HELICOPTER LOGGING PRODUCTIVITY IN DISPERSED AND AGGREGATE PARTIAL RETENTION SYSTEMS

by

CHARLES KEVIN LYONS

B.S.F. The University of British Columbia, 1997

A THESIS SUBMITTED IN PARTIAL FULFILMENT OF

THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF FORESTRY

in

THE FACULTY OF GRADUATE STUDIES

FACULTY OF FORESTRY

We accept this thesis as conforming

to the required standard

THE UNIVERSITY OF BRITISH COLUMBIA

July 1998

HELICOPTER LOGGING PRODUCTIVITY IN DISPERSED AND AGGREGATE PARTIAL RETENTION SYSTEMS

by

CHARLES KEVIN LYONS

B.S.F. The University of British Columbia, 1997

A THESIS SUBMITTED IN PARTIAL FULFILMENT OF

THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF FORESTRY

in

THE FACULTY OF GRADUATE STUDIES

FACULTY OF FORESTRY

We accept this thesis as conforming

to the required standard

THE UNIVERSITY OF BRITISH COLUMBIA

July 1998

In presenting this thesis in partial fulfilment of the requirements for an advanced degree at the University of British Columbia, I agree that the Library shall make it freely available for reference and study. I further agree that permission for extensive copying of this thesis for scholarly purposes may be granted by the head of my department or by his or her representatives. It is understood that copying or publication of this thesis for financial gain shall not be allowed without my written permission.

Department of FORESTRY.

The University of British Columbia
Vancouver, Canada

Date SEPT 16, 1998.

DE-6 (2/88)

Abstract

This study evaluated several factors that affect helicopter logging productivity in partial cutting operations. The harvest treatments applied to the 4 units in this study were 75% aggregated retention, 40% dispersed retention, 40% aggregated retention, and 15% dispersed retention. The flight record data included turn time, turn mass, and the number of logs per turn for each unit, while there was only limited detailed sampling of the in-unit turn time elements, and of turn merchantable volume to mass ratios.

The treatments applied in this study did not appear to have a dramatic effect on helicopter productivity. There was little correlation detected between turn time and turn mass, turn time and the number of logs per turn, and turn mass and the number of logs per turn. The distance to the unit from the landing appeared to have the greatest affect on total turn time, while the lifting component of the in-unit time dominated the variation of the in-unit timing. The turn cycles with choker drops and aborts increased the average total turn time in units 2 and 5 by less than 7 %. Turn mass did not vary greatly between the units, and this is attributed to the ability of the hooktenders to compensate for the varying conditions.

Regression equations were developed to estimate total turn time and turn volume. These equations demonstrate that productivity increases with reduced horizontal distance to the unit, increased log size, and increased volume of merchantable wood per unit mass. However, more detailed sampling is required to identify nonlinear relationships between log volume and turn volume, and horizontal distance and turn time. Also more research is needed to identify factors that link turn time and turn volume to stand conditions at higher levels of retention.

Table of Contents

Abstract ii

Table of Contents iii

List of Tables iv

List of Figures v

Acknowledgements vi

1.0 Introduction 1

2.0 Helicopter Logging Background 6

3.0 Butte Timber Sale Description 9

3.1 Description of forest cover and topographic features 9
3.2 Helicopter Description 11
3.3 Logging Crew Organization 13

4.0 Methods 17

4.1 Data Collection Methods 17
4.11 Flight record data 17
4.12 Detailed production data 18
4.121 In-unit turn time data collection 18
4.122 Turn mass to turn volume data collection 19
4.2 Data analysis methods 20

5.0 Data analysis 23

5.1 Analysis of in-unit turn time 23
5.2 Analysis of total turn time 28
5.3 Analysis of turn mass 37

6.0 Regression analysis 40

6.1 Testing for correlation 40
6.2 Regression equation for turn time 43
6.3 Regression equation for turn volume 45
6.4 Productivity analysis 48

7.0 Comparison of turn time and turn volume predictions 54

8.0 Discussion 57

8.0 Conclusions 60

9.0 References 63

List of Tables

Table 1: Initial total stand density and basal area for the Demo, Butte timber sale. 9
Table 2: Volume of timber removed from the Butte timber sale....................................... 10
Table 3: Difference between mean total in-unit and standardized mean total turn times.... 30
Table 4: Unit 2 and 5 standardized total turn times filtered for aborted turns and choker drops. 37
Table 5: Testing correlation... 42
Table 6: Turn mass to merchantable volume rations. 47
Table 7: Comparison of turn time predictions. 54
Table 8: Comparison of turn volume predictions. 55

<u>**List of Figures**</u>

Figure 1: Butte DEMO timber sale location. 4
Figure 2: Butte DEMO block map. 5
Figure 3: Kaman K-MAX 1200. 12
Figure 4: Dual hook assembly. 12
Figure 5: Moving a turn to the processing area in helicopter landing number 1. 15
Figure 6: Landing a turn at helicopter landing number 1. 15
Figure 7: Frequency distributions of the in-unit timing element, position. 24
Figure 8: Frequency distributions of the in-unit timing element, hook. 24
Figure 9: Frequency distributions of the in-unit timing element, lift. 25
Figure 10: Frequency distributions of the in-unit timing element, clear. 25
Figure 11: Total in-unit time without choker drops or aborted turns. 27
Figure 12: Frequency distributions of total turn time (all turns). 29
Figure 13: Frequency distributions of total turn time standardized for distance (all turns). 31
Figure 14: Unit 2 frequency distributions of total turn time standardized for distance and with aborts and choker drops filtered out. 34
Figure 15: Frequency distributions of total turn time standardized for distance and with aborts and choker drops filtered out. 35
Figure 16: Frequency distributions of turn mass (all turns). 39
Figure 17: Correlation between total turn time and turn mass (all turns). 41
Figure 18: Average unit turn time as a function of the average distance from the landing to the unit. 44
Figure 19: Residual error plots for equation E3. 49
Figure 20: Line fit plots for predicted and observed turn volume. 49
Figure 21: KMAN-1200 helicopter productivity design chart (Butte timber sale). 51

Acknowledgements

I would like to thank the United States Forest Service for their financial support, and specifically Roger Fight, Jim White, and the district staff from the Randle Ranger Station for their assistance in organizing and gathering much of the field data used in this study. The staff and logging personnel from Superior Helicopters were a great help in collecting data, and freely gave advice and valuable insight into the operation.

Also, I would like to thank my advisors Dr. Joe McNeel for initiating this study and Dr. John Nelson for his help in completing this study. My other committee members Dr, David Tait, and Doug Bennett, and also Dr. Val LeMay provided much needed advise at critical times, which greatly improved this report.

1.0 Introduction

Operational considerations such as maximizing profit, or the availability of machinery are no longer the leading concerns in the design of cut blocks. Often, the first priority in cut block design is to protect non-timber values such as wildlife habitat, water quality, and the visual quality of landscapes. Cut block design was simpler when the primary objective was to minimize logging costs. Today, many constraints are added to harvesting operations when treatments designed to protect non-timber values are included in silviculture prescriptions.

Partial cutting, where a percent of the original stand is left as reserve trees, is a popular treatment to limit the impact of harvesting on non-timber values. Partial cutting may entail leaving only a few trees in order to provide structural diversity in the regenerating stand, or a high percent of the original stand may be left in order to maintain the existing ecosystems. Depending on the objective, reserve trees may be left as groups (aggregate retention) or as single trees (dispersed retention).

Treatments such as partial cutting increase the complexity of logging. The reserve trees may impose physical limits that preclude the use of certain harvesting systems. The increased complexity in harvesting may even increase costs to the point where harvesting becomes uneconomical. In most cases the effect of partial cutting will be less dramatic, so while costs may increase this usually does not prevent harvesting. The danger is to accept these cost increases without trying to maximize profits while still achieving the new management goals. Before cut block layout begins it is important to understand how harvesting systems react to the number of trees reserved and the pattern of the reserve trees. This will allow the design of cut blocks that take advantage of harvesting system strengths.

Change in logging productivity is a useful measure of the effect a prescribed treatment has on a harvesting operation. To design an experiment that will compare logging productivity in different types of partial cuts, it is necessary to locate experimental units that have similar timber types, ground conditions, and harvesting parameters. Since it is difficult to locate experimental units that are similar in all these attributes, replicating the treatments becomes a problem and statistical comparisons of treatment effects are not possible. It is possible to use regression equations to examine trends in the level of productivity resulting from variation in the independent variables. Also, the development of the regression equations will indicate what factors have the greatest effect on productivity.

The Butte Timber sale, which is located in the Randle Ranger district of the Gifford Pinchot National Forest in Washington State (Figure 1), is used as a case study. This timber sale is part of the Demonstration of Ecosystem Management Options (DEMO) project, which is a federally funded research project initiated to study the effectiveness of partial cutting in providing:

- "a sustainable rate of timber harvesting, and
- maintaining late successional forest characteristics" (USDA F.S., 1996).

The Butte timber sale provides the opportunity to examine helicopter logging productivity in partial cuts at three levels of retention using both dispersed and aggregate patterns (Figure 2). Five cut blocks were treated, though only four have useable data:

- 15 % dispersed retention (unit 5),
- 40 % dispersed retention (unit 3),
- 40% aggregated retention (unit 4), and

- 75% aggregated retention (unit 2).

The two objectives of this thesis are:

1. to identify the main factors that affect helicopter logging productivity in partial cuts, and
2. to test the sensitivity of helicopter logging productivity (m^3/minute) to these factors with regression equations.

There were three sources of data collected in this study:

1. flight record data that contained for each turn the total turn time, turn mass and the number of logs per turn,
2. limited detailed sampling of the in-unit turn time elements, and
3. limited detailed sampling of the merchantable volume to mass ratios for selected turns.

The flight record data and the in-unit turn time data are examined to determine if they are strongly affected by the treatments in this study. The flight record data is then tested for correlation between turn time, turn mass, and the number of logs per turn. The flight record and volume to mass data are used to develop regression equations that predict turn time, turn volume, and helicopter productivity. The predictions by the equations developed in this study are compared to the actual unit averages and to predictions by other published equations for turn time and turn volume.

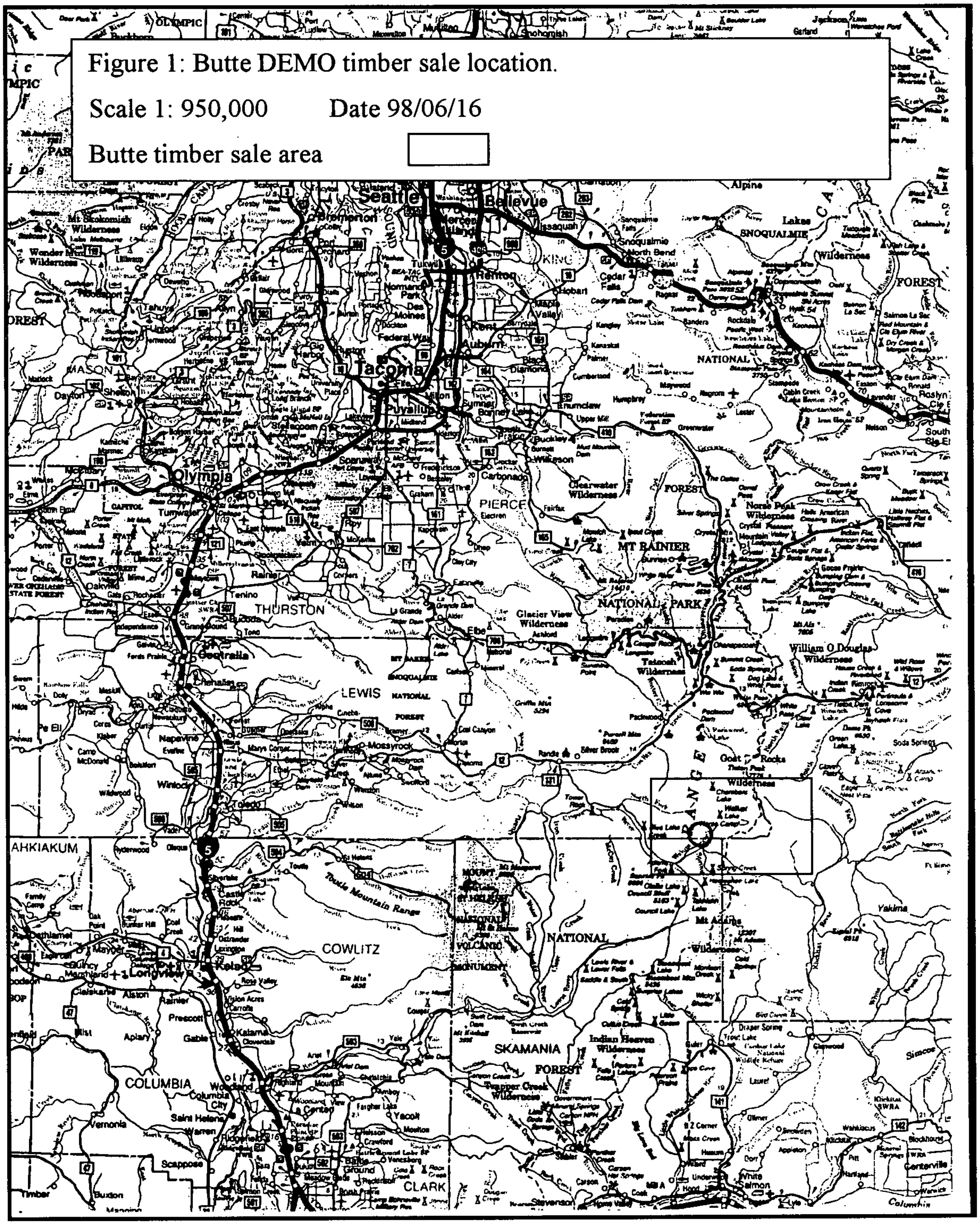


Figure 1: Butte DEMO timber sale location.

