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Rigging Configurations Efficiency Case Studies

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EXECUTIVE SUMMARY

The primary goal of the Future Forests Research (FFR) harvesting programme is to reduce costs and improve worker safety in steep land harvesting by increasing the productivity and efficiency of these operations. There are many different ways to achieve this goal including new equipment and work methods, but cable logging contractors often use the systems and techniques with which they are most comfortable or experienced. Few previous studies have measured the differences in productivity between various cable rigging configurations, and even less is known about the skyline tension behaviour and the operational efficiency of these configurations. Improving the logging industry’s understanding of the different cable rigging configurations by way of comparing their associated operational efficiency is essential for improving the productivity and cost effectiveness of cable logging.

In this project different cable rigging configurations were evaluated and compared in terms of the different measures of operational efficiency, such as productivity, skyline tension efficiency and payload efficiency. The three targeted rigging configurations were North Bend (as the most commonly used New Zealand rigging configuration), standing skyline using a motorised slack pulling carriage (as a modern rigging configuration with potential to increase productivity), and a live skyline using a motorised grapple carriage (a configuration to fully mechanise cable extraction). Eight studies were conducted of targeted logging operations where relevant stand and terrain parameters were related to measured productivity and continuous skyline tension monitoring.

Results showed that cycle times were significantly different between rigging configurations and that production information could be used to compute measures of labour and energy consumption. Measurement of dynamic tensions showed that peak and average tensions, as well as amplification factors and the payload-to-tension relationship varied between configurations. The safe working load of the skyline cable was exceeded in seven of the eight study sites, across 14 of the 16 spans measured and in 53% of all cycles recorded. The tension monitoring data collected could be used to compute measures of payload and tension efficiency, which provided insight into operational performance.

The New Zealand logging industry should give serious consideration to the operational measurement of skyline cable tension using tension monitors. Tension monitors have many potential benefits to improve cable logging operations. Monitoring tensions can help contractors and yarder operators to adopt more appropriate rigging configurations and to learn new techniques, validate results of payload analysis software, and help evaluate new technology and machinery.

INTRODUCTION

The New Zealand forestry sector, supported by the New Zealand Government through the Primary Growth Partnership, has identified improving cost-effectiveness of steep country harvesting as the key to achieving greater profitability in forestry (FFR 2010). Steep country forests already contribute more than 40% of New Zealand's annual log harvest, and this is forecast to rise to over 60% in coming years (Raymond 2012). If New Zealand is to remain competitive in international log markets, then improvements in cable logging operations in terms of production and safety will be necessary. The primary goal of the Future Forests Research (FFR) Steep Land Harvesting Programme is to realise substantial gains in productivity and reduce the cost of harvesting on steep country. In cable logging planning, one of the most important issues affecting productivity is determining the maximum log load (payload) and the resulting tension in the skyline in relation to the terrain and the defined constraints of the cable dimensions and carriage weight. Tensions in the skyline must be within allowable limits when the carriage is loaded with logs, to avoid excessive cable wear and possible skyline failure.

Skyline analysis techniques have been available for over four decades for determining the maximum payload in standing skylines (e.g. Carson and Mann, 1971; Carson, 1976; Falk, 1981; Woodruff, 1984; Kendrick, 1992; Jarmer and Sessions 1992) but little effort has been directed towards field measurements of skyline tension, so that knowledge about the increases in cable tension due to the load in single span cable yarders is still limited in New Zealand.

In this project, entitled Rigging Configurations Efficiency, in order to better understand cable logging operations, a survey was carried out in 2010 to establish the use and knowledge of different cable logging rigging configurations in New Zealand (Harrill and Visser, 2011). In 2011 a panel of New Zealand cable logging experts was formed to determine the advantages and disadvantages of different rigging configurations (Harrill and Visser, 2012). Further work in 2012 then used a model yarder to demonstrate dynamic tension behaviour between configurations (Harrill and Visser, 2013). In 2013 a comprehensive review of the existing body of cable logging literature was undertaken to provide information on the development of cable logging systems and previous research (Harrill and Visser, 2014).

This review found that there was little information relating to which rigging configurations are more productive or safer under various stand and terrain conditions. There is limited knowledge of the dynamic forces generated during cable logging, and how static and dynamic forces differ between various rigging configurations.

Further work, described in this report, is aimed at improving the operational efficiency of cable logging operations in New Zealand. The project evaluated eight different cable logging operations using three different cable rigging configurations in terms of productivity and continuous skyline tension monitoring under various stand and terrain conditions, and developed some measures of operational efficiency. The full text of this Doctorate of Philosophy in Forest Engineering thesis is available online at: http://ir.canterbury.ac.nz/bitstream/10092/9923/1/thesis_fulltext.pdf (Harrill, 2014).

Rigging Configurations

Cable logging methods are defined by the skyline system which is being used. There are four main types of cable systems: Highlead (no skyline), Standing Skyline, Live Skyline and Running Skyline. The cable logging method is further defined by the rigging configuration. A rigging configuration refers to the combination of rigging (blocks, ropes and carriage type) being used (Figure 1).

There are about ten different rigging configurations which can be used, and some are more preferred than others in a given location (Liley 1983; Studier and Binkley 1974). Deciding which rigging configuration to use can be challenging and is usually based on the available equipment and the stand and terrain conditions, but often depends on the experience and preference of the crew. A survey of the New Zealand logging industry in 2011 found a dependence on three non-carriage based rigging configurations – North Bend, Grabinski ("scab skyline"), and gravity return or "Shotgun" (Harrill and Visser 2012). Improving cable logging practitioners' understanding of the different rigging configurations and the optimal application of each one may help improve profitability. Comparing the associated operational efficiency of each rigging configuration may help in the training of crews, planning, implementation and cost effectiveness of cable logging (Samset 1985).

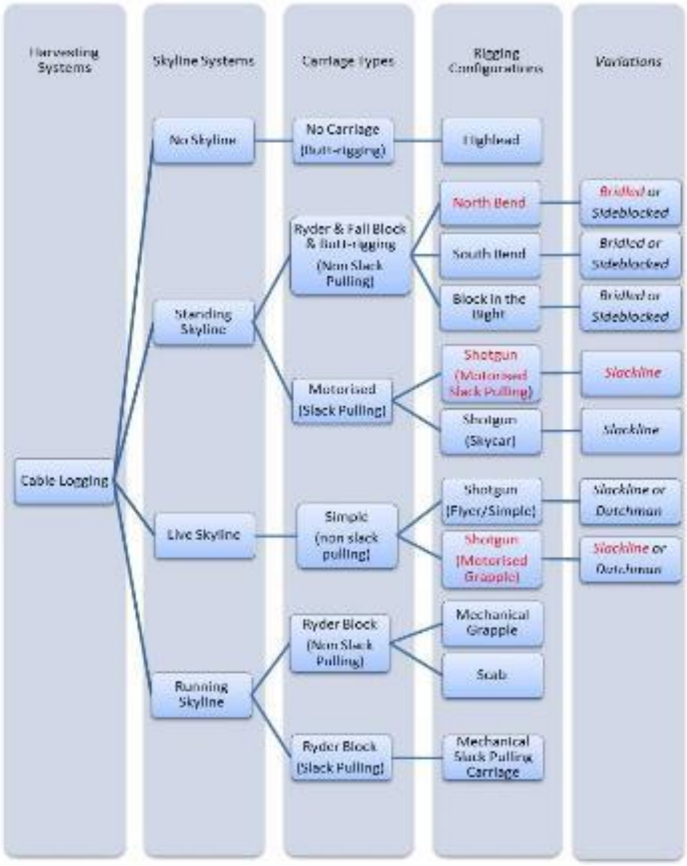

Figure 1: Rigging configurations used in New Zealand cable logging operations

Targeted case studies in this project (highlighted in red in Figure 1) included the following rigging configurations:

(1) North Bend (as the most commonly used New Zealand rigging configuration);

(2) standing skyline with motorised slack pulling carriage (a modern carriage type with potential to increase productivity); and

(3) live skyline with motorised grapple carriage (an option to fully mechanise cable extraction).

Efficiency

Efficiency can most simply be defined as a ratio of total inputs used to total outputs produced. In the early 1920s, efficiency was first applied to forestry with the introduction of the concept of "control," adopted from industrial engineering processes (Silversides and Sundberg 1987). Practitioners were trying to benchmark costs and production data with the aim of identifying inefficiencies.

Control in forest operations, including cost control, deals with a much larger area than accounting and is concerned with improved operations, future planning and conservation of resources. Production data are essential, and normally the relations between inputs and outputs are shown in pure physical terms, in contrast to cost and price data which show economic relations only. These measured relations of inputs and outputs dictate the level of control over an operation and are known as measures of operational efficiency. Operational efficiency aims to economize human or man-made inputs, or to allocate labour and machines in a rational fashion (Silversides and Sundberg 1987).

For many years mechanisation has been the most preferred and successful way of achieving operational efficiency in forestry. Mechanisation of operations significantly increases productivity and capacity, while decreasing the requirement for labour. However, along the years of development there were periods where profitability reduced to an extent where a new method or machine was developed, requiring a step change in the harvesting process.

Nominal costs of any logging operation will always increase over time, and increasing costs erode profitability. The only way to decrease the operational costs is to introduce new methods (techniques), a new organization of the work (planning), or by introducing new equipment (Samset 1985).

The international trend and driver to forest harvesting research, technology and machine development has been to increase efficiency. Better understanding of the capabilities and limitations of present methods (i.e. rigging configurations) and machinery and how to optimize these will lead to improved production and economic viability of these systems. Furthermore, a better understanding of these systems permits more precise and effective planning for future operations, which is paramount for reduced infrastructure cost, minimised environmental disturbance and improved operational safety.

Productivity

Cable logging productivity is often the single most important metric used to describe, evaluate or select an appropriate rigging configuration. Productivity is expressed as volume (m^3) or tonnes produced per unit of time. Therefore production, being the denominator in the equation of cost per unit volume ($/$m^3$), plays an important role in the overall economics of a logging operation; hence the importance of quantifying the productive potential of new equipment and methods (Dykstra 1975, 1976).

Cost effectiveness is generally improved by either decreasing the associated input costs (such as labour or equipment), or increasing production outputs. Interest in improving cost effectiveness in recent years has led to innovation in terms of new equipment and technology developments in the New Zealand forest industry (Visser *et al.* 2014). This study targeted a motorised slack pulling carriage (Acme carriage) and a new motorised grapple carriage (Falcon Forestry Claw) as two carriage types with potential to improve productivity and cost effectiveness. A grapple carriage is also an option to fully mechanise cable extraction and increase productivity.

Rates of production are however very difficult to compare between cable logging operations, because conditions are often highly variable between and within harvesting sites. This problem is compounded by the variety of cable yarders and rigging configurations used. In the past some studies examining productivity of cable logging operations aimed to compare different rigging configurations, especially in similar working conditions, such as Dykstra (1975), Dykstra (1976), Kellogg (1987) and Forrester (1995). Each comparative study found that a variety of rigging configurations were practical and while one particular configuration was most productive under the conditions studied in the logging operation, conditions may change on a monthly, daily or even an hourly basis, and so does the productivity of each configuration.

Continued research into the relative efficiencies of rigging configurations is essential if the capabilities and utility of these cable systems are to advance. Other measures of efficiency, aside from productivity, were examined in this project.

Tension Monitoring

Most of the previous cable tensions research has been summarised in the recent literature review by Harrill and Visser (2014). Dynamic cable tension monitoring has been described by Carson and Jorgensen (1978) and Pyles (1988), noting that static tensions are rarely corroborated in real operations. Alternative ways that dynamic tensions could be recorded and how to model them have been identified (Carson *et al.* 1982; Kroneberger-Stanton and Hartsough 1992; Lyons 1997; Pyles *et al.* 1994; Womack 1994). The behaviour of some logging systems has been investigated by Visser (1998) and Miles *et al.* (1993), and tension monitors were found to provide results and benefits to contractors (Hartsough 1993; Smith 1992). As such, most cable tensions research was related to guy lines rather than working ropes, and none aimed to compare tensions between rigging configurations.

There is a gap in knowledge as to when or why safe working loads are exceeded during logging operations. There is limited understanding of the dynamic forces generated during logging, and whether static or dynamic forces differ between various rigging configurations. This project aimed to measure the dynamic skyline tensions of the three targeted rigging configurations in a series of case studies.

METHOD

Objectives

This project aimed to provide an analysis of the application of several rigging configurations employed in New Zealand cable logging operations, including their productivity and skyline tensions. The study was designed so that operating conditions were kept as similar as possible between study sites to allow a fair comparison of the configurations studied. The objectives of the study were to:

1. Establish cycle times, payloads and hence productivity for a selected set of rigging configurations.
2. Determine which variables affect the cycle times of rigging configurations.
3. Compare and contrast the differences in production, delays, labour and energy.
4. Quantify the skyline tensions for each rigging configuration.
5. Determine which variables affect the tensions of rigging configurations.
6. Compare and contrast the differences in the payload-to-tension relationship, dynamic load behavior (amplifications) and other performance characteristics.
7. Identify further research needs in determining the efficiency of cable logging operations.

Study Sites

A total of eight different cable logging operations were studied in both North and South Island between August, 2013 and February, 2014. The operations were conducted on privately owned, steep terrain forest plantations, representative of typical New Zealand conditions. Each study site was motor-manually felled prior to the start of operations, and mature (approximately 25 to 30 years old) tree length radiata pine (*Pinus radiata)* was extracted, with the exception of Study 7 where Douglas fir (*Pseudotsuga menziesii*) was harvested. All operations studied utilised either a live or standing skyline system, and all employed a bulldozer as a mobile tail hold machine (Table 1).

Table 1: Summary of observed study sites and yarding corridor details

Study Site	Region	Yarder	Yarding System	Configurations	Span (m)	Chord Slope (%	Deflection (%)	Avg. Yarding Dist. (m)	Piece Size (m³)
1	Canterbury	Madill 171	Live Skyline	Falcon Slackline	345	-26	6.1	249	1.6
					352	-27	5.9	185	
					364	-27	7.4	244	
2	Nelson	Madill 171	Live Skyline	Falcon Shotgun	316	-47	5.7	221	1.4
					338	-46	5.8	229	
3	Gisborne	BE-85	Standing Skyline	North Bend	940	-14	5.2	280	2.4
				North Bend Bridled	920	-14	5.1	124	
4	Gisborne	Madill 172	Standing Skyline	Acme S28 Slackline	335	-17	4.2	181	2.1
					330	-18	6.1	278	
5	Nelson	Berger C19	Live Skyline	Falcon Shotgun	602	-30	6.1	184	1.6
6	Marlborough	Dispatch-85	Standing Skyline	North Bend Bridled	1100	-43	3.8	311	2.4
7	Nelson	BE-70LT	Standing Skyline	North Bend	395	0	8.4	337	1.2
					398	1	10.1	248	
8	Otago	Madill 071	Standing Skyline	Acme S28 Slackline	284	-20	6.9	230	1.5
				Acme S28 Slackline	296	-21	6.2	191	
				Acme S28 Shotgun	354	-23	6.2	145	

Table 2 provides an overview of both the yarder and carriage specifications used at the sites, with the Madill 171 used at two different locations. All the yarder machines were classed as large tower yarders (>21m tower height) with 1 1/8th inch (28mm) skyline with the exception of the Madill 071, which is a medium sized machine, with a 14m tower running 1 inch (25mm) skyline.

Table 2: Specifications of the cable yarders and carriages in the operations studied

Yarder Model	Madill 171	BE-85	Madill 172	Berger C19	Dispatch-85	BE-70LT	Madill 071
Rated Engine Power (kW)	335	335	335	391	335	335	212
Tower Height (m)	22	26	22	22	26	21	14
Skyline Diameter (mm)	28.7	28.7	28.7	28.7	28.7	28.7	25.5
Skyline Safe Work Load (tonnes)	21.3	21.3	21.3	21.3	21.3	21.3	18.6
Mainline Diameter (mm)	22.3	19.1	19.1	22.3	25.5	19.1	19.1
Haulback Diameter (mm)	19.1	17.5	19.1	19.1	19.1	17.5	15.9
Carriage Type	Falcon	Fall Block	Acme S28	Falcon	Fall Block	FallBlock	Acme S28
Carriage Weight (kg)	2,200	1,000	860	2,200	1,000	1,000	860
Carriage Engine Power (kW)	43	0	21	43	0	0	21

Each operation was the subject of a short study (one to two days) during normal work operations. The aim of each study was to record detailed information for a minimum of 30 yarding cycles using one or more rigging configurations. Other parts of each cable logging operation such as log processing, loading and trucking were outside the scope of the project.

Rigging Configurations Studied

Cable logging operations observed in this project comprised two skyline systems (live skyline and standing skyline) using three rigging configurations (North Bend, motorised slack pulling carriage, and motorised grapple carriage), with two variations of each treated as separate configurations.

North Bend

North Bend is the most commonly used configuration in New Zealand (Harrill and Visser 2011). It is a simple system in that it does not require a sophisticated yarder, and non-powered carriages can be used. The configuration is classified as a standing skyline system, and requires a skyline, mainline, and haul back line (Studier and Binkley 1974). The configuration is unique in that it uses a fall block that the mainline passes through to generate lift, through tensioning the haul back and the mainline simultaneously (Figure 2).

The main advantage of this configuration is that it is very simple and easy to operate. In addition it has some versatility in different terrain and settings, and can even yard logs lateral to the skyline through a slight variation of the configuration called North Bend Bridled. In this case, to achieve lateral yarding, the haul back blocks are offset perpendicular to the skyline rather than directly under it.

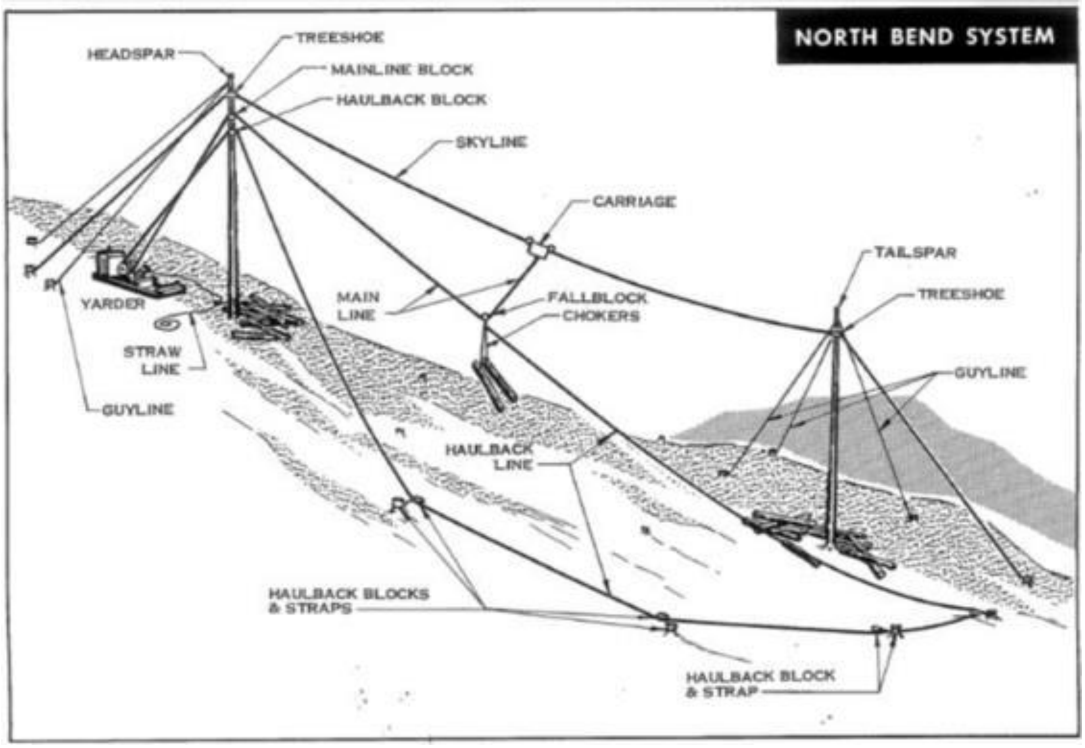

Figure 2: Standing skyline operating the North Bend rigging configuration (Studier and Binkley 1974)

Motorised Slack Pulling Carriage

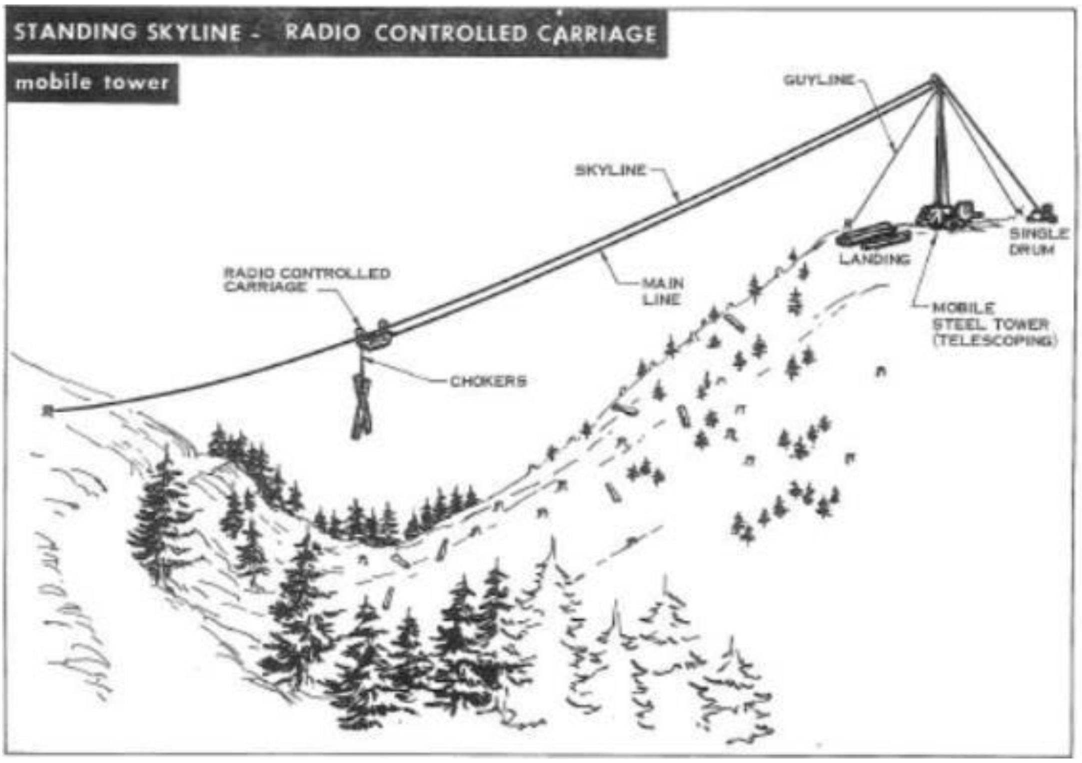

Figure 3: Standing skyline with radio-controlled motorised carriage in shotgun configuration (Studier and Binkley 1974)

The motorised carriage is usually operated as a standing skyline system, and can be operated either in the Shotgun or Slackline configuration. In the Shotgun configuration, the carriage is returned along the skyline (outhaul) by gravity, and the mainline is used to pull the carriage and payload back to the landing (Figure 3). Where the chord slope of the skyline is not adequate for Shotgun (< 20% slope) or the logs must be pulled from the back face (opposing side) of a valley, the carriage must be used in the Slackline configuration. In this configuration the haul back line is attached to the back of the carriage to facilitate outhaul.

