felling	D C Engineering Winch Assist Excavator	30t excavator w Satco boom & felling head
Hauler	Madill 171 (60ft Tower)	BE 60 (60ft Tower)
Skyline diameter	1¼”	1”
Processing	Mechanised	Mechanised
Skid operation	Bell loader and front end wheeled loader	2x Excavators with log grapple
Tailhold	Dozer	Tailspar rigged at 363m
Total Crew	7	7
Weather Conditions	Clear and dry	Wet with snow and precipitation

At both operations the Falcon Forestry Carriage Series 2 (FFCS2) was the most commonly used carriage during the study, but both sites also used alternative methods. For example, 18 cycles were recorded at Operation 1 using the Falcon Forestry Carriage Series 1 (FFCS1) after the Series 2 model broke down and five cycles were recorded at Operation 2 using a simple shotgun carriage with chains; this was because the crew were awaiting the Falcon Forestry Carriage to return from repairs.

The tail hold at Operation 1 was a bulldozer which was mobile and was shifted regularly to compensate for the inability of the system to lateral yard. The tail hold in Operation 2 was a spar tree and stems were shovelled to the spar tree with two excavators in the cutover feeding stems. This resulted in a large area being harvested with one tail hold and the majority of the stems being excavator fed, to the carriage (i.e. handed from the excavator into the grapple of the carriage).

The comparability between operations was improved by the fact that the equipment, methods and manpower was similar. Both were tower yarders with a fully mechanised operation and a crew size of 7.

5.3 Cycle Data Collection

Data was collected while the crew performed regular logging operation. Data was recorded from a safe zone that was either located on the skid or to the side of the skid. This allowed accurate view of both operation of the grapple at the skid and the view of logs that were extracted to the skid from the cutover.

Cycle times were recorded initially using a stop watch and spread sheets to record times and all cycle variables. The recording of times was changed to the Time Motion Study application before study at the second site.[2] This app allowed more accurate recording of times with easy and quick backing up of data.

Each cycle was split into four cycle elements that were recorded separately. An explanation of element categorisation is provided in Table 3.

Table 3: Cycle element definition for the operation of the Falcon Forestry Carriage Series 2

Cycle Element	Explanation
Carriage out	Element recorded from when carriage begins moving on skyline to leave the landing until the carriage first stops on the skyline in an area that is associated with picking up stems.
Accumulate	Element recorded from when the carriage first stops on the skyline in an area that is associated with picking up stems until the time when it is loaded and begins movement back along the skyline towards the landing.
Carriage in	Element begins when carriage has loaded out in the haul corridor and first begins movement along the skyline back towards the landing. Element ends when carriage first stops movement on the skyline over the landing.

[2] Time Motion Study application sourced from: https://play.google.com/store/apps/details?id=com.nextw3.timemotionstudy&hl=en

Unhook	Element recorded from the time carriage first stops on the skyline when over the landing until carriage begins movement on the skyline to leave the landing.

In addition to the cycle elements the following variables were recorded as associated with each cycle.

- Cycle Distance - The distance the carriage moves from the landing to the first stop associated with picking up stems. This was recorded as a % of the total distance of that corridor and was validated regularly with a rangefinder. Corridor length was recorded with a rangefinder.
- Number of grapples - Number of attempts that the operator has at grappling stems. Defined as the number of times the grapple claws closes (e.g. the claw closing around a stem is one attempt, if that stem was to slip out and is then grappled again that would be two attempts).
- Logs extracted - The number and classification of logs extracted by the carriage. These are defined as a top (containing the top but not the butt section), stem (log containing both butt section and a portion of where the live crown would be located) or butt section (a log that contains the butt and is clearly not an entire stem) of the log respectively.
- Operator – Crew member currently operating the hauler and carriage.
- Fed – Whether the stems extracted in the cycle were fed to the grapple carriage by an excavator in the cutover or picked up from the ground. A dummy variable that can be either 0 or 1.
- Bunched – Whether the logs were taken from a surge pile or picked up individually. A dummy variable that can be either 0 or 1.

5.4 Delay Data Collection

Delays were categorised into each of the three categories of operational, personal or mechanical delays. Operational delays are those regularly required as a part of the continued operation. Operational delays include the fuelling of equipment as well as normal maintenance. Personal delays are those delays caused by a crew member deciding to take a break; which includes stops in operation for a crew member to get a drink or food. Mechanical delays are those caused by mechanical breakdown of equipment. In addition to delay type a breakdown of the specific delay cause was recorded. The cause included the item, individual or action causing the delay and the reason it was causing a delay.

5.5 *Stem Measurement*

Stems were measured in order to provide an accurate measurement of cycle volume. Measurement took place during breaks of work on a random sample of the last stems that were extracted preceding the break. Measurement of five logs was typically completed in each break. Stems measured were classified into stem, butt and top in the same manner as the time study.

Large end diameter of stems was measured in addition to the diameter every four meters. Diameter was measured in cm to one decimal place. The length of logs was also measured to the nearest 10cm. These measurements were converted to volume with each 4m section treated as a cylinder. The average taper of the stem was calculated and used to predict small end diameter, this allowed the volume between the last diameter measurement and the small end to be calculated. Sections were summed to calculate the total volume of the stem (Table 4).

Table 4: Summary of stem volume sampled at Operation 2 and processor head data collected at Operation 1

	Stem	Butt	Top	Processor Head
Number of samples	41	16	2	277
Min Volume (m^3)	0.50	0.15	0.17	n/a
Max Volume (m^3)	3.01	1.30	0.45	n/a
Average Volume (m^3)	1.71	0.64	0.31	1.03
StDev Volume (m^3)	0.61	0.36	0.19	n/a

Due to a lack of time at Operation 1 a sufficient sample could not be taken. Therefore the volume processed and number of stems processed was obtained from the processing head and used to calculate the average volume. In this case proportions similar to those used in other studies were implemented to calculate the volume of top and butt log sections. (Mcfadzean, 2012) (Nuske, 2014). These proportions are shown in Table 5.

Table 5: Proportions of stem volume used in analysis of Operation 1

Stem	= 1 × average piece size
Butt	= .8 × average piece size
Top	= .2 × average piece size

5.6 Model Computation

Linear models were created to estimate the delay free cycle time and the productivity. The following variables were used in these models.

Delayfree -	Total delay free time of the cycle (minutes)
Prod -	Represents productivity (m^3/productive machine hour) of that cycle
Cycle dist -	Maximum distance the carriage reached from the landing
Carriage -	Carriage used for cycle (1= FFCS2, 2= Shotgun w chains, 3= FFCS1)
Bunched -	Factor for bunched or non-bunched stems (1=bunched, 0=non-bunched)
Fed -	Factor for excavator feeding logs to grapple (1=fed , 0=non-fed)
Operator -	Factor for operator controlling hauler and grapple (operators labelled as number 1 to 5).
Cycle vol -	Continuous variable representing volume of logs extracted during cycle

Linear models were created using all appropriate and significant predictors. The coefficient of these predictors allowed quantification of the effect of each variable. For multilevel factor predictors (e.g. carriage and operator) the coefficient represents the effect of the variable in comparison to one level of the factor (the dummy variable).

5.7 Operator Effects

Data was recorded while the hauler and carriage was being operated by a total of five different operators. While all operators apart from Operator 3 were experienced in hauler operation only Operator 1 and 5 usually operated the hauler.

The effect of operator upon productivity was calculated by the adjustment of recorded values. The recorded values were adjusted by the factors cycle distance, bunching and fed to provide a standard cycle of 150m with no bunching or feeding. Adjustments used were taken from the linear equations or cycle time and productivity. Adjustment allowed comparability between the datasets of different operators. A Tukey HSD test was conducted upon the standardised data in order to determine significant differences between the productivity of operators.

Only data collected using the Falcon Forestry Carriage Series 2 was used to compare operators or feed methods.