Scale 1: 950,000 Date 98/06/16

Butte timber sale area

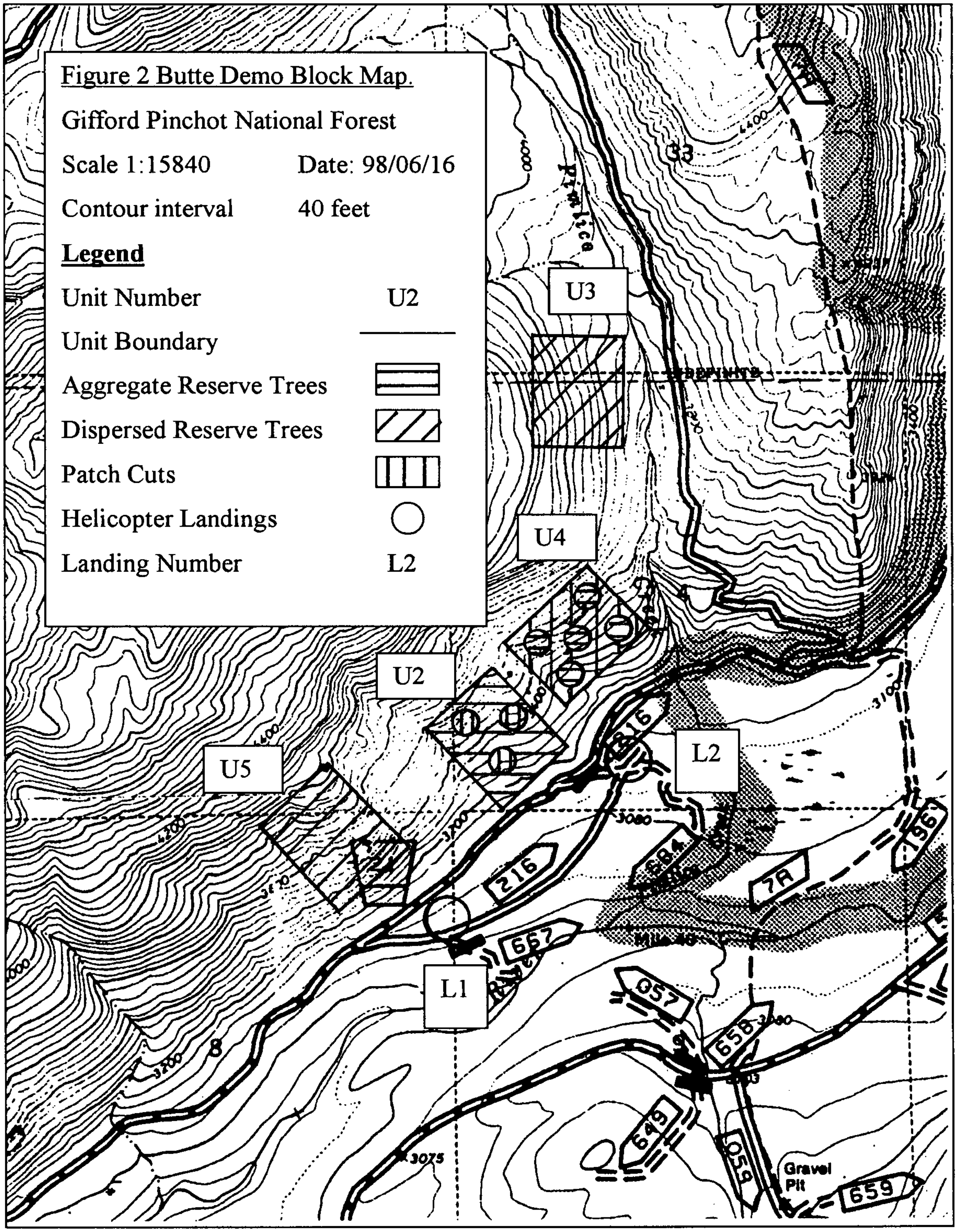


Figure 2 Butte Demo Block Map.

2.0 Helicopter Logging Background

Timber harvesting practices are changing in an attempt to reduce the impact on non-timber values. Some of the harvesting techniques employed in the past are no longer permitted, or the post-harvesting treatments make the operations economically unfeasible. Since the 1970's there has been a renewed interest in helicopter logging as an alternative harvesting method which avoids many of the adverse environmental impacts caused by conventional systems (Halkett, 1982).

Dykstra (1975) states that the helicopter is the most mobile of any yarding system and that it is virtually unhampered by terrain and silvicultural system. The ability of a helicopter to yard logs is limited by the maximum external load it can lift. Dykstra also discusses the role of "ground effect", when the helicopter is within one-half the rotor diameter of the ground additional lift is gained by compressing the air below the rotors. When helicopter logging with long tag lines the helicopter is usually over 46m (150ft) above the ground, and is "out of ground effect".

Heinimann (1996) considers helicopter logging operations to consist of three levels "(1) the operational unit level, (2) the shift level, and (3) the load cycle". An inductive approach is often used to make operational level conclusions, from detailed timing data at the load cycle level. This approach can miss effects (such as the learning curve effect) that may develop over time if the detailed timing period does not extend over the whole project. Limited sampling of turn times in a helicopter logging operation (which tend to cover ground very quickly) may miss variation:

- within a pilots' two week shift,

- between the different pilots, and
- between the different units in the project.

Krag and Clark (1997) found the average cycle time to collect and fly a turn of logs to the landing increased as the number of reserve trees increased for both aggregate and dispersed retention. However, they found that the mass of the turn did not vary greatly until high levels of retention were reached (85% dispersed retention). They found when compared to clear cuts, the changes in turn cycle time and turn mass resulted in a decrease in productivity of 3.9% in patch-cuts, and up to 18.5% in the 85% dispersed retention.

Halkett (1982) suggests that the time spent flying from the cut block to the landing is constant over a range of horizontal distances for a given difference in elevation. The reason for this is the maximum rate of decent is fixed for a given helicopter, and thus there is a minimum time required to drop the vertical distance to the landing. If the horizontal distance to the landing is increased, but the vertical distance remains constant, the pilot can increase the horizontal speed of the helicopter to maintain the minimum flight time imposed by the rate of descent. This minimum flight time remains constant until the pilot has reached the maximum airspeed speed of the helicopter; at this point the horizontal distance will begin to limit the flight time.

Since there are many situations where helicopters may be used, each operation needs to be examined separately for the factors that affect production rates. Curtis (1978) suggests production is generally a function of maximum payload, the percentage utilization of lift capacity and average turn cycle time. Halkett (1982) states that production rates are also likely to be affected by stand and log quality, volume per hectare, understorey vegetation, and payload size.

In helicopter logging, the most expensive element is the cost of the helicopter. With a capital investment of approximately $3, 500, 000 US for the K-Max 1200, the annual utilization of the helicopter becomes very important (Sloan 1997). Tollenaere (1994) estimated the cost of operating the KMAX to be $1, 713 / hr at an annual usage rate of 1000 hours and $1324/hr at an annual usage of 1500 hours. Factors such as down time due to weather or scheduling become very important when considering the economic feasibility of an operation. Helicopter logging is generally considered the most expensive method of harvesting, thus "each alternative must be developed in sufficient project detail to allow for specific cost estimates, environmental impacts, and risk assessment" (Sloan 1997).

3.0 Butte Timber Sale Description

3.1 Description of forest cover and topographic features

The Butte timber sale is in the northern half of the Gifford Pinchot National Forest. The 4 experimental units used in this study are located mid slope, overlooking the Cispus River, and are centered on Pimlico Creek. As can be seen in Figure 2, all the units except unit 3 occupy a similar slope position (1067 m and 1219 m elevation, respectively). Unit 3 lies farther up the Pimlico drainage, and is exposed to different weather conditions and has a significantly different flight path than the other units.

The terrain within the units is generally even with a few rock outcrops and small gullies. The steepest slopes can be found in the bottom of unit 5 (up to 80%) with most slopes averaging 30 to 70%. Refer to Table 1 for the initial stand density and basal area of the units.

Table 1: Initial total stand density and basal area for the Demo, Butte timber sale.

	Density (stems/ha)				Basal Area (m^2/ha)			
Unit #	Mean	SD	Min	Max	Mean	SD	Min	Max
$2_{75\%\ \text{aggregate retention}}$	1781	763	700	3425	51	8	36	70
$3_{40\%\ \text{dispersed retention}}$	1019	510	500	3400	49	15	12	82
$4_{40\%\ \text{aggregate retention}}$	1281	589	575	3450	57	11	37	80
$5_{15\%\ \text{dispersed retention}}$	759	235	250	1350	56	14	21	79

(Data supplied by C. Halpern, University of Washington, 1997)

The stands are approximately 70 years old, having regenerated naturally after the 1918 fires, though unit 3 may have had some planting in 1933 (E Tompkins, 1996). Units 2, 4, and 5 are similarly dominated by *Pseudotsuga menziesii* (Douglas-fir) with minor components of *Tsuga heterophylla* (western hemlock) and *Thuja plicata* (western redcedar), with some large Douglas-fir veterans (survivors of the last stand replacing disturbance). The major tree species in Unit 3 is Douglas-fir, though there is a large component of western hemlock and *Abies amabilis* (pacific silver fir), with a few *Chamaecypais nootkatensis* (yellow cedar) at the base of the block.

The volume per hectare of timber removed from each unit is based on the pre-sale Forest Service cruise. Fixed area plots were established, and the trees marked for removal were tallied. Cruise estimates of the volume to be removed from each unit are found in Table 2. The treated area in Table 2 is calculated as:

Treated area (ha) = total area of the unit – area of aggregate green tree reserves – area of sensitive site reserves.

The volume per hectare removal is calculated using the treated area only.

Table 2: Volume of timber removed from the Butte timber sale.

Unit	Total Area (ha)	Treated Area (ha)	Volume Removed (m^3/ha)	Total Volume Removed (m^3)
$2_{75\%\ aggregate\ retention}$	13.0	2.8	273	773
$3_{40\%\ dispersed\ retention}$	13.0	12.6	106	1325
$4_{40\%\ aggregate\ retention}$	13.0	8.1	368	2979
$5_{15\%\ dispersed\ retention}$	13.0	13	288	3726

(US Forest Service 07/24/96 pre sale cruise; conversion of Mbf to m^3 is 3.7 m^3 / 1Mbf)

The total volume removed from units with the same level of retention should be similar (compare unit 3 to unit 4). Also the units with aggregate retention (units 2 and 4) should have similar volume per hectare removals. Using these criteria there is a noticeable difference between the stand attributes of units, 2, 3 and 4, and this limited the comparisons that could be made between the data.

3.2 Helicopter Description

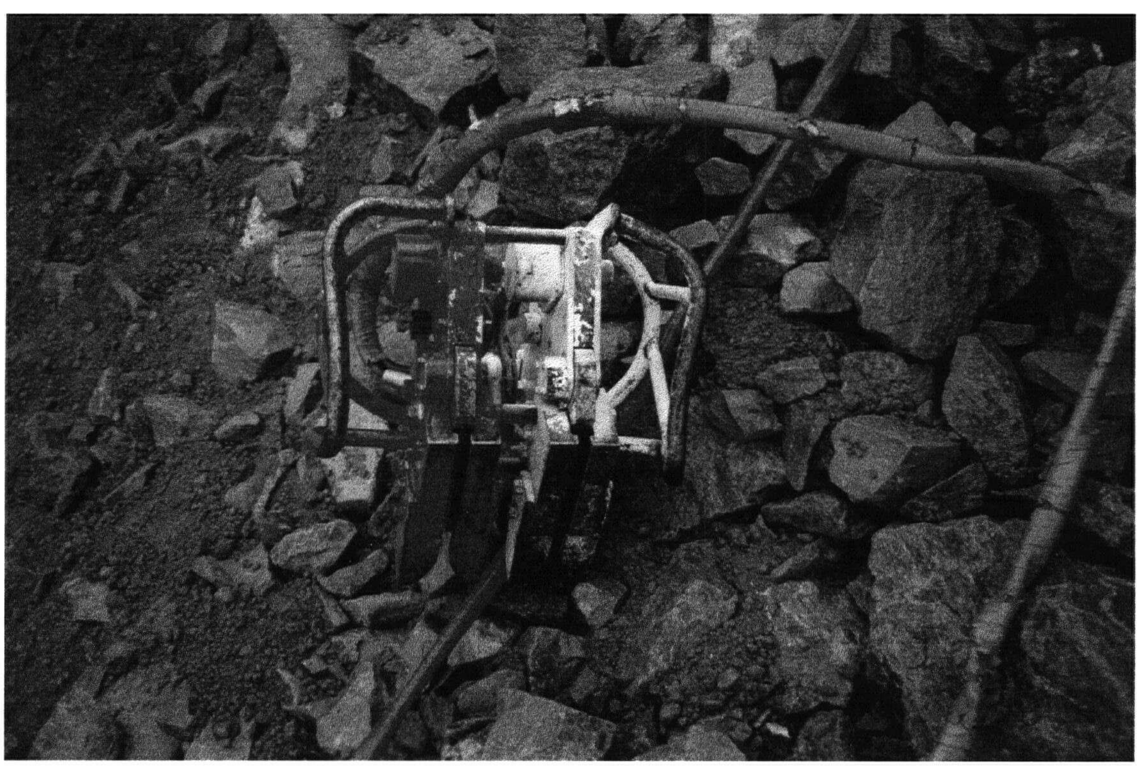
The helicopter used on this timber sale was the Kaman K-MAX 1200. This is a medium lift helicopter (2721kg (6000 lb.) external load) with side-by-side, intermeshing, counter-rotating rotors (Figure 3). This helicopter has a single seat and during logging, flies about an 80 minute cycle before landing and refueling.

The pilots noted they felt the K-MAX 1200 was more sensitive to wind than previous helicopters they had flown (Boeing 107 Vertol, Sikorsky S-61 and S-64). A representative of Kaman Aerospace Corporation indicates that this is due to the K-Max 1200 employing a lightly loaded rotor system (Daniels, 1997 – p.com). This means that each square meter of rotor disc (the surface described by a rotation of the rotor) carries a lower payload than conventional helicopters. Thus, the pilots may sense more of the turbulence than they would in helicopters with more heavily loaded rotor disks. Also, Daniels identifies the increased visibility of the K-MAX as creating a more exposed sensation for the pilots. With increased flight hours, the pilots in this study experienced less difficulty with wind.

In the Butte timber sale a 61m (200 ft) long line was used. Two hooks were suspended as a single unit from the long line (Figure 4). The target average turn mass was 2040 kg (4500lb); however, depending on the amount of fuel being carried (time into the cycle) the turn mass could increase to a maximum of 2721 kg.

Figure 3: Kaman K-MAX 1200.

Figure 4: Dual hook assembly.



The objective in having two hooks was to put at least a minimum turn mass into the red hook (1360-2300 kg) and then place another 450 kg in the white hook. This allowed the pilots to abort the white hook if the turn mass was underestimated, or if the turn hung-up. The turn mass values were measured from an onboard load cell with a display in the cockpit. The flight crew consisted of one pilot on site, with two pilots rotating on two-week shifts. Also, on site was one mechanic, responsible for scheduled maintenance, minor repairs, and fueling.

3.3 Logging Crew Organization

This operation normally had four hooktenders setting turns for the helicopter. The hooktenders were arranged along the contour of one or more units so that the flight paths would not conflict. The distance between the hooktenders within a unit ranged from 50 to 200 meters, depending on how many were in the unit.

The hooktenders would preset chokers organized into turns. The number of turns a hooktender would have pre-set varied from 2 to over 10, and this was mostly a matter of personal preference. The number of chokers used in a turn varied from 1 to over 10 depending on the weight of the logs, and the distance that had to be covered in order to connect all the logs to the hook.