Until recently motorised carriages were not a popular rigging configuration in New Zealand (as found in the 2011 survey), but are gaining popularity due to their versatility in a wide range of operating conditions (Harrill and Visser 2012). A motorised slack pulling carriage has an internal motor used to pull the mainline through the carriage, so that the breaker-outs can easily carry the cable and chokers to the logs. One of the main advantages is that it is very good at lateral yarding due to its slack pulling capability and control when extracting logs. The disadvantage of the motorised carriage compared to North Bend carriage is the high associated cost (capital and operating costs), and the risk of damaging the carriage if it collides with the ground or logs. The motorised carriages in this study were all Acme model S28 carriages, and are referred to as Acme.

Motorised Grapple Carriage

Mechanical grapple carriages are not widely used in New Zealand except on swing yarders which employ a running skyline system (Harrill and Visser 2012). The grapple is opened and closed by altering the lengths of the three cables used in the running skyline system. When mechanical grapples are used they have been found to be productive and cost effective, since they do not require choker-setters to attach chokers to logs, but they are limited to short distances of less than about 200 m (Studier and Binkley 1974).

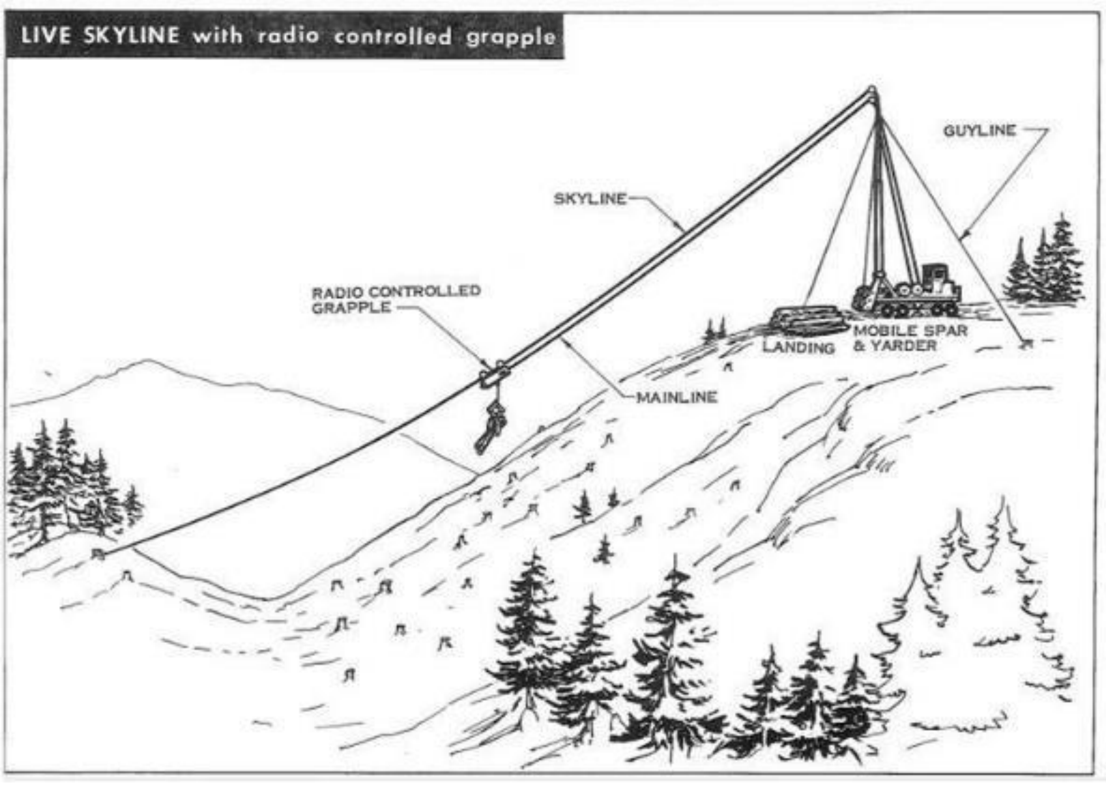

Figure 4: Live skyline with radio-controlled motorised grapple carriage in shotgun configuration (Studier and Binkley 1974)

One recent New Zealand grapple innovation is the Falcon Forestry Claw motorised grapple carriage, referred to in this report as Falcon. This carriage has an internal motor which opens, closes and rotates the grapple. This type of carriage simplifies the cables required as they do not need to control the grapple, and makes the concept of grappling extendable to a wide range of yarders over extended haul distances. Since the motorised grapple configuration does not have the ability to pull slack, it must be employed on a live skyline system, where the skyline is raised and lowered during each cycle to reach the logs on the ground. Just like the other motorised carriages (such as Acme) it can be operated in the Shotgun configuration (Figure 4) or Slackline configuration. While this versatility is an advantage, it has the same disadvantages as the motorised slack pulling carriage in its high capital cost (approximately NZ$130,000) and operating cost, and the risk of damaging the carriage if it collides with the ground or logs.

Data Collection

Shift level information was collected by researchers on site, including start and stop time, as well as all delays over 10 minutes in duration. Relevant crew information such as the number of crew members and their job role was recorded. The make, model and wire rope specifications of the yarder used was obtained from the logging crew. In addition, the carriage type or butt rigging and its weight were also obtained from the crew. The yarding corridors and profiles were established by recording the position and elevation of the yarder and the corresponding tail hold using a GPS unit. An additional GPS unit, which provided more detailed information on the carriage position during the hauler cycle, was mounted to each carriage at study sites 2-8. The slope from yarder to tail hold, orientation, and slope length were measured using an inclinometer, compass, and laser range finder respectively.

Time study techniques were conducted to capture minor delays and to estimate the average delay-free cycle time based on the following observed elements:

Outhaul: *Begins when the carriage moves away from the landing empty towards the cutover; and ends when the carriage stops along the skyline in preparation for the hook phase.*

Hook: *Begins when the carriage stops along the skyline after outhaul; and ends either when the carriage grapples a stem or when stems are hooked by breaker-outs (choker-setters), and the load starts to move along the skyline back towards the landing.*

Inhaul: *Begins when the carriage moves loaded towards the landing from the cutover; and ends when the carriage stops at the landing in preparation for the unhook phase.*

Unhook: *Begins when the carriage stops on return to the landing and drops the payload; and ends when the carriage moves away from the landing towards the cutover, marking the start of the outhaul phase.*

In addition to the dependent variable of delay-free cycle time, the following independent variables and factors expected to influence the cycle time elements were also recorded:

Span: *The horizontal distance (in metres) from the yarder tower to the tail hold.*

Chord Slope: *The slope of the skyline (expressed in percent) from the yarder's skyline fairlead to where the skyline is connected to the tail hold.*

Deflection: *The amount of sag in the skyline measured at mid-span and expressed as a percentage of the total span length.*

Configuration: *The rigging configuration employed by the yarding crew: North Bend, North Bend Bridled, Acme Shotgun, Acme Slackline, Falcon Shotgun, or Falcon Slackline.*

Breakerouts: *The number of breaker-outs (choker-setters) employed.*

Chokers: *The number of chokers attached to the rigging or carriage.*

Chasers: *Whether or not a chaser (poleman) was employed to unhook chokers; (0= none/electronic chokers, 1= chaser unhooks chokers)*

Distance: *The yarding distance (in metres) measured from where the stems are hooked to the landing.*

Pieces: *The number of pieces yarded each cycle.*

Cycle Volume: *The total volume extracted per cycle (in cubic metres) measured by the researcher at the landing.*

Piece Size: *The average volume of pieces yarded = CycVol/Pieces.*

During the time study one researcher recorded the cycle elements by stop watch, while noting their associated factors and independent variables. The same researcher was also responsible for the setup of tension monitoring and video recording of operations. Video was captured by mounting a GoPro digital camera in the cutover on or near the anchor machine. The number of pieces per cycle and their type (stem, log, or top), their corresponding diameters (cm), length (m), and time of arrival were all recorded on the landing by a second researcher. The second researcher was also responsible for the setup and collection of the carriage-mounted GPS data.

Data Analysis

The recorded data were synchronized by clock time and then entered and analysed in Microsoft Excel 2010[1], with statistical analysis performed in Minitab[2]. The data were screened for normality and outliers were removed before being used to produce generalized linear models predicting delay-free cycle time. The cycle volumes measured were matched to their corresponding cycle by time of arrival to the landing, and used in conjunction with the cycle time to calculate productivity (m^3/PMH). Labour and energy consumption were calculated by dividing the total number of workers and total power (in kW) of machinery, respectively, by the calculated productivity.

The GPS points from recording the position of the yarder and the corresponding tail hold for each yarding corridor were loaded into ArcMap 10.1[3] GIS software, in which the Skyline XL[4] program add-in tool was used to measure the distance and elevation along each corridor, to create a profile. The computer drawn profile was then exported to Skyline XL for payload analysis of the standing or live skyline system using the corresponding yarder and carriage combination. Each yarder and carriage combination was customised to match the specifications of the actual machines on site, in terms of tower height, yarder power (kW), rope sizes and carriage weight.

[1] Microsoft Excel Version 14.0.7109.500. Microsoft Corp., Redmond, Washington, USA
[2] Minitab Version 16.2. Minitab Inc., State College, PA, USA
[3] ArcMap Version 10.1. Environmental Systems Research Institute. Redlands, CA, USA
[4] SkylineXL Version 14.0, USDA Forest Service Research and Technology Development Center. San Dimas, CA, USA

RESULTS

Production Measurement

Cycle and Element Times

Table 3 presents a summary of the data collected at each of the eight sites. Subsequently, the data set is combined and analysed with regard to productivity. The detailed results of cycle time and productivity measurement and skyline tension analysis for each study site are presented in Appendices to this report.

Table 3: Summary of observed cycle times, cycle volume and productivity of the operations studied

Study	Rigging Configuration	No. Cycles	Cycle Time (min)	Cycle Volume (m^3)	Productivity (m^3/PMH)
1	Falcon Slackline	54	2.93	2.23	46.5
2	Falcon Shotgun	31	2.20	2.09	56.8
3	North Bend and North Bend Bridled	19	9.60	6.50	45.5
4	Acme S28 Slackline	22	7.44	6.00	48.8
5	Falcon Shotgun	34	2.84	2.20	47.7
6	North Bend Bridled	34	9.26	4.70	32.2
7	North Bend	23	7.70	5.40	43.9
8	Acme S28 Slackline and Shotgun	42	5.57	3.20	36.1

The results from each study site were then combined to create a database of cycle times by rigging configuration. The average cycle times and element times as a percentage of cycle time are summarised in Table 4. The Falcon Shotgun configuration had the shortest average delay-free cycle time of 2.54 minutes, with 38% of its cycle consumed by the inhaul element (0.97 minutes). The North Bend Bridled configuration had the longest average delay-free cycle time of 8.96 minutes, with 43% of total cycle consumed by the hook element (3.87 minutes).

Table 4: Average element times and percentage of productive time for each element

	North Bend		North Bend Bridled		Acme Shotgun		Acme Slackline		Falcon Shotgun		Falcon Slackline	
Cycle Element	**(min)**	**%**	**(min)**	**%**	**(min)**	**%**	**(min)**	**%**	**(min)**	**%**	**(min)**	**%**
Outhaul	1.06	13	1.32	15	0.28	6	0.61	9	0.41	16	0.54	18
Hook	3.35	42	3.87	43	3.01	59	3.76	57	0.84	33	1.18	40
Inhaul	1.91	24	2.42	27	1.31	26	1.63	25	0.97	38	1.08	37
Unhook	1.67	21	1.35	15	0.49	10	0.55	8	0.31	12	0.14	5
Delay-Free Cycle Time	7.99		8.96		5.10		6.55		2.54		2.93	

There are some general characteristics that can be highlighted from these results:

1. The variations of each configuration (e.g. Shotgun & Slackline for both the Acme and Falcon carriages) performed very similarly in comparison to other configurations (such as North Bend and North Bend Bridled).
2. The shotgun configuration, for both the Acme and Falcon carriages, had a comparatively shorter outhaul time and total cycle time than the Slackline configuration using the same carriage.
3. The configurations using the Falcon grapple carriage had the quickest hook element (0.84-1.18 min) compared to other configurations (3.01-3.87 min) as they did not require logs to be attached by chokers.
4. Unhook times were longest when a poleman or chaser (person to unhook chokers) was required as observed during the North Bend and North Bend Bridled operations (1.67 minutes & 1.35 minutes respectively), as compared to the self-releasing chokers used in the Acme Shotgun and Acme Slackline operations (0.49 minutes and 0.55 minutes, respectively). The unhook times for

the grapple carriage operations, as observed in the Falcon Slackline and Falcon Shotgun configurations, were the quickest (0.14 minutes and 0.31 minutes, respectively).

Element Time Regression Analysis

In order to determine how site conditions affected productive cycle time of each configuration, regression analysis was performed using the measured variables from each cycle. The range of these values recorded during the time study and their averages are summarised in Table 5. Differences between the configurations can be noted, such as the average haul distance and cycle volume which explains some of the differences in cycle time and production rates.

Table 5: Representative values of the variables recorded for each configuration during the study

Independent Variables		North Bend	North Bend Bridled	Acme Shotgun	Acme Slackline	Falcon Shotgun	Falcon Slackline
Span (m)	Min	395	920	354	284	338	345
	Max	940	1100	354	335	602	364
	Average	577.8	1080.5	354.0	308.8	480.8	353.3
Chord Slope (%)	Min	-14	-43	-23	-21	-47	-27
	Max	1	-14	-23	-17	-30	-26
	Average	-4.3	-39.9	-23.0	-19.4	-37.9	-26.7
Deflection (%)	Min	5.2	3.8	6.2	4.2	5.7	5.9
	Max	10.1	5.1	6.2	6.9	6.05	7.4
	Average	8.0	3.9	6.2	6.1	5.9	6.3
Breakerouts (# men)	Min	2	2	2	1	0	0
	Max	3	3	2	4	0	0
	Average	2.5	2.1	2.0	2.5	0.0	0.0
Chokers (# in use)	Min	3	2	2	2	0	0
	Max	3	3	2	3	0	0
	Average	3.0	2.3	2.0	2.4	0.0	0.0
Chasers (# men)	Min	1	1	0	0	0	0
	Max	1	1	0	0	0	0
	Average	1	1	0	0	0	0
Distance (m)	Min	195	100	122	155	118	94
	Max	374	473	170	314	291	275
	Average	285.3	289.5	145.1	226.6	203.5	216.9
Pieces (#/cycle)	Min	2	1	1	1	1	1
	Max	6	4	3	11	3	4
	Average	4.2	1.9	2.1	2.4	1.5	1.4
Cycle Volume (m^3)	Min	2.9	0.3	2.3	0.7	0.3	0.2
	Max	9.3	9.4	5.0	9.1	4.4	5.8
	Average	5.9	4.6	3.6	4.3	2.1	2.2
Piece Size (m^3)	Min	1.2	2.4	1.5	1.5	1.4	1.6
	Max	2.4	2.4	1.5	2.1	2.4	1.6
	Average	1.6	2.4	1.5	1.8	1.5	1.6
Yarding Corridors		2	2	3	2	2	3
Cycles		33	37	15	49	65	54

In order to quantify the relationships between yarding time and site conditions so that production rates for future sites can be predicted, regression equations were developed for each element of the yarding cycle and for total cycle time.

Variables are only included in these equations if their associated coefficient is significantly different from zero at an acceptable probability level. In this study variables were included in the final predictive equation only if their P-value was less than 0.01 (**) or between 0.05 and 0.01 (*). Regression equations also have an R^2 value known as the multiple correlation coefficient, which is a measure of fit between the observed time and the calculated time. An R^2 value of 100% indicates a perfect fit between the observed and predicted times. The individual equations, their R^2 value and the level of significance of each variable included in the model were calculated.

Outhaul

Outhaul time was found to be significantly influenced by distance, span and configuration:

Outhaul time =	**-0.17441**	**R^2= 77.53%**
	+0.002326 (Distance)	**
	+0.000844 (Span)	**
	+0.004329 (Chord Slope)	*
	Configuration	**
	+0.01461 (North Bend)	
	+0.07842 (North Bend Bridled)	
	-0.07858 (Acme Shotgun)	
	+0.08585 (Acme Slackline)	
	-0.12842 (Falcon Shotgun)	
	-0.02812 (Falcon Slackline)	

Hook

Hook time was found to be significantly influenced by piece size, configuration, and the number of pieces. In both cases increasing piece size and number of pieces increased the hook time.

Hook time =	**0.7468**	**R^2= 66.58%**
	+0.9000 (Piece Size)	**
	+0.15435 (Pieces)	*
	Configuration	**
	+0.5249(North Bend)	
	+0.6650(North Bend Bridled)	
	+0.5964 (Acme Shotgun)	
	+0.9514(Acme Slackline)	
	-1.5094(Falcon Shotgun)	
	-1.2283(Falcon Slackline)	

There are perhaps some hidden influences that are nested within configurations. For instance knowing the configuration does not tell us how many choker-setters were employed or how many chokers were used, and there is little variation within configurations in these two metrics. An additional equation was developed, which highlights this issue. Knowing only the number of choker-setters and the number of chokers used, we have arrived at a similar fit (R^2), but this equation shows how when using chokers, the number of chokers affects the time, and so does the number of choker-setters.

Hook time =	**2.0303**	**R^2= 66.09%**
	+0.7247 (Piece Size)	**
	-0.3834 (choker-setters)	*
	Chokers	**
	-2.1699 (No Chokers)	
	+0.8106 (2 Chokers)	
	+1.3593 (3 Chokers)	

Inhaul

Inhaul was found to be significantly influenced by configuration, span, distance and chord slope much like outhaul. However it is more time consuming than outhaul because there is resistance from the load, which is why cycle volume was found to be statistically significant.

Inhaul time =	**-0.2608**	**R^2= 67.16%**
	+0.00937 (Span)	**
	+0.019629 (Chord Slope)	**
	+0.007232 (Distance)	**
	+0.03859 (Cycle Volume)	*
	Configuration	**
	-0.5773 (North Bend)	
	+0.0469 (North Bend Bridled)	
	+0.503 (Acme Shotgun)	
	+0.18157 (Acme Slackline)	
	-0.02907 (Falcon Shotgun)	
	-0.1251 (Falcon Slackline)	

Unhook

The unhook time was found to be significantly influenced by the number of pieces and the number of chokers, and whether or not these had to be unhooked by a person (chaser).

Unhook time =	**0.6697**	**R^2= 67.32%**
	+0.0583 (Pieces)	**
	Chokers	**
	-0.17201 (No Chokers)	
	+0.03023 (2 Chokers)	
	+0.14178 (3 Chokers)	
	Chasers	**
	+0.3638 (1 Chaser)	
	-0.3638 (0 Chasers)	

A different model defining unhook time, where the factor variables of ‘chokers’ and ‘chasers’ are replaced with the variable ‘configuration’, has a similar degree of fit. However, it may be less useful due to nesting, as also highlighted with the two hook equations.

Unhook time = 0.57774 **R^2= 68.54%**

+0.05218 (Pieces) *

Configuration **

+0.7092 (North Bend)

+0.50331 (North Bend Bridled)

-0.19403 (Acme Shotgun)

-0.1593 (Acme Slackline)

-0.34627 (Falcon Shotgun)

-0.51291 (Falcon Slackline)

Delay-Free Cycle Time

The total delay-free cycle equations developed did not include all of the variables presented in the various cycle element equations because they did not have a P-value of <0.05, and although some variables affected element times, we cannot be certain they affect the total cycle time. The total delay-free cycle time was found to be significantly influenced by the distance, piece size and configuration, and to a lesser extent the number of pieces. The equation provides a reasonable explanation of the variation in cycle time considering the total number of observations (n= 253) as indicated by the R^2-value of 81.8%.

Cycle Time = 1.0349 **R^2= 81.83%**

+0.005013 (Distance) **

+1.7536 (Piece Size) **

+0.21141 (Pieces) *

Configuration **

+1.8441 (North Bend)

+1.8544 (North Bend Bridled)

+0.336 (Acme Shotgun)

+0.7644 (Acme Slackline)

-2.5005 (Falcon Shotgun)

-2.2960 (Falcon Slackline)

However, although piece size and number of pieces are significant, they still provide relatively little explanation of cycle time variation, most of which is explained by configuration and distance. A simplified equation containing only configuration and distance shows how much these two factors explain cycle time variation as indicated by the R^2 value of 79.33%.

Cycle Time = 4.4937 **R^2= 79.33%**

+0.005013 (Distance) **

Configuration **

+2.0033 (North Bend)

+2.9436 (North Bend Bridled)

-0.0912 (Acme Shotgun)

+0.8699 (Acme Slackline)

-3.0245 (Falcon Shotgun)

-2.7011 (Falcon Slackline)

Using the more complex equation for delay-free cycle time, and using the average variables observed for each configuration, an estimate of how cycle time might change with changes in distance only can be gained (Figure 5). Each line segment on the graph has been plotted over the range of distances which were observed for the corresponding configuration during the time study.