6. Results

6.1 Results Overview

Table 6: Mean values obtained from results of study for three primary measurements.

Variable	Mean Value
Cycle Distance (m)	207.7
Cycle Time (min/cycle)	3.33
Productivity (m^3/PMH)	54.9

Table 7: Average values of data obtained for cycles with accumulation method of extracted from the ground.

Variable	Value
Productivity (m^3/PMH)	55.7
Cycle time (min)	1.69
Cycle distance (m)	107.0
Carriage out (min)	0.25
Accumulate (min)	0.59
Carriage in (min)	0.58
Unhook logs (min)	0.26

Table 8: Overview of data gathered by site, showing the minimum, maximum, average value and standard deviation of each variable.

Variable	Calculation	Site 1	Site 2
Extracted from Ground Proportion	Mean	28%	0%
Bunching Proportion	Mean	72%	1.30%
Excavator Fed Proportion	Mean	0%	98.70%
Data Captured (hours)	Total	21.6	26.4
Cycle Distance (m)	Min	18.5	10
	Max	205.2	363
	Avg	123.6	308.8
	Std Dev	48.4	104.8
Stems (#/cycle)	Min	0	1
	Max	7	4
	Avg	2.35	2.15
	Std Dev	1.39	0.72
Volume (m^3/cycle)	Min	0	0.31
	Max	7.24	6.83
	Avg	2.22	2.85

	Std Dev	1.45	1.31
Carriage out (min)	Min	0.07	0.05
	Max	2.37	4.82
	Avg	0.42	1.33
	Std Dev	0.25	0.58
Accumulate	Min	0.83	0.04
	Max	8.52	3.66
	Avg	1.07	0.64
	Std Dev	1.16	0.51
Carriage in (min)	Min	1.16	0.02
	Max	6.17	3.35
	Avg	0.76	1.35
	Std Dev	0.76	0.52
Unhook logs (min)	Min	0.03	0.05
	Max	5.6	2.73
	Avg	0.49	0.64
	Std Dev	0.85	0.28
Number of Grapple attempts	Min	1	1
	Max	5	3
	Avg	1.26	1.03
	Std Dev	0.62	0.18
Productivity	Min	0	3.02
	Max	273.3	221.9
	Avg	60.9	47.5
	Std Dev	41.5	31

6.2 Cycle Elements

Carriage in was observed to account for 31.2% of the average delay free cycle time, while unhook was the shortest cycle element at 17% of average cycle time. The greatest variation time was found in accumulation time with a standard error of 0.045 min or 2.7 seconds (Figure 3).

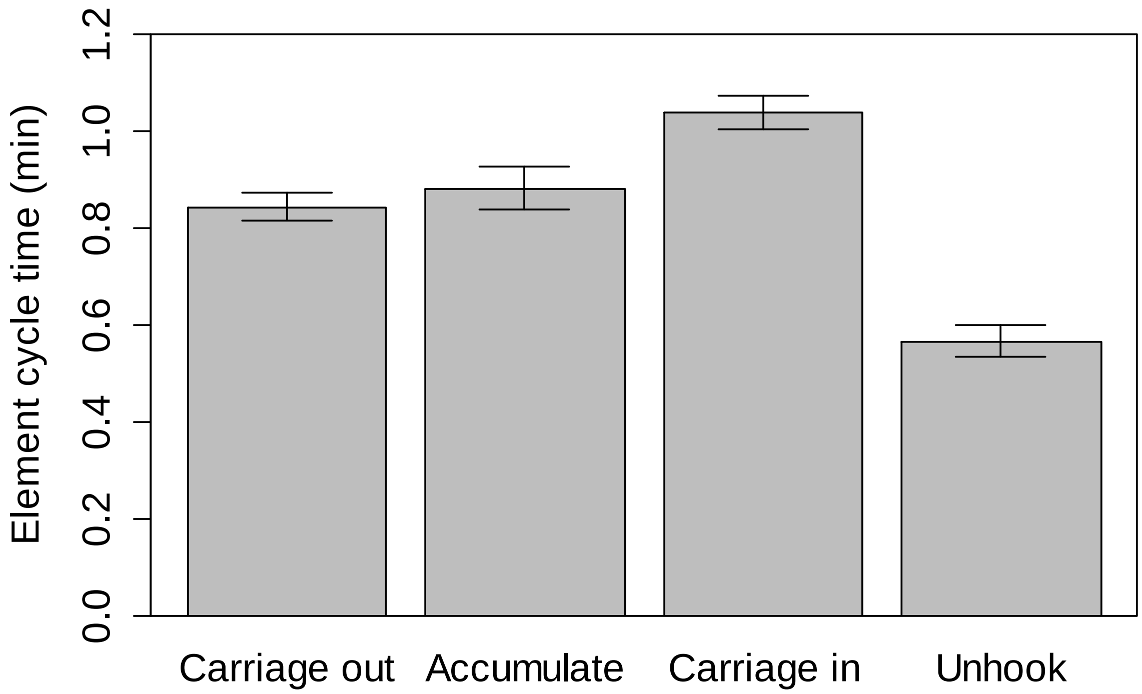

Figure 3: Average delay free cycle time of observed cycle elements, error bars indicate standard error of cycle element

6.3 Delay Free Cycle Time Model

Delay free cycle time of the FFCS2 was able to be modelled using the variables recorded. Only variables that could be predicted before the harvest of a setting began were included as predictors in the model. This enhances usability of the model to forest managers and contractors. Predictors that were found to be important were cycle distance, feed type (excavator feeding) and log bunching. The following equation was produced with significant predictors (significance level was p = 0.05). The model was found to explain 29.65% of the variation within the data ($r^2 = 0.3$).

$$Delay\ Free\ Cycle\ time\ ({}^{min}/_{cycle}) = 0.943 + 0.0073 \times dist + 0.8656 \times feedtyp + 1.267 \times bunch$$

The equation indicates that the average cycle time is shown to increase by 0.87 minutes when the cycle is fed by an excavator. Cycle time was shown to increase by 1.27 minutes when the wood was bunched. Delay free cycle time increased with distance at a rate of 0.007 minutes/m (Figure 4).