The helicopter would take 2 turns from a hooktender and then move to the next hooktender along the contour. If the helicopter aborted a turn (dropped the chokers on both the white hook and the red hook) it would then skip to the next hooktender in line. This gives the hooktender who had the aborted turn, time to reorganize and prepare to hook a new turn.

Logs from the 4 units were flown to one of two landings: 1) units 5 and 2 were flown to landing 1, and 2) units 4 and 3 were flown to landing 2 (Figure 2). The landings were approximately 1.0 ha in size and were ovals in shape (Figures 5 and 6). There was also one service landing, where the service trailer and fuel truck were situated. Each landing had space to:

- store chokers removed from landed turns,
- land turns,
- buck, brand, and sort logs,
- store sorted logs and load trucks, and
- store waste material (tops and culls).

The equipment and usual number of personnel used in the landing were one Cat 322 hydraulic loader, one Cat 950 wheel loader, 2 chasers, one bucker, and one brander.

The helicopter dropped the turns along the narrow axis, in the center of the landing. When the hooktenders required chokers, the helicopter would hover over the stored chokers and a coil of 10 to 20 chokers would be placed in the hook.

Once the turn was released on the landing 2 to 3 chasers would unhook the chokers, also sometimes the wheel loader was needed to untangle the chokers from the logs. These chokers were then coiled and stored. The wheel loader would then organize and move the turn to the bucking area. At the bucking area the tops, broken ends, and limbs were removed. Once the ends of the logs were bucked the brander would brand and paint both ends of each log. After branding, the logs were sorted by the shovel loader and decked in position to be loaded. Once the shovel loader had finished sorting the merchantable logs, the wheel loader would then move the waste to piles located around the edge of the landing.

Figure 5: Moving a turn to the processing area in landing 1.

Figure 6: Landing a turn at landing 1 (note the waste pile, in the rear right of the figure.

In addition to the yarding and landing personnel, 2 flag persons were required because the flight paths from the units to the landings crossed an active Forest Service road. There was also a data collector who entered the turn data radioed by the pilot into a laptop computer. There was always at least one project manager on site supervising the operation and occasionally filling one of the operational positions.

Superior Helicopters uses one falling contractor on most of their timber sales. The owner of the falling company both falls timber and provides supervision and training for the individual fallers he employs. The contractor has a core group of about 8 fallers; however, on the Butte sale where falling was behind schedule extra fallers where hired. The addition of a number of fallers for short periods of time confounds the difference in falling production between treatments. Also, the manner in which these extra fallers laid out the wood varied greatly and sometimes created problems for yarding. It is difficult to determine if the problems with laying out the wood were a result of the treatment prescriptions and unit layout, or whether they were due to faller practices.

On the Butte sale the timber was generally small enough that log lengths could be maximized without concern for mass. Only the large fir veterans had to be cut as short logs so their mass would be below 2040 kg.

4.0 Methods

4.1 Data Collection Methods

Initially this study was to use shift level and flight record data to estimate helicopter productivity (volume / minute) in each of the treatment units. However, once on site it was evident this data alone would not be sensitive to the effects that the retention levels had on harvesting production. Between-unit variation in the volume per hectare, the stems per hectare, distance to the landings, and the fact that tops were left attached to the logs confounded the treatment effects on helicopter productivity. Thus, the shift level and flight record data had to be augmented with detailed measurements in order to produce hourly production rates (kg/hr and m^3/hr).

4.11 Flight record data

Superior Helicopters, as a normal part of their operation, collected the flight record helicopter data. The following data were obtained from the production reports:

- Turn Weight (1000s of lb.): this was read from the onboard load cell by the pilot and radioed to the data collector. This gave the gross weight of the turn and chokers, and was converted to Turn Mass by the factor of 2.205 lb. / kg.
- Turn Time (minutes): the data collector recorded this with a stopwatch. A turn cycle consisted of the helicopter leaving the landing empty and returning with a load of logs. If the helicopter aborted a turn, the time spent up to that point was included in the next turn that reached the landing. Since more than one unit was active at a time it was possible (though uncommon) to have the time from an aborted turn added to a turn from another unit.

- Number of pieces flown: the hooktender informed the pilot how many pieces were in the turn, and pilot radioed this to the data collector once the turn was accepted.

4.12 Detailed production data

The sampling methods used to collect these data were developed on site after it was realized that the flight record data were insufficient to identify treatment effects on production. The effects the treatments had on the flight record data were confounded by the variation in flight distance to the units from the landings, and the different levels of waste being flown from the units. The detailed information had to be collected by the researcher in the course of other duties, and thus a formal sampling design was not possible. To limit bias in this data, the timing periods were kept to complete helicopter cycles and where possible, were spread over several days. The samples were taken from different hooktenders on a given day, which resulted in the sampling being spread along the contours of a unit. Also, samples were taken over several different days to capture variation due to elevation.

4.121 In-unit turn time data collection

Detailed timing was required to determine if the level or pattern of green tree retention affected the productivity of the helicopter. Field observations indicated the time the helicopter spent at the units collecting turns was the function that was most sensitive to the treatments. The time the helicopter spent at the unit to successfully remove a turn was collected using a stopwatch.

The following elements define the in-unit helicopter time.

- Position: This element began when the pilot started to decelerate while approaching the unit after returning from the landing, and ended once the hook was positioned so the hooktender could reach it. This element could also begin after the pilot had dropped a bundle of chokers in the unit and was then the time taken to reposition the hook for the hooktender.
- Hook: This element began when the hooktender could reach the hook, and ended when the hooktender had connected the chokers to the hook and was in a clear position so that the pilot could lift the turn.
- Lift: Once the hooktender was clear the pilot could attempt to lift the turn, and this could require several attempts to break the turn free. The lift element ended when the pilot had finally accepted the mass of the turn and began to leave the unit.
- Clear: This element began after the lift element was completed and ended when the pilot had cleared the turn from obstructions (reserve trees, and the surrounding timber edge) and was able to head to the landing unhindered.

4.122 Turn mass to turn volume data collection

It was not possible to use the trucked scale from the shift level data as a measure of the merchantable volume removed from a unit, because the unit identity of the timber was lost once it was decked in the landings. The turn mass reported by the helicopter included the merchantable timber, as well as waste, cables, and the hook. The percent of the turn mass that was composed of waste varied between the units, thus it was necessary to use unit specific factors to convert turn mass to merchantable volume.

The merchantable volume flown out of the Butte timber sale was estimated by scaling turns in the field, and then recording the mass reported by the pilot. The minimum log size specified by the Forest Service was 2.5m (8 ft) long, with a 12.5cm (5 inch) top diameter. It was noted the minimum top diameter sorted by Superior Helicopters had a large variation (7.5 to 15.0 cm). The minimum log size scaled in the field had a top diameter inside bark of 9cm and a minimum length of 2.5 m.

There was little decay noted in the felled and bucked timber, so the gross scale of the logs was a good estimate of the merchantable volume (cubic volume not board foot scale). The greatest errors experienced in this sampling occurred when the scaler missed a buried log, or when logs broke or were lost when the turn was lifted. To minimize these errors the scaler watched each turn being lifted and attempted to account for changes in the log count. If the scaler was unsure of the changes, the turn was omitted.

4.2 Data analysis methods

Dykstra (1975) found in operational timber sales that the narrow range of observations possible for the independent variables limited comparative analysis of data. In the Butte timber sale confounding effects from the between unit variation of attributes that affected productivity, and missing information such as the time it took to land turns exacerbated this problem. The data analysis in this study will follow a similar format to that used by Dykstra (1975) where frequency distributions were examined for factors affecting productivity, and regression equations were used to identify trends in productivity over a range of values for these factors.

Frequency distributions were used for a qualitative analysis of the trends in the following data sets:

- in-unit timing elements (from the detailed timing),
- total in-unit turn time (the sum of the individual timing elements for a unit),
- total turn time (from the flight record information), and
- turn mass (from the flight record information).

In order to remove the influence of flight distance, the frequency distributions for total turn time were shifted to a standard position of 475m horizontal distance. This was accomplished by subtracting an estimated constant representing the increase in flight time to the unit from the standard distance of 475m. The unit 5 and unit 2 data sets for standardized total turn time were filtered to remove turns that were affected by aborted turns and by choker drops, in order to assess the effects these factors had on the average standardized total turn time.

The flight records contained data for total turn time, turn mass, and the number of logs per turn. To estimate turn time and turn mass it was necessary to determine if there was a strong correlation between these variables. The Pearson product moment correlation coefficient (PPMC) was calculated to test for correlation between turn time and turn mass, turn time and the number of logs per turn, and for turn mass and the number of logs per turn. The PPMC was tested for significance as described by Bluman (1995, pg 387). There was little correlation between turn time and turn mass in the flight record data set, thus productivity could be estimated with separate equations for total turn time and turn mass (or volume).

Microsoft Excel (© Copyright 1994, Microsoft Corporation) was used to fit linear regression equations for turn time and turn volume. A simple linear regression equation was developed to predict the average total turn time for a unit as a function of the average horizontal distance from the unit to the landing. A multiple linear regression equation was developed to predict the average volume per turn as a function of the average volume per log and the average merchantable volume per unit mass. Note the mass includes the mass of the merchantable wood, waste (tops and culls), and the cables (tag line and chokers)

The productivity of the helicopter was estimated by dividing the predicted average turn volume by the predicted average turn time. Thus, productivity was calculated as a function of the average horizontal distance to a unit from the landing, the average volume per log, and the average merchantable volume per unit mass. Helicopter productivity was then examined for sensitivity to variation in the independent variables.

5.0 Data analysis

5.1 Analysis of in-unit turn time

The in-unit timing elements were sampled in units 2, 3 and 5. The frequency distributions for each timing element are shown for each unit in figures 7, 8, 9, and 10. These elements do not include time for aborted turns or for choker drops. The following qualitative observations can be made regarding the frequency distributions of the in-unit turn time elements.

- The mean time for the position element was higher in unit 2 than for units 3 and 5. This was unexpected and is most likely due to the fact that deceleration, which defines the beginning of the position element, was difficult to assess when viewing the helicopter from certain angles. The range of the position element observations were quite narrow and suggesting that this element acts as a constant portion of the total in-unit turn time for these units.
- The mean time for the hook element was similar in all the units sampled. This was expected, since the only real variation in the element comes from the time it takes the hooktender to move into a safe position after hooking the turn. The time to move into the clear will only begin to be a factor under very rugged conditions, or where over-head hazards require the hooktender to move farther away to be in a safe position.

Figure 7: Frequency distributions of the in-unit timing element, position.

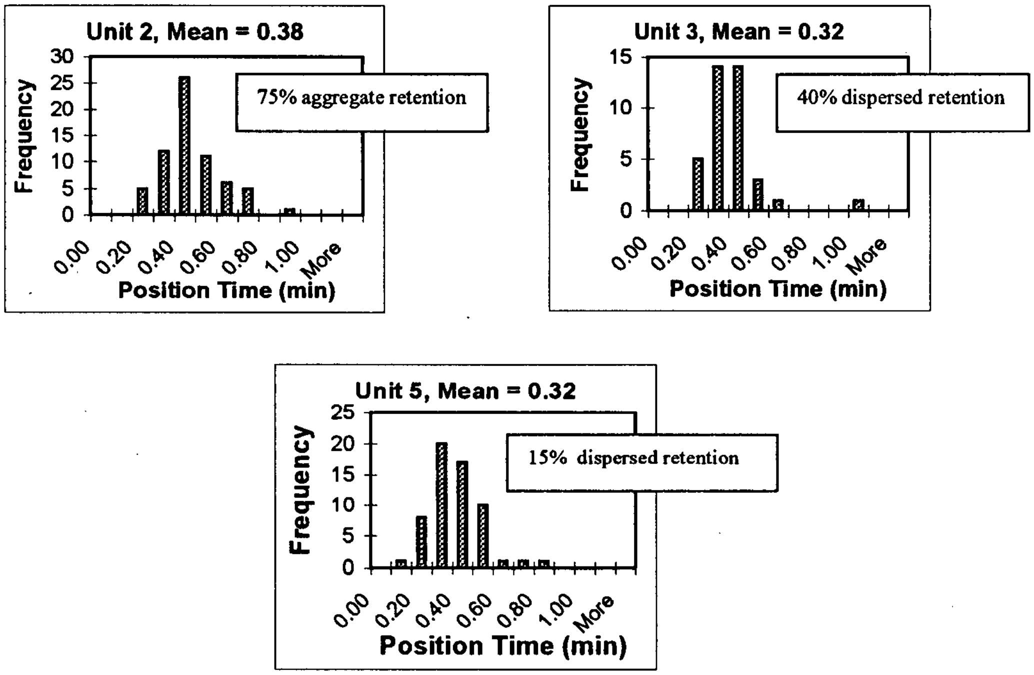


Figure 8: Frequency distributions of the in-unit timing element, hook.

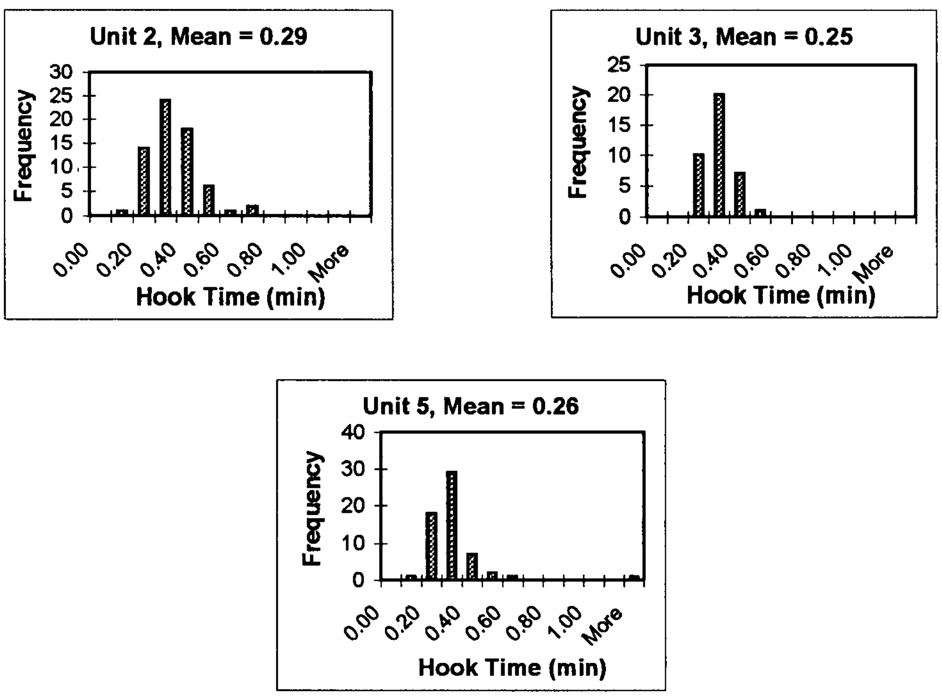


Figure 9: Frequency distributions of the in-unit timing element, lift.