The purpose of restricting the lines to the distances observed is to avoid inappropriate extrapolation of cycle times. In other words, the cycle time may increase or decrease at different rates outside of these distances.

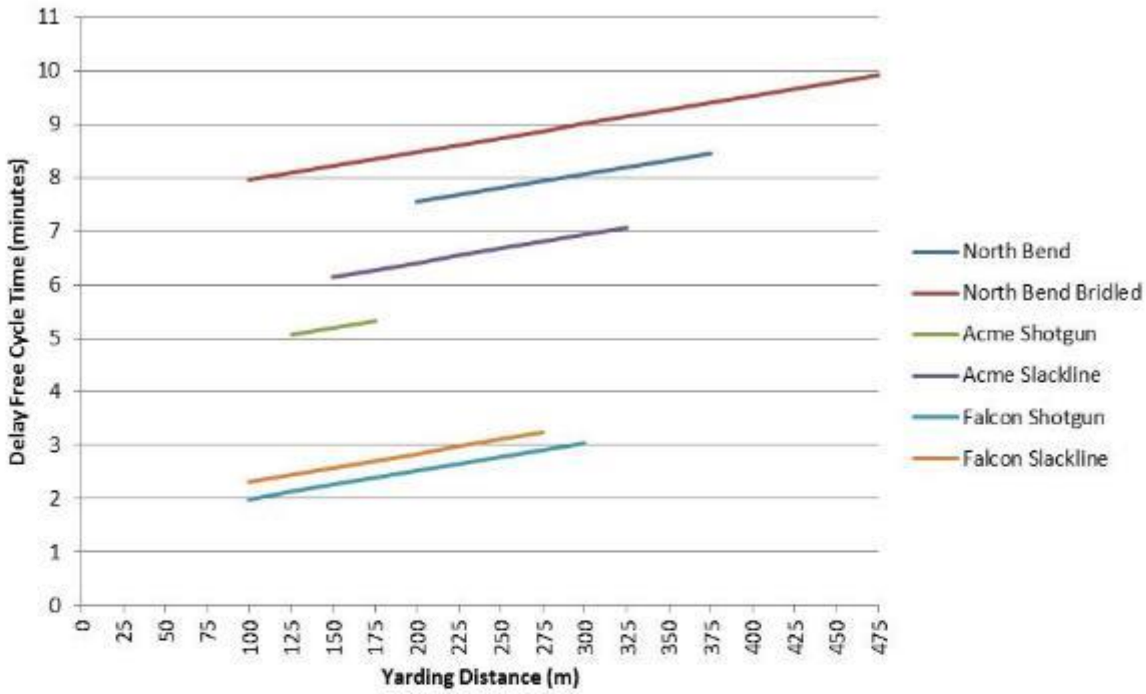

Figure 5: Predicted delay-free cycle time (min) as a function of yarding distance (m) for the rigging configurations studied

Skyline Tension Measurement

The tension monitoring results for each cycle of each configuration at every study site were summarised to compare the maximum and average tensions for the configurations studied.

Maximum Skyline Tension

Results showed the highest average of maximum (or peak) skyline tensions measured were associated with the North Bend Bridled, Acme Slackline and Falcon Shotgun configurations, respectively (Figure 6). The average of these peak tensions was higher than the other configurations, most likely due to the profiles which had minimal deflection and/or long skyline spans. North Bend Bridled showed high average maximum tensions in all elements of the cycle, due to the effect of off-setting the haul back blocks, which contributes to an extra plane of force in the skyline. The live skyline systems such as Falcon Shotgun and Falcon Slackline have higher outhaul and hook tensions than standing skyline system alternatives such as Acme Shotgun and Acme Slackline. North Bend performed quite well compared to others, with relatively low tensions in all elements of the cycle except for inhaul.

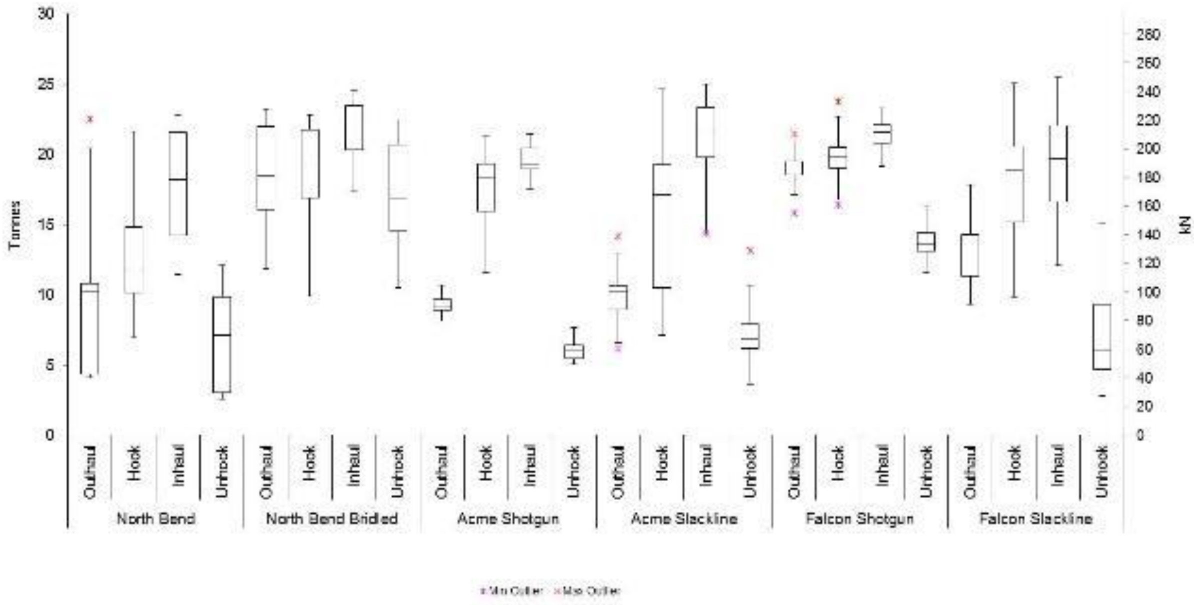

Figure 6: Peak skyline tensions recorded by yarding cycle element for all cycles of each configuration studied

Average Skyline Tension during the Cycle

In addition to measuring maximum skyline tensions, knowing that these peaks may only occur for only a small portion of the total cycle time, it was important to investigate the average skyline tension over the whole cycle for each rigging configuration. Skyline tensions recorded every 10 Hz were averaged for each cycle for each configuration and converted to a percentage of the skyline safe working load for comparison between configurations (Figure 7).

North Bend Bridled had the greatest average tension per cycle, operating at 81% of the safe working load, followed by Falcon shotgun which operated at 63% of the safe working load per cycle. The inconsistent element times and associated tensions compounded by averaging data over more than one site produced greater variability in average tension per cycle for North Bend and North Bend Bridled, and to a lesser extent Acme Slackline.

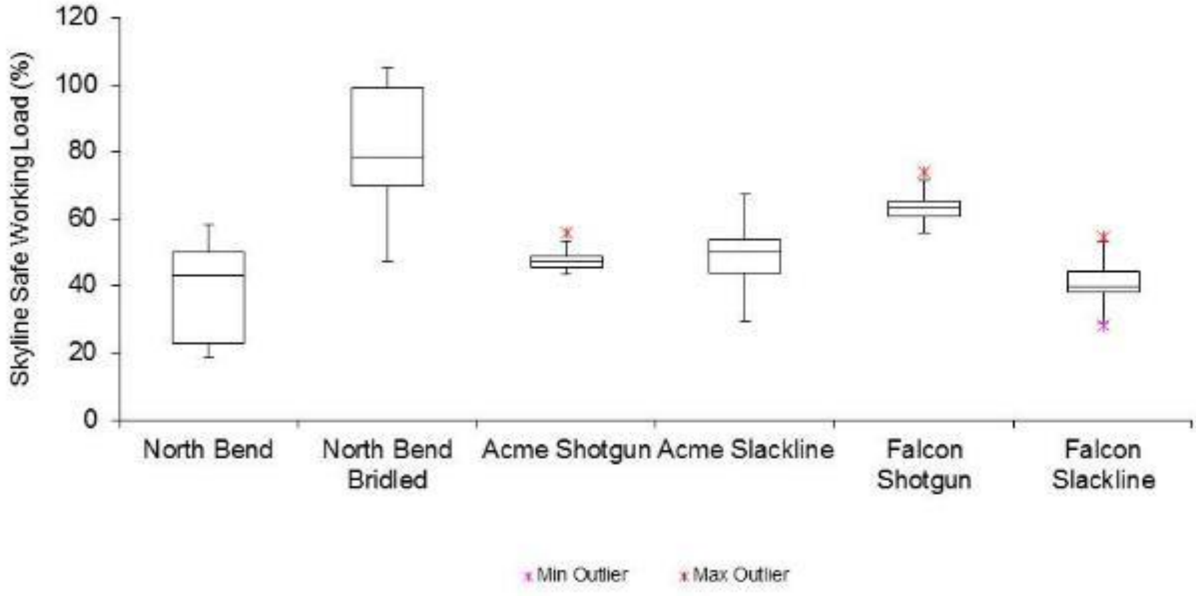

Figure 7: Average percent of the skyline safe working load per cycle for all cycles of the configurations studied

Regression Model for Skyline Tension

In order to determine which factors affected skyline tension of each rigging configuration, regression analysis was performed using the measured variables from each cycle. The range of these values recorded during the time study and their averages are summarised in Table 6.

Table 6: Summary of representative values of the variables recorded for each configuration during the study.

Independent Variables		North Bend	North Bend Bridled	Acme Shotgun	Acme Slackline	Falcon Shotgun	Falcon Slackline
Span (m)	Min	395	920	354	284	338	345
	Max	940	1100	354	335	602	364
	Average	602.3	1076.9	354.0	308.8	480.8	353.3
Chord Slope (%)	Min	-14	-43	-23	-21	-47	-27
	Max	1	-14	-23	-17	-30	-26
	Average	-4.9	-39.3	-23.0	-19.4	-37.9	-26.7
Deflection (%)	Min	5.2	3.8	6.2	4.2	5.7	5.9
	Max	10.05	5.1	6.2	6.9	6.05	7.4
	Average	7.8	4.0	6.2	6.1	5.9	6.3
Pieces (#/cycle)	Min	2	1	1	1	1	1
	Max	6	4	3	11	3	4
	Average	4.2	1.9	2.1	2.4	1.5	1.4
Carriage Payload (tonnes)	Min	3.9	1.3	3.2	1.5	2.5	2.4
	Max	10.3	11.5	5.9	10.0	6.6	8.0
	Average	6.9	5.9	4.4	5.2	4.3	4.4
Piece Size (m^3)	Min	1.2	2.4	1.5	1.5	1.4	1.6
	Max	2.4	2.4	1.5	2.1	2.4	1.6
	Average	1.6	2.4	1.5	1.8	1.5	1.6
Yarding Corridors		2	2	3	2	2	3
Cycles		23	34	42	27	34	54

Variables are included in the equation only if their associated coefficient was significantly different from zero at an acceptable probability level. In this study, variables were included in the final predictive equation only if their P-value was less than 0.01 (**) or less between 0.05 and 0.01 (*). Regression equations also have an R^2 value known as the multiple correlation coefficient, which is a measure of fit between the observed time and the equations calculated time. An R^2 value of 100% indicates a perfect fit between the observed and predicted tension. The equation, R^2 value and the level of significance of each variable included in the model were calculated:

Average Skyline Tension (tonnes) = 12.538 **R^2= 78.05%**

-1.1721 (Deflection) **

+0.00863 (Span) **

+0.22509 (Carriage Payload) **

Configuration **

-1.36810 (North Bend)

-1.2967 (North Bend Bridled)

-0.4906 (Acme Shotgun)

+0.9471 (Acme Slackline)

+2.6463 (Falcon Shotgun)

-0.4380 (Falcon Slackline)

All variables included in the final equation were statistically significant (P-value <0.01). Deflection was found to have the greatest influence of all independent variables on average cycle tension, followed by carriage payload and span. A one-way ANOVA test indicated that configuration alone was statistically significant (p-value <0.01), and the configuration alone explained nearly half of the variation in tensions (R^2= 54%). The ANOVA test also showed that North Bend Bridled and Falcon Shotgun were significantly different from all other configurations, while there was no significant difference between Acme Shotgun, Acme Slackline and North Bend. Additionally, there was no significant difference between Acme Shotgun, North Bend and Falcon Slackline. However, these two groups of three configurations were significantly different from one another despite having commonality with the North Bend configuration.

Using the above general linear model equation for skyline tension (tonnes), and using the average variables observed for each configuration, an estimate of how average tension might change with changes in deflection only was determined (Figure 8).

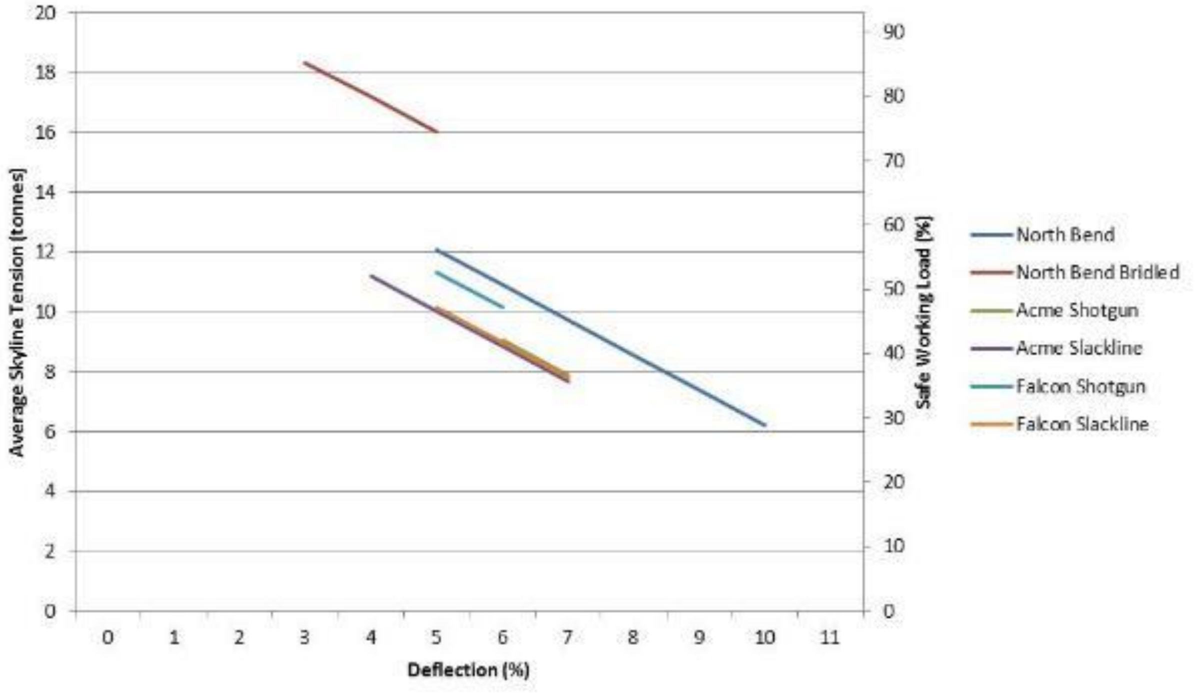

Figure 8: Predicted average cycle skyline tension for each configuration studied

Each line segment on the graph has been plotted over the range of deflections which were observed for the corresponding configuration during the time study. The purpose of restricting the predicted tensions to the distances observed is to avoid inappropriate extrapolation of average tension over higher or lower deflection. This equation is applicable to the conditions studied, and other equations may indicate that the relationship between tension and deflection is not linear.

DISCUSSION

Productivity Analysis

Delay-free cycle equations are most commonly used to estimate hourly productivity. The regression equation developed for delay-free cycle time was combined with the average pieces and piece size values to give an estimate of productivity over varying distances for each configuration (Figure 9).

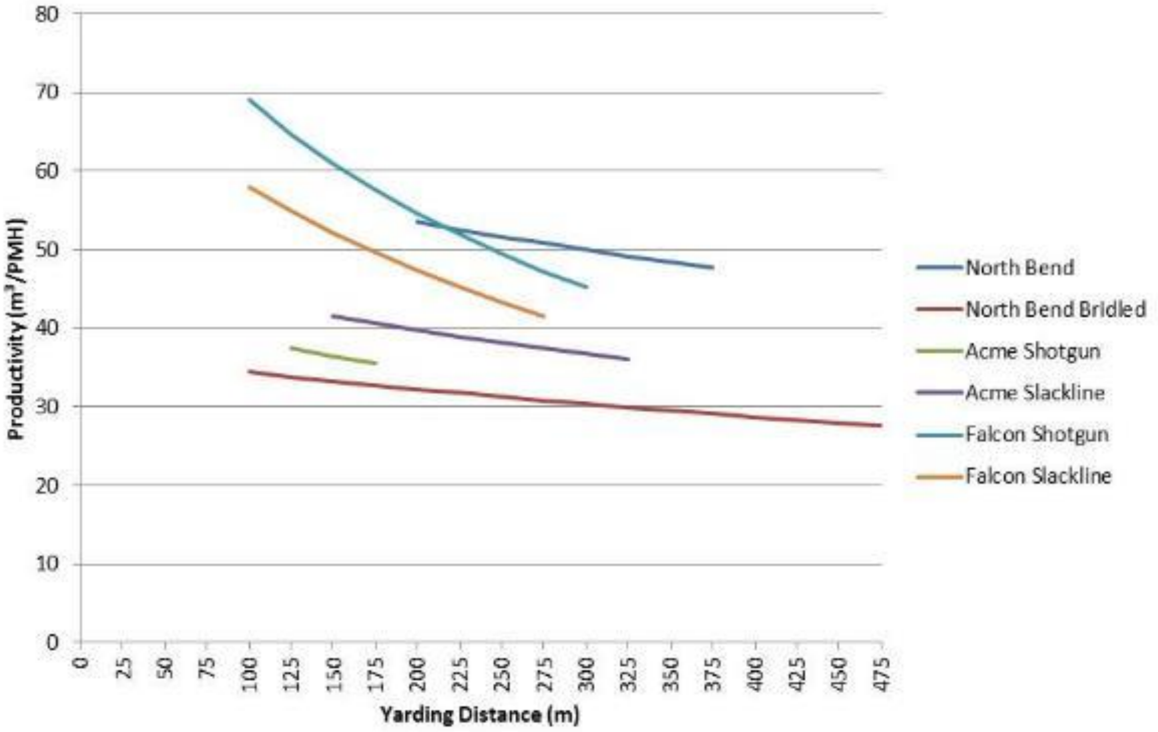

Figure 9: Predicted productivity (m^3/PMH) as a function of yarding distance (m) for the rigging configurations studied

North Bend, despite having a longer cycle time than Falcon Shotgun, was just as productive as Falcon Shotgun at haul distances between 200-225 metres, and became more productive at longer haul distances. These estimates of production at varying distances should be viewed with some caution as there is considerable variability around these average values.

The average rate of production (m^3/PMH) was also calculated for each cycle based on observed data by multiplying the measured cycle volume by the number of cycles per delay-free hour (Figure 10).

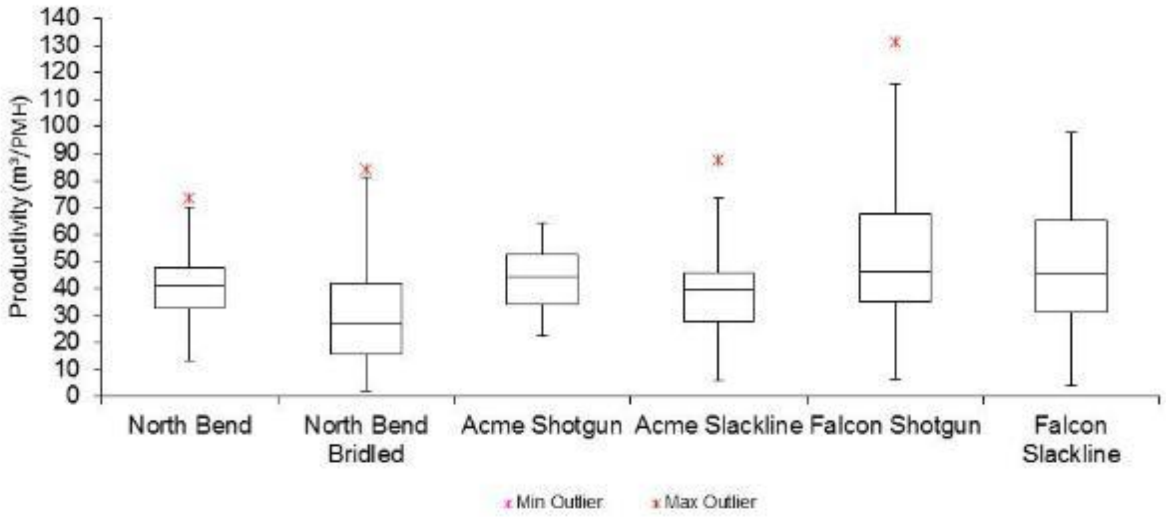

Figure 10: Average observed productivity (m³/PMH) and range for the rigging configurations studied

The highest rate of production was achieved by the Falcon shotgun configuration (46.5 m³/PMH). However, the Falcon shotgun configuration also had the largest range in productivity and was similar to Falcon Slackline in both average productivity (44.3 m³/PMH) and range. North Bend had similarly high average production rate (46.1 m³/PMH), but also had a smaller range. Although very similar in operation to North Bend, the North Bend Bridled configuration had the lowest average production (32.8 m³/PMH), but had a large range and was capable of higher production.

Some of the variability in production can be explained by the changes in distance as predicted by the increase in cycle time. However, even when distance changes little (i.e. on the cycle-to-cycle level) there is still considerable variability in production (Figure 11).