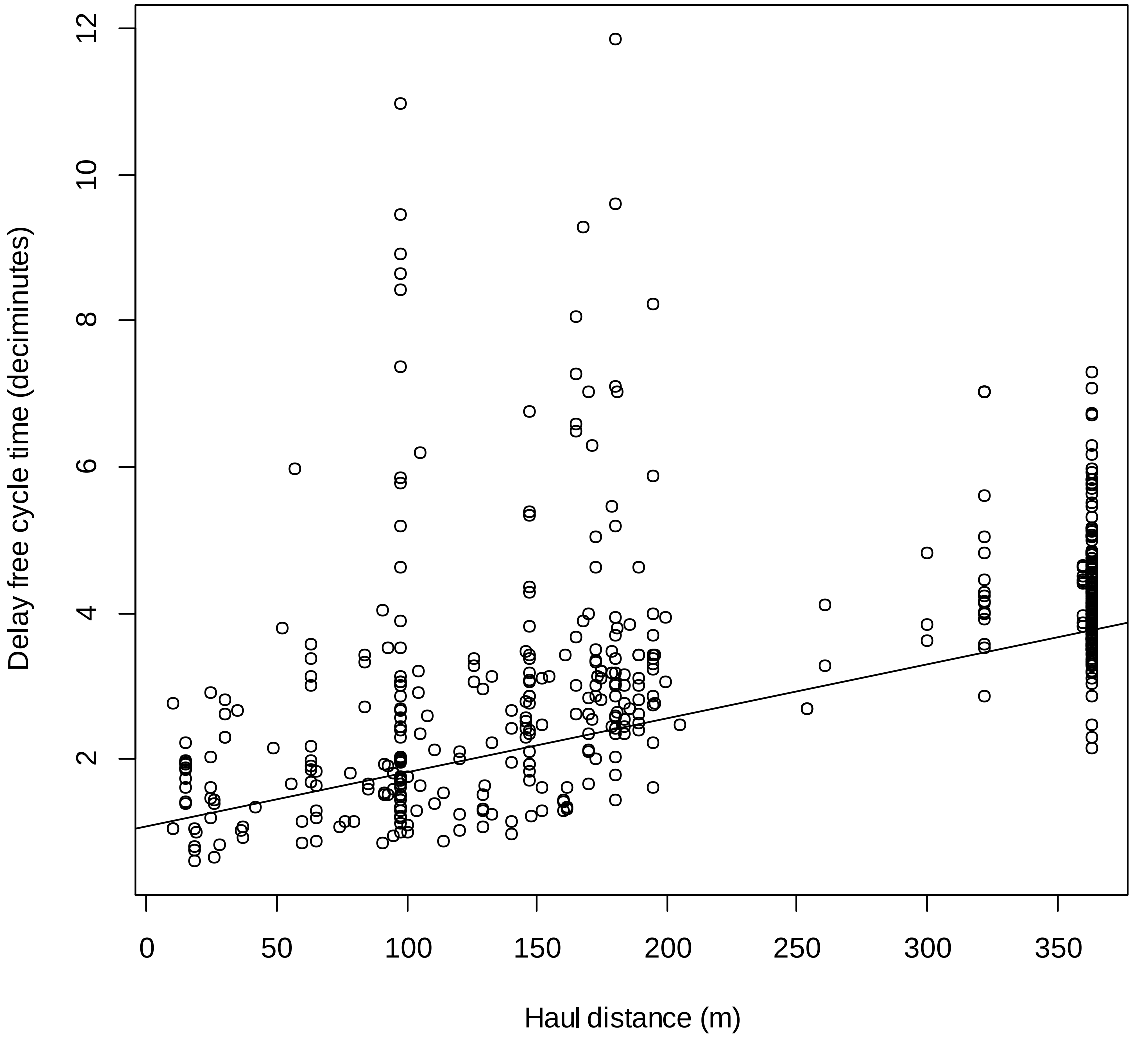

Figure 4: Delay free cycle time at given distance with model trend line shown.

Note that the trend line in Figure 4 does not include the effects of feed type or bunching.

Carriage out

Cycle distance was found to be a significant predictor of carriage out time (p value < 0.000001). Carriage out was found to increase by 0.004 minutes for each meter of cycle distance (Intercept = 0.0351 minutes).

Accumulate

It was found that the number of logs extracted and the number of grapple attempts made were significant predictors (p value <0.05) of the time taken for the accumulate cycle element. The accumulate time (min) could be predicted according to the equation below ($r^2 = 0.32$).

$$Accumulate = -0.5858 + 1.0842 \times number\ of\ grapples + 0.0914 \times number\ of\ logs$$

It will take a longer time to accumulate more logs and where a grapple is not made successfully another attempt will is made, taking further time. The average time taken to accumulate logs on cycles that were not bunched was 0.62 minutes in comparison to a time of 1.26 minutes for cycles that were bunched.

Other effects such as cycle distance of haul, feeding methods and bunching were also investigated. It was found that the effect of operation was significant with a mean grapple logs time of 1.09 min at Operation 1 and 0.63 min at Operation 2. This was similar to the effect of feeding the grapple with an excavator where fed cycles recorded a mean grapple logs time of 1.09 minutes and non-excavator fed cycles recorded a mean grapple logs time of 0.61 minutes. This may be a confounding effect caused primarily by excavator feeding, operator or another factor. This is noted because Operation 2 included all excavator fed cycles and a different operator than Operation 1 (Figure 5).

When distance was included in the above model it was found to be a significant predictor (p value < 0.05) with a coefficient of -0.00107. This indicates that the time taken to grapple stems at a longer distance was less than that at a short distance. It is noted that stems grappled at very short distances tended to be dropped or previously missed logs; this would increase difficulty of grappling due to the presentation of logs not being excavator placed (i.e. bunched). This may also be a confounding error due to the large number of cycles recorded at a long distance with excavator feeding at Operation 2. Therefore feeding has not been included in the model.

<u>Carriage in</u>

$$Carriage\ in = 0.2429 + 0.003283 \times dist + 0.04364 \times vol$$

It was found that the volume extracted on a given cycle increased the time taken to inhaul by 0.0436 minutes for each m^3 of volume extracted. Volume was found to be a significant predictor (p value < 0.05). Cycle distance was also a significant predictor (p value < 0.000001) with inhaul time increasing by 0.003 minutes for each additional meter extracted.

Unhook

There were no logical predictors that were found to be significant in the prediction of the unhook cycle element.

6.4 Productivity Model

Productivity of the Falcon Forestry Carriage Series 2 was able to be modelled using the available predictors. Predictors that were logical and could be known by forest managers before an operation commenced were included. Only predictors that were significant at the $p < 0.05$ level were used. Significant predictors were found to be cycle distance, whether the cycle was fed by an excavator (as opposed to logs picked up from the ground) and whether the logs were bunched. The r^2 for the model was 0.1291. The equation for the model to predict productivity is shown below.

$$Productivity\ \left({}^{m3}/_{PMH}\right) = 73.1004 - 0.1476 \times dist + 19.8726 \times iffed + 8.9291 \times ifbunch$$

This shows that productivity increased by 19.9 m^3/PMH when the cycle was fed by an excavator. Bunching the wood increased productivity by 8.93 m^3/PMH. Cycle distance was found to decrease productivity by 0.148 m^3/PMH for each meter of total extraction distance. The relationship between productivity and cycle distance can be seen in Figure 2 below.

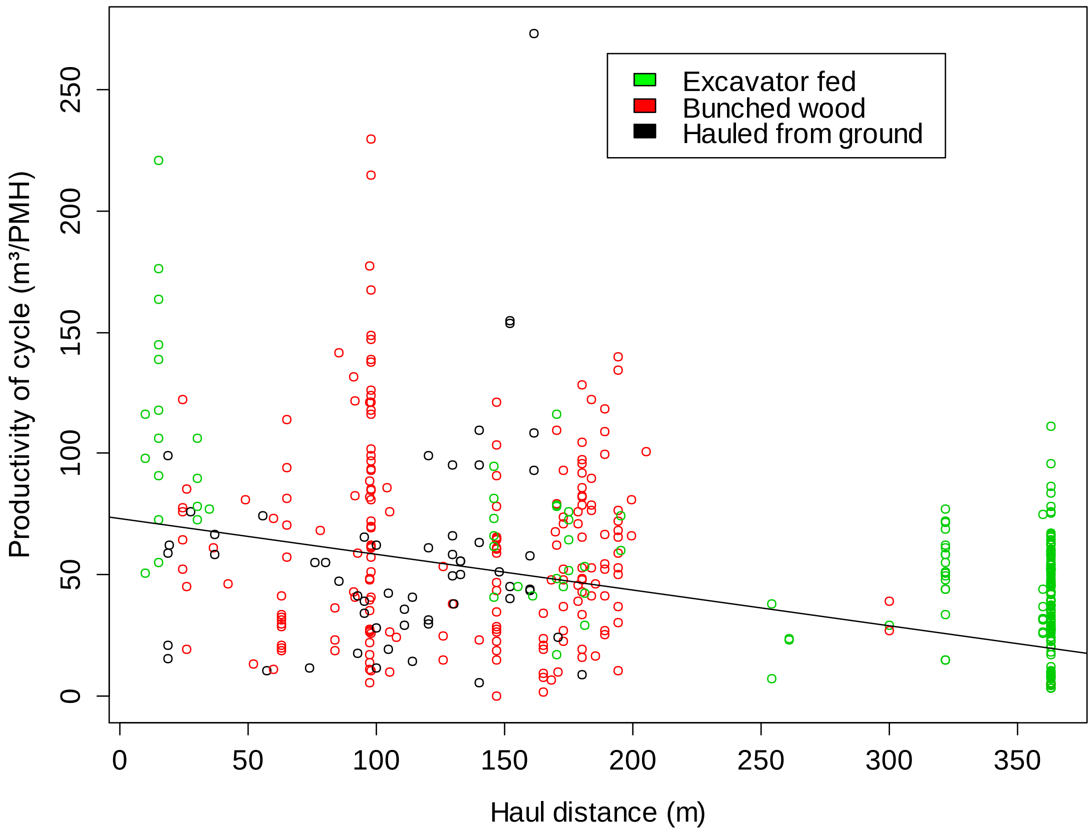

Figure 5: Productivity of each cycle at given cycle distance, shown by accumulation type (m^3/PMH)

6.5 *Existing Research Comparison*

The results of this analysis are comparable with existing research that has been undertaken on steep terrain harvesting systems. This includes research upon both motorised grapple carriages and other harvesting systems.