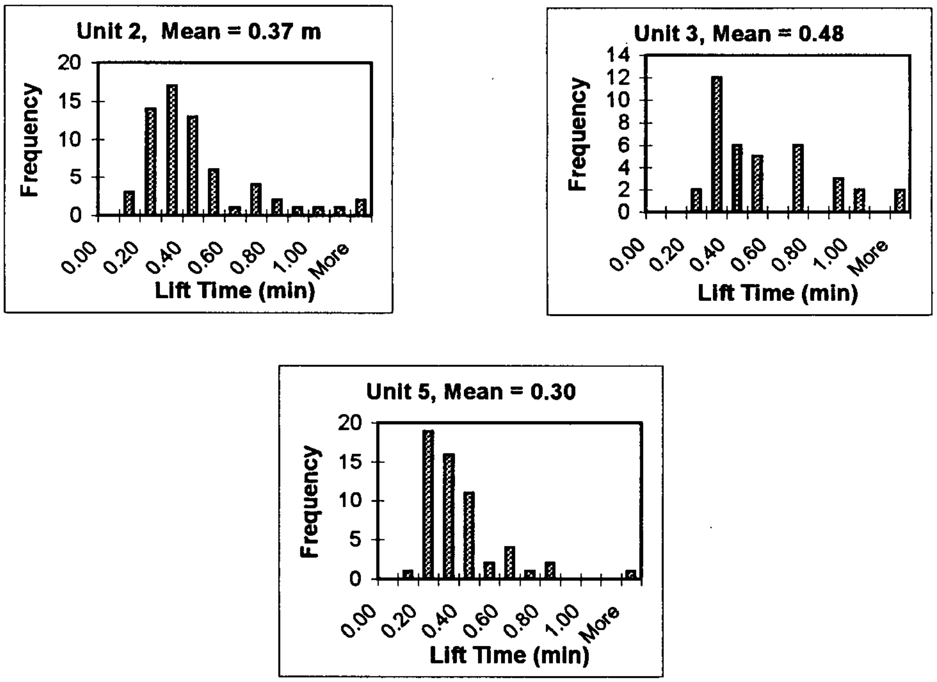
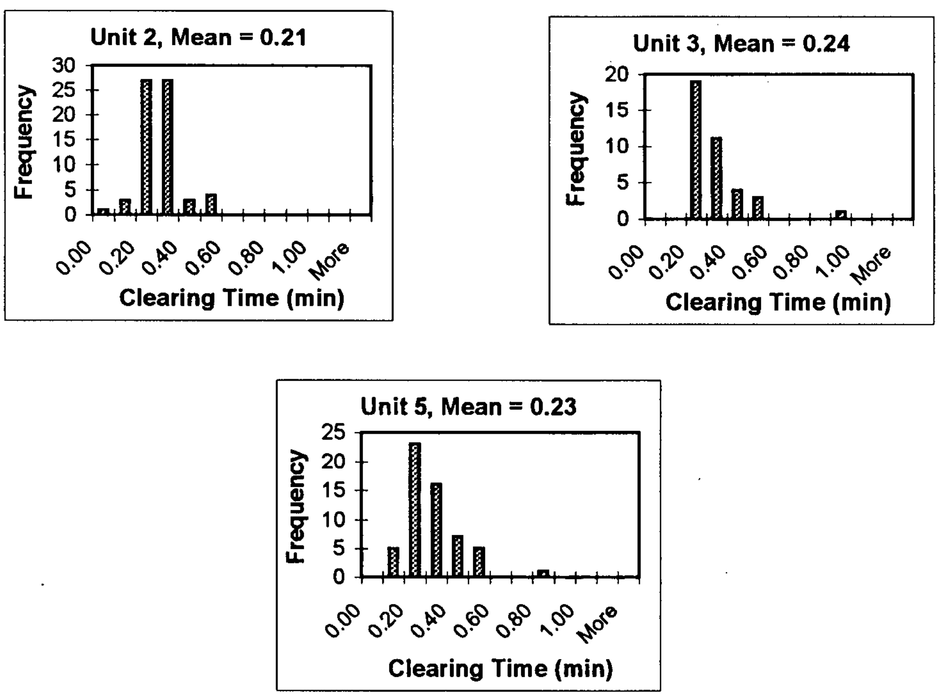


Figure 10: Frequency distributions of the in-unit timing element, clear.

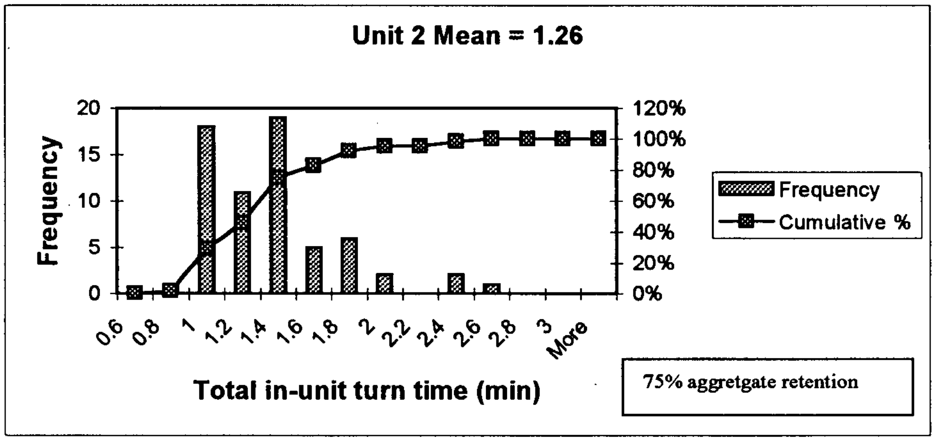


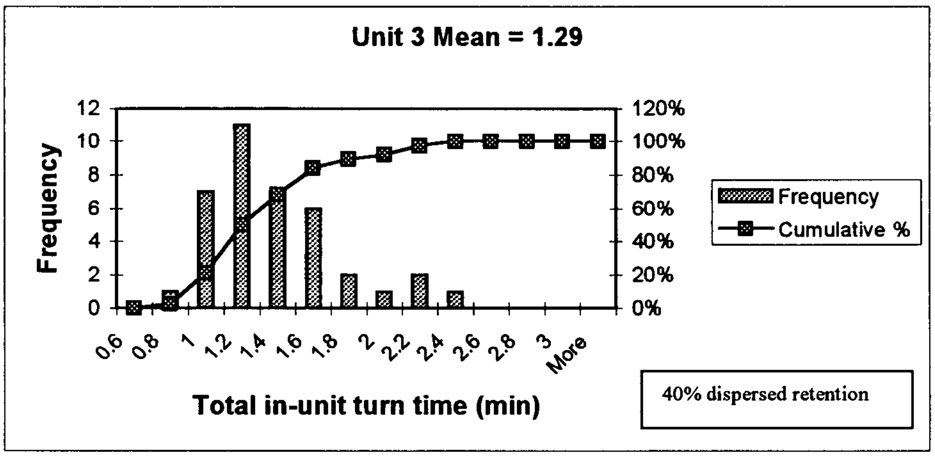
- The lifting element had the most variation of the in-unit timing elements, both within a unit and between the units. The logs that were included in a turn strongly affected this element. If the hooktender included logs in the turn that were hung-up, the pilots would often spend up to a minute pulling on the turn from different directions in an attempt to break the logs free. The placement of the timber after falling, and the number of obstacles (such as reserve trees) affected the number of turns with hang-ups.

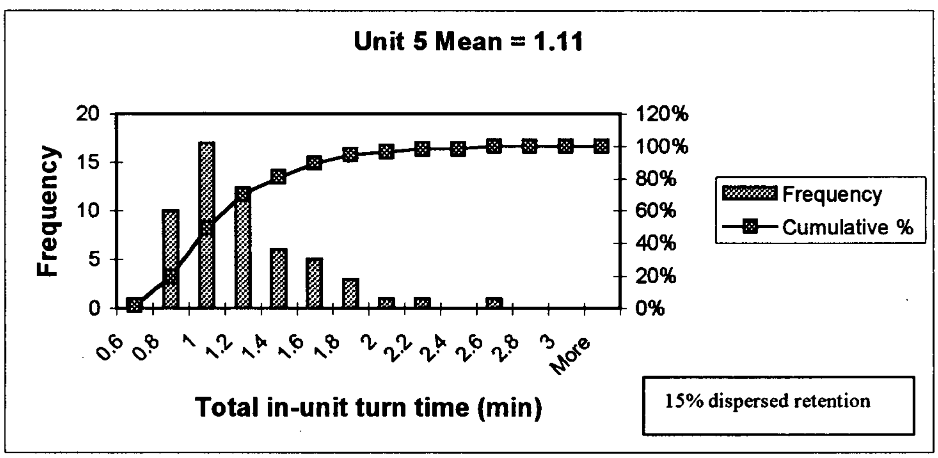
  In unit 3 the number of reserve trees was sufficiently high to make them difficult to avoid when selecting logs for a turn. In unit 2, though it was a patch cut, there were numerous understory reserve trees that had to be avoided. The small opening sizes in unit 2 also resulted in more timber edge for a given area harvested, and this combined with the understory trees made breaking turns free more difficult. In unit 5 the reserve trees were spread far enough apart so they did not create many problems with hang-ups.

- The clear element had little variation either within the units or between the units. The higher dispersed retention levels tended to produce more negative skew in the distributions, however, rather than indicating shorter turn times this indicated the helicopter had to climb vertically above the canopy after lifting the turn off the ground. If the helicopter was able to climb gradually through the canopy toward the landing, it was able to simultaneously build momentum and move towards the landing while clearing the canopy. It is more efficient to build momentum towards the landing than to lift the turn vertically, and then change direction.

Figure 11: Total in-unit turn time without choker drops of aborted turns.







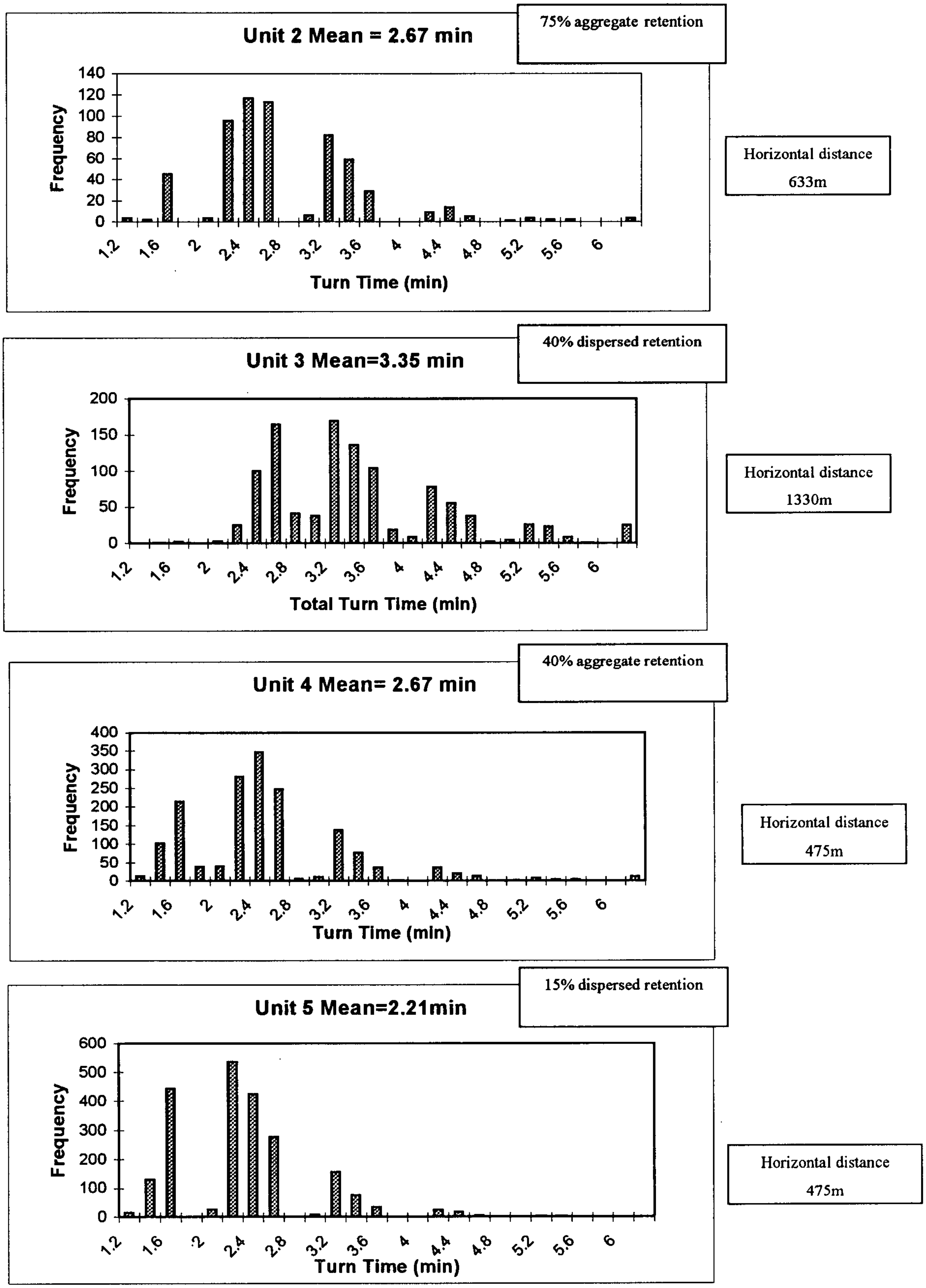
The in-unit timing elements were summed to give observations for total in-unit turn time (Figure 11). The distributions for the total in-unit turn time have a lognormal shape. The minimum values for each of the three distributions are quite similar (0.8 minutes for units 2 and 3 and 0.6 minutes for unit 5), and these could be considered to represent delay-free or efficient turns. This indicates that the different levels of retention and the confounding effects from the between unit variation in other attributes, either cancelled each other out, or had little effect on the in-unit time of delay-free turns.

5.2 Analysis of total turn time

Frequency distributions of the total turn time data from the helicopter flight records are presented in Figure 12. The frequency distributions are all roughly lognormal, with minimum values that are offset to the right following the trend in the average horizontal distance to the units from the landing.