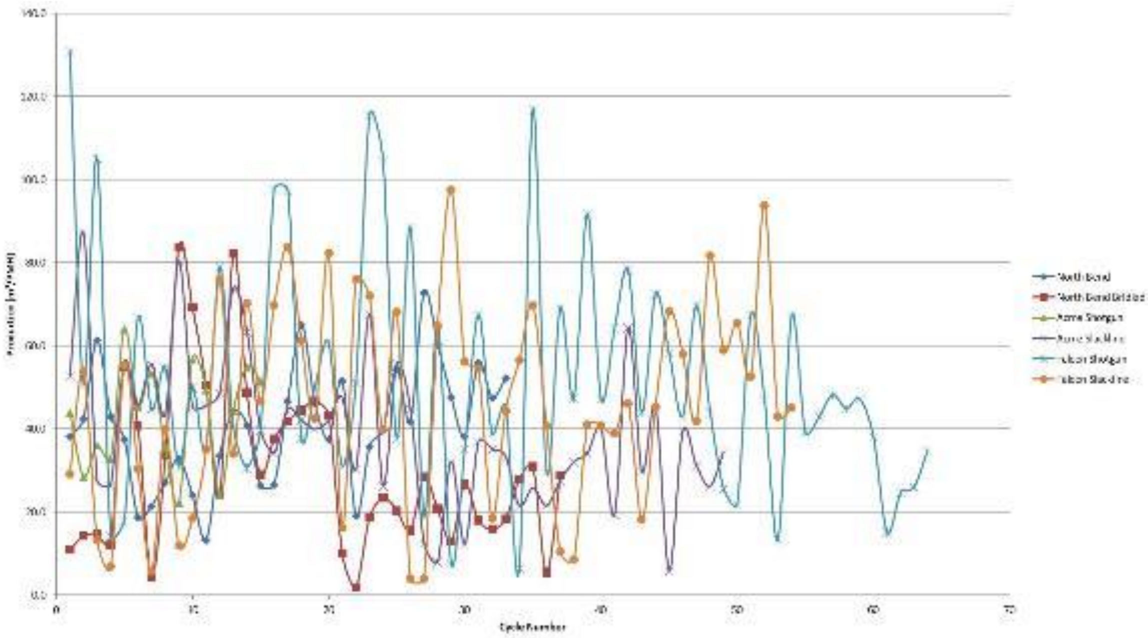

Figure 11: Cycle to cycle variability in productivity (m³/PMH) for each of the configurations studied

Delay Analysis

The regression equations used to predict productivity are based on a delay-free or productive machine hour (PMH) basis, meaning they do not account for delay time. To determine what the production might be across an entire day, or to estimate what costs might be, it is necessary to consider delay time. This is because labour and fixed costs are usually incurred whether or not the configuration is operated. If configurations have different proportions of time that are non-operative, their cost on a unit basis ($/m³) will differ as well.

Assessing the impact of delays as they relate to a specific rigging configuration is inherently complex, as delays occur randomly over time and shift-level data would need to be collected over many months to establish accurately the estimates for delays (Spinelli and Visser 2008). These time and motion studies set out to establish productive cycle time, and the following analysis provided is simply an indication of the delays that occurred during the study.

The total delay time for all studies was 5.6 hours, relative to 21.9 total productive hours, resulting in an estimated delay factor of 20%, or average machine utilisation of 80%. The types of delays observed for each configuration were recorded to determine their frequency per cycle (Figure 12).

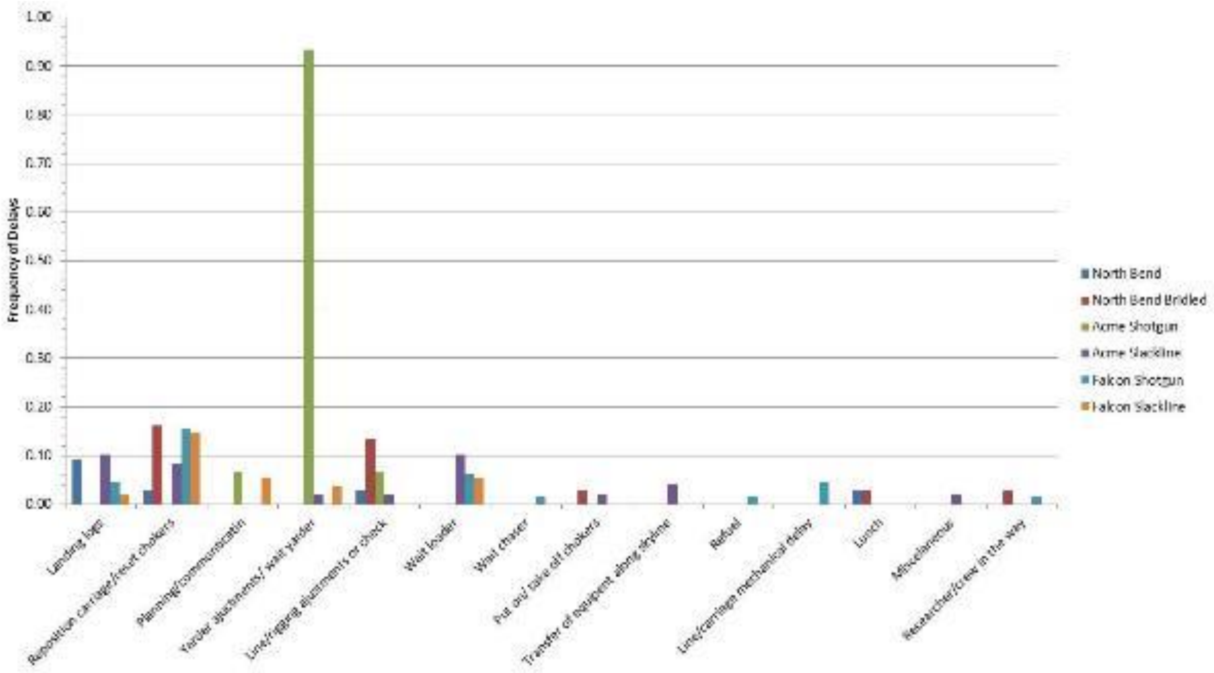

Figure 12: Frequency of observed delays by type for the six configurations studied

The delay with the greatest frequency was due to yarder adjustments with the Acme slack pulling carriage in the shotgun configuration. This is likely because of the rock bluffs encountered during the operation of this configuration, where the yarder had to adjust the length of mainline to lift the payload over the bluff, a delay which occurred nearly every cycle.

The most common delay to all other configurations was due to repositioning the carriage, especially for the Falcon shotgun, Falcon Slackline and North Bend Bridled configurations. The grapple carriages experienced this type of delay because they had lost a log out of the grapple and had to pick it up, or the first placement of the carriage after outhaul was not adequate to pick up (or "grapple") the log. The North Bend Bridled configuration experienced repositioning delays due to when the carriage stopped moving and the fall block dropped and moved laterally. Sometimes it was difficult to land the rigging this way and the choker-setters had to communicate with the yarder operator to land the rigging.

There were also a number of delays associated with the landing itself, such as “waiting for the loader” to clear the chute (an interaction delay between machines), and “landing logs” a difficulty which was usually due to the logs not resting properly on the landing (due to inadequate space) or due to tangled chokers.

The average delay time for each category observed for each configuration was also calculated to determine which type of delays were consuming the most productive time per delay (Figure 13).

Although some delays, like yarder adjustments with the Acme Shotgun configuration, were frequent, they accounted for very little time on average (0.02 minutes per delay). On the other hand infrequent delays, such as line and rigging adjustments, or personal delays such as lunch breaks, accounted for a relatively large average delay time (>10 minutes, and >30 minutes respectively). The most time consuming delay that was also most frequent was the “reposition carriage” delay associated with the North Bend Bridled configuration. As previously discussed this delay occurred often due to the nature of the operation, but also due to its difficulty, it took on average 2.4 minutes per delay.

The delays recorded during the time studies are a good indication of delays that might be expected when operating each of the configurations studied. They should be used with caution as some delays, as previously discussed (e.g. Acme Shotgun yarder adjustments), were very specific to unique site conditions encountered. Additionally, not every operation was studied for the same time period, or over the same range of operating hours (i.e. half day *vs* full day).

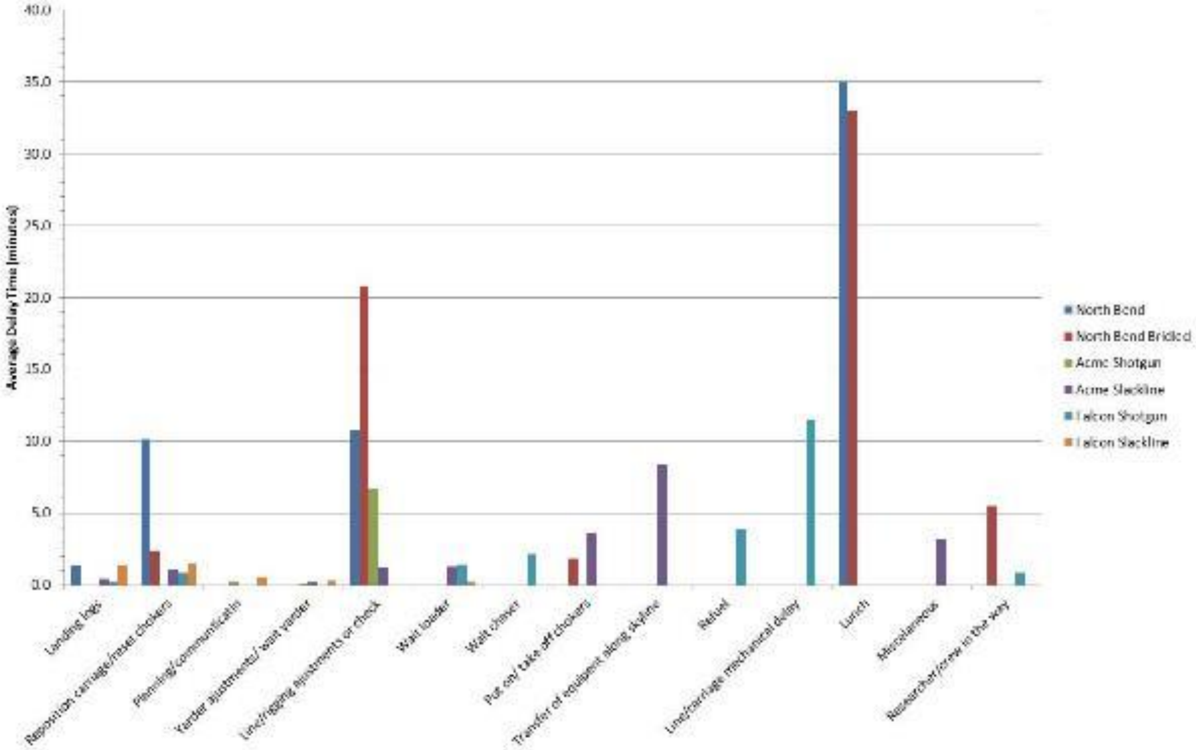

Figure 13: Average delay time (minutes) categorised by each type of delay for the six configurations studied

An attempt was made to normalize delay times by excluding infrequent large delays, research related delays and delays that have common times to all configurations but were not captured during the time study (e.g. lunch and line shifts). The machine utilisation rate was calculated for each configuration by calculating the productive machine time as a ratio of total scheduled time (sum of delays and productive time). This is presented in both observed time and adjusted (or normalized) time in Table 7. The highest utilisation rate was achieved by the Falcon Slackline configuration, while the lowest was achieved by the North Bend Bridled configuration. It is interesting to notice that the adjusted utilisation rates are similar between variations of configurations with exception to North Bend and North Bend Bridled. This is most likely due to the high frequency (13%) of line/rigging adjustment delays (due to off-setting haul back blocks), and the long average time for this type of delay (>20 minutes) which were not observed with the North Bend configuration.

Table 7: Productive time, delay times (adjusted and non-adjusted) and machine utilisation rate (%) for each configuration studied

	North Bend	North Bend Bridled	Acme Shotgun	Acme Slackline	Falcon Shotgun	Falcon Slackline
Productive Time (min)	264	331	76	321	165	158
Delay Time (min)	60	158	9	38	56	16
Adjusted Delay Time (min)	25	120	9	35	27	16
Utilization Rate (%)	81	68	89	89	75	91
Adjusted Utilization Rate (%)	91	73	89	90	86	91

Labour and Energy Consumption

Each configuration had a different average production rate (m³/PMH), but productivity alone does not tell us which configuration is the most profitable. For example, each configuration has different requirements for labour (number of workers), and can be used on a variety of different yarders with different fuel consumption rates. Unless the proportion of costs associated with fixed, variable and labour components is known on a productive machine hour basis, cost competitiveness cannot be compared. Collecting detailed cost data was not within the scope of this study. The data obtained from these eight study sites do not represent a full factorial study of all rigging configurations, labour and yarder energy consumption. As such the data presented in this section should be interpreted as case study-based only.

Despite these limitations, cost competitiveness can be compared through the rates of consumption of labour (man hours/m³) and energy from the yarder and carriage combination (kW/m³). The consumption of labour in the extraction phase was computed by dividing the number of workers (sum of choker-setters, chasers and the yarder operator) by the production rate (m³/PMH). An index of energy consumption was computed by dividing the sum of the carriage and yarder kW by the production rate (m³/PMH). Rates of labour and energy consumption provide insight to the relative amount of effort expended to produce each cubic metre of wood on an hourly basis (Table 8).

Table 8: Average and range of labour and energy consumption for each configuration studied

Consumption Rate		North Bend	North Bend Bridled	Acme Shotgun	Acme Slackline	Falcon Shotgun	Falcon Slackline
Labor	Min	0.04	0.05	0.05	0.05	0.02	0.02
(man hours/m³)	Max	0.57	2.06	0.14	0.84	0.87	0.50
	Avg	0.12	0.29	0.08	0.13	0.07	0.09
Energy	Min	4	4	4	4	3	4
(kW/m³)	Max	38	172	11	98	164	95
	Avg	9	25	7	11	15	17

The lowest rate of labour consumption was achieved by the Falcon Shotgun configuration which was similar to that of the Falcon Slackline, as these configurations use a grapple carriage and require only a yarder operator and one additional worker to move the tail hold machine. The highest rate of labour consumption was achieved by the North Bend Bridled configuration, which used four or sometimes five workers. The difference in labour consumption between North Bend and North Bend

Bridled, even though they used the same number of workers, was attributable to the higher production rate of the North Bend configuration.

A similar (but not as extreme) trend was found between the Acme carriage configurations and the Falcon carriage configurations, where the shotgun variation had a higher rate of production. The Acme carriage configurations were between the North Bend and either Falcon configurations in terms of labour consumption, due to higher production than North Bend with the same amount of workers.

Energy consumption was lowest with the Acme Shotgun configuration, followed closely by North Bend. This was due to both having relatively low total engine power (kW), and both achieved relatively high rates of production. The highest rate of energy consumption was the North Bend Bridled configuration. Despite not having a powered carriage, the low production rate of the North Bend Bridled configuration overrode its lower power requirement. Despite having a high production rate and the same yarder power (kW) as other configurations, the Falcon configurations had relatively high energy consumption due to the increased total kW from the carriage (15-17 kW/m³). There is also a similar trend as observed with labour consumption where the Shotgun variation of the Acme and Falcon configurations consumed less energy, which was attributed to the higher associated rate of production.

Skyline Tension Analysis

Payload to Tension Relationships

One of the objectives of this project was to investigate the total payload (sum of log and carriage weight) to tension relationship for each configuration. Deflection, as previously discussed, has a significant influence on tension.

The varying ranges of deflection measured were categorised into classes (minimal = <5%; low = 5-7%; medium = 7-10%; high = >10%) for ease of plotting the carriage payload to tension relationship for each configuration (Figure 14).

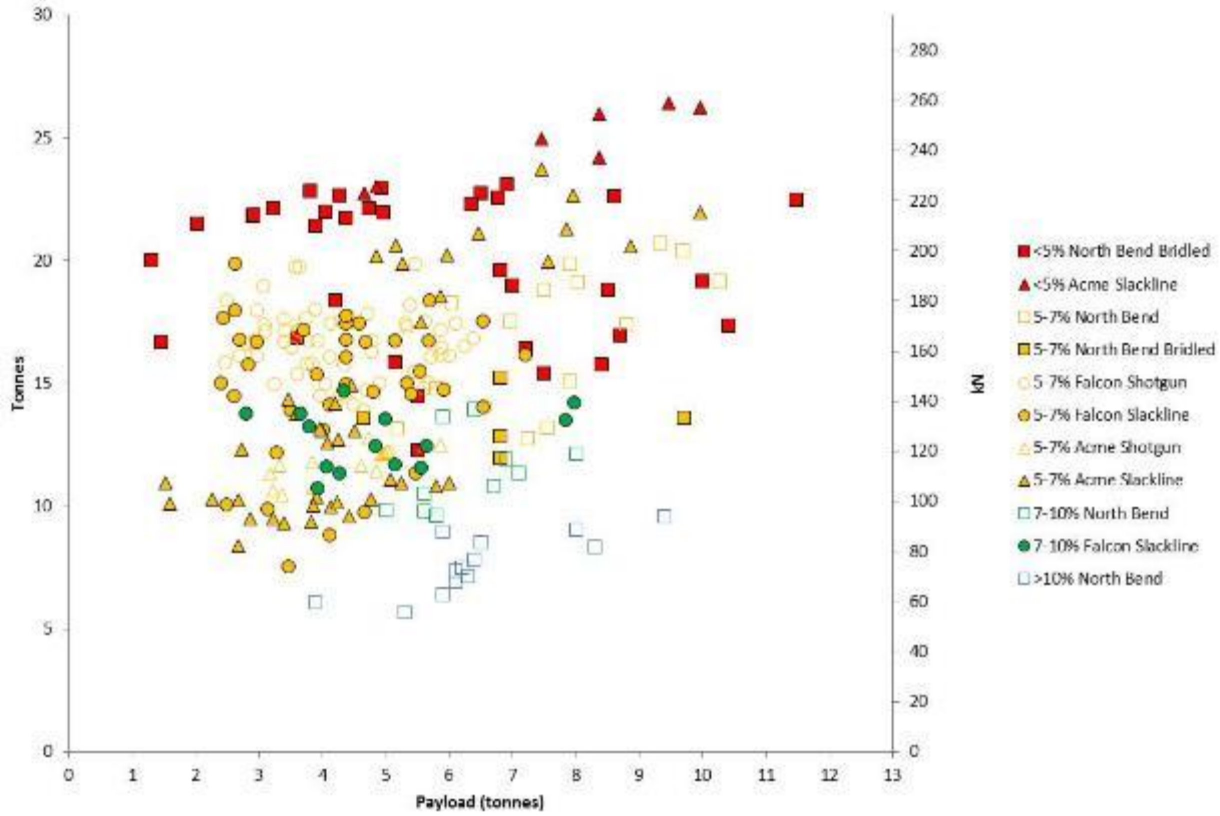

Figure 14: Payload to average skyline tension during inhaul relationship by percent deflection for all configurations studied

The scatter plot of data showed that reduced deflection increases the skyline tension during inhaul, for an equivalent carriage payload. This showed the variability in tension for similar payloads when using the Falcon Shotgun and Falcon Slackline configurations (indicated by empty and solid circles respectively in Figure 14).

The variability in tensions for the grapple carriage configurations were not well explained by the deflection, due to the nature of operating this type of live skyline system, where the carriage height above the ground (and therefore the skyline deflection) are altered during each cycle. The variation in carriage height for the Falcon Shotgun configuration compared to North Bend was shown in the carriage GPS positional data acquired (Figures 15 and 16). Therefore the deflection estimates for the grapple carriage configurations are imperfect, and represent only the maximum allowable deflection measured for each profile studied.