Two research papers that contain existing research upon the Falcon Forestry Carriage Series 1 have been selected for comparison. These are titled:

- A comparative study of mechanised cable harvesting systems in New Zealand – S. Nuske (2014)
- Falcon Forestry Claw, A Productivity and Ergonomic Study of a Motorised Hydraulic Grapple Carriage – S. McFadzean (2012)

A comparison of the values found by these two studies is given in comparison to the results observed.

Table 9: Comparison of mean delay free cycle time by accumulation method from two existing research papers, values shown are those that have been reported and were a combination of mean values and those produced from a predictive equation.

Research Paper	Cycle time by Accumulation Method (min)		
	Extracted from Ground	Bunched Wood	Excavator Fed
Results	1.81	3.14	4.03
S. Nuske (2014)	4.35		
S. McFadzean (2012)	4.22	2.64	2.12

Table 10: Comparison of mean productivity by accumulation method from results and two existing research papers (m^3/PMH), values shown are those that have been reported and were a combination of mean values and those produced from a predictive equation.

Research Paper	Cycle time by Accumulation Method (m^3/PMH)		
	Extracted from Ground	Bunched Wood	Excavator Fed
Results	55.7	64.6	75.6
S. McFadzean (2012)	32.7	63.3	76.3
S. Nuske (2014)	59.5	85	81

6.6 DELAY ANALYSIS

A breakdown of total recorded time by productive time and delay type is shown below in Figure 6.

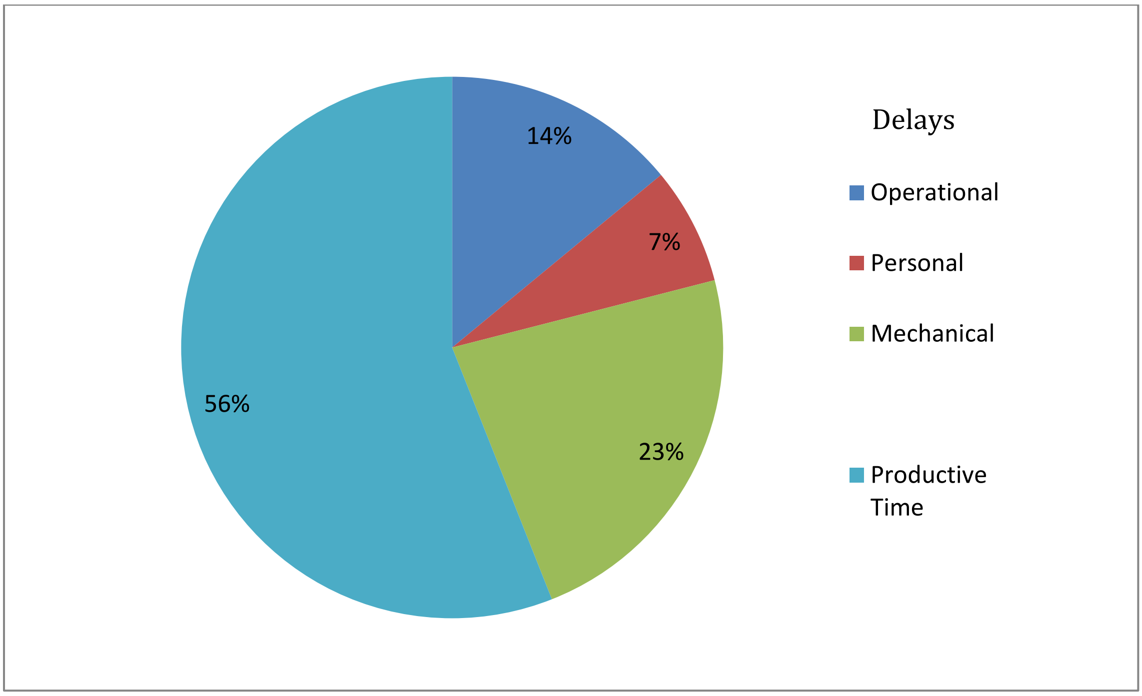

Figure 6: Proportion of total study time classified as utilisation or delay by type.

Delays accounted for 44% of the operation with the largest proportion from the mechanical delays section at 23%. The average utilisation rate for the study was 56%.

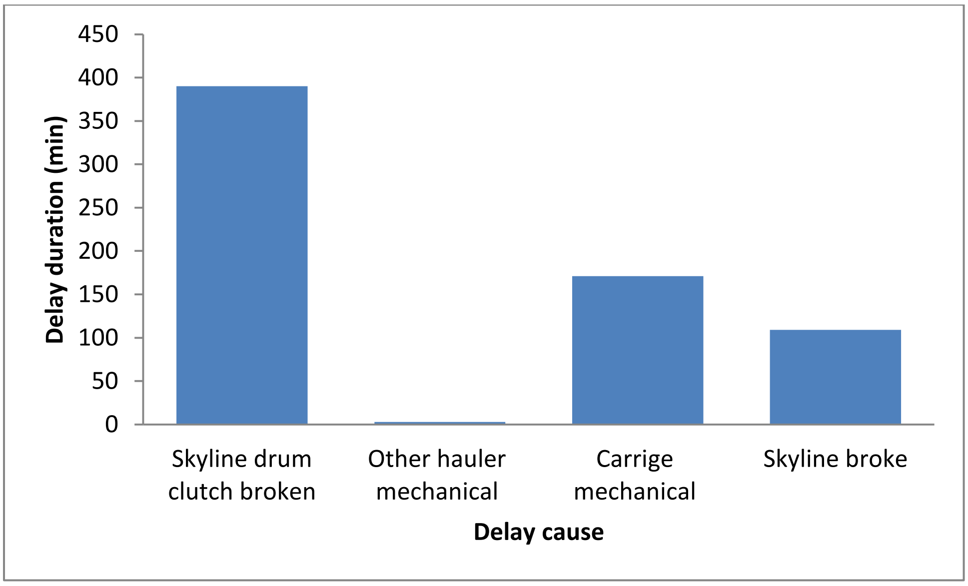

Figure 7: Duration of mechanical delays given by cause.

Mechanical delays were caused by four issues centred on the hauler, the Falcon Forestry Carriage Series 2 and the skyline (Figure 7). The largest cause of delay was the clutch on the skyline drum of the hauler. The replacement of the clutch caused over half a day of delay at Operation 2. The next largest cause of delay was six mechanical carriage breakdowns that accounted for a total of 171 minutes of delay, with an average length of 28.5 minutes each. These were caused by a range of issues including electrical (battery and switches) and hydraulic (piping) issues. The skyline snapped at Operation 1, causing a single delay of 109 minutes before work could commence.