It was found there was little difference between the total in-unit turn times of delay-free turns for the different units. The minimum total turn times from the flight record data are also examples of delay-free turns. The increase in flight time to travel from one unit to a more distant unit could be estimated by taking the difference between the total turn times of the delay-free turns. Knowing the increase in flight time for delay-free turns to the more distant units, the distributions for these units could be standardized for distance to the proximal unit. Since units 4 and 5 already had similar average horizontal distances of 475m, this was used as the standard distance.

Figure 12: Frequency distributions of total turn time (all turns).



To limit the influence of suspiciously short turn times in the unit 3 data, the minimum total turn times for the units were taken as the midpoints of the classes to which 5% of the observations were equal, or less than. The minimum total turn times by this definition are: unit 2) 1.6 minutes, unit 3) 2.4 minutes, unit 4) 1.4 minutes, and unit 5) 1.4 minutes. Thus, to standardize the unit 2 distribution, 0.2 minutes were subtracted from the unit 2 observations, and 1.0 minute was subtracted from the unit 3 observations. The frequency distributions for total turn time at the standard distance can be found in Figure 13.

If the standardization process removed the effect of the increase in flight distance, then the difference in the standardized mean total turn times should be the result of the change in total in-unit turn time between the units (Table 3). This assumes that the increase in total turn time from choker drops, and aborted turns is similar between the units.

Table 3: Difference between mean total in-unit and standardized mean total turn times.

Units being compared	**A** Change in mean total in-unit turn time (min)	**B** Change in mean standardized total turn time (min)	**A – B** (min)
Unit 5 to Unit 2	0.15	0.24	-0.09
Unit 5 to Unit 3	0.18	0.14	0.04

Figure 13: Frequency distribution of total turn time standardized for distance (all turns).

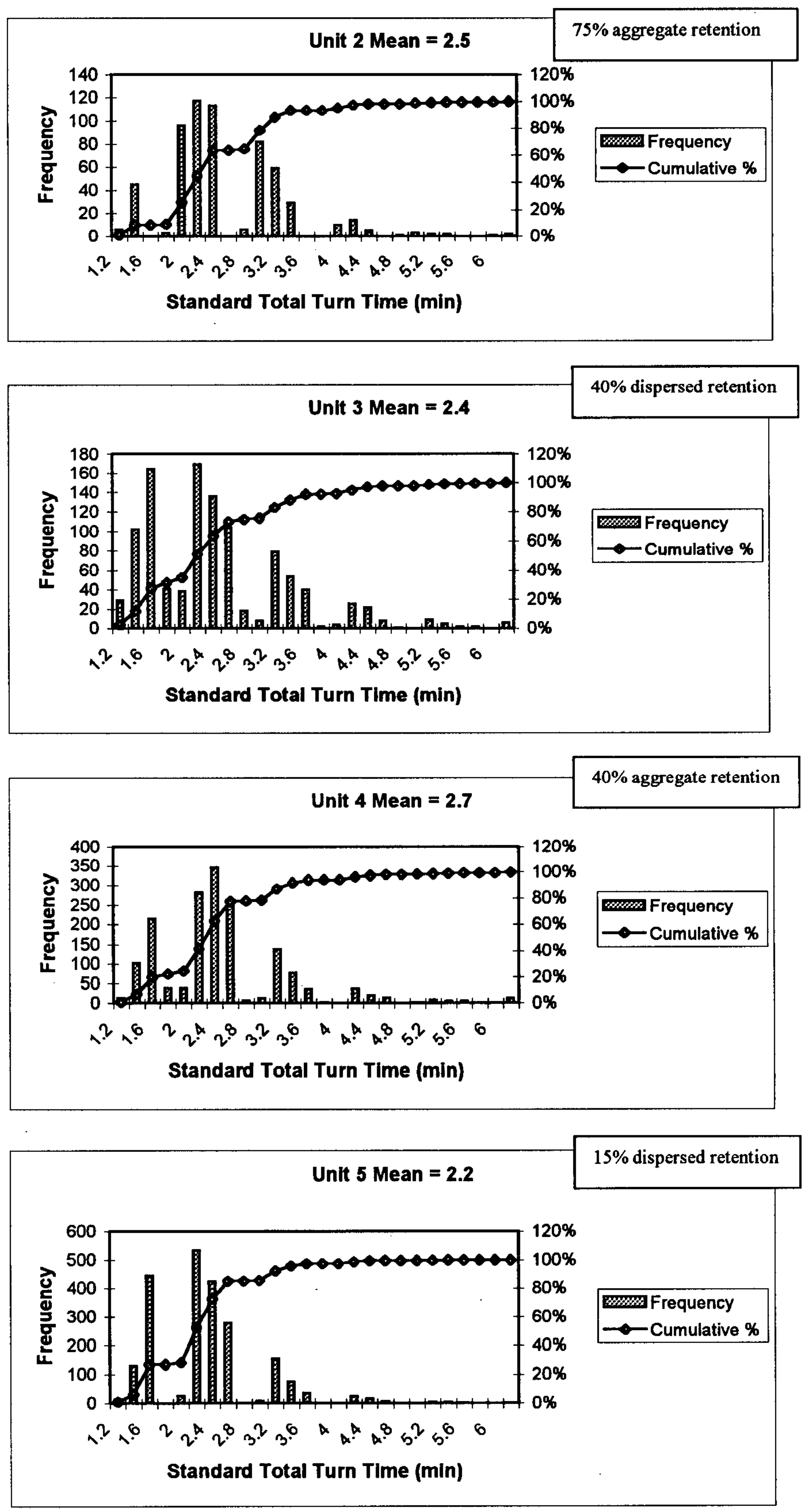


Table 3 indicates the standardization process removed much of the influence that the variation in flight distances had on the mean total turn times. Based on the standardized total turn time histograms, the following observations can be made.

- Unit 4 has the highest mean standardized total turn time for three reasons. First, units 3 and 4 were harvested at the same time and some of the longer turn times from unit 3 may have been incorrectly assigned to unit 4. Second, in unit 4 there were large logs mixed in with numerous small logs, and this made it more difficult to set delay-free turns. Third, the orientation of the groups of reserve trees resulted in strips of trees having to be removed along gullies. The fallers were instructed not to fall trees into either the standing timber, or the gullies, and this resulted in logs that were poorly laid out causing more hang-ups.

- Unit 2 has the second highest mean standardized total turn time. This may be due in part to the large number of understory residual trees and to the boundary placement of the small patch cuts. However, unit 2 was harvested at the beginning of the operation, and the pilots seemed to have fewer delays after the first two weeks. The learning curve effect may have had a stronger influence on the average total turn time.

- Unit 3 had a higher percentage of the observations in the right hand side of the distribution than the other units. However, the mean standardized total turn time was one of the lowest, there are three possible reasons for this. First, before standardizing the unit 3 observations a few turns were observed with total times that appeared too short to be from unit 3. These turns may actually have been incorrectly assigned unit 4 turns. Second, the higher level of dispersed retention did cause a higher rate of hang-ups and aborts as logs could get hung-up in the reserve trees. However, the lower number of logs being removed per hectare improved the visibility of individual logs, making it simpler for the hooktenders set turns with out hang-ups. Third, the correction factor used to standardize the distribution could be overestimating the increase in travel time to unit 3.

- Unit 5 had the lowest mean standardized turn time. In unit 5 the low number of retained trees did not create many obstacles for the hooktenders or the pilots. Also, the timber in unit 5 was more uniform in size and the fallers were able to lay it out parallel to the contours. This simplifies the task of trying to set turns without hang-ups, and thus reduces the number of turns with delays.

For units 2 and 5 it was possible to identify, in the flight records, the turns that contained either choker drops or aborts. The standardized total turn time data sets for units 2 and 5 were filtered to first remove the turns that contained aborted turns, and second to remove the turns that contained either aborted turns or turns with choker drops (Figures 14 and 15).

In both units 2 and 5 the turns with aborts had standardized total turn times that were greater than the standardized mean total turn time, and thus removing them from the data sets tended to reduce the right hand tail of the distributions. However, it can be seen in Figures 14 and 15 (distributions without aborts) that not all the turns at the extreme right of the distribution were a result of aborted turns. The remaining turns with very long total turn times may have resulted from problems the pilots had with fog. Sometimes the helicopter would be delayed at the unit by fog moving in and limiting visibility. If, after circling, the pilot could find an opening in the fog and collect a turn, the delay time up to that point would be included in the total turn time.

Figure 14: Unit 2 frequency distribution of total turn time standardized for distance (turns with aborts or choker drops removed).

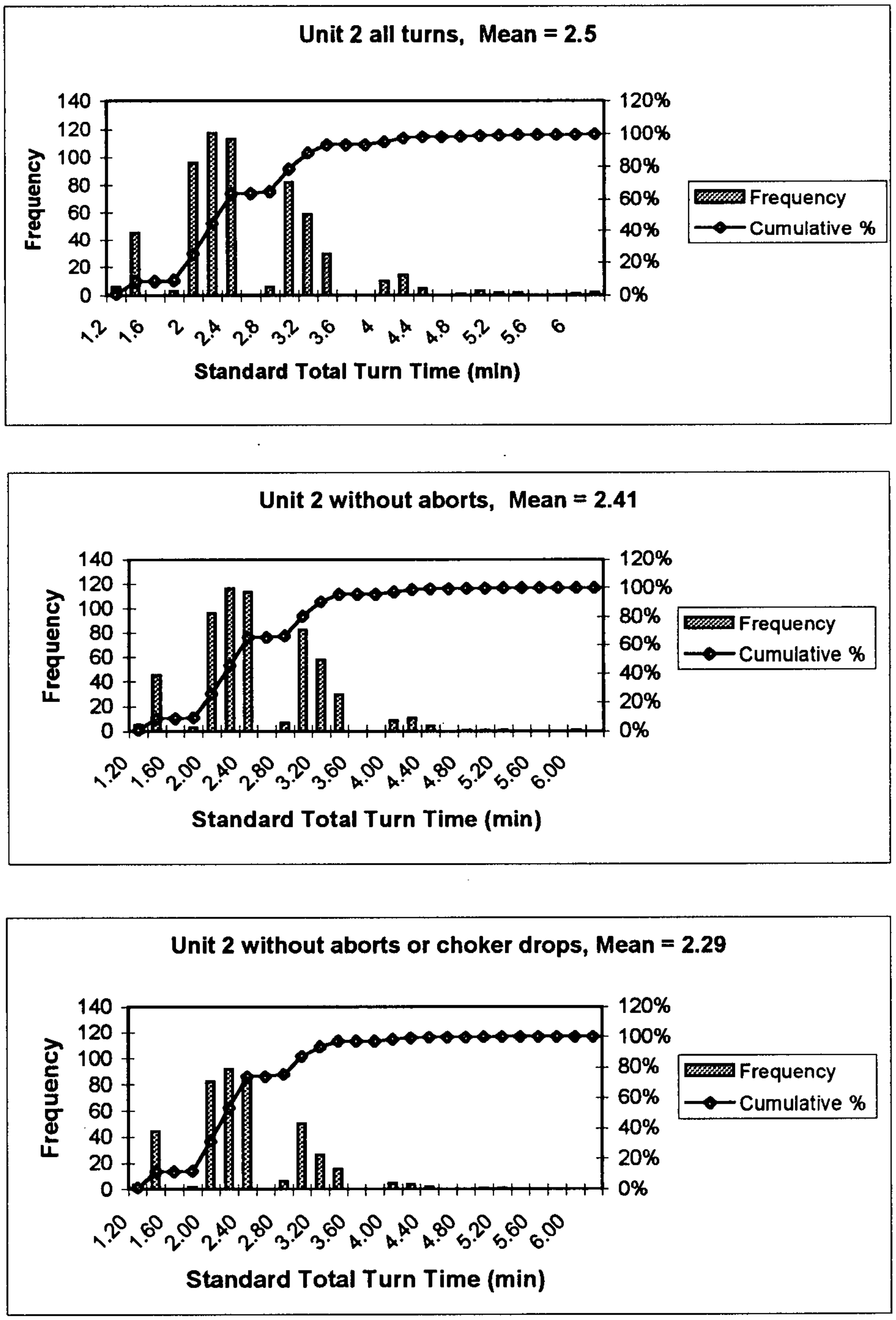
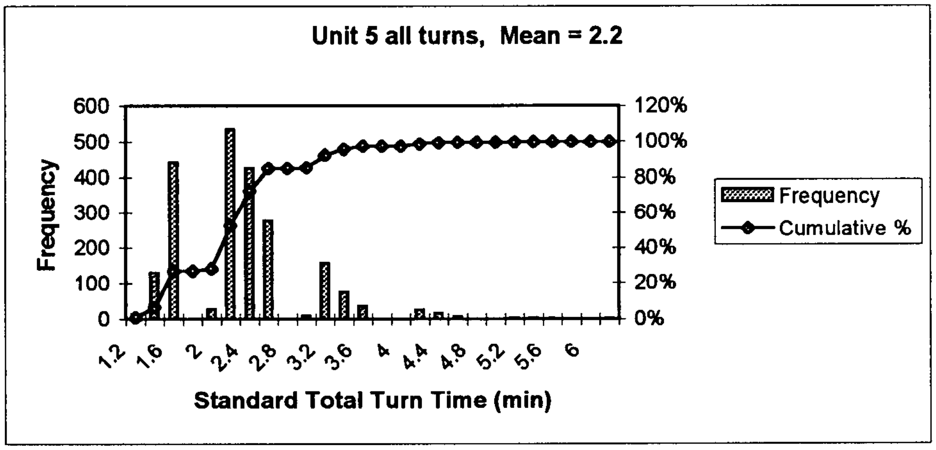
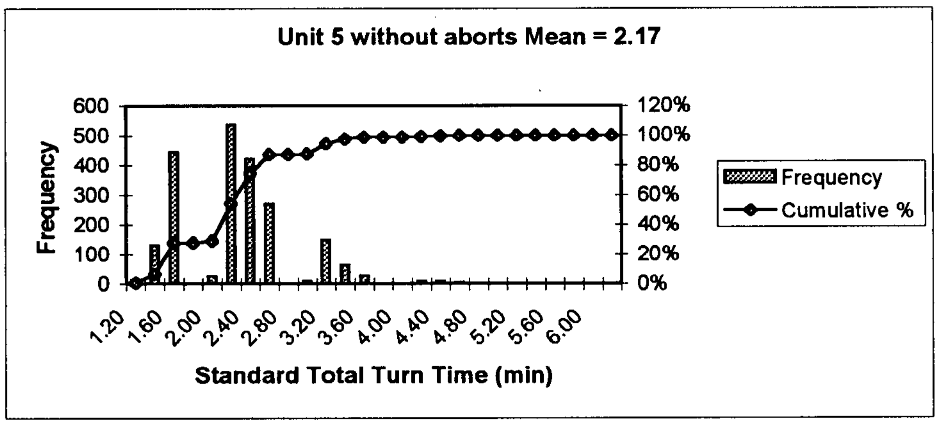
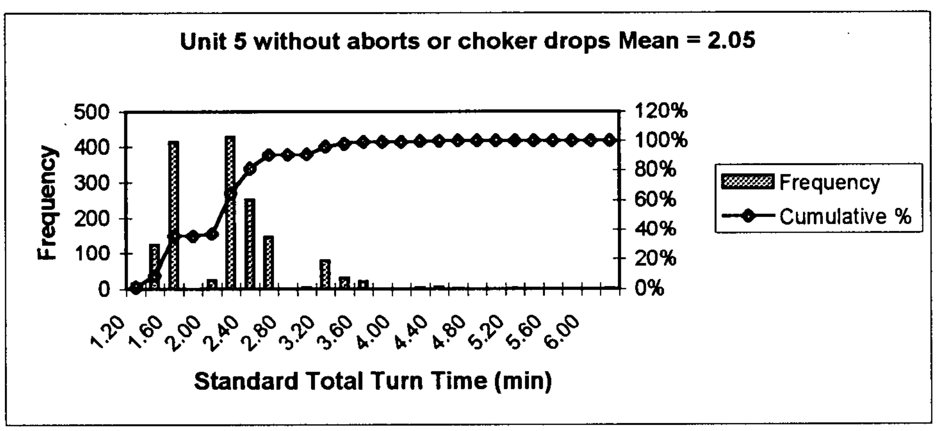


Figure 15: Unit 5 frequency distribution of total turn time standardized for distance (turns with aborts or choker drops removed).