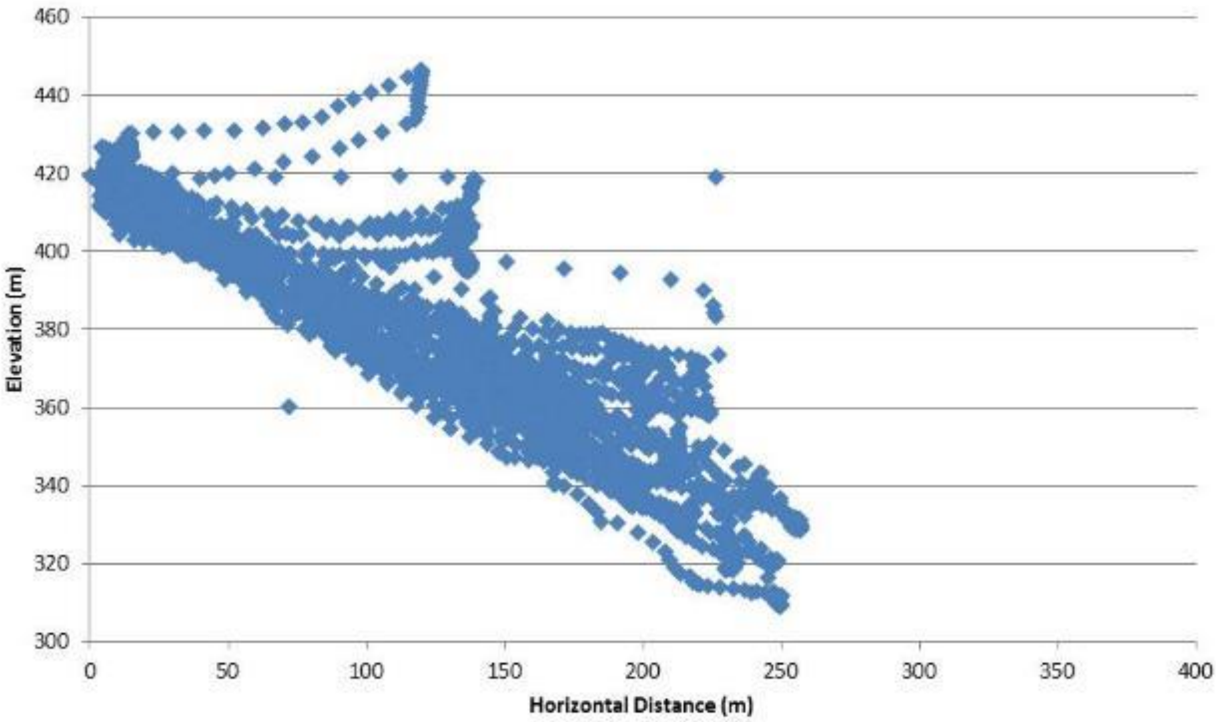

Figure 15: Carriage mounted GPS positional data for study site 5, profile 1, Falcon Shotgun configuration

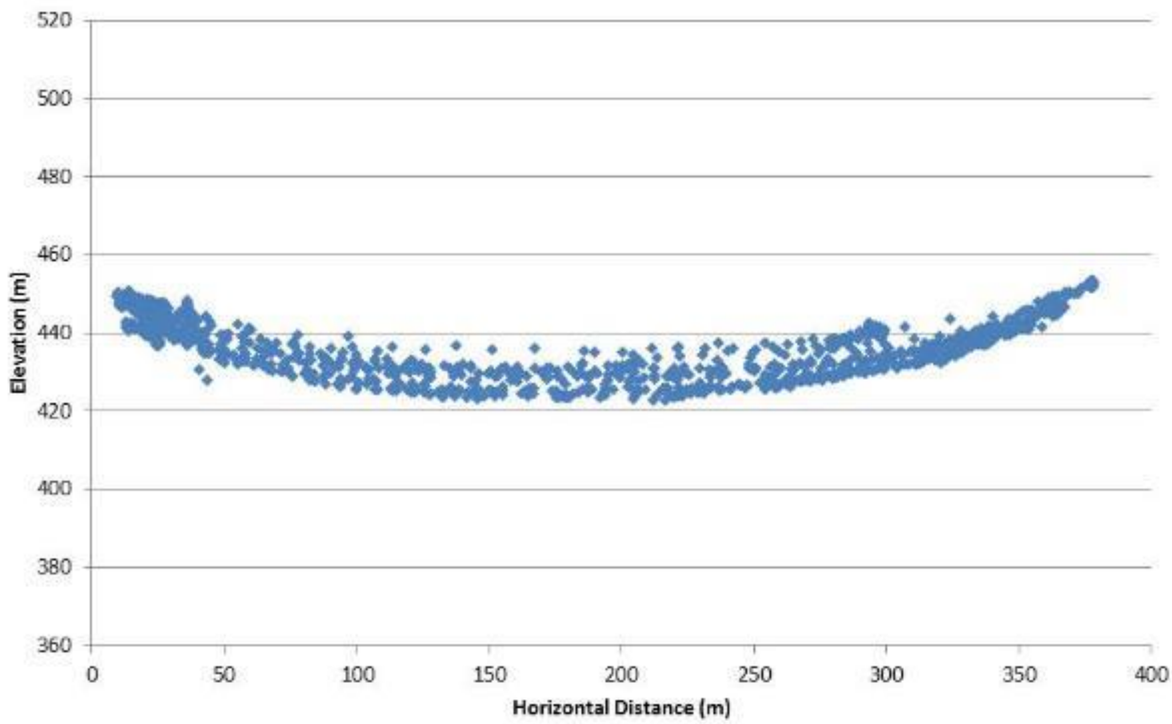

Figure 16: Carriage mounted GPS positional data for study site 7, profile 2, North Bend configuration

Another interesting trend in the payload-to-tension relationship was the high tension generated for low carriage payload when the North Bend Bridled configuration was used, compared to the very similar North Bend configuration (Figure 17).

For example, in the North Bend Bridled configuration operated at minimal deflection (<5%), equally high tensions were recorded during inhaul for a 4-tonne and 8-tonne carriage payload. The same flat relationship between payload and tension indicated by the trend lines in Figure 17 was observed for North Bend Bridled when operated at low deflection (5-7%). The data showed that the same increase in payload (four tonnes) for the North Bend configuration resulted in a tension increase of nearly five tonnes, a positive relationship shown by the trend lines. The resulting high tensions are likely a result of the added plane of force in the skyline when the haul back blocks are off-set from the skyline as previously discussed.

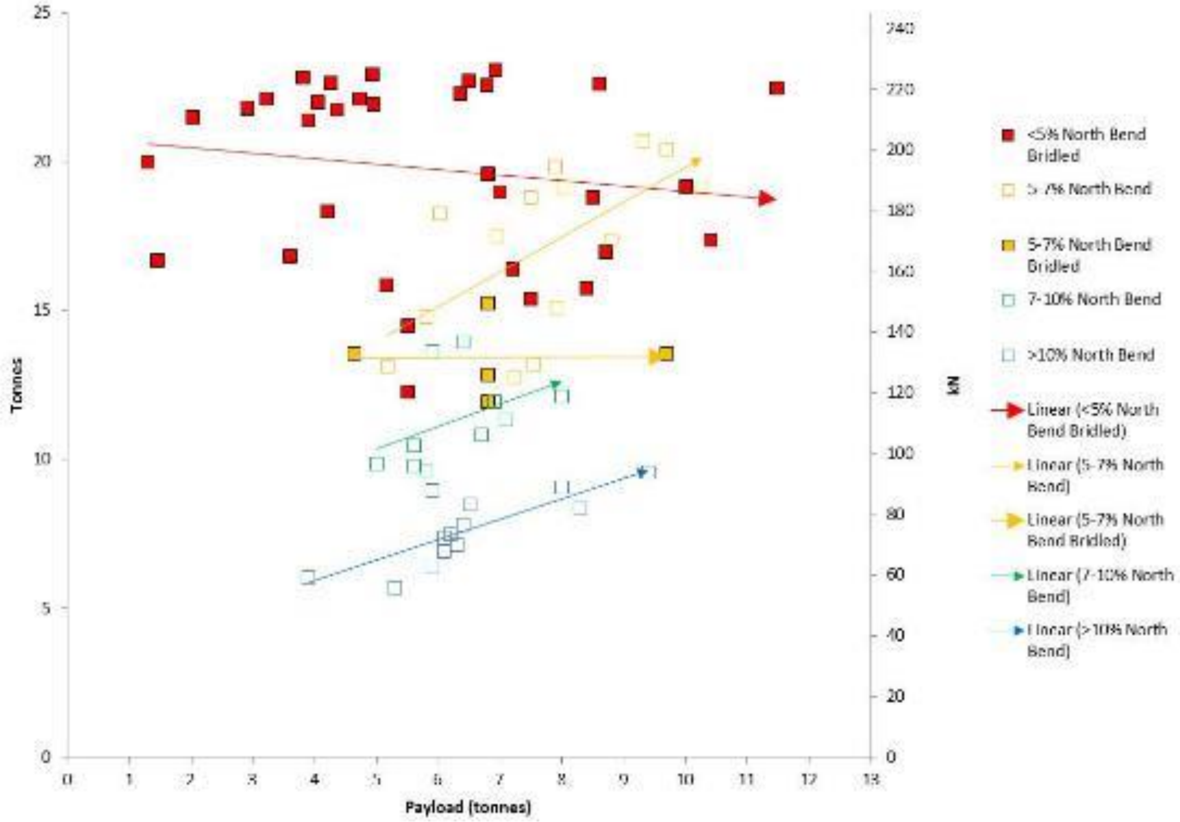

Figure 17: Trend in payload to average skyline tension during inhaul relationship by deflection class for North Bend and North Bend Bridled configurations

Skyline Dynamic Behaviour

Amplifications

Another objective of the project was to investigate dynamic load behaviour (referred to as shock loading), and compare the dynamic load behaviour between rigging configurations. Dynamic load magnitude is possibly the most valuable parameter that tension monitoring of logging cables could produce (Pyles *et al.* 1994).

The two types of dynamic load amplifications calculated from the tension monitoring results were the breakout tension factor and the maximum cyclic load factor. The breakout tension factor is the amplification of skyline pretension expressed as a factor of the skyline pretension; or how much tension is generated in the skyline to get the load to start moving. The maximum cyclic load amplitude factor is defined as the greatest peak-to-peak change in tension during inhaul, expressed as a percent of the skyline pretension.

Results (Figure 18) showed that the breakout tension factor was lowest for the North Bend and North Bend Bridled configurations, where little tension in the skyline is needed to start the load moving due to the fall block creating a purchase in the mainline, and the extra plane of force when bridling.

However, breakouts at mid-span even with high deflection (>10%) can produce a large breakout factor.

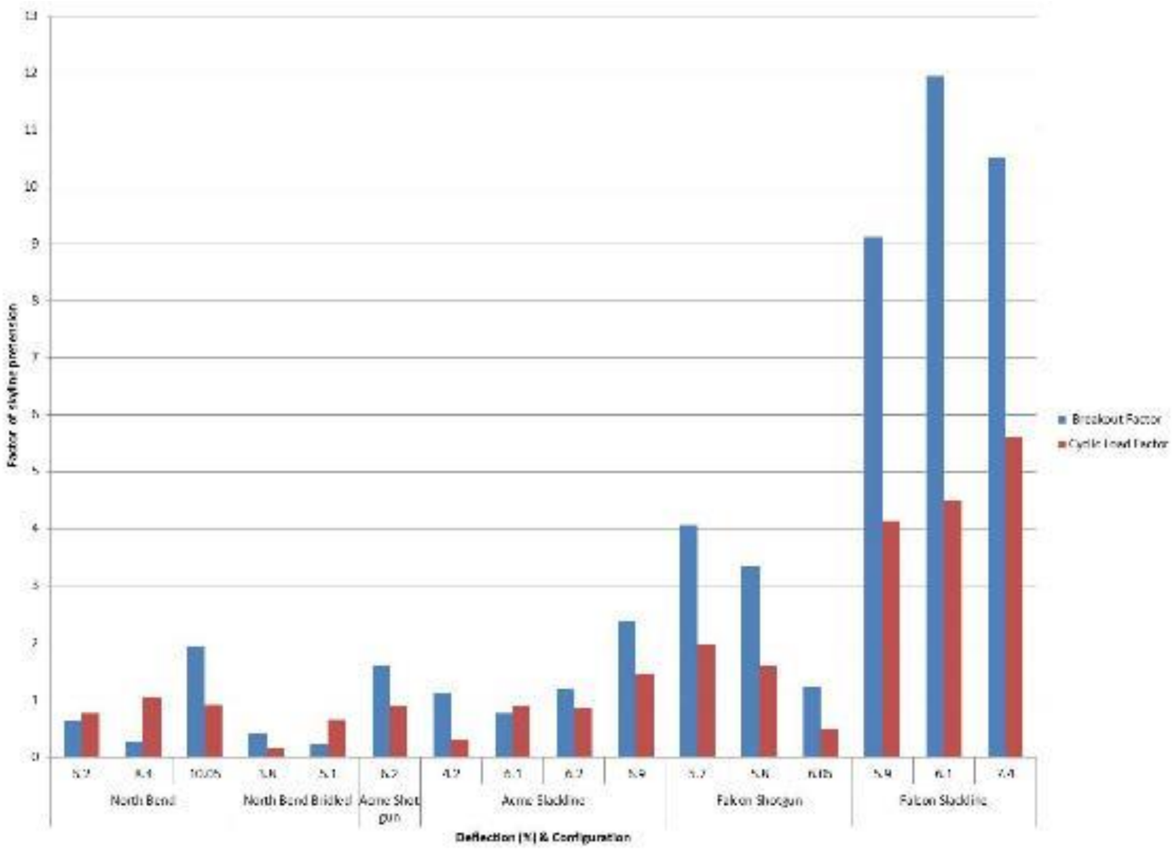

Figure 18: Dynamic skyline load magnitude averages for various rigging configurations and their corresponding span deflection (%)

The breakout tension factor was highest for the Falcon Slackline and Falcon Shotgun configurations, where the skyline was purposely tensioned to facilitate breakout of the load. Despite similar spans, lower average safe working load per cycle and lower average peak tensions for each element of the cycle, Falcon Slackline had more than twice the breakout tension factor of Falcon Shotgun. The difference in amplification factors between the two grapple carriage configurations can be attributed to the style of operation described, where at Study Site 1 with the Falcon in a slackline configuration, the carriage was raised to facilitate inhaul directly to the landing versus following the terrain slope during inhaul and performing several smaller lifts along the way.

The maximum cyclic load factor was greatest for the Falcon Slackline configuration, due to the high tensions during inhaul and occasional load contact with the ground, especially as it approached the landing. Contact with the ground showed increased cyclic load factors as highlighted by the comparison between Acme Slackline in the 4.2 % deflection profile and the 6.1% deflection profile where the operator purposely kept the logs in contact with the ground. The lowest cyclic load factors were observed during the use of the North Bend Bridled configurations; as previously discussed there was something of a dampening effect to the skyline with the extra plane of force from off-setting the haul back blocks.

Hang-Up during Breakout

Hang-ups or collisions with ground objects can cause large dynamic skyline load magnitudes. For example, at Study Site 7 (North Bend configuration), there were two different profiles with 8.4% and 10.1% deflection respectively. All of the cycles in the first profile were extracted from the back face, whereas the first cycles of the span with 10.1% deflection were extracted from an incised gulley at mid-span. Cycle 13 from this span had a hang-up during breakout where the butt ends of one or more stems were lodged into the lip of the gulley. The payload of logs in the cycle was approximately 4.9 tonnes but generated a peak tension of over 20 tonnes (196 kN) which was greater than all other cycles from that profile (Figure 19). Cycle 13 had a breakout factor of 4.5 compared to all other cycles from that span, which had a maximum breakout factor of 2.3. Cycles from the two profiles had similar average cyclic load factors 1.04 and 0.92, respectively, but very different breakout factors (0.26 and 1.95), due to the latter extracting loads near mid-span.

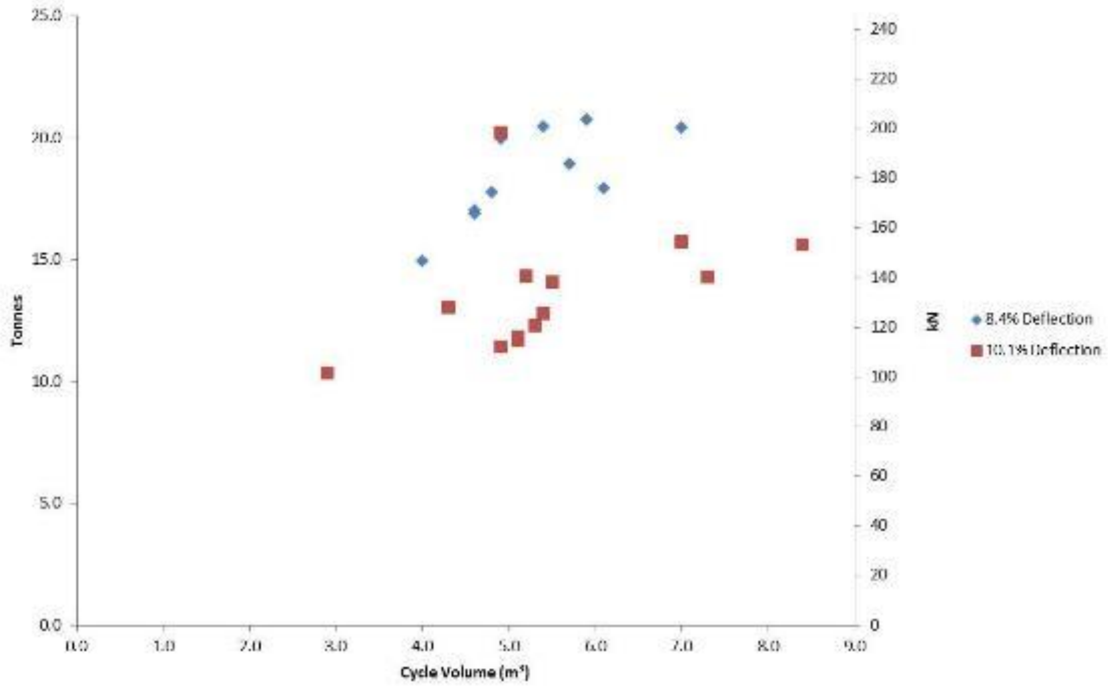

Figure 19: Peak tensions during inhaul based on cycle volume for Study Site 7, profiles 1 and 2, North Bend configuration

Partial or Full Suspension

During inhaul, payloads can either be partially suspended or fully suspended. Partial suspension shares the weight of the load with the ground so in theory there is less tension in the skyline at a given deflection. However, partially suspending loads means they are also more subject to shock loads due to hang-ups with objects, and to a lesser extent the resistance due to the coefficient of friction with the ground. As previously discussed in the results from Study Site 4, profile 2, where the Acme Slackline configuration was operated, stems were partially suspended form the back face of the canyon. The operator stated that he knew high tensions were occurring during inhaul because his tension monitor in the cab would ring an alarm when the safe working load was exceeded. He was concerned that fully suspending loads from the back face was a potential hazard.

The effect of partial versus full suspension on skyline behaviour can be fairly compared by the inhaul of cycle 16 and 17 (Figure 20). In cycle 17 the operator was advised to fully suspend one stem rather than partially suspending two stems across the canyon. The payload was reduced from 4.7 to 3.6 tonnes, but the inhaul time reduced from 3.5 to 2.0 minutes, which resulted in an increase in productivity of more than 10 tonnes/PMH. Even though the peak tensions were similar during inhaul of cycle 16 and 17, the maximum cyclic load amplification was reduced from 1.5 to 0.68.

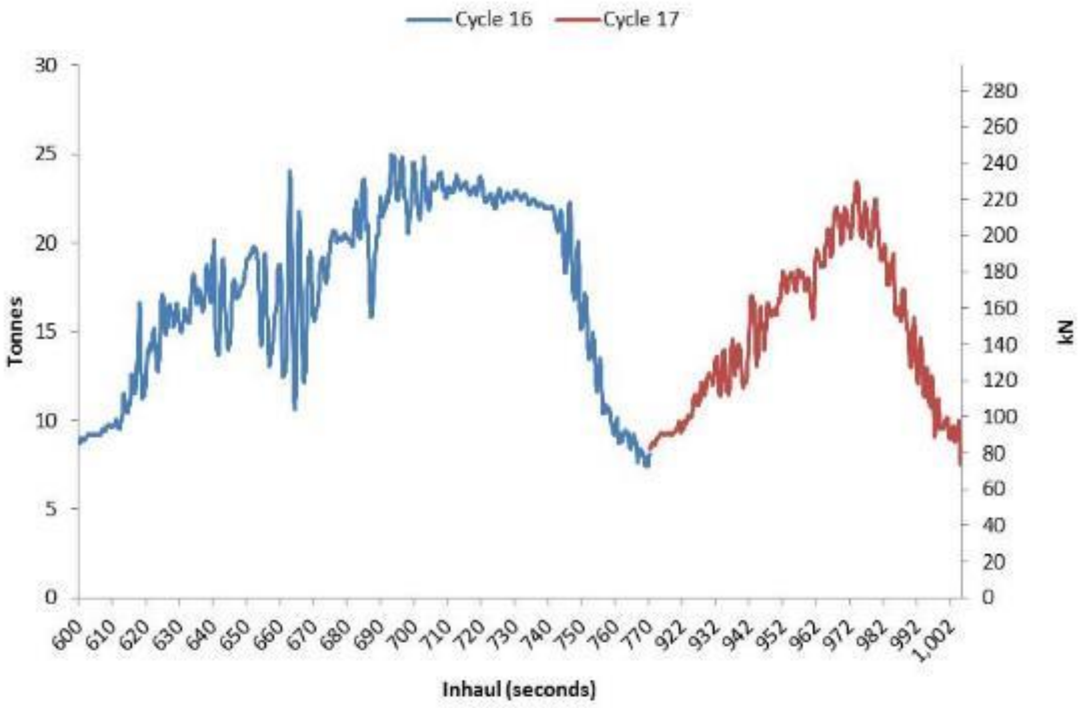

Figure 20: Comparison between inhaul tensions from Study Site 4, profile 2, cycles 16 and 17, Acme Slackline configuration

Cyclic Load Frequency

During the monitoring of skyline tensions across a total of 259 hauler cycles, the tension monitor was knocked off the skyline where it was clamped on two occasions (at Study Sites 2 and 6). Further investigation into these events found that they were a result of high tensions during inhaul and outhaul. In the case of Study Site 6 (North Bend Bridled), the safe working load was exceeded on 22 out of 34 cycles during inhaul (65% frequency). On one occasion during inhaul the skyline drum band brake slipped at 27 tonnes (265 kN) which was 127% of the safe working load (42% of skyline breaking strength) and nearly reaching the endurance limit of the skyline (50% breaking strength). This indicated that the band brake was not calibrated or functioning correctly. The event caused several wraps of cable to come off the drum all at once. The result was a large shock load wave which travelled down the skyline to the tail hold which slammed the tension monitor into the ground, knocking it loose from the skyline.

In the case of Study Site 2 (Falcon Shotgun), the carriage was hauled out to extract stems 25 metres in front of the anchor. Due to the steep chord slope (47%) and carriage weight (2.2 tonnes) the carriage was able to outhaul at an extremely high speed (15m/sec) and the peak skyline tension (21.2 tonnes, 209 kN) nearly reached the skyline safe working load. The tension monitor did not make impact with the ground as in Study Site 6, but was still disconnected from the skyline. The video analysis showed the tension monitor begin to shake violently as the carriage approached the anchor. Further investigation revealed that the maximum cyclic load factor (1.6) was similar to other cycles, but the frequency of cyclic load peaks was not similar (Figure 21). Results showed that although peak tensions were similar both before and after the 1,155 second mark of outhaul, the frequency nearly doubled from 1.6 to 3.5 Hz. Measuring the natural frequency was not within the scope of this study, but it is possible that the carriage could have caused a resonance effect as suggested by Pyles and others (1994). Perhaps of greater concern, would be the potential wear on the skyline where it passes over sheaves or is shackled, with this high frequency behaviour at high outhaul tensions. It has been previously highlighted that this behaviour could induce wear to the skyline due to stress reversal fatigue, and that higher average frequencies reduced skyline life (Carson and Jorgensen 1978).