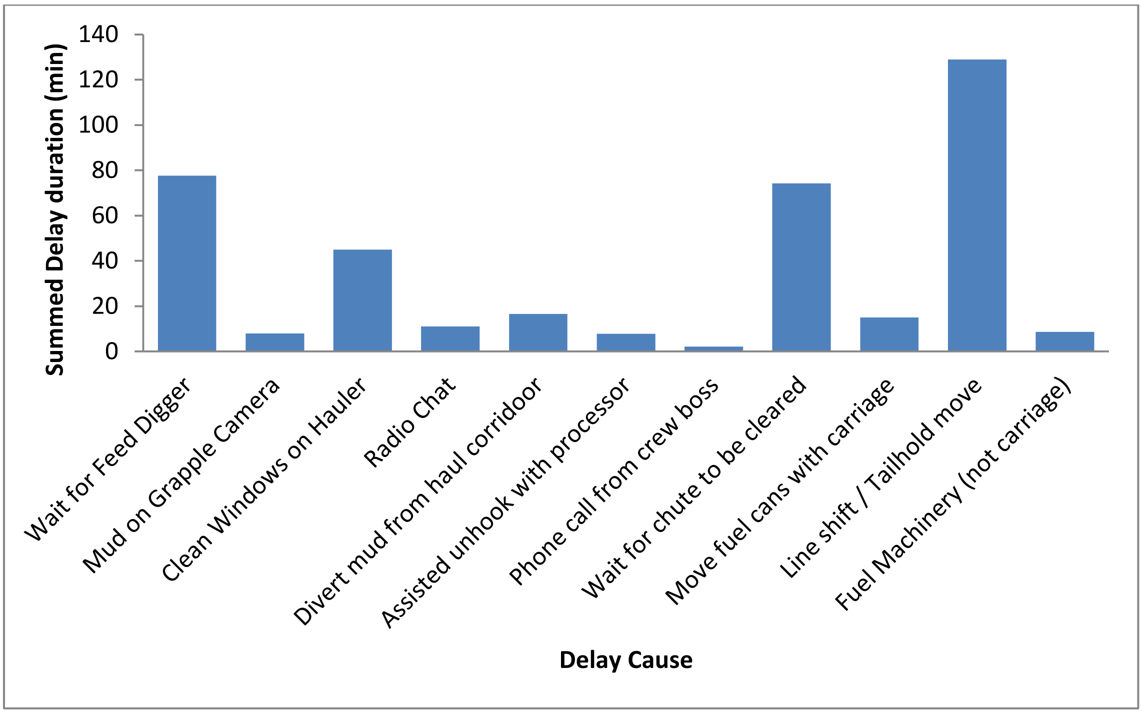

Figure 8: Duration of operational delays by cause.

The greatest cause of operational delays was to allow for the tail hold to move and shift the skyline to a new corridor (Figure 8). In total 28 line shifts were carried out at an average duration of 4.6 minutes. The second largest cause was waiting for the feed digger to shovel wood to the skyline corridor. This occurred on 13 occasions with an average duration of 6 minutes. Other major causes of operational delays were waiting for the chute to be cleared before logs could be landed and cleaning the windows on the hauler when they became covered in mud. These delays are not integral to the operation as line shifts are and would not occur in an ideal operation. However, it was noted that it can be difficult for the processer head to keep up with the hauler production rate; particularly during short extraction distances and even when using a surge pile on the landing. The necessity of the hauler operator to clean the windows of his cab was identified by crew members as a cause of delay and they discussed options for avoiding this, such as a shield from the mud. The issue was caused by excessive mud on the site that was dropping from the mainline on to the windows of the cab.

Personal delays were attributed to only two causes, lunch breaks and operator personal breaks. The average lunch break was 32.7 minutes between cycles, while the average personal break was 7.9 minutes.

6.7 Operator Analysis

The operator controlling the hauler and carriage was recorded in order to investigate this effect upon both productivity and delay free cycle time. The predictor of the factor "operator" was included in the models created in results part 5.1 and 5.2. A summary of the operators in the study is given below in Table 11.

Table 11: Operators with given sample size and operation number

Operator	Operator Usage	Operator Experience	Number of samples	Operation number
1	Regular	Experienced	151	1
2	Intermittent	Experienced	80	1
3	New Operator	Inexperienced	15	1
4	Irregular	Some	15	1
5	Regular	Experienced	226	2

All operators were experienced at operating the hauler with the exception of Operator 3 who was undergoing initial training at the time of data collection. Four of the operators were from Operation 1 where Operator 1 was normally responsible for operating the hauler. Operator 5 was located at Operation 2 where he normally operated the hauler. However, the operation number (1 or 2) was not found to be significant when used in a complete model to predict delay free cycle time (p value = 0.6466); indicating that the delay free cycle time was determined by other factors. Therefore operators from different sites may be compared.

Analysis focussed mainly upon Operators 1, 2 and 5 due to the small sample size collected from other operators.

The equation used to predict delay free cycle time and productivity included the predictors of cycle dist, bunch, fed and the factor operator. In order to put the effects of operator in perspective the appropriate model has been used to calculate the productivity or delay free cycle time of an average cycle. A typical cycle has been defined as a 150m extraction distance pulling bunched logs, but not excavator fed. The quantitative effect of operator number upon cycle time is shown in comparison to Operator 1 in Table 12 below.

Table 12: Effects of operator upon cycle time

Operator number	Average Cycles Distance	Cycle time model adjustment (minutes)	Cycle time of average 150m non-bunched cycle (minutes)	Tukey HSD Grouping ($p < 0.05$)
1	111.5	0	2.22	a
2	160.0	+0.5098	3.40	c
3 (Training)	97.5	+3.2789	5.68	
4	93.0	+0.7852	3.15	a, b, c
5	305.8	-0.3698	4.02	b

In the sample of data taken the difference between the fastest operator (Operator 5) and the slowest operator (Operator 3) was 278% which was found to be significantly different despite Operator 3 having a small sample size (Figure 9). Only the delay free cycle time of Operator 4 was found to be not significantly different to multiple other operators (not different to operators 1, 2 and 5). Operator 4 however, had a small sample size (15 cycles) which negated the credibility of this result.

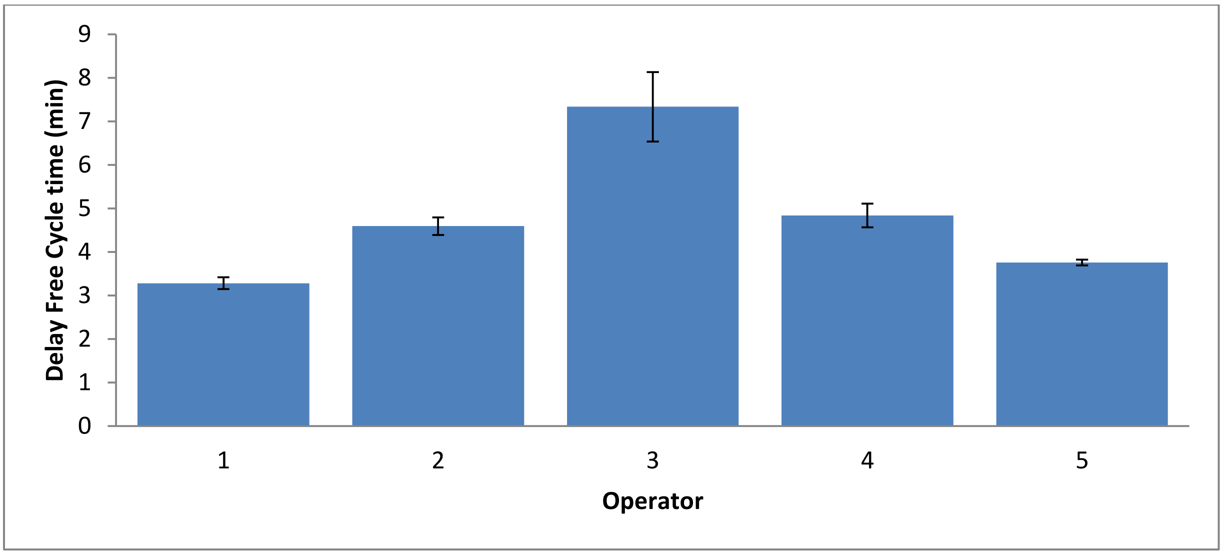

Figure 9: Values of average operator delay free cycle time, adjusted to represent 150m non-bunched cycle. Error bars indicate standard error.