In units 2 and 5 the turns with choker drops could be found in all but the minimum time classes of the standardized total turn time distributions. However, the turns with choker drops were concentrated in the time classes that were above the mean, and removing them from the data reduced the mean standardized total turn time (Figure 14 and 15).

To support the assumption that choker drops and aborted turns were having similar effects on the standardized mean total turn times in the different units, the data sets filtered for turns with aborts, and for turns with aborts and choker drops can be compared (Table 4). It can be seen in Table 4 that the actual change in the standardized mean total turn time (minutes), as a result of choker drops and aborts, is the same for units 2 and 5. However, the lower standardized mean total turn time in unit 5 results in a slightly higher percentage increase in the mean, from choker drops and aborts.

The choker drops and aborted turns had a similar effect on the standardized mean total turn times in units 2 and 5. This supports the assumption that the difference between the standardized mean total turn times is a reflection of the difference between the mean total in-unit turn times (which do not include aborts or choker drops).

Table 4: Unit 2 and 5 standardized total turn times filtered for aborted turns and choker drops.

	Unit 2	Unit 5
A) Standardized mean total turn time, all turns (min)	2.45	2.21
B) Standardized mean total turn time, without aborts (min)	2.41	2.17
(A – B) change from aborts (min)	0.04	0.04
Percent change from aborts **(A – B) / A %**	1.6 %	1.8 %
C) Standardized mean total turn time, without aborts or choker drops (min)	2.29	2.05
(B – C) change from choker drops (min)	0.12	0.12
Percent change from choker drops **(B – C) / B %**	5.0 %	5.5 %
(A – C) change from aborts and choker drops (min)	0.16	0.16
Percent change from aborts and choker drops **(A – C) / A %**	6.5 %	7.2 %

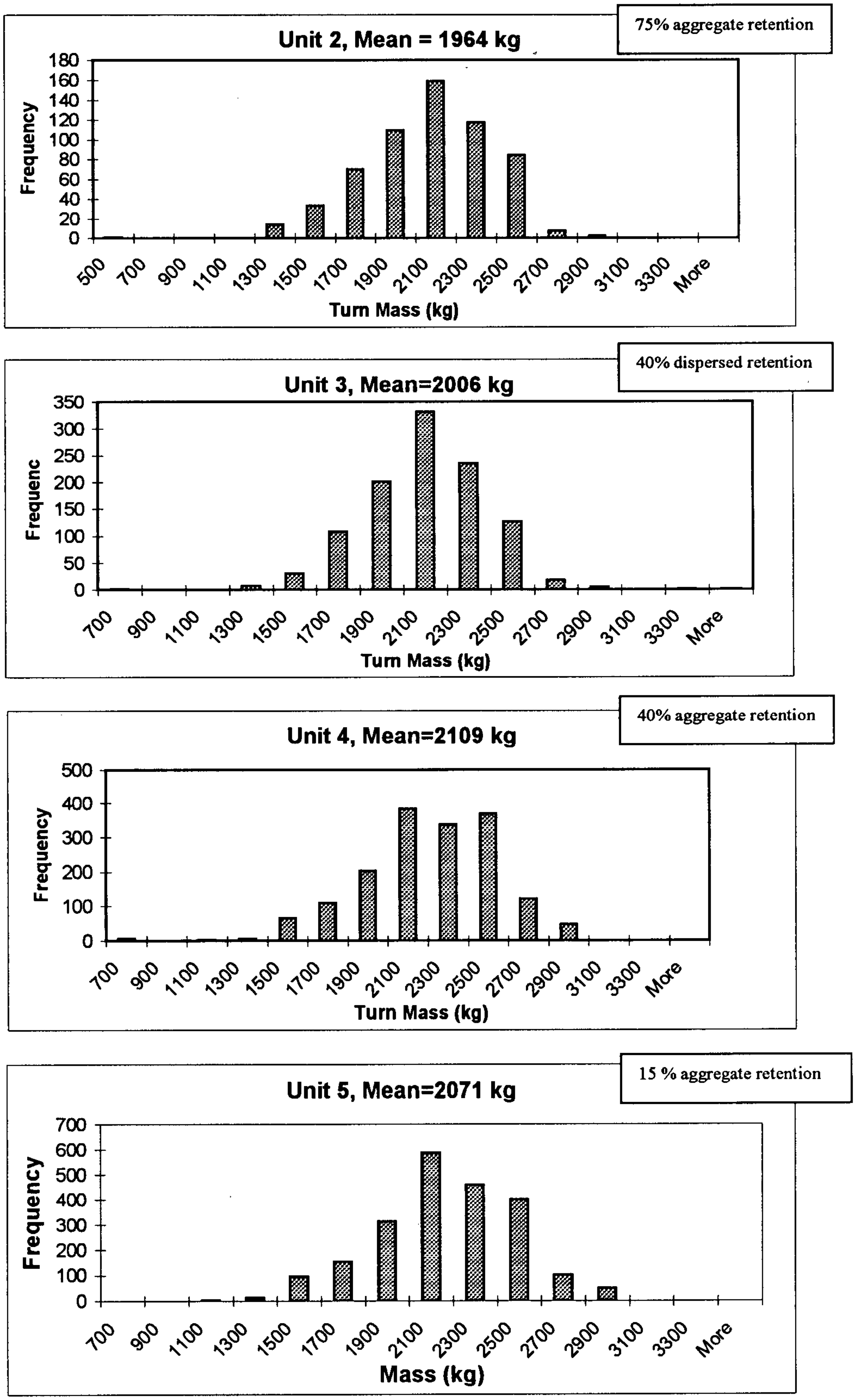
5.3 Analysis of turn mass

The frequency distributions of the turn mass observations are presented in Figure 16. The hooktenders in this operation were striving to maintain an average turn mass of 2040 kg. However, it was considered a success to achieve a higher average turn mass, if they did not increase the frequency of aborted turns. The average turn mass values for the 4 units in this timber sale were all quite similar and are centered on the target average of 2040 kg. The maximum and minimum values from the different units are also similar. This is because the upper limit is defined by the maximum lifting capacity of the helicopter, and the lower limit is defined by the smallest turn size that the pilots felt was worthwhile flying to the landing.

The turn mass frequency distributions for units 2, 4, and 5 have a slight positive skew. The positive skew was expected as the hooktenders were trying to hook turns that were as close to the maximum turn mass (2721 kg) as possible without exceeding it. However, the turn mass distribution for unit 3 is almost normal. The difference in the shape of the unit 3 turn mass distribution is a result of the difficulty the hooktenders had in making larger turns, without creating hang-ups with the more numerous reserve trees. In unit 3 the hooktenders were instructed to make smaller turns rather than risk hang-ups and possibly knock over the reserve trees.

The average turn mass was relatively insensitive to the treatments that were applied in this timber sale. However, unit 3 may be approaching the limit where the number of reserve trees or the distance between the logs to be removed will adversely affect the average turn mass. The skill of the fallers and how they laid the wood out, or the locations of the cutting boundaries as they affected falling, also had a strong effect on the average turn mass that could be constructed without increasing the frequency of aborted turns.

Figure 16: Frequency distributions of turn mass (all turns).



6.0 Regression analysis

The objectives in producing regression equations in this paper were to demonstrate trends that certain key factors have on helicopter productivity on the Butte timber sale. Since there are a very limited number of observations to develop the regression equations it would be inappropriate to use these equations as cost predictors for other timber sales.

6.1 Testing for correlation

Helicopter productivity is measured in kg/hr or m^3/hr, and thus the size of the turns and the helicopter time it takes to fly them to the landing must both be estimated. It is necessary to prove that total turn time and turn mass are not strongly correlated if they are to be estimated separately, and then combined to estimate helicopter productivity. For each unit, plots were constructed with total turn time as the dependent variable and turn mass as the independent variable (Figure 17). Viewing Figure 17, the distributions of the observations are uniform, indicating that there was little correlation between total turn time and turn mass in these data sets.

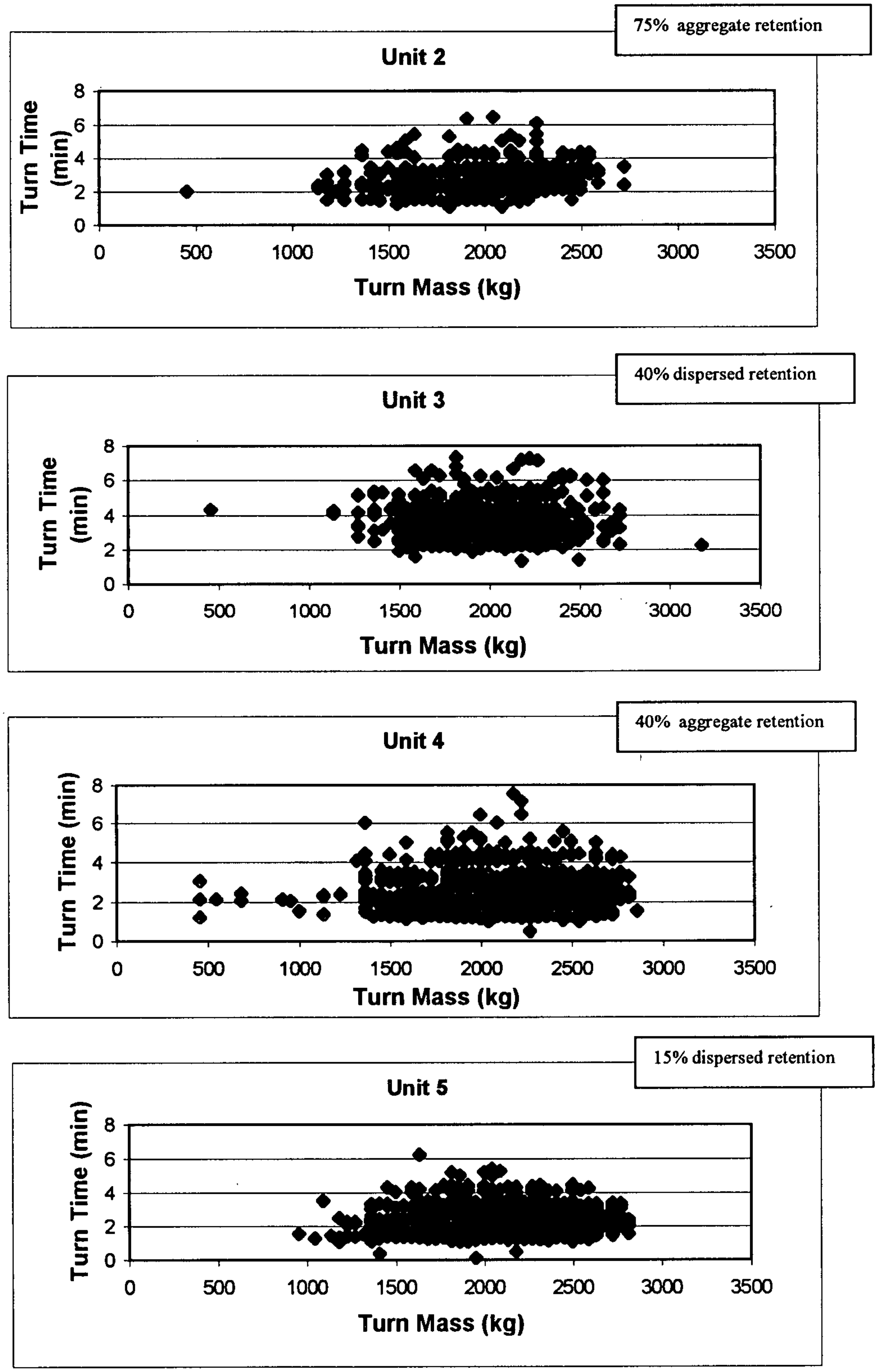
The flight record data includes observations of the number of logs per turn as well as the mass and total time for the turns. The Pearson product moment correlation coefficient (PPMC) was calculated to test for correlation between turn time and turn mass, turn time and logs per turn, turn mass and logs per turn in each unit, and tested for significance. The hypothesis test was:

H_0: PPMC = 0

H_1 : PPMC $<>$ 0 .

$\alpha = 0.05$.

Figure 17: Correlation between total turn time and turn mass (all turns).



The results of the tests for significance can be found in Table 5. Note, instead of calculating separate t values for every comparison, the critical PPMC value is calculated for each unit.

$$PPMC_{critical} = \left(\left(\frac{N-2}{t_{crit,alph0.05}^{\;2}} \right) + 1 \right)^{-1/2}$$

Table 5: Testing correlation.

	Unit 2	Unit 3	Unit 4	Unit 5
PPMC Time / Mass	0.2120	-0.0001	-0.0361	0.1032
PPMC Time / Logs	-0.0398	0.0612	0.0202	-0.0474
PPMC Mass / Logs	0.0543	0.0534	-0.0528	0.1782
Degrees of freedom	593	1065	1645	2167
$PPMC_{critical,\ 0.05}$	0.080	0.057	0.046	0.042
Comparisons with significant correlation	Time/Mass	Time/Logs	Mass/Logs	Time/Mass Time/Logs Mass/Logs

The results of the correlation tests did not show strong correlation between turn time and turn mass, turn time and the number of logs in a turn, or turn mass and the number of logs in a turn. However, there were several comparisons that did show a significant level of correlation at the 95% confidence interval. The high number of observations tested reduces the interval about zero where the hypothesis PPMC = 0 cannot be rejected, though not being able to reject the hypothesis does not guarantee a strong correlation as Figure 17 demonstrates.