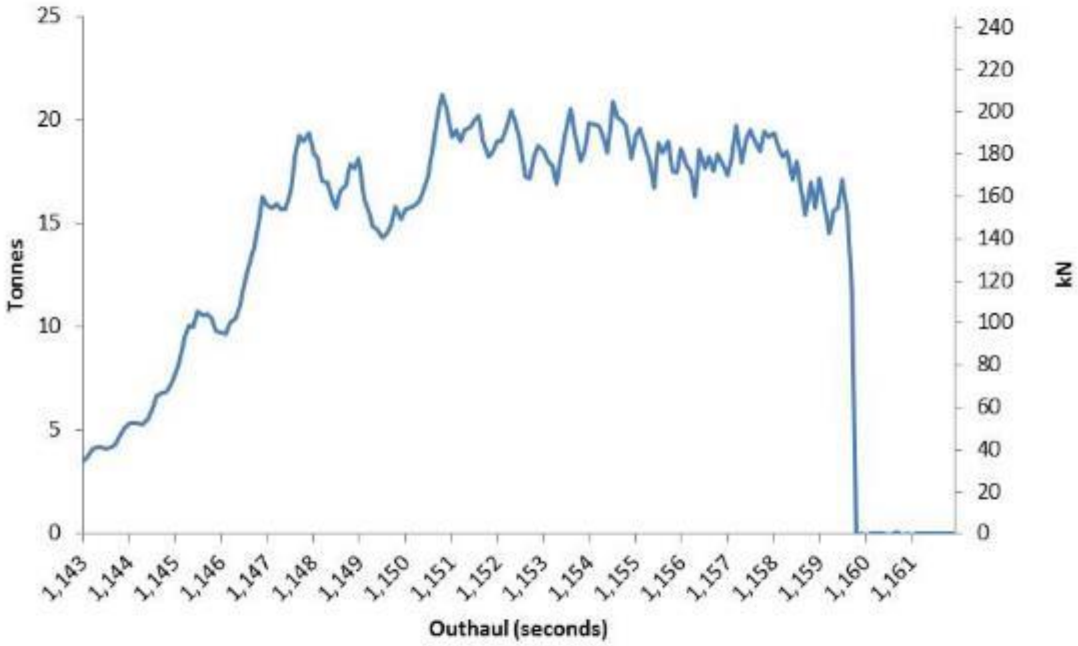

Figure 21: Outhaul tensions for Study Site 2, profile one, cycle 16, Falcon Shotgun configuration

Payload & Tension Efficiency

Two measures of efficiency were calculated for each rigging configuration: payload efficiency and tension efficiency (Figure 22). The payload efficiency is the measure of how close an individual cycle payload was to the predicted payload derived from payload analysis software at the same extraction distance. Tension efficiency is the measure of how close the average tension of a cycle was to the safe working load of the skyline.

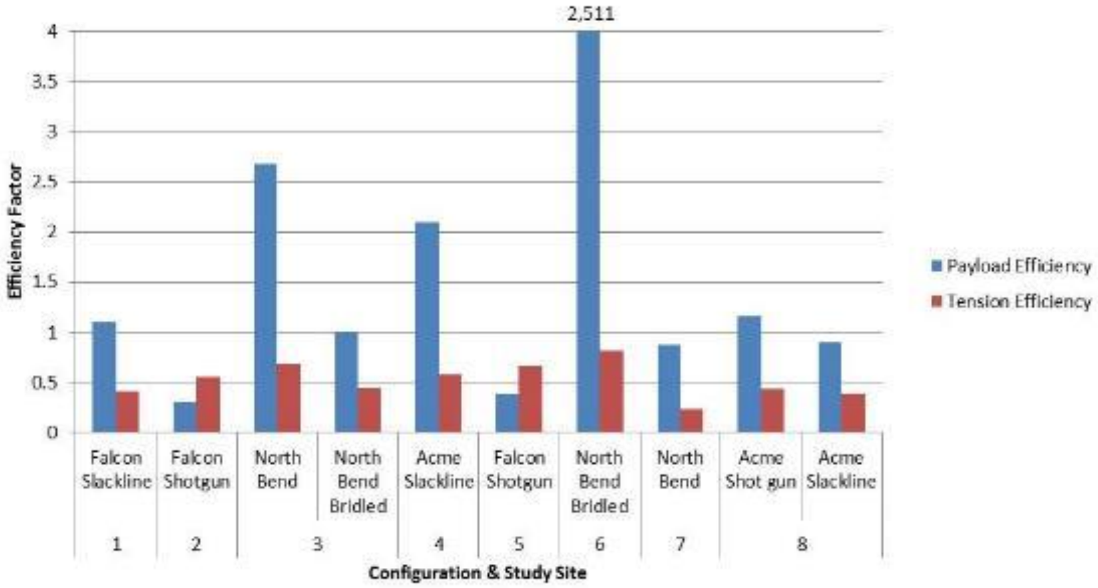

Figure 22: Average payload and tension efficiency for each configuration and study site observed

By comparing these measures side-by-side we can determine whether the payloads or tensions were limiting the configuration from achieving higher production. Results showed the greatest payload efficiencies were achieved through the use of North Bend and North Bend Bridled rigging configurations. However, these measures are inflated due to payload analysis software predicting low payloads. This is a known issue as current payload software does not have a dedicated algorithm for the North Bend and North Bend Bridled configurations – they are analysed using the standing skyline procedure (Woodruff 1984). Although they are technically a standing skyline system, the fall block and terminal functions of the mainline and haul back differ. For example the North Bend Bridled operation at Study Site 6 had minimal deflection and a blind lead area where little log suspension could be generated. The payload analysis software indicated no stems could be yarded from this area. However, the mainline and haul back were able to pull the loads along the ground at this point similar to the highlead configuration, and production continued.

Payload efficiency may never reach a factor of one for many configurations and setups, as yarder mechanics may limit their capability to lift and transport the load (Wilbanks 1985). Additionally, peak skyline tensions may deter one from maximizing payload. The more concerning trend is when payload efficiency is less than tension efficiency, which indicates that higher payloads could be achieved. The Falcon Shotgun configuration at study sites 2 and 5 showed that payload efficiency was less than tension efficiency because only 1.5 and 1.4 stems were grappled on average, resulting in payload efficiency of 0.30 and 0.39 respectively. This was compared to when two stems were grappled, payload efficiency was 0.53 and 0.47 respectively. It is interesting to note that the Falcon Slackline configuration had the opposite trend between payload and tension efficiency due to the difference in operating style as previously discussed; even though payload efficiency was above a factor of one, tension efficiency was less than 0.50. Additionally, the operating style of the Acme Slackline configuration at study site 4, where the operator was trying to partially suspend the loads, showed this technique maximized the payload efficiency while it had a relatively low tension efficiency despite exceeding the safe working load briefly during nearly every cycle.

The process of collecting data and analysing these measurements in this study has been difficult because of the cost and time of personnel required, and the time lag in analysis, interpretation of results and putting them into practice. New commercial technology such as carriage-mounted cameras, GPS units, electronic measuring devices for estimating payloads and cable tension data loggers could be retrofitted into existing yarders to provide real-time feedback to operators and new measures of efficiency.

If these data were logged and synchronized they could be used for analysis of performance and to aid in planning future operations. New technologies in terms of computers and applications are also becoming cheaper and faster in the collection and analysis of data. There is a relatively new field of “Precision Forestry,” in which operational data are collected and viewed in real time, which should aid in the understanding of the application of rigging configurations. Such integrated technologies will reduce the time and effort required for traditional data collection and analysis methods, which in turn will speed up the feedback loop back to contractors and operators to aid their decision making processes.

CONCLUSIONS

This project was conducted to compare the operational characteristics of rigging configurations used in New Zealand. Based on previous literature and studies, the most commonly used configuration (North Bend/North Bend Bridled) was studied along with other popular and newly developed configurations (Acme Shotgun/Slackline and Falcon Shotgun/Slackline). These configurations differed in terms of delay free cycle times, productivity and incurred delays, rates of labour and energy consumption and skyline tensions. These differences existed between the unique configurations and also between the variations of the configurations.

Hauler Cycle Times and Productivity

Regression equations were developed to predict hauler cycle element times and total delay-free cycle times. This analysis showed that rigging configuration was a significant variable (P-value <0.01) for predicting each element time. Total delay-free cycle time was significantly affected by haul distance, piece size and the configuration used. The shortest predicted cycle times were associated with the Falcon motorised grapple carriage in a shotgun configuration, while the largest predicted cycle times were associated with the North Bend Bridled configuration. The shotgun configurations with both the Acme slack pulling carriage and the Falcon grapple carriage were shown to have shorter cycle times than the respective slackline configurations due to the speed of gravity return outhaul. Hook time was faster with the Falcon carriage configurations as they do not involve manual choker-setters (breaker-outs) to attach logs. Unhook times were significantly different between configurations based on whether or not chokers or a grapple was used and whether or not chokers were unhooked manually or self-releasing chokers were used.

Hourly productivity varied significantly between configurations and was heavily influenced by the associated cycle time and haul volume. The highest average production rate was achieved by the Falcon Shotgun configuration (46.5 m^3/PMH), closely followed by North Bend (46.1 m^3/PMH) and Falcon Slackline (44.3 m^3/PMH). The lowest average production rate was achieved by the North Bend Bridled configuration (32.8 m^3/PMH). Although there were differences in the predicted and observed production rates, there was considerable variability in each configuration and from cycle to cycle.

Delay analysis showed that the characteristics of how each configuration is operated and the conditions under which they were studied had an effect on both the frequency and duration of delays. Having to raise the load during inhaul in a corridor with rock bluffs proved to be the most frequent delay for the Acme Shotgun configuration (90%), but resulted in very little time on average (0.02 minutes/delay). The largest delays were experienced when using the North Bend Bridled configuration because of the average length of time it took to offset haul back blocks (>20 minutes) which resulted in a machine utilisation rate of <73% (adjusted).

Labour and Energy Consumption

Labour consumption was heavily influenced by the number of workers relative to the production rate associated with each rigging configuration. Results showed that the lowest labour consumption occurred with the Falcon Shotgun configuration (0.07 man hours/m^3) due to only two workers being required and the high rate of production. Labour consumption was highest with the North Bend Bridled configuration (0.29 man hours/m^3) due to four or five workers being required and the associated low rate of production.

Energy consumption was similarly influenced by the associated productivity of each configuration. The highest rate of energy consumption occurred with the North Bend Bridled configuration (25 kW/m^3) despite this configuration not having a powered carriage. The lowest energy consumption rate was achieved by the Acme Shotgun configuration (7 kW/m^3) due to the combination of carriage and yarder having the lowest total power (kW) than other configurations while maintaining relatively high productivity. Despite having higher productivity than the Acme slack pulling carriage configurations, the increased power of the motorised grapple carriage showed the Falcon Shotgun and Falcon Slackline configurations consumed more energy.

Skyline Tensions

This study compared the skyline tension behaviour of rigging configurations used in New Zealand. These configurations differed in maximum tensions by cycle element, average cycle tensions, payload to tension relationship, dynamic behaviour and measures of payload and tension efficiency.

Peak tensions during outhaul were greatest for the Falcon Shotgun and North Bend Bridled configurations, and both configurations had similar high tensions in other cycle elements. North Bend had the lowest peak tensions for the hook element, and Falcon Shotgun had the largest due to the skyline having to lift the load for breakout. North Bend had the lowest maximum inhaul tensions, while North Bend Bridled and Acme Slackline had the largest peak inhaul tensions. North Bend Bridled had the greatest peak tensions during the unhook cycle element due to the off-setting of the haul back blocks. The Falcon Shotgun and Falcon Slackline configurations had some of the lowest peak tensions during the unhook element as the skyline is lowered before the stems are released from the grapple.

Average tension per cycle was highest with the North Bend Bridled configuration, operating at 81% of the safe working load, followed by Falcon Shotgun which operated at 63% of the safe working load per cycle. North Bend had the lowest average cycle tension but had similarly high variability in average cycle tension, as did North Bend Bridled, while other configurations had very consistent average cycle tensions.

A regression equation was developed to predict average cycle tension by rigging configuration. This showed that tension increased with increased payload and span, but also that tension was significantly affected by the amount of deflection. ANOVA tests indicated that there was a significant difference in average cycle tension between rigging configurations. The largest predicted average cycle tension was associated with the North Bend Bridled configuration, while the lowest were predicted for the Acme Slackline configuration.

A payload to tension relationship was plotted for all configurations used, which showed that skyline tension increased with decreasing deflection for the same carriage payload. Each configuration showed a positive trend in increased tension with increasing carriage payload, with the exception to North Bend Bridled which had similar high tensions regardless of carriage payload, exhibiting an almost flat trend. The Falcon Shotgun and Falcon Slackline configurations had high variability in tensions with similar carriage payload due to variability in carriage height during inhaul from cycle to cycle.

Amplification factors of skyline pretension for breakout and maximum cyclic loads were greatest for the Falcon Slackline configuration due to tensioning the skyline before breakout and partial suspension near the landing. North Bend Bridled had the lowest breakout and cyclic load amplification factors, since little force was required with the fall block purchase during breakout and because of the extra plane of force in the skyline. Hang-ups during breakout were found to nearly double the breakout factor when extracting from a gulley with the North Bend configuration. Partial suspension of logs from the back face of a canyon with the Acme Slackline configuration was found to double the cyclic load factor, while increasing inhaul time and reducing productivity with little difference to peak inhaul tension. Normal cyclic loads during outhaul but with high frequency loads of more than 3 Hz at tensions near the safe working load were a cause of the tension monitor coming un-clamped from the skyline with the Falcon Shotgun configuration.

Measures of Efficiency

Measures of payload efficiency and tension efficiency were calculated for each rigging configuration studied. Payload efficiency estimates were unusually inflated for North Bend and North Bend Bridled configurations, as payload analysis programmes do not accurately predict their payloads. A payload efficiency less than the tension efficiency, as shown with the Falcon Shotgun configuration, indicated that production could be improved if more than one stem could be grappled for inhaul. The Acme Slackline configuration showed that partially suspending the loads improved the payload efficiency, but there was a trade-off with reduced cycle time, decreased production and a higher cyclic load factor.

Conclusion Summary

This study was limited to comparing six different rigging configurations at eight different operations, over a limited number of profiles and hauler cycles measured. Limitations in the size and range of conditions in the data set limit the applications of results. Regardless, the study has shown that there are differences in the productivity and skyline tension behaviour of rigging configurations, despite their wide overlap in applications. The extent to which these configuration are best applied depends largely on the ability to predict overall efficiency on a cost per unit basis ($/m³). In order to better understand the characteristics of other rigging configurations used in New Zealand, and to estimate the efficiency of these configurations, more studies need to be undertaken.

Incorporating a dedicated routine for the North Bend configuration into existing payload analysis software will help better plan harvests using New Zealand's most common rigging configuration. Tension monitoring of all wire ropes in a configuration, collected with GPS positional data for all components in the model (i.e. carriage and haul back blocks) could help improve the payload analysis estimates by software, such that it could be modelled and planned in a 3D environment such as ArcGIS. Alternative running line tension monitors rather than clamping tension monitors used in this study could be used to measure the tensions of the other working ropes and monitor configurations employed with running skyline systems. Additionally, yarder performance capabilities could be modelled and included in payload analysis software to better predict production capability.

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APPENDIX 1

Study 1: Falcon motorised grapple carriage in a slackline configuration

Study site 1 was in Canterbury where the Falcon motorised grapple carriage in a slackline rigging configuration was observed for two days across a total of three spans (Figure 1).

Figure 1: Live skyline using Falcon motorised grapple carriage in a slackline configuration

The three skyline corridors measured were located side by side, with relatively smooth terrain and were concave in shape (Figure 2).

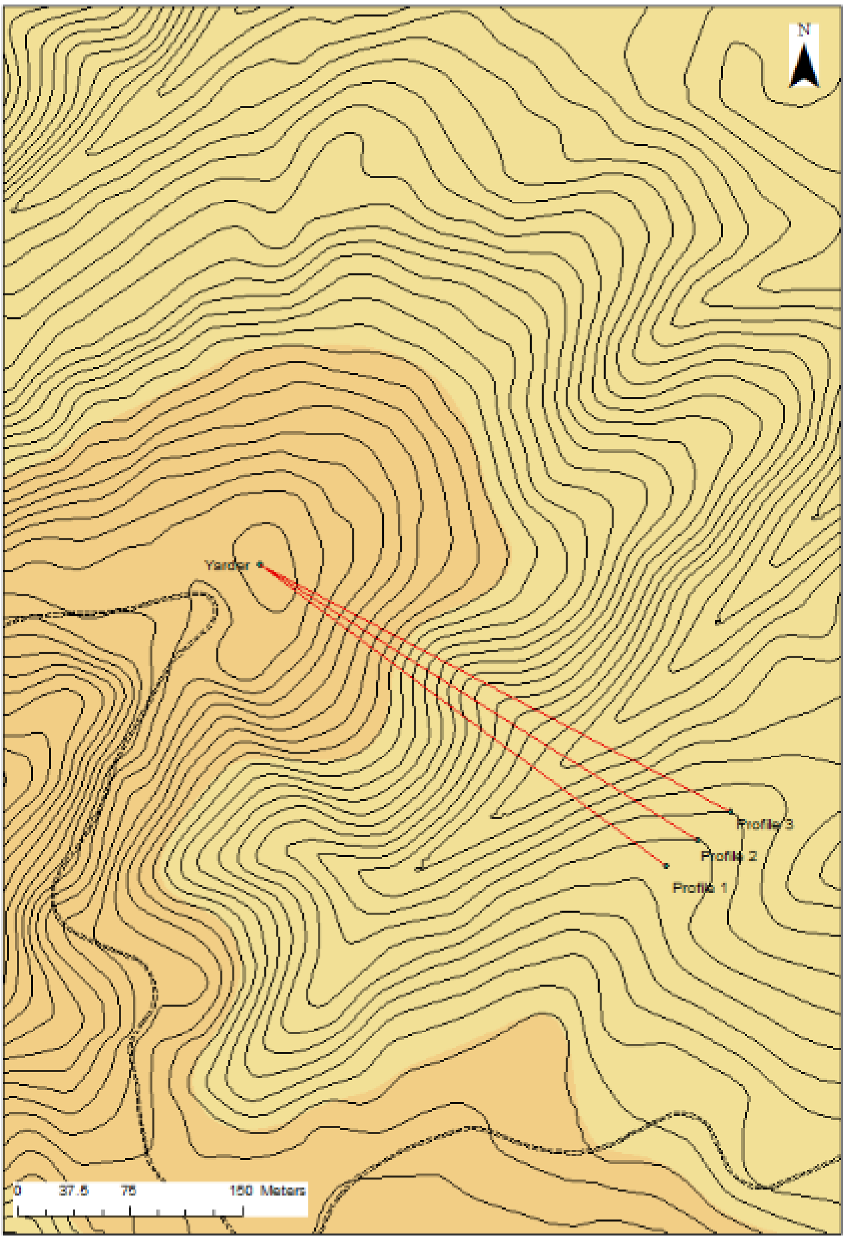


Figure 2: ArcMap 10-metre contour elevation showing profiles for payload analysis of each yarding corridor at Study Site 1 in Canterbury

In total 54 cycles were recorded and the average cycle time (2.93 minutes) and haul volume (2.23 m^3) resulted in average productivity per productive machine hour (PMH) of 46.5 m^3/PMH (Table 1).

Table 1: Summary of the 54 observed cycle times and variables at Study Site 1 in Canterbury

Cycle (#)	Corridor (#)	Outhaul (min)	Distance (m)	Hook (min)	Pieces (#)	CyclVol (m^3)	Inhaul (min)	Unhook (min)	Delays (min)	Cycle Time (min)	Productivity (m^3/PMH)
1	1	0.87	258	0.87	1	1.3	0.82	0.10	0.00	2.65	29.2
2	1	0.52	253	0.98	1	2.2	0.87	0.05	0.00	2.42	53.9
3	1	0.53	249	2.73	2	1.1	1.50	0.13	0.00	4.90	13.2
4	1	0.63	251	1.65	1	0.4	1.13	0.17	0.00	3.58	6.9
5	1	0.67	266	0.87	2	2.5	1.03	0.12	0.48	2.68	55.5
6	1	0.48	265	1.03	1	1.3	0.87	0.12	0.53	2.50	30.5
7	1	0.72	262	0.97	2	0.3	1.17	0.17	0.00	3.02	5.6
8	1	0.75	259	1.00	2	1.9	0.98	0.15	0.00	2.88	40.0
9	1	0.45	110	0.58	1	0.5	1.27	0.17	1.92	2.46	11.9
10	1	0.75	257	0.93	3	0.9	1.23	0.10	0.00	3.02	18.5
11	1	0.63	257	0.87	2	1.8	1.48	0.13	0.00	3.12	35.0
12	1	0.68	275	0.78	1	3.3	1.02	0.10	0.00	2.58	75.9
13	1	0.72	257	1.75	4	2.5	1.72	0.17	0.00	4.35	34.1
14	1	0.73	267	2.52	2	5.0	0.85	0.17	0.00	4.27	70.3
15	2	0.55	130	0.72	1	1.5	0.57	0.10	0.00	1.93	46.6
16	2	0.28	127	0.80	1	1.9	0.45	0.12	0.00	1.65	69.8
17	2	0.30	150	1.32	1	3.5	0.65	0.23	0.00	2.50	83.8
18	2	0.27	118	2.38	2	4.3	1.50	0.10	1.05	4.25	61.3
19	2	0.45	153	1.17	2	1.7	0.68	0.12	0.00	2.42	42.5
20	2	0.43	94	0.63	1	2.2	0.37	0.15	0.00	1.58	82.2
21	2	0.43	157	1.05	1	0.6	0.75	0.10	0.00	2.33	16.2
22	2	0.32	149	0.62	1	2.4	0.85	0.08	1.37	1.87	76.0
23	2	0.43	158	1.43	2	3.1	0.57	0.18	0.00	2.62	72.0
24	2	0.25	170	2.83	1	3.2	1.65	0.10	1.70	4.83	39.8
25	2	0.40	159	1.57	1	3.3	0.72	0.25	0.18	2.93	68.1
26	2	0.38	174	2.07	1	0.2	0.95	0.22	0.00	3.62	4.0
27	2	0.42	183	1.70	1	0.2	0.72	0.13	0.00	2.97	4.0
28	2	0.62	180	0.95	1	3.7	1.60	0.27	0.00	3.43	64.8
29	2	0.50	189	0.82	1	3.5	0.72	0.10	0.00	2.13	97.6
30	2	0.35	195	0.90	1	2.2	0.92	0.15	0.00	2.32	56.2
31	2	0.55	214	0.88	1	2.2	0.83	0.12	0.00	2.38	54.6
32	2	0.42	245	1.03	1	0.8	0.93	0.10	0.00	2.48	18.6
33	2	0.42	233	1.10	1	2.2	1.27	0.15	1.32	2.93	44.4
34	2	0.57	224	0.55	1	2.2	0.98	0.20	0.00	2.30	56.6
35	2	0.53	238	1.15	2	4.3	1.87	0.18	0.00	3.73	69.8
36	2	0.62	244	0.70	1	2.2	1.72	0.17	1.17	3.20	40.7
37	2	0.47	247	1.00	1	0.4	0.87	0.12	0.00	2.45	10.5
38	2	0.42	243	1.63	1	0.4	0.87	0.12	0.00	3.03	8.5
39	2	0.60	200	1.23	2	2.6	1.85	0.12	0.12	3.80	41.1
40	2	0.87	236	1.92	2	2.9	1.35	0.18	0.00	4.32	40.9
41	3	0.57	216	0.63	1	1.5	0.90	0.13	0.00	2.23	39.0
42	3	0.48	204	0.72	1	1.6	0.75	0.12	0.00	2.07	46.2
43	3	0.55	219	0.63	2	0.6	0.70	0.07	0.57	1.95	18.2
44	3	0.40	235	1.13	1	2.1	1.17	0.12	0.00	2.82	45.4
45	3	0.62	239	1.00	2	2.9	0.85	0.12	0.00	2.58	68.3
46	3	0.60	236	0.80	2	2.8	1.37	0.12	0.00	2.88	58.1
47	3	0.50	225	0.73	1	1.9	1.23	0.20	1.57	2.67	41.9
48	3	0.55	247	1.45	2	5.6	2.00	0.13	0.00	4.13	81.7
49	3	0.65	258	1.35	1	3.4	1.35	0.15	0.00	3.50	59.0
50	3	0.92	260	0.82	1	3.4	1.18	0.15	1.42	3.07	65.5
51	3	0.65	272	1.07	1	2.6	1.17	0.12	0.00	3.00	52.6
52	3	0.48	268	1.63	1	5.8	1.45	0.13	2.65	3.70	93.7
53	3	0.68	263	0.77	2	1.7	0.87	0.10	0.00	2.42	43.0
54	3	0.57	273	1.08	1	2.1	0.97	0.13	0.00	2.75	45.2
Min		**0.25**	**94**	**0.55**	**1.0**	**0.20**	**0.37**	**0.05**	**0.00**	**1.58**	**4.0**
Max		**0.92**	**275**	**2.83**	**4.0**	**5.78**	**2.00**	**0.27**	**2.65**	**4.90**	**97.6**
Avg		**0.54**	**217**	**1.18**	**1.4**	**2.23**	**1.08**	**0.14**	**0.30**	**2.93**	**46.5**
SD		**0.15**	**49**	**0.55**	**0.6**	**1.33**	**0.38**	**0.04**	**0.62**	**0.78**	**24.5**

Payload analysis indicated that the limiting payload located at mid-span was 1.9 tonnes, 1.7 tonnes and 2.4 tonnes for profiles 1-3, respectively (Figure 3). The yarder operator had a skyline tension monitor with display unit operating, and the safe working load (21.3 tonnes) was exceeded during 21 of the 54 cycles (39% frequency).