Table 13: The effects of operator upon productivity with grouping according to a Tukey HSD test ($p < 0.05$)

Operator number	Productivity adjustment in predictive model (m^3/PMH)	Productivity of average 150m non bunched or fed cycle (m^3/PMH)	Productivity as a percentage of operator 1 (%)	Tukey HSD Grouping ($p < 0.05$)
1	0	57.5	100	a
2	-12.5	51.0	88.6	a, b
3 (Training)	-32.5	30.0	52.2	a, b, c
4	-51.9	10.7	18.5	c
5	-22.9	50.9	88.4	b, c

Operator 2 was operating on the same setting and equivalent weather conditions as Operator 1 but attained productivity equivalent to 88.6% of Operator 1, although differences were not found to be significantly different in a Tukey HSD test (p value = 0.11) (Table 13). Operator 2 was understood to operate the hauler during times when Operator 1 was not present. Operator 5 was operating on a different site to all other Operators with poor weather conditions. Operator 5 attained productivity equivalent to 88.4% of that obtained by Operator 1 which was significantly different (p value <0.05). Operator 3, who was undergoing training (had not previously operated the hauler before) achieved productivity of 52.2% of that of Operator 1 during a short period of operation (93 minutes). The productivity of Operator 4 is noted to be much lower than all other operators; however this will be ignored due to the small sample size of Operator 4 (15 cycles). Operator 4 was noted to operate the hauler on an irregular basis when required. The mean productivities calculated indicate that those operators who were new to hauler operation or operated the machine infrequently were less productive than those who usually operated the hauler (Figure 10). However this statement could not be justified due to a lack of significant differences and small sample sizes.

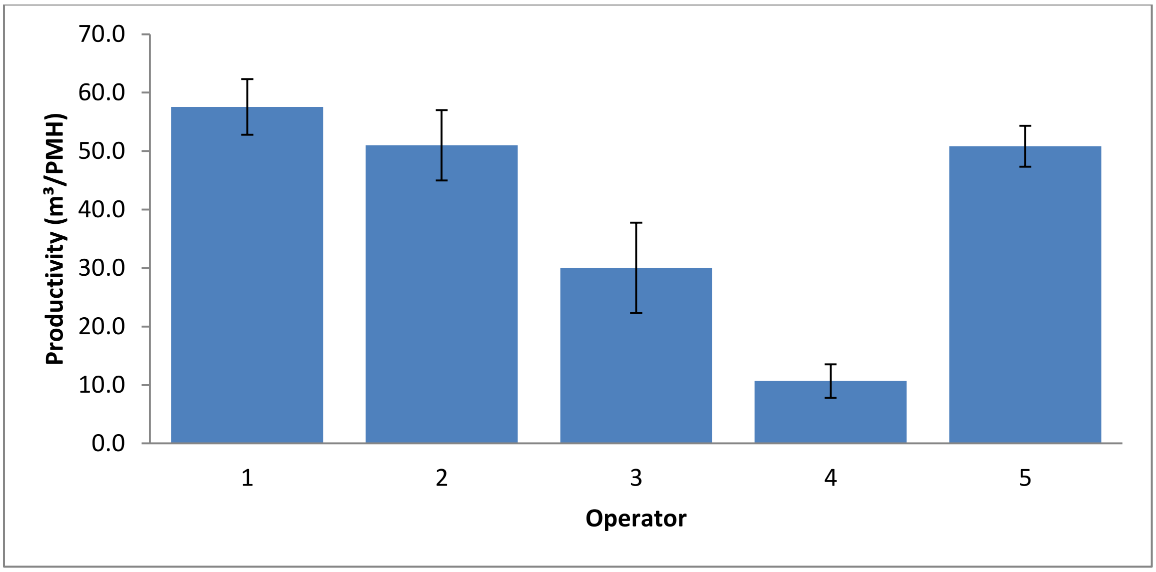

Figure 10: Values of average operator productivity, adjusted to represent 150m non-bunched cycle. Error bars indicate standard error.

6.8 Carriage Analysis

Analysis of data taken from the two alternative carriages was done in order to investigate differences in productivity and delay free cycle time between these carriages. A two linear models were created to access the difference in cycle time and productivity while taking into account all previous factors analysed (Table 14).

Table 14: Delay free cycle time, productivity and sample size of carriages observed

Carriage	Delay Free cycle time adjustment (minutes)	Productivity adjustment (t/PMH)	Number of samples
Falcon Forestry Carriage Series 2	0	0	487
Steel Shotgun Carriage w chains	+0.7603	7.25	5
Falcon Forestry Carriage Series 1	-0.7949	-25.22	18

Productivity and delay free cycle time estimates for the Falcon Forestry Carriage Series 1 were found to be significantly different from those of the Falcon Forestry Carriage Series 2. Productivity and delay free cycle time estimates for the Steel Shotgun Carriage with Chains were not found to be significantly different, perhaps due to the limited sample size that could be obtained. Despite the inability to draw a significant conclusion it is noted that the Steel Shotgun Carriage was more productive than the Falcon Forestry Carriage Series 2, despite a longer cycle time. This is due to a higher average cycle volume (FFCS2 = 2.54m^3, SSC = 3.67m^3).

In order to provide the best comparison a subset of 18 cycles were taken from data on the FFCS2 that were comparable to those observed in the operation of the FFCS1 (Table 15). The subset of samples was from the same day with the same operator and all samples were taken extracting stems from the ground. Cycle distance was comparable for the subset, although the deviation of cycle distance was larger.

Table 15: Comparison of cycles recorded from the FFCS1 and a comparative sample of the FFCS2.

Carriage	Cycle Distance (m)	Standard Deviation in Cycle Distance (m)	Productivity m/PMH	Delay Free Cycle Time (min)	Cycle Payload (m3)
FFCS2	99.1	42.6	50.7	1.72	1.15
FFCS1	98.8	21.0	51.0	1.5	1.1

7. Discussion

The average delay free cycle time found by Nuske (2014) was 2.32 minutes in comparison to the average delay free cycle time observed of 3.32 minutes. The study by Nuske (2014) used a shorter cycle distance averaging 140.3m (averaged upon time), compared to the average cycle distance observed of 207.7m (Table 6). It is has been established that cycle distance has a significant effect upon cycle time in results section 7.3. This cycle distance from Nuske (2014) is based upon the average distance over three sites where the Falcon Forestry Carriage Series 1 was tested. The average distances for these sites were weighted proportionally to the hours of observation at each site. The shorter cycle distance associated with the observations by Nuske (2014) may account for the difference in average delay free cycle time. No cycle time was available from the study Nuske (2014) to investigate the effects of bunching or excavator feeding.

The bunching of logs and the excavator feeding of logs was found to increase cycle time. This was different to previous studies where it was found that bunching and handling decreased cycle time (Mcfadzean, 2012) (Nuske, 2014). The delay free cycle time reported by McFadzean (2012) for extracting wood from the ground was 2.41 minutes greater than the value found, for extracting bunched wood was 0.5 minutes less than the value found and for extracting excavator fed wood was 1.91 minutes less than the value found.

The mean cycle time for logs extracted from the ground was 1.81 minutes in comparison to a value of 4.22 minutes found by McFadzean (2012). This may be a result of a decreased cycle distance. While the average cycle distance of observed cycles was 207.7m the average cycle distance of observed cycles with logs accumulated from the ground was 133.0m. This was shorter than the cycle distance of 210m used by McFadzean (2012) and would explain a shorter cycle time.