Though Figure 17 does not indicate a strong correlation between turn time and turn mass, this may have been affected by the procedures used to collect the data. The recorded mass of a turn was the mass that was finally brought to the landing, and this mass could have been less than the original mass of the turn if the pilot dropped the logs in the white hook. Also, the data do not show which aborted turns were a result of over-size turns, or hang-ups due to the mass and location of the logs in the turn.

In the analysis it was found that distance had a strong effect on total turn time. However, the only observations with both distance and turn time are unit average values, and this provides only 4 observations for a turn time regression equation. Given this low number of observations and the weak correlation observed in Table 5, turn mass and turn time will be considered not to have a strong correlation allowing productivity to be estimated with separate equations.

6.2 Regression equation for turn time

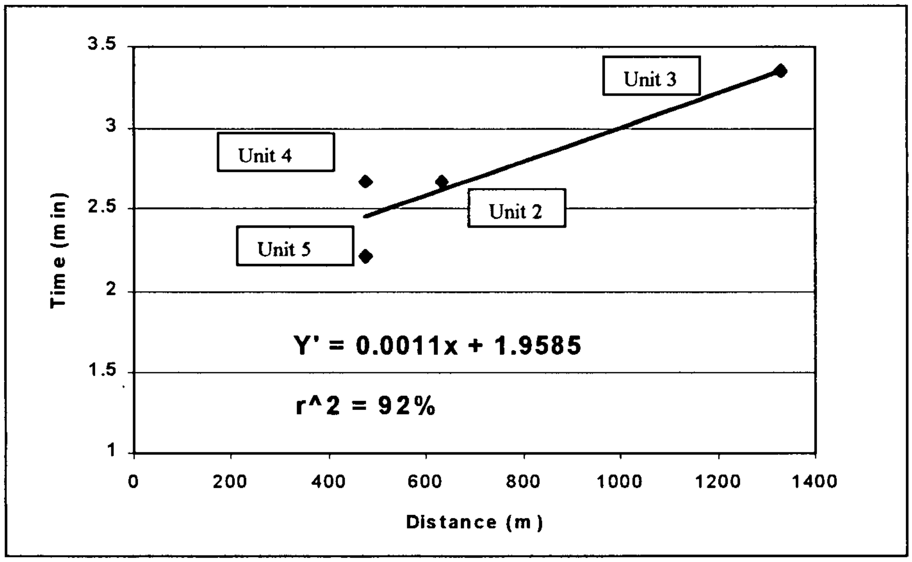
The flight record data showed that distance had a strong influence on the mean total turn time for a unit. Since the total turn time observations did not include distance, it was necessary to use the mean total turn time as the dependent variable and the average distance to the unit from the landing as the independent variable. A simple linear regression equation was fitted to the unit average data (Figure 18) giving the following equation:

$$TT' = 0.0011 * HD + 1.9585 \qquad \text{(E1)}$$

Where: TT' is the predicted total turn time, and

HD is the horizontal distance from the landing to the turn.

Figure 18: Average unit turn time as a function of the average distance from the landing to the unit.



The variation that was explained by equation E1 was 0.6091, while the total variation was 0.6619; this produces a coefficient of determination of 92%. However, as described by Bluman (1995, pg 408) with such a small number of observations (only 4) problems begin to arise with errors in estimating the slope and intercept of the equation, which may become large in comparison with the standard error of the estimate. This implies that with only a few points there may be a line which fits quite well; however, this does not mean the slope and intercept of the line are the true values of a larger population.

For the interval being examined, this equation shows a strong linear trend in the increase in turn time as a result of the increase in HD. However, as discussed by Halkett (1982) below a certain flight distance the minimum turn time will be controlled by the maximum rate of descent of the helicopter. This potential non-linear relationship between flight time and flight distance makes it unadvisable to extrapolate beyond the limits of the data used to develop equation E1.

6.3 Regression equation for turn volume

An equation can be developed which estimates either turn mass or turn volume, as either can be used as an estimate of helicopter production. Volume per turn was selected because estimates of volume would normally be available from operational timber cruise data. The flight record data provides observations of turn mass which were converted to turn volume by unit specific conversion factors, developed from the turn mass to turn volume sampling. The turn mass analysis showed there was little variation between the average turn masses for the units. However, the range of the individual turn masses for a unit spanned the maximum and minimum values that the pilots would accept.

A number of factors were noted in the field that appeared to affect the mass, and thus the volume of the turns the hooktenders could construct:

1. the distance between the logs in a turn,
2. the size of the logs, and
3. the volume of merchantable wood per mass, where mass includes the mass of the merchantable wood, mass of waste material (tops, limbs, cull logs), and the mass of the cables.

There was limited sampling in units 3, 4, and 5 for turn mass and turn volume. Individual turn mass to turn volume measurements from the three units were considered independent observations, and provided 65 observations with which to develop a regression equation to predict turn volume. Refer to Table 6 for the average results of the turn mass to turn volume sampling and the average turn radius. Note that the regression equation was developed from the individual observations in the turn mass to turn volume data.

Observations for two of the independent variables, merchantable volume per mass and merchantable volume per log, were available directly from the turn mass to turn volume data. The third independent variable, average turn radius, had to be estimated by multiplying the number of logs in the turn by the estimated area per log, and then taking the square root of the resulting value.

Where: area per log = Treated area of the unit (m^2) / Total number of logs in unit (from the flight record data).

Table 6: Turn mass to merchantable volume rations.

Unit	# of Turns Sampled	Estimated area per log (m^2)	Average logs/turn	Estimated average turn radius (m)	Average kg/m3	Average m3/log
3	20	17.96	5.55	9.91	1031	0.37
4	31	7.66	5.32	6.38	877	0.51
5	14	10.70	4.64	7.05	809	0.69

The average turn radius does not have a strong correlation with turn volume, though it is significant at the 95% confidence interval when the PPMC is calculated for the turn mass to turn volume data set.

H_0: PPMC = 0

H_1: PPMC <> 0, α = 0.05 two tail.

Where: the PPMC for turn volume to average turn radius = -0.3625

the number of observations = 65

$t_{0.05} = -3.087$, Critical Value = ± 1.960

Therefore reject H_0, the PPMC <> 0, and thus there is a level of correlation between turn volume and the average turn radius. However, the average turn radius was not selected as an independent variable for the regression equation to predict turn volume because:

- it was not measured in the field, instead it is derived with a roughly estimated constant, and
- to simplify the equation for use in a design chart it was preferable to use only 2 independent variables to calculate turn volume.

The regression equation developed to estimate turn volume is:

TV' = 0.1587 + 0.5893 V/L + 1636 V/M (E2)

Where: TV' is the predicted turn volume (m^3/turn)

V/L is the average volume per log in the turn (m^3/log)

V/M is the merchantable volume per mass (m^3/kg)

The coefficient of determination (r^2 value) for equation E2 was 0.757, and the standard error of the estimate was 0.356. To view the plots of the residual errors, and the plots of the predicted and observed turn volumes as functions of the 2 independent variables, refer to Figures 19 and 20.

6.4 Productivity analysis

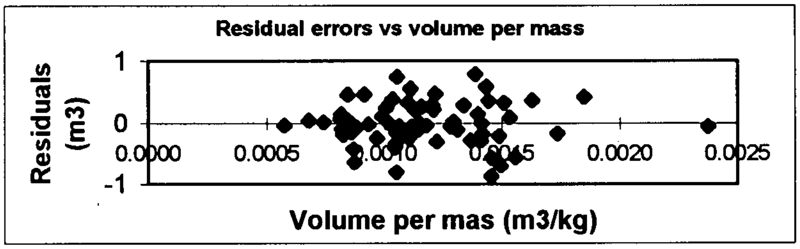
Using equations E1 and E2 the productivity (PR') of the helicopter in terms of m^3/minute can be estimated.

Where: $$PR' = \frac{TV'}{TT'}$$

or $$PR' = \frac{0.1587 + 0.5893\ \mathrm{V/L} + 1636\ \mathrm{V/M}}{0.0011 * \mathrm{HD} + 1.9585} \qquad \text{(E3)}$$

It must be remembered that TT' does not included down time from sources such as weather, mechanical breakdowns, or regular maintenance. Dykstra (1975) suggests that the appropriate way to account for the down time and delays would be to multiply TT' by a constant factor, that would be estimated on site for a given operation. The constant for down time was not included in this paper because equation E3 was developed to examine trends in the data, not to predict exact costs.

Figure 19: Residual error plots for predicted turn volume equation E3.



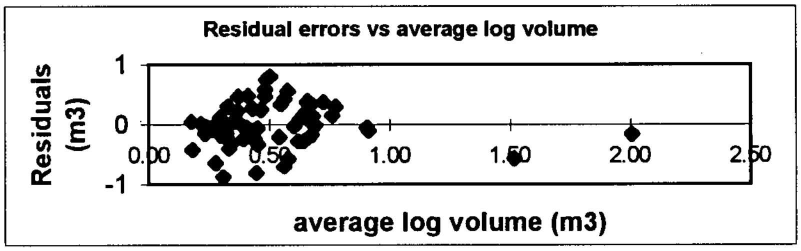
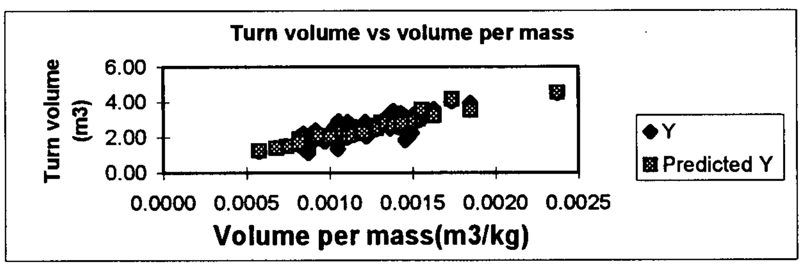
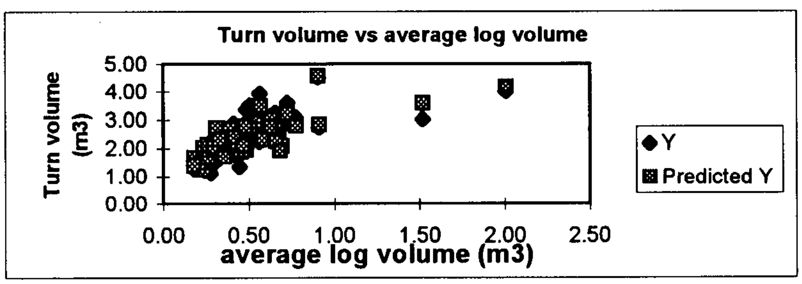


Figure 20: Line fit plots for predicted and observed turn volume.





If an operation required a specific level of productivity from the helicopter in order to optimize the landing functions, equation E3 can be reorganized to estimate the required turn volume. Where the concern is for helicopter payload, the turn mass could be written in terms of the required turn volume.

$$TV' = PR'*TT'$$

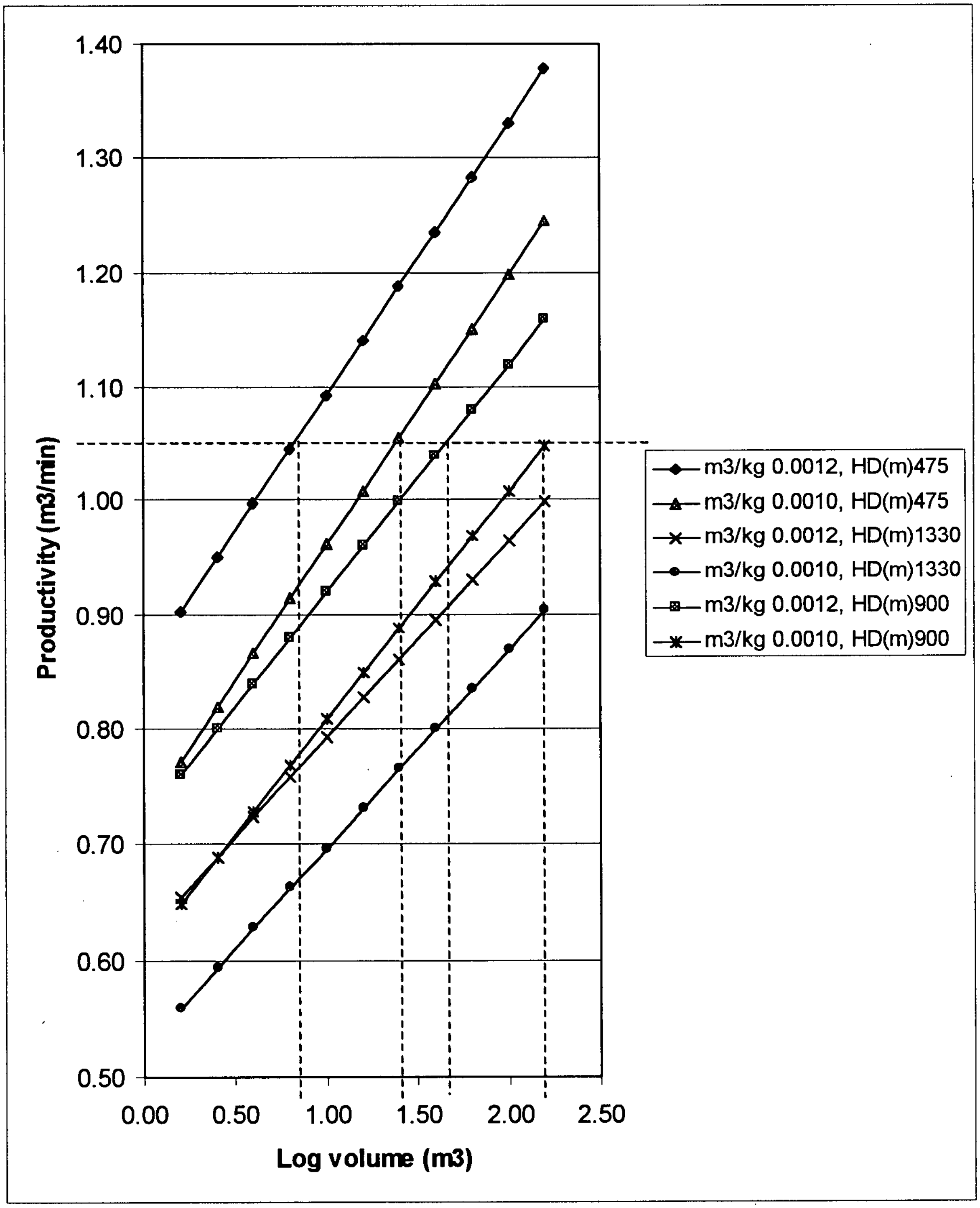
$$TV' = TM'*\frac{V}{M}$$

$$TM' = PR'*(0.0011*HD + 1.9585)*\left(\frac{V}{M}\right)^{-1} \qquad \text{(E4)}$$

Another method to view the relationships between the dependent and independent variables is through a design chart. A family of curves can be generated for productivity over a range of values for the independent variables. Plotting these curves on one chart would allow one of the unknown variables in equation E3 to be estimated, provided values are known for the other three variables (Figure 21).