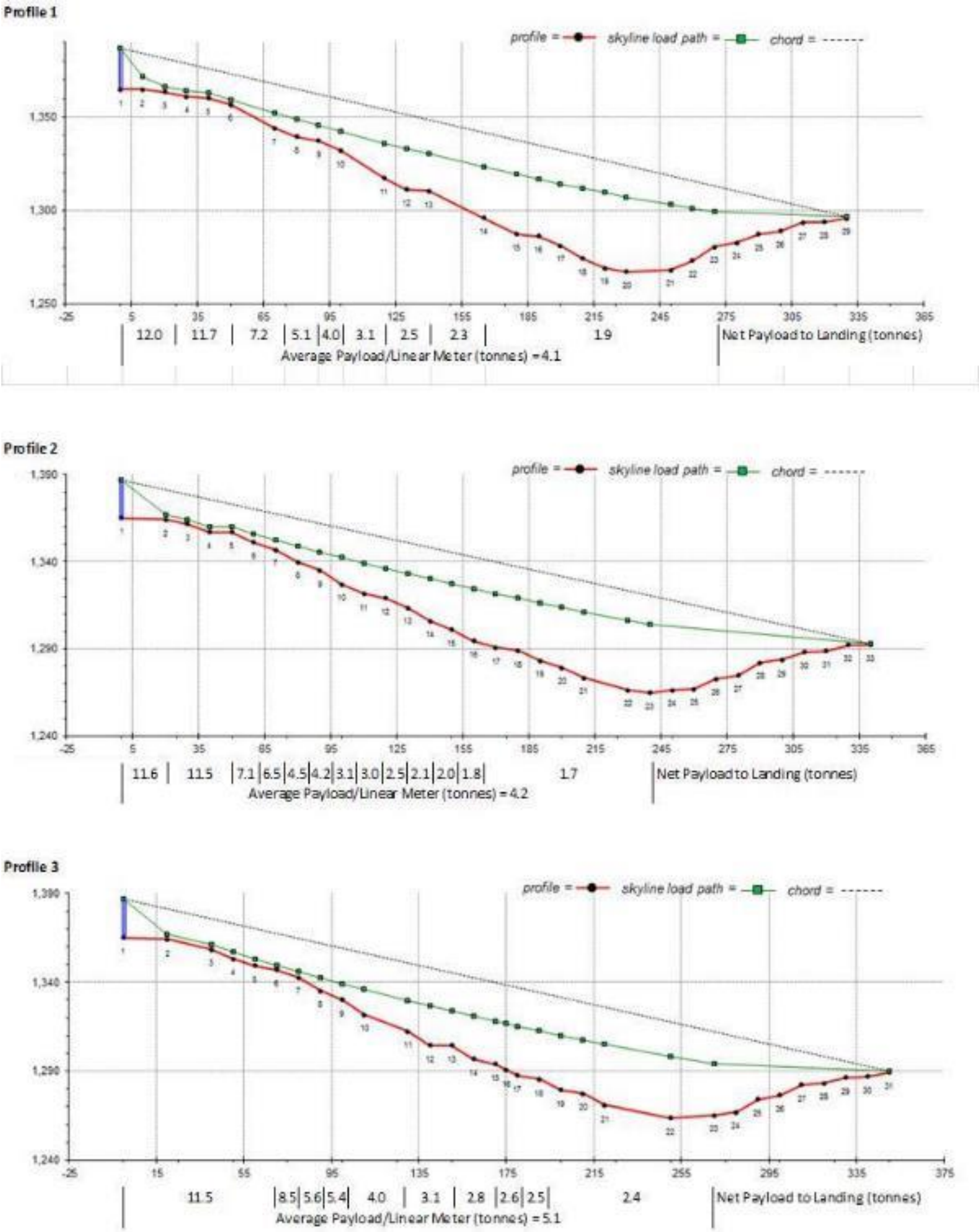


Figure 3: SkylineXL profile and payload analysis results for the Falcon Slackline operation

Cycles 1-14 were recorded along the first profile, of which four cycles exceeded the safe working load (21.3 tonnes, 209 kN), either during inhaul or both hook and inhaul elements (Figure 4). The high tension behaviour during the hook element, and carrying over into the inhaul element was due to how the configuration was operated. During each cycle, after the stems were grappled by the carriage, the skyline was tensioned to raise the carriage before inhaul, so that there was adequate clearance when the load approached the landing. The technique described facilitates fast inhaul speeds but at the sacrifice of increased skyline tension, even when transporting small loads. The maximum hook tension occurred during cycle 9, which transported a small load (0.5 tonnes) compared to cycle 14 which carried a large load (5.0 tonnes). The maximum inhaul tensions occurred during cycles 13 and 14 where payloads of 2.5 and 5.0 tonnes both exceeded the calculated limiting payload of 1.9 tonnes.

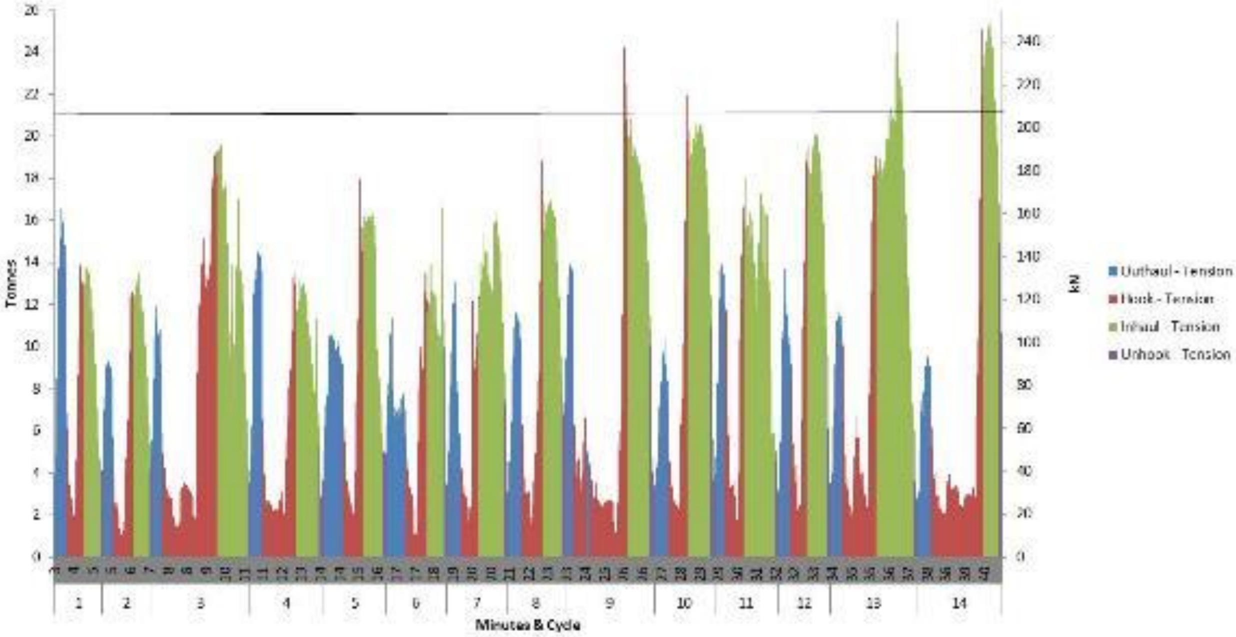


Figure 4: Skyline tensions for profile 1, cycles 1-14, Falcon Slackline configuration

Cycles 15 to 40 were recorded along the second profile which had less available deflection (5.9%), than the first profile, and therefore had higher maximum tensions which often exceeded the safe working load (Figure 5). The extraction distance for each cycle gradually increased as the carriage worked towards mid-span. However, the cycles extracted close to mid-span did not appear to generate higher skyline tensions, and there was considerable variation in tensions between cycles. The variation in tensions during hook and inhaul again highlight the variability in carriage height obtained through tensioning the skyline before inhaul.

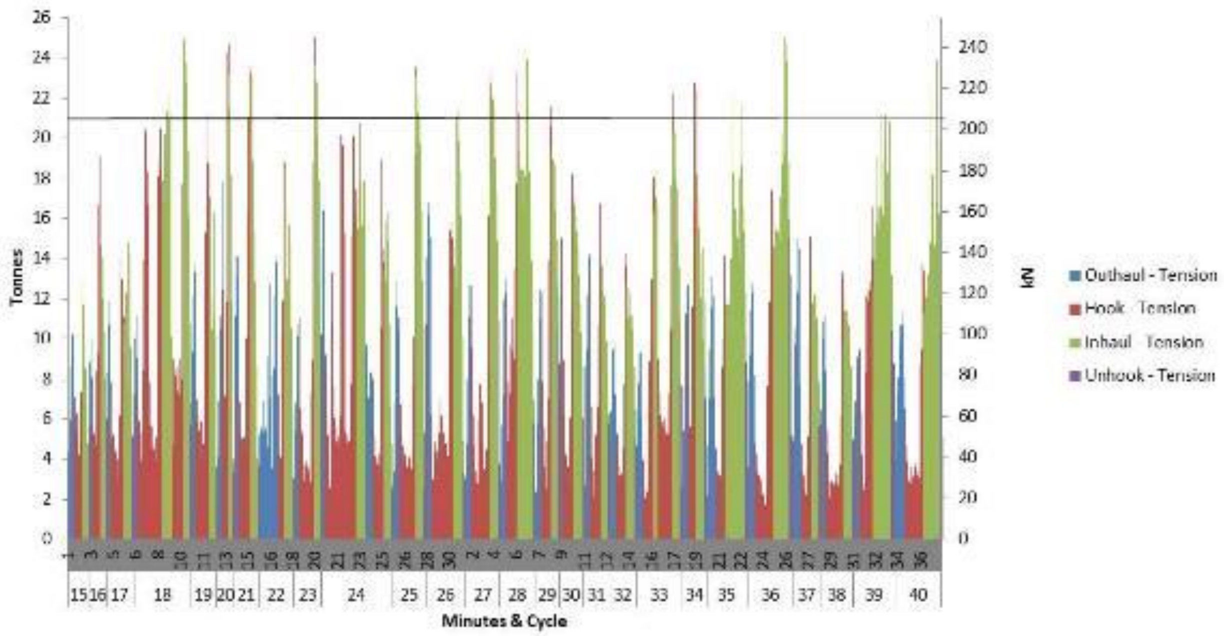


Figure 5: Skyline tensions for profile 2, cycles 15-40, Falcon Slackline configuration

In the third profile observed at this study site, cycles 41-54 were recorded (Figure 6). The deflection was greater (7.4%) than the second profile as indicated by the lower maximum tensions recorded, where only four cycles exceeded the safe working load. It is interesting to note the high peak tensions during outhaul with this configuration for all cycles observed (average 12.9 tonnes), compared to the low skyline pretension observed during the unhook element (approximately 4 tonnes). The high outhaul peak tensions appear just as variable as the inhaul peak tensions, because the skyline is tensioned in the same way to raise the carriage for clearance near the landing, in addition to the empty carriage weight of over two tonnes.

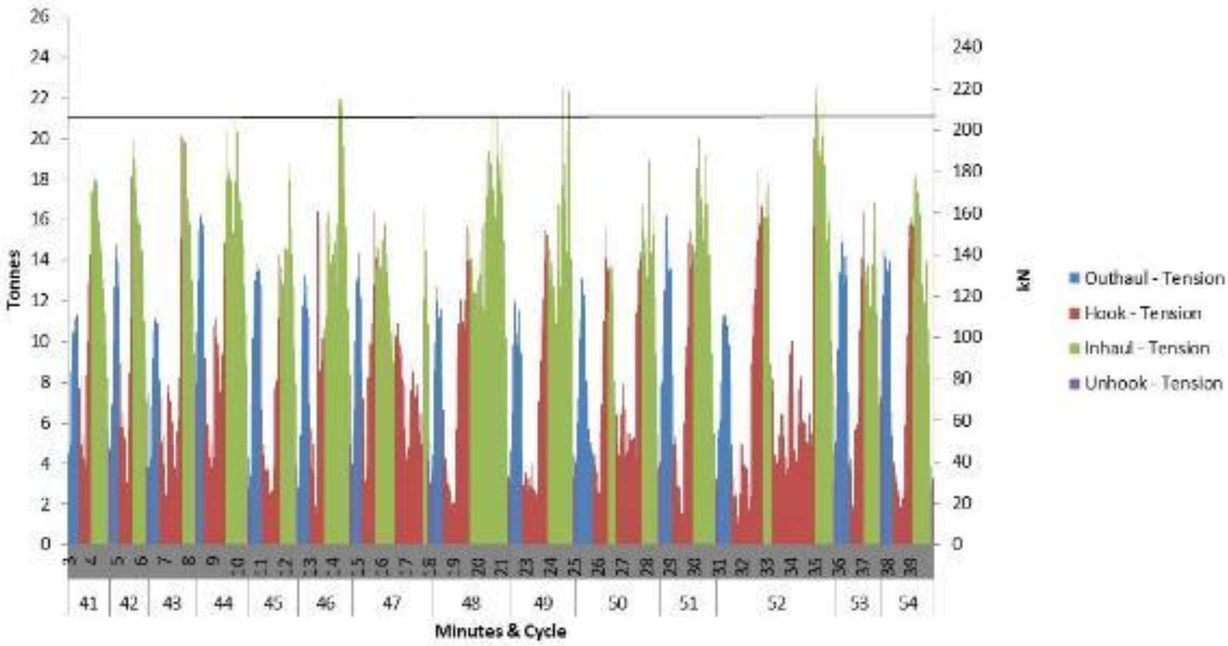


Figure 6: Skyline tensions for profile 3, cycles 41-54, Falcon Slackline configuration

APPENDIX 2

Study 2: Falcon motorised grapple carriage in a shotgun configuration

The operation at study site 2 in Nelson was observed for one day across two spans. The Falcon motorised grapple carriage in a shotgun rigging configuration was the only configuration in use at this study site (Figure 1).

Figure 1: Live skyline using Falcon motorised grapple carriage in a shotgun configuration

The adjacent corridors had relatively smooth terrain, were steep and straight to slightly concave in shape, and the anchor was placed on a slight ridge to provide deflection (Figure 2).

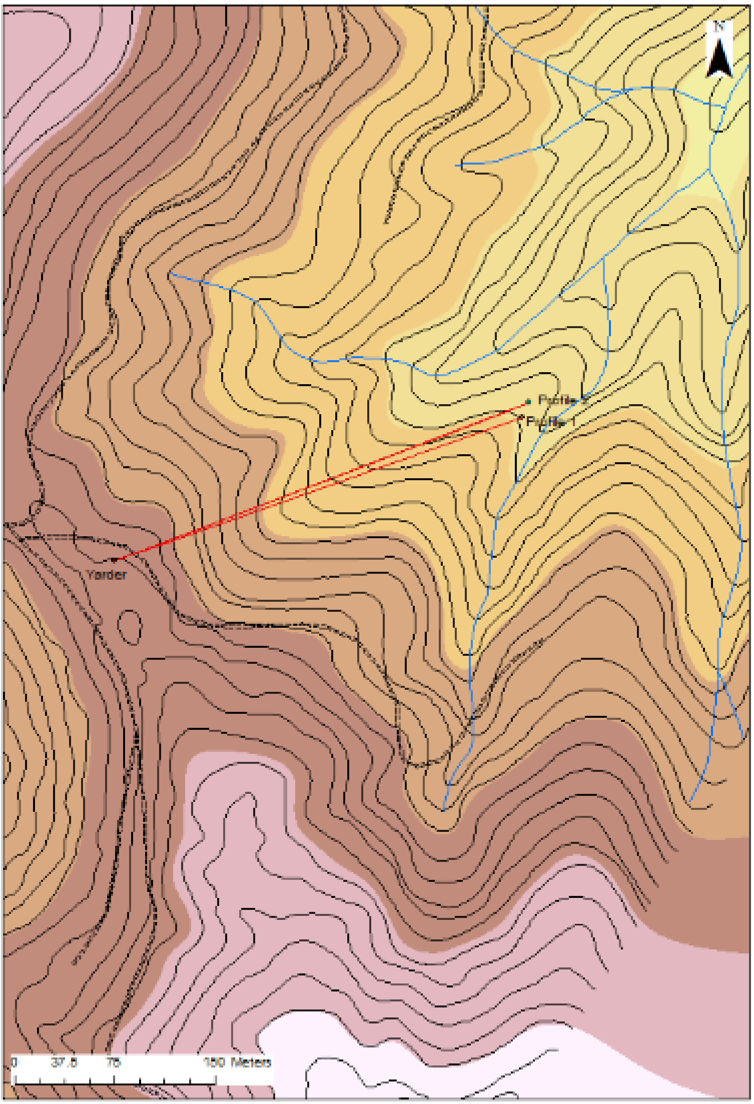


Figure 2: ArcMap 10-metre contour elevation showing profiles for payload analysis of each yarding corridor at Study Site 2 in Nelson

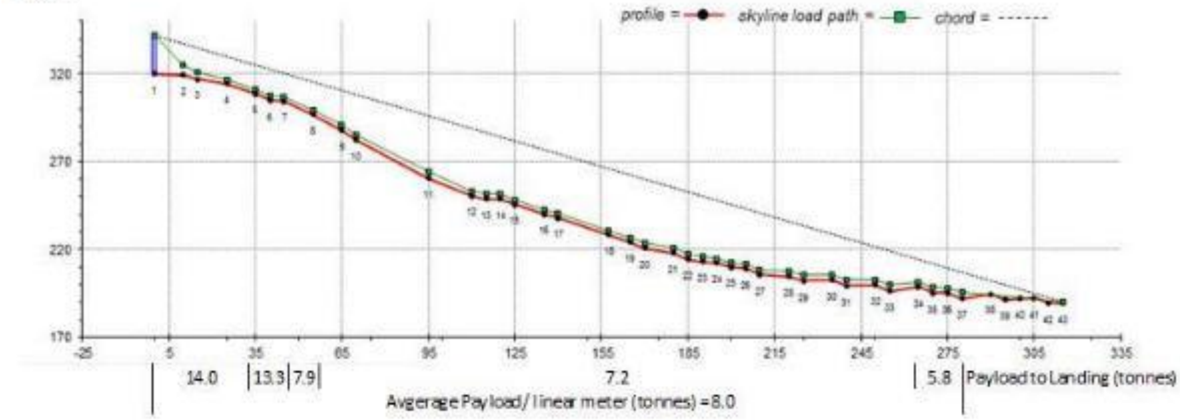
In total, 31 cycles were recorded (Table 1). The average cycle time of 2.20 minutes and haul volume of 2.09 m³ resulted in average productivity of 56.8 m³/PMH.