A greater observed cycle time than that found by McFadzean (2012) when extracting bunched and excavator fed wood may be due to attempts to extract a greater numbers of trees. It was observed that when extracting bunched stems there was difficulty in getting the grapple to grip the stems out of a multi layered pile of stems, resulting in multiple attempts to accumulate logs. The time taken to accumulate stems from bunched wood was double the time taken for non-bunched stems (Results 5.3). The study by McFadzean (2012) does not note a difficulty in pulling bunched stems where the cycle time was reduced by 0.55 minutes with the use of bunching. This may be due to a different technique being used by the operator or due to the stems being bunched in a different way.

The use of an excavator to feed logs was found to increase cycle time by 0.87 minutes which was different to the study by McFadzean (2012) where it decreased cycle time by 0.79 minutes (Table 9). The average cycle distance of excavator fed cycles was greater than that for non-excavator fed cycles (308.7m compared to 125.7m) and the many cycles were noted to require radio communication in order to coordinate the accumulation of stems. This may have resulted in a longer time taken to accumulate the stems in the grapple. All excavator fed cycles were recorded at Operation 2 where the weather conditions were inclement and wet (Table 8). Although this did not result in a greater mean number of grapple attempts (1.26 attempts at Operation 1 in comparison to 1.03 at Operation 2) it was observed to make the stems slip and require re-tightening or moving of the grapple before they could be taken from the excavator head. This may have resulted in an increased accumulation time.

The average productivity of bunched or excavator fed cycles was greater than that of non-bunched or excavator fed cycles during the production of a linear model (bunched and excavator handed wood increased productivity by 19.87m^3/PMH and 8.93m^3/PMH respectively)(Table 10). The volume of cycles that were bunched was greater than that of cycles that were not bunched (2.56m^3 and 2.47m^3 respectively) and the volume for cycles that were fed by an excavator was higher than that for cycles not fed by an excavator (2.86m^3 and 2.21m^3 respectively). Results show that although bunched and excavator fed cycles took longer they were also more productive due to the larger payload that was carried.

The productivity found by McFadzean (2012) was similar to the results found for cycles with bunched stems and excavator fed stems (Table 10). The difference seen could be due to a smaller payload being extracted during the cycles recorded by McFadzean (2012), as a shorter cycle time was recorded for these cycles as discussed above. This may have been a result of the FFCS2 weighing less and therefore being able to extract a greater payload than the FFCS1 studied during McFadzean (2012), although other variables such as operator effect or weather conditions may also have had an effect on this. Piece size during bunched and excavator fed cycles was slightly larger during the study by McFadzean (2012) in comparison to observed (1.6m^3 in comparison to 1.37m^3). The productivity found by McFadzean (2012) for cycles extracted from the ground was less than that found in the results (32.7m^3/PMH and 55.7m^3/PMH respectively), although this may be resultant of a shorter cycle distance and time as discussed above.

The productivity found by Nuske (2014) was higher for bunched (20.4m^3/PMH higher), excavator fed cycles (5.4m^3/PMH higher) and cycles extracted from the ground (5.4m^3/PMH higher). The average cycle distance for the study by Nuske (2014) was 140.3m (averaged upon hours of data); this is less than the average cycle distance of 207.7m for the observed values and may be a cause of difference in productivity. Other factors that were not quantified but could have affected productivity include operator, weather conditions and specific site or operational differences. As discussed above the mean cycle distance for cycles extracted from the ground was 133.0m which is comparable to the average cycle distance during the study by Nuske (2014) of 149.3m, this would provide some explanation as to why similar values were attained for cycles extracting logs from the ground. The average cycle distance for the data attained by Nuske (2014) by accumulation method is not known.

Harill (2014) investigated a number of cable harvesting sites, including three sites that were using the FFCS1. All these sites were extracting stems that were motor-manually felled and can be compared to the data obtained using this accumulation method. The average cycle distances observed by Harrill (2014) were longer (226m, 225m and 184m) than the observed average value for stems that were not bunched or excavator fed (107.0m as shown in Table 7). However this was not consistent with the resulting average delay free cycle times of 2.31min, 1.63min and 2.84min for sites referred to as number 1, 2 and 5 respectively. Two of these sites had a longer cycle time than the observed (1.69min) as expected based upon cycle distance, while site 2 was shorter (1.63min). The results presented by Harill (2014) showed that site 2 had a longer carriage out and carriage in time than the observed (by 10 and 26 seconds respectively) but the accumulate cycle element was shorter by 31 seconds and the unhook element shorter by 10 seconds. The FFCS1 and FFCS2 are known to have a similar grapple closing time and pressure; therefore it is likely that other factors (e.g. operator or topography) were affecting these times.

The average cycle volume observed by Harill (2014) over the sites was greater (2.17m^3) than the observed (1.73m^3). This is despite the sites observed by Harill (2014) having a smaller piece size of 1.6t, 1.4t, and 1.6t respectively, in comparison to stated piece size at the observed Operation 1 of 1.93t. The average number of pieces extracted at the sites observed by Harill (2014) was 1.43 pieces per cycle. This was less than the average number of pieces observed to be extracted (1.7 pieces per cycle). This may be a result of the accumulation method of extracting stems from the ground being used to clean up stems that were not bunched by the excavator at the observed site, in comparison to being the primary accumulation method used. Payload may also have been influenced by differences in deflection, which was not measured at the observed sites. This may have resulted in more broken or difficult to reach stems being extracted. The productivity found by Harill (2014) was lower than the observed (55.7m^3/PMH, Table 7) for those sites with a longer cycle time (sites 1 and 5) but was higher for site 2 (56.8m^3/PMH). This is a result of the interaction between cycle time and cycle volume.

The analysis of delays found that the utilisation rate (56%) was very similar to that found by previous studies (56% and 53% found by McFadzean (2012) and Nuske (2014) respectively).

The proportion of delays classified as operational was observed to be 14% which was similar to the 18% and 15% that was found by Nuske (2014) and McFadzean (2012) respectively. McFadzean (2012) recorded a wire rope breakage as an operational delay, rather than a mechanical breakdown as was recorded in this study. This could account for a 1% increase in operational delay proportion, although the margin of error is likely to be higher than this. Other than this discrepancy the causes of operational delays observed were similar to those found by McFadzean (2012) with the majority of time accounted for by line shifts, waiting for bunching / feeding and clearing the chute (Figure 4). The issue of cleaning the windows on the hauler and the camera on the grapple were not recorded by McFadzean (2012) or Nuske (2014). This may have been a result of the poor weather conditions present at the observed site. The study by Nuske (2014) included two hauler shifts in the operational delays and was the largest cause of operational delays. In comparison the observed delays did not include any hauler shifts. This would explain a 4% higher proportion of operational delays that was found by Nuske (2014). Other operational delays recorded by Nuske (2014) were the same as those observed with line shifts, waiting for bunching / feeding and clearing the chute major causes of delay.

Nuske (2014) observed that 8% of total time was recorded as personal delays which similar to that observed. No delays were categorised as personal by McFadzean (2012) where 14% of delays were categorised as caused by “other” factors.

The observed proportion of delay time that was caused by mechanical delays (23%) was higher than that found by McFadzean (2012) or Nuske (2014) who observed that 15% and 21% of delays were of a mechanical cause respectively. A large proportion of the observed mechanical delay time observed was caused by the breakage of the skyline drum clutch (390min or 58% of mechanical delay), although this was similar to a breakdown encountered by (Mcfadzean, 2012) when the hauler lost a track (accounting for 360 min or 20% of total delays). Also consistent with McFadzean was the breaking of a wire rope (the Dutchman); this was similar to the delay of breaking the skyline wire rope that was observed. McFadzean (2012) also noted that carriage mechanical delays were present (15% of total delay time) which was similar to the proportion of carriage mechanical delays observed (13.4% of total delay time). The frequency of carriage mechanical delays was not mentioned by McFadzean (2012). Nuske (2014) was consistent in noting that mechanical delays were few in number but large (long duration), although specific causes of mechanical delay were not given.