Figure 21 shows productivity estimated with equation E3 as a function of log volume ranging from 0.2 to 2.2 m^3/log. Curves for productivity were generated for 2 levels of volume per mass (0.0012 and 0.0010 m^3/kg), and 3 levels of horizontal distance (475, 900, and 1330 m). The curves in Figure 21 show that productivity increases with increasing log volume and volume per mass, and decreases with increasing horizontal distance to the landing. It can also be seen that decreasing the horizontal distance increases the slope of the curves. Therefore, increasing the average volume per log or the volume per mass results in a greater increase in productivity at shorter distances.

Figure 21: KMAN-1200 helicopter productivity design chart (Butte timber sale).



The trends in productivity that were demonstrated with equation E3 might not be true outside the range of values found for the independent variables in this study. At some point, depending on the lift capacity of the helicopter, increasing log size may begin to adversely affect productivity. If only large logs are available to the hooktender it can be difficult to divide the mass between the red and white hooks, so if the logs in the white hook are dropped there is still sufficient mass in the red hook to make a turn. Also as noted in section 6.2, if the horizontal distance as compared to the difference in elevation between the unit and the landing, is below some level, the decrease in flight time may become nonlinear.

The following is an example of how Figure 21 may be used. This example is presented to demonstrate the potential value of a design chart for productivity. This design chart is not suitable for predictions in operational settings at this time, because the equations were developed with limited data and have not been tested with other data sets. The scenario description is as follows.

- The breakeven helicopter cost per cubic meter is known to be $\$27.2/m^3$ (an arbitrarily selected value).
- The cost per minute for the KMAN-1200 helicopter is estimated to be \$28.6/min (Sloan 1994).
- The required productivity of the helicopter to break even is,

  $$(\$28.6/\text{min}) / (\$27.2/\text{m}^3) = 1.05\ \text{m}^3/\text{min}.$$

- Assume there were two possible landing locations with horizontal distances to the unit of 475m, or 900 m, and the volume per mass for the unit is estimated to be between 0.0010 and 0.0012 m^3/kg.

Referring to Figure 21 a horizontal dotted line has been plotted at the 1.05 productivity level, where this line intersects the productivity curves vertical lines have been dropped down to the axis representing log volume. From Figure 21 it can be seen for the given volume per mass the required productivity could be maintained using either landing, provided the average log volume is large enough. If the average log volume was less than about 1.4 m^3, then only the nearer landing could be used if the required productivity level was to be attained.

The design chart for helicopter productivity developed in this study was derived from relatively simple equations. The simplicity of the equations is in part a reflection of insensitivity of helicopter logging operations to ground conditions. However, the simplicity of the equations was also dictated by the lack of suitable data. One of the goals for future research should be to determine if there are factors that affect both turn time and turn mass, and that are tied to stand conditions such as the spacing of the logs or reserve trees.

<u>7.0 Comparison of turn time and turn volume predictions</u>

Many equations used to predict helicopter turn time have independent variables that are not specific to the model of helicopter. It is the regression coefficients that are specific to the helicopter and to the operation where the data were collected. If different helicopters and helicopter operations react similarly to factors that affect turn time, then the turn time equations from these operations will be interchangeable. Turn time equations from four different helicopter operations were used to estimate the average turn time for the units in the Butte timber sale (Table 7).

Table 7: Comparison of turn time predictions.

	Butte Timber Sale		**Other Sources**		
	Actual (1998)	**Regression E1 (1998)**	**Krag and Clark (1995)**	**Dykstra (1975)**	**Heinimann (1996)**
Helicopter	KMAX-1200	KMAX-1200 (% difference from actual)	S-64 (% difference from actual)	Vertol (% difference from actual)	KMAX –1200 (% difference from actual)
Turn Time Unit 2 (min)	2.67	2.65 (-1%)	2.32 (-13%)	2.60 (-3%)	2.32 (13%)
Turn Time Unit 3 (min)	3.35	3.42 (2%)	2.90 (-13%)	3.43 (2%)	2.94 (-12%)
Turn Time Unit 4 (min)	2.67	2.48 (-7%)	2.12 (-20%)	2.37 (-11%)	2.35 (-12%)
Turn Time Unit 5 (min)	2.21	2.48 (12%)	2.37 (7%)	2.30 (4%)	2.42 (10%)

In Table 7 the greatest percent error in predicting the average turn time for a unit with equation E1 is 12%. Most of the average turn times predicted with the equations from sources other than the Butte timber sale fall within ±12% error. This suggests there are factors affecting the average turn time that are independent of the harvest treatments and the model of the helicopter.

Heinimann (1996) produced a simple linear equation to predict the average turn volume for a helicopter. Heinemann used the maximum external load of the helicopter as the independent variable, thus this equation can be used to predict the average turn volume for different models of helicopters. The accuracy of this equation will be limited if the volume to mass ratio varies greatly from the operation where the data were originally collected. Refer to Table 8 for a comparison of the predicted turn volumes to the actual average turn volumes from the Butte timber sale units.

Table 8: Comparison of turn volume predictions.

	Butte Timber Sale		**Heinimann**
	Actual (1998)	**Regression E2 (1998)** (% difference from actual)	**(1996)** (% difference from actual)
Turn Volume Unit 2 (m^3)	2.24	2.23* (0%)	2.06 (-8%)
Turn Volume Unit 3 (m^3)	1.95	1.80 (-8%)	2.06 (6%)
Turn Volume Unit 4 (m^3)	2.40	2.32 (-3%)	2.06 (-14%)
Turn Volume Unit 5 (m^3)	2.57	2.59 (1%)	2.06 (-20%)

* Turn volume to mass data were not available for unit 2; therefore, the volume to mass ratio from unit 4 and the unit 2 flight record data for log size were substituted.

In units 3, 4, and 5 the volume to mass ratios were respectively 0.00097 m^3/kg, 0.00114 m^3/kg, and 0.00124 m^3/kg. The percent error in the turn volume estimates using Heinimann's equation increases with the increasing reduction in the volume to mass ratio. Heinimann could have avoided this problem by using turn mass as the dependent variable, allowing for on site conversion of turn mass to turn volume.

This suggests that turn time is relatively insensitive to the model of the helicopter, timber types, and to the harvesting treatments. The turn volume predictions were dependent on the model of helicopter used and on the volume to mass ratio of the turns. Future research should concentrate on developing equations to predict turn volume. These equations need to include independent variables that represent the lift capacity of the helicopter, and the volume to mass ratios of the turns.

8.0 Discussion

This study did not show a strong correlation between turn time and turn mass, though this may not always be true. In order to reduce damage to the residual trees in unit 3, the hooktenders began to alter their criteria for selecting logs to include in a turn. If the level of dispersed retention is increased, the spacing of the reserve trees may become a common factor that reduces turn mass and increases turn time. The distance between the reserve trees that affects helicopter productivity would depend on the average turn size the operation was attempting to maintain, the size of the logs, and the distance between the logs.

Equation E3 shows the factors that increase turn volume or decrease turn time will increase productivity. Some factors that a logging manager may have control over are as follows.

- Helicopter size: Increasing the lift capacity of the helicopter will allow the manager to increase the turn size. However, a larger turn may cover more area, create more hang-ups resulting in longer turn times, particularly in high retention treatments.
- Bucking strategy: The manager could choose to buck finished log lengths in the woods in order to reduce congestion in the landing, though this may reduce log volume and helicopter productivity. The wood could also be left long with the objective of increasing log volume and helicopter productivity. However, the longer logs may create more hang-ups, increasing turn time, reducing productivity, and possibly causing more damage to the reserve trees.
- Landing location: The increase in productivity from reducing turn time by building landings closer to the cut blocks may offset the increased development costs. However, if the landing is below the threshold distance where the difference in

elevation limits turn time, then the increase in development cost will not be offset by increased productivity.

The use of Global Positioning Systems (GPS) as suggested by Heinimann (1996) to collect data for helicopter velocity and acceleration, would allow a detailed study of the effects that horizontal and vertical distance have on turn time.

More detailed sampling is required to examine the spatial relationship that the logs in a turn and the reserves trees have with respect to changes in helicopter productivity. In this study the detailed sampling of in-unit turn time, and turn volume and turn mass were conducted separately. What is required is a comprehensive sampling method that includes:

- in-unit and out-of-unit timing elements,
- the scale and mass of the logs in the turn,
- the length of the major and minor axis of the area covered by the turn,
- the number of obstacles (such as reserve trees) within the area covered by the turn, and
- the cause of delays such as hooktenders setting turns with hung-up logs.

To obtain a comprehensive data set such as this would be expensive, and thus it may not be possible to gain sufficient data to construct reliable productivity design charts over a range of conditions. An alternative method would be to develop a spatial simulation model that could predict turn size and turn time. This model could not be completely deterministic since some factors that affect helicopter productivity occur by chance. The model would have to rely on stochastic inputs to estimate events such as delays from logs hanging-up. If the simulation model could account for the spatial attributes in an operation, then detailed sampling would be required only for those elements that can not be solved deterministically, and for confirming the results of the model.

8.0 Conclusions

This study found that different levels and patterns of retention did not have a dramatic effect on total turn time or turn mass. The flight distance to the unit from the landing had the greatest effect on the total turn time, while delays from sources such as choker drops and aborted turns had a relatively small effect on the average turn time. Turn time was found to be weakly correlated to turn mass and the number of logs per turn, and turn mass was weakly correlated to the number of logs per turn. The lifting function was the only in-unit timing element found to have a frequency distribution with a relatively wide range. Thus, much of the within unit variation in total in-unit turn time, for turns without aborts or choker drops, is assumed to be a result of the lifting function. In the four units sampled the average turn masses were similar, and this indicates the hooktenders were able to compensate for the changing conditions in these units.

Production equations were developed to estimate turn time and turn volume in order to calculate helicopter productivity. The turn time equation estimates only the actual flight time of the helicopter while logging. Down time due to weather, mechanical breakdowns, or scheduled maintenance is not included in the estimate of turn time. The turn time equation is a simple linear function with the horizontal distance from the landing to the unit as the independent variable. The turn volume equation is a multiple linear function with the average volume per log and the volume per mass of the timber as the independent variables. Note that volume per mass is not just the inverse of the density of the wood, it also includes the mass of the tagline, hook, chokers, and waste.

A design chart for helicopter productivity was developed as a function of log volume, horizontal distance, and volume per mass. This chart was produced to illustrate trends in productivity when varying the independent variables. The design chart appears to be a useful way to present these relationships and producing a reliable chart for operational use may be a goal for future research. Future research should include a comprehensive sampling plan that collects both stochastic data and spatial data. There should be a concerted effort to determine if there is a factor that links turn volume and turn time, as this may become more important at higher levels of retention.

This harvesting study was part of a research project with much broader objectives than just harvesting costs. This created confounding effects in addition to those commonly found when the researcher has no direct control over the harvesting operation. The analysis of between treatment variation was limited by not having replication of the treatments in each unit. The variation in the initial stand conditions and the distance of the units to the landing confounded much of the between unit variation. In general, two units were active and being flown to the same landing at any given time and this resulted in the loss of unit identity for the wood and the actual scale of the logs being flown from the units. Also, the requirement to leave the tops of the trees attached to the logs combined with variation in stand conditions, made it difficult to estimate the merchantable volume of timber from the turn mass in the flight records.

In future studies, an initial commitment to detailed field measurements by research staff may limit many of the problems experienced in collecting and analyzing data in this study. This would allow the development of sampling procedures that could collect the required information for the attributes of interest in the study. Since the research staff would be collecting the data, much of the uncertainty in the quality and completeness of the data would be eliminated. This study proposed some potential independent variables for describing helicopter productivity, and presented a possible format for using these in an operational design chart. However, more research is required to identify all the variables needed to predict productivity accurately.

9.0 References

Bluman, Allan G. 1995. *Elementary Statistics A Step by Step Approach, second edition*. Wm. C. Brown Publishers, Dubuque, Iowa. 684 p.

Curtis, Richard. 1978. *Production rates of skyline, balloon and helicopter yarding systems from gross time study analysis*. O.S.U., School of Forestry, (Cited by J. C. Halkett, 1982).

Dykstra, P. Dennis. 1975. *Production Rates and Costs for Cable, Balloon, and Helicopter Yarding Systems in Old-Growth Douglas-fir*, Research Bulletin 18, Forest Research Laboratory, School of Forestry, Oregon State University, Corvallis, Oregon. 57 p.

Halkett, J.C. 1982. *Helicopter Logging a Review*, N.Z Logging Industry Research Association, Project Report No.17. 44 p.

Heinimann, Hans. 1996. *Helicopter Logging in Switzerland, Analysis of Selective Logging Operations*, 9th Pacific Northwest Skyline Symposium, Campbell River, May 1996, FERIC, Vancouver, Canada. pp. 45-50.

Krag R.K., and Clark Marvin. 1995. *Helicopter Logging in Clearcut, Patch-Cut, and Single-Tree Selection Harvests: Queen Charlotte Islands, British Columbia*, IUFRO Subject Group 3.06, Forest Operations Under Mountainous Conditions, Tampere, Finland. pp. 54 – 72.

Microsoft Corporation. 1994. *Visual Basic® User's Guide*, Microsoft Corporation, United States of America. 344 p.

Saunders, George. 1975. *Dynamics of Helicopter Flight*, John Wiley and Sons, inc., New York. 304 p.

Shapiro, Jacob. 1955. *Principles of Helicopter Engineering*, Temple Press Limited, London.

Sloan, Hank, John Tollenaere, and Chris Croff. 1994. *Technology Advances in Helilogging: A Case Study of The K-MAX In Appalachian Hardwoods*, Proceedings Advanced technology in forest operations: applied ecology in action, Council In Forest Engineering, Portland. pp. 237-245.

Sloan, Hank, and Jim Sherar. 1997. *Hurricane Fran Helicopter Salvage Case Study*, Forests for sustainable forestry and a healthy economy, Council In Forest Engineering, Rapid City, South Dakota. pp. 107-113.

Tompkins, Ed. 1996. *Integrated Resource Prescription Butte DEMO Timber Sale*, US Forest Service, Gifford Pinchot National Forest, Randle Ranger District, (Internal report). 25 p.

USDA Forest Service, DEMO. 1996. *A Study of Green-Tree Retention Levels and Patterns in Western Oregon and Washington (draft)*, Gifford Pinchot and Umpqua National Forests, US Forest Service, (Internal report). 34 p.