The effect of operator was significant and the comparison of two operators at the same site with similar conditions and a large sample size was valuable (comparison of Operator 1 and Operator 2). The difference between Operator 1 and Operator 2 was found to be 6.5m^3/PMH. This was equivalent to 11.3% of the mean productivity during the study. Based upon this difference in productivity between operators the selection of operator may be of interest to managers and contractors. This finding is supported by the conclusion of European study of the influence of operator upon productivity. In this study it was found that the difference in productivity between experienced operators was a factor of 1.8; although this was in the operation of single grip wheeled boom harvesters (F. T. Purfurst, 2011).

Comparison of total cycle time taken between the best and worst operators was found to have a large range of 3.28 minutes to 7.33 minutes (values adjusted to represent a 150m non-bunched cycle) or a proportional difference of 2.23. This difference in cycle time was comparable to previous research using a model yarder in a Norwegian study where cycle time varied from 5.39 minutes to 8.75 minutes or a proportional difference of 1.62 (G. Ottaviani, 2014). This study was also using a sample of operators ranging from expert to inexperienced (G. Ottaviani, 2014). This indicates large reductions in cycle time can be made with the training and experience of operators. It was noted that the inexperienced operators in the Norwegian study had more time to improve their ability as they completed a total of 30 cycles compared to the 15 cycles undertaken by Operator 3 (G. Ottaviani, 2014). This may be a cause of the smaller proportional difference observed by G. Ottaviani (2014).

8. Conclusions

The average observed productivity was found to be 54.9m^3/PMH. Productivity was variable with a standard deviation of 37.7m^3/PMH and a range from 3.1m^3/PMH to 273.3m^3/PMH.

Productivity was found to be influenced by a number of factors, some of which could be known by managers and contractors before harvesting began. Bunching and excavator feeding stems was found to significantly increase the time taken to grapple logs and the total cycle time (p value < 0.05). However an increased payload resulting from bunching or excavator feeding logs resulted in higher productivity for these accumulation methods. Bunching the stems that were presented to the grapple was found to increase productivity by 8.9m^3/PMH while feeding the grapple with an excavator was found to increase productivity by 19.9m^3/PMH.

Increasing cycle distance was found to decrease the productivity of the system by 0.15m^3/PMH. This was evident during the comparison of results to other studies. Mcfadzean (2012) had a similar cycle distance and piece size during testing of the FFCS1 and attained similar results of productivity, although the observed value for cycle volume was lower and delay free cycle time higher. A conclusion could not be drawn to say whether the differences between these studies were resultant from differences in carriage or other site factors such as deflection. In comparison to other studies such as Nuske (2014) and Harill (2014) the results were inconclusive due to a large difference in cycle distance.

The use of a steel shotgun carriage with chains was found to increase productivity by 7.25m^3/PMH in the production of a linear model. However only 5 cycles were recorded and they were at a long cycle distance (363m). The ability of the steel shotgun carriage to extract a larger cycle payload (cycle payloads FFCG2 = 2.54m^3, SSC = 3.67m^3) may have been an advantage with long cycle distances. The steel shotgun carriage was replaced by the FFCS2 as soon as it was available on site, due to the exposure conditions that the breaker outs were working in. This speaks for the practical value of the Falcon Carriage, which doesn't require breaker outs to operate.

Comparison with other observed carriages such as the steel shotgun carriage with chains or FFCS1 were inconclusive due to the small sample size obtained. However during comparison of a similar sample of data from the FFCS2 it was found that there was little difference in the productivity obtained.

The proportion of time utilised as productive time (56%) was similar to that found by previous studies (Mcfadzean, 2012) (Nuske, 2014). The largest causes of operational delays were line shifts, waiting for bunching/feeding and clearing the chute. These key causes of delay were the same as previous studies by Mcfadzean (2012) and Nuske (2014). While a motorised carriage operation will always require line shifts it is noted that production could be enhanced if the delays of waiting for bunching/feeding and clearing the chute could be eliminated. Other similarities in delays were found in mechanical delays where McFadzean (2012) also recorded a large mechanical breakdown (excavator throwing a track) and breakage of a wire rope. McFadzean (2012) also recorded a similar proportion of carriage mechanical delays at 15% of total delay time (compared to the observed value of 13.4% of total delay time) while Nuske (2014) did not specify the cause of mechanical delay. This supports a conclusion that mechanical delays of about this proportion can be expected during operation of the Falcon Forestry Carriage Series 1 or 2. McFadzean (2012) specified one cause of mechanical carriage delay with a hydraulic ram shearing off the carriage. The causes of carriage mechanical breakdown observed included electrical (battery and switches) and as well as also having hydraulic issues with hoses. A conclusion as to the expected causes of delays could not be drawn from this.

Despite limitation by sample size the operator experience level was found to have a large effect upon the productivity of the hauler operation, after values were adjusted for cycle distance and accumulation method. Operator 4 who was inexperienced was found to have a productivity of just 18.5% of that of the experienced Operator 1 at the same operation (p value < 0.05). Operator 3 who was inexperienced and was new to operation of the hauler was found to have productivity equal to 52.2% of that of Operator 1, although this difference was not statistically significant. It can be concluded that large differences in productivity exist between operators at different experience levels.

Differences in productivity were also found between experienced operators. Operator 2 and 5 had a productivity that was 11.4% and 11.6% less than that of Operator 1 respectively. During comparison of Operator 1, 2 and 5 the difference between Operator 1 and Operator 5 was found to be statistically significant (although at different sites). Although this indicated that a difference between the productivity of experienced operators exists it is difficult to draw this conclusion due to the wide range of other factors that are variable between sites (weather etc.)

9. LIMITATIONS

The quantity of data and the range of variables which was obtained limited the quality of the analysis. For example, the quantity of data for some operators limited the quality of difference in productivity that could be determined. Also the inclusion of just two sites in the study limited its applicability in a wider forestry usage to differing sites. For example, the applicability of the study to downhill yarding would be largely unknown.

The data was recorded using actual times on a continual time scale. This meant that if an error was made in the recording of one time then it will also affect the time recorded for the subsequent cycle. Any errors that were recognised during data collection were noted to assist with the later screening of data in the lab. If the start and end times of the cycle were still available then this was used to calculate the total cycle time. This meant that some cycles with incomplete data could still be used to calculate productivity or delay free cycle time, although the times from effected cycle elements could not be used.

The r^2 of the model predicting cycle time was found to be 0.30. This means that the model explained 30% of the variation within the data. This level of accuracy indicates that other factors are effecting the element and cycle times. Due to the nature of a harvesting operation there are many factors that affect the time taken for an individual cycle or element. Examples of this are the small scale topography within the haul corridor, the fatigue of all personal involved and the specific placement of the tree in relation to the haul corridor. The inclusion of all these factors in a time study at this level is not practical.

10. Further Research

There is opportunity for further and more comprehensive research on this topic. As outlined in the limitations above further data recording would provide a larger sample size and greater range of variables. This could be important for comparison between variables and factors such as operator. Further investigation could include:

- Improved data collection techniques such as automatic data collection. If data collection could be automated it would allow the collection of large volumes of data (e.g. time study data for an entire year for a number of crews) which could better quantify the effects of infrequent but large delays. It would also allow more accurate investigation into the effects of different sites.
- The method of measuring cycle distance could be improved, for example by attaching a GPS to the carriage. This would improve the accuracy of cycle distance measured and allow for a more accurate model to be created.
- The ability to measure the logs related to each cycle would improve the accuracy of the cycle payload prediction. This would allow more accurate calculation of productivity.
- Further research could be made on the sampling of multiple operators at one site. This would allow more accurate calculation of the effects of different operators.

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