Table 1: Summary of the 31 observed cycle times and variables at Study Site 2 in Nelson

Cycle (#)	Corridor (#)	Outhaul (min)	Distance (m)	Hook (min)	Pieces (#)	CyclVol (m^3)	Inhaul (min)	Unhook (min)	Delays (min)	Cycle Time (min)	Productivity (m^3/PMH)
1	1	0.27	138	0.73	2	4.2	0.70	0.22	0.00	1.92	130.9
2	1	0.37	213	1.13	1	2.0	0.73	0.15	0.00	2.38	50.9
3	1	0.37	206	0.83	3	3.7	0.75	0.15	0.00	2.10	105.1
4	1	0.37	202	2.33	2	0.9	0.95	0.15	0.00	3.80	14.2
5	1	0.35	153	0.65	2	0.5	0.47	0.17	29.38	1.63	18.0
6	1	0.12	170	0.72	2	2.6	1.30	0.17	0.00	2.30	66.8
7	1	0.30	208	0.90	0	1.6	0.78	0.12	1.32	2.10	44.9
8	1	0.28	202	1.55	1	2.5	0.77	0.15	0.00	2.75	54.8
9	1	0.38	232	0.28	1	0.8	0.70	0.12	0.00	1.48	31.1
10	1	0.35	208	0.48	1	1.4	0.67	0.13	0.00	1.63	50.0
11	1	0.43	269	0.72	2	1.2	0.73	0.15	0.00	2.03	35.1
12	1	0.35	242	1.07	2	3.1	0.75	0.22	0.00	2.38	79.0
13	1	0.30	263	1.08	2	1.4	0.62	0.12	0.00	2.12	40.5
14	1	0.35	213	0.50	1	0.9	0.67	0.18	0.00	1.70	30.7
15	1	0.40	272	1.07	2	1.6	0.85	0.15	0.00	2.47	39.9
16	1	0.25	273	0.87	2	3.8	1.05	0.17	0.00	2.33	97.7
17	1	0.37	291	1.03	2	4.0	0.98	0.10	3.90	2.48	97.6
18	2	0.38	223	0.57	1	1.3	1.00	0.13	0.00	2.08	38.0
19	2	0.35	218	0.80	1	1.9	0.97	0.17	0.00	2.28	50.2
20	2	0.37	242	0.57	1	1.9	0.80	0.18	0.00	1.92	60.7
21	2	0.37	234	0.38	2	0.9	0.77	0.18	0.00	1.70	31.1
22	2	0.37	224	0.43	2	1.7	1.00	0.18	0.00	1.98	51.1
23	2	0.32	220	0.35	2	3.7	1.07	0.17	0.13	1.90	115.6
24	2	0.42	252	0.90	1	3.7	0.63	0.15	0.00	2.10	104.6
25	2	0.37	250	0.78	1	1.4	0.97	0.17	0.00	2.28	37.8
26	2	0.38	225	0.75	2	3.4	1.03	0.15	0.00	2.32	88.6
27	2	0.42	257	0.55	1	0.6	0.80	0.20	0.00	1.97	19.2
28	2	0.35	205	1.55	2	3.4	0.97	0.25	0.00	3.12	65.5
29	2	0.42	210	0.48	1	0.3	0.95	0.17	4.73	2.02	7.7
30	2	0.40	193	0.90	1	1.2	0.58	0.18	2.38	2.07	35.4
31	2	0.33	253	1.48	1	3.2	0.92	0.10	0.00	2.83	67.6
Min		**0.12**	**138**	**0.28**	**0.0**	**0.26**	**0.47**	**0.10**	**0.00**	**1.48**	**7.7**
Max		**0.43**	**291**	**2.33**	**3.0**	**4.18**	**1.30**	**0.25**	**29.38**	**3.80**	**130.9**
Avg		**0.35**	**225**	**0.85**	**1.5**	**2.09**	**0.84**	**0.16**	**1.35**	**2.20**	**56.8**
SD		**0.06**	**35**	**0.43**	**0.6**	**1.20**	**0.18**	**0.03**	**5.33**	**0.47**	**31.8**

Payload analysis indicated that the limiting payloads of 7.2 tonnes and 7.3 tonnes were located at mid-span for profiles 1 and 2 respectively (Figure 3). The yarder operator had a skyline tension monitor with display unit, and the safe working load (21.3 tonnes) was exceeded during 20 of the 31 cycles (65% frequency).

Profile 1



Profile 2

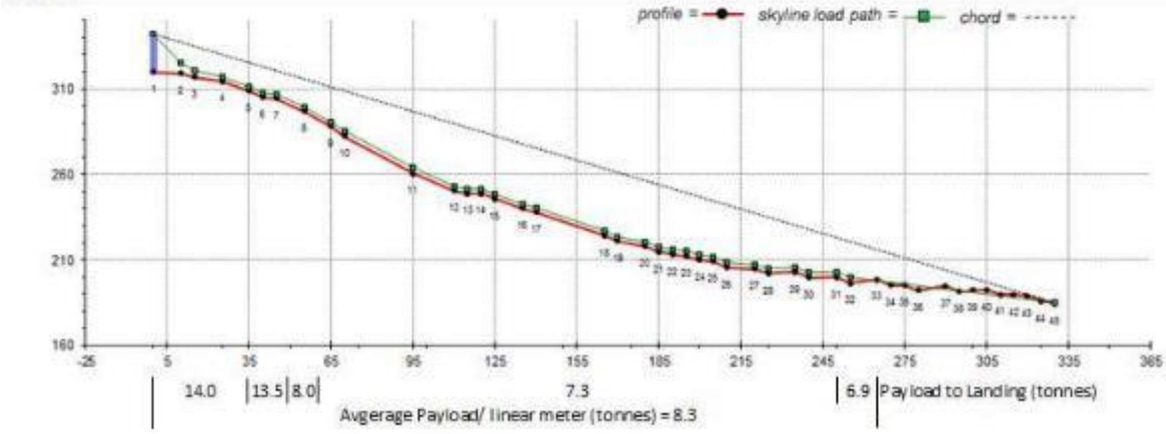


Figure 3: SkylineXL profile and payload analysis results for the Falcon Shotgun operation

Cycles 1-17 were recorded along profile 1, of which 10 cycles exceeded the safe working load of 21.3 tonnes, or 209 kN (Figure 4). Skyline tensions exhibited similar behaviour to the Falcon Slackline configuration at Study Site 1, with high tensions observed during the hook and inhaul elements of the cycle. However, the configuration was operated differently than the first study site, whereby the skyline was tensioned to lift the carriage and logs only to what was adequate to start inhaul.

Once inhaul commenced, one or more skyline “lifts” (i.e. further tensioning of the skyline) were performed to achieve clearance over terrain before arriving at the landing. In other words, the operator was trying to mirror the ground slope with the carriage during inhaul in an attempt to maximize deflection, most likely due to the poor available deflection of (5.7%). The steep chord slope (-47 %) allowed fast outhaul of the carriage (0.3 to 0.4 minutes) compared to Study Site 1 even over similar distances.

There were some issues with stems slipping out of the carriage grapple during inhaul, as evident in cycle 7, where the stem was re-grappled before inhaul continued. Maximum tensions during outhaul were high (average 17 tonnes) compared to the skyline pretension (approx. 4 tonnes), and the highest (21.2 tonnes) was recorded during cycle 16. This high tension, probably together with the high frequency vibration, knocked the tension monitor off the skyline when the carriage came within 25 metres of the anchor machine.

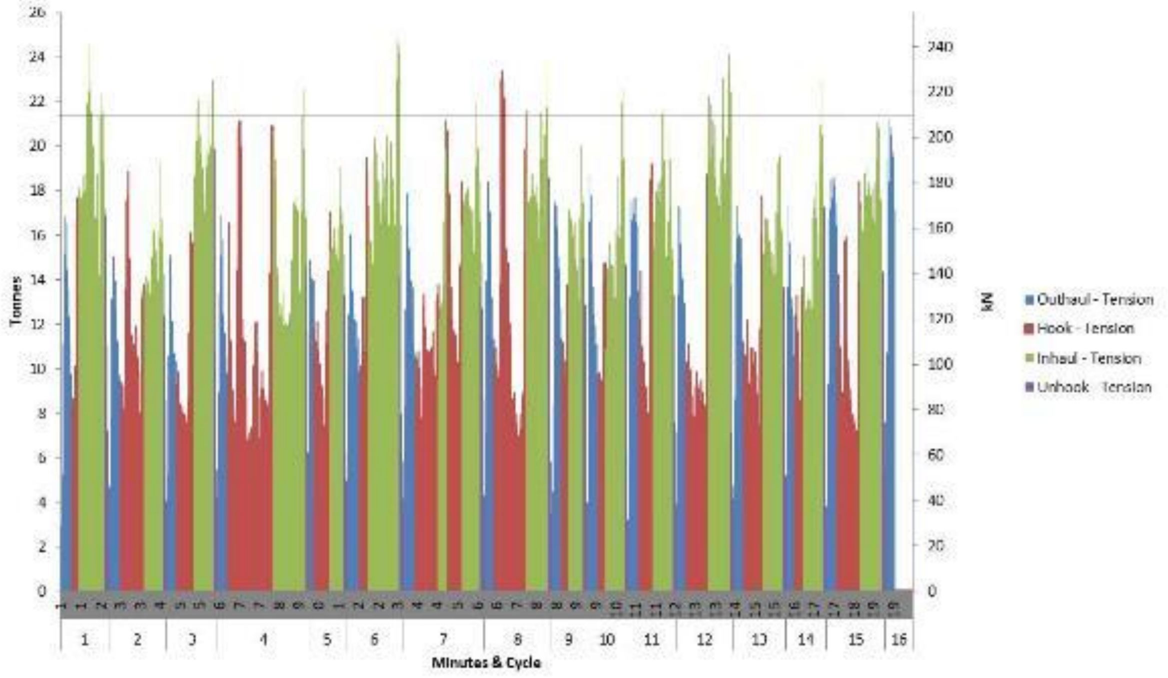


Figure 4: Skyline tensions for profile 1, cycles 1-16, Falcon Shotgun configuration

A skyline shift allowed the tension monitor to be reconnected to the skyline, and tension monitoring resumed for cycles 18 to 31 which were all recorded across the second profile (Figure 5). Delays recorded during cycles 29 and 30 were due to checking the carriage hydraulic oil and refuelling the carriage. Similar problems existed with stems slipping out of the grapple and having to be re-grappled as evident in cycle 29. It is also interesting to note, in comparison to Study Site 1, the high cyclic loading which occurred during inhaul in both profile 1 and 2. The cyclic loading indicated by the peak to peak differences in tension are a result of the different operating procedures; where the stems had more ground contact during inhaul at Study Site 2.

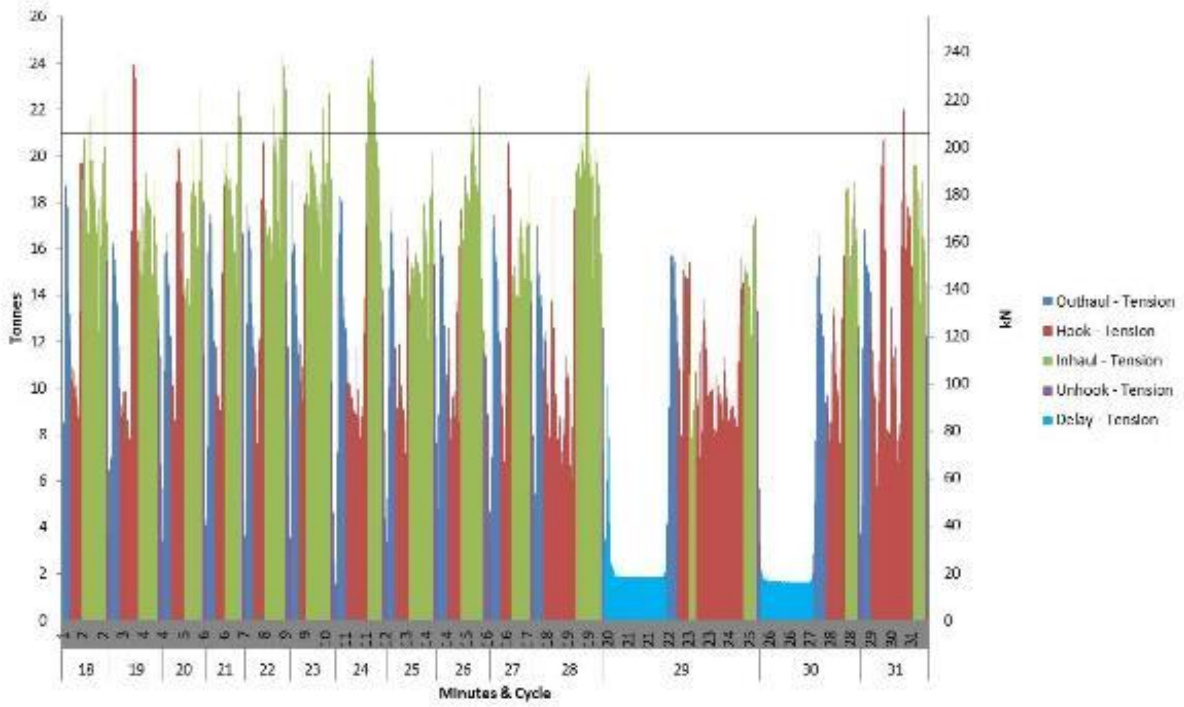


Figure 5: Skyline tensions for profile 2, cycles 18-31, Falcon Shotgun configuration

APPENDIX 3

Study 3: North Bend and North Bend Bridled configurations

The operation at Study Site 3 in Gisborne was observed for two days across two long spans of over 900 m. Butt rigging with a rider and fall block in both North Bend & North Bend Bridled configurations was used (Figure 1).

Figure 1: Standing skyline using North Bend & North Bend Bridled configurations

The corridors were located next to one another over steep and broken terrain, and the anchor was situated on the other side of the valley to provide deflection (Figure 2). North Bend was the primary configuration used at this site. However, topography in an area located close to the yarder but off-set laterally (>100 m) did not provide an adequate anchor location. In order to reach stems in this difficult area without being able to move the skyline required the use of the North Bend Bridled configuration.

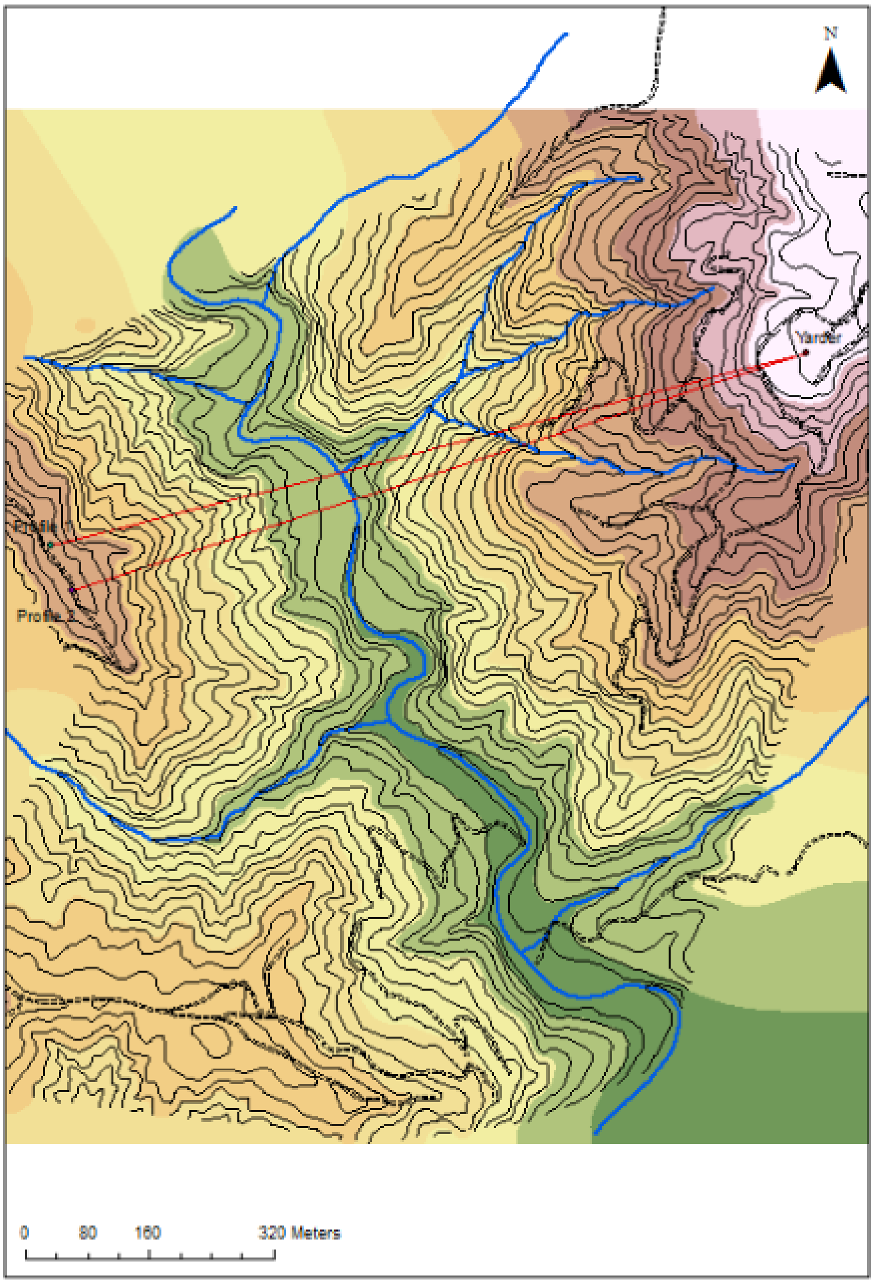
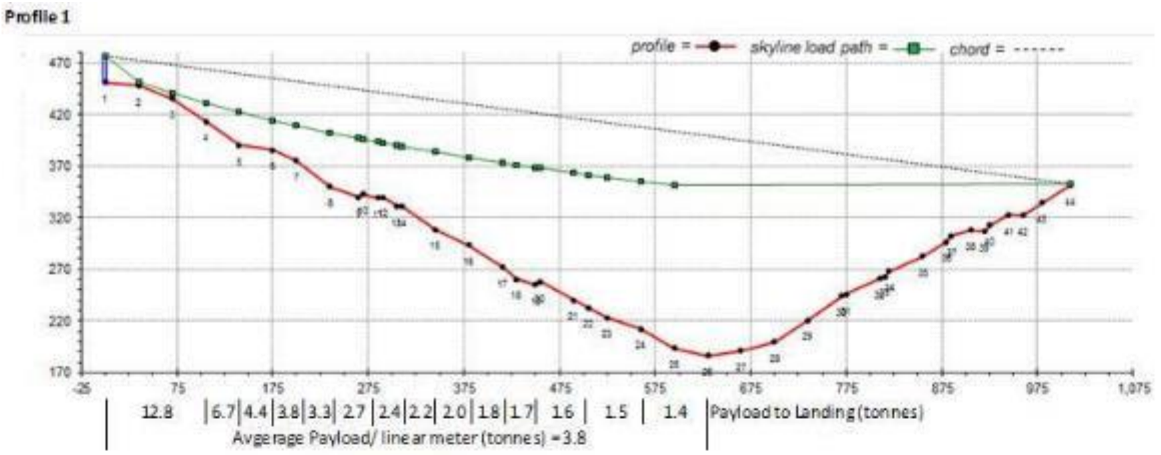


Figure 2: ArcMap 10-metre contour elevation showing profiles for payload analysis of both yarding corridors observed at Study Site 3 in Gisborne

In total, only 19 cycles were recorded at Study Site 3. Significant delays in the operation on both study days did not provide the opportunity to collect the desired minimum 30 cycles. The average cycle time of 9.60 minutes and average haul volume of 6.5 m^3 resulted in average productivity of 45.5 m^3/PMH (Table 1).

Table 1: Summary of the 19 observed cycle times and variables at Study Site 3 in Gisborne

Cycle (#)	Corridor (#)	Outhaul (min)	Distance (m)	Hook (min)	Pieces (#)	CyclVol (m³)	Inhaul (min)	Unhook (min)	Delays (min)	Cycle Time (min)	Productivity (m³/PMH)
1	1	1.48	245	5.93	4	6.5	1.42	1.83	0.00	10.67	36.5
2	1	0.52	250	2.33	3	7.0	1.23	0.58	0.00	4.67	90.3
3	1	1.23	240	3.43	3	6.0	1.12	0.87	0.00	6.65	53.8
4	1	1.02	250	2.57	4	9.3	1.67	0.82	0.00	6.07	91.7
5	1	1.58	285	3.75	3	8.7	2.18	1.13	0.00	8.65	60.3
6	1	1.93	285	3.70	3	8.3	2.72	0.87	0.00	9.22	54.2
7	1	1.20	260	3.77	3	5.0	1.43	3.85	0.00	10.25	29.4
8	1	1.28	260	5.72	4	6.9	2.35	3.15	0.00	12.50	33.1
9	1	0.57	290	5.03	4	7.8	1.57	1.60	0.00	8.77	53.3
10	1	4.17	300	3.93	3	6.2	2.70	0.57	0.00	11.37	32.9
11	1	1.13	310	1.58	2	6.5	3.00	0.75	10.17	6.47	60.7
12	1	1.75	310	3.48	2	4.2	2.40	0.87	0.00	8.50	29.5
13	1	1.28	310	12.47	2	6.9	2.07	2.43	0.00	18.25	22.7
14	1	2.45	320	6.10	2	4.8	5.93	0.25	9.58	14.73	19.6
15	2	1.33	100	3.43	1	3.6	1.03	0.48	2.90	6.28	34.8
16	2	1.12	100	5.80	2	5.8	1.17	1.43	46.65	9.52	36.6
17	2	4.38	120	4.80	3	8.7	1.58	1.08	0.00	11.85	44.1
18	2	1.13	140	3.10	2	5.8	1.78	0.88	0.00	6.90	50.4
19	2	1.42	160	6.52	2	5.8	2.35	0.80	0.00	11.08	31.4
Min		**0.52**	**100**	**1.58**	**1.0**	**3.6**	**1.03**	**0.25**	**0.00**	**4.67**	**19.6**
Max		**4.38**	**320**	**12.47**	**4.0**	**9.3**	**5.93**	**3.85**	**46.65**	**18.25**	**91.7**
Avg		**1.63**	**239**	**4.60**	**2.7**	**6.5**	**2.09**	**1.28**	**3.65**	**9.60**	**45.5**
SD		**1.03**	**75**	**2.35**	**0.9**	**1.6**	**1.10**	**0.94**	**10.87**	**3.32**	**20.2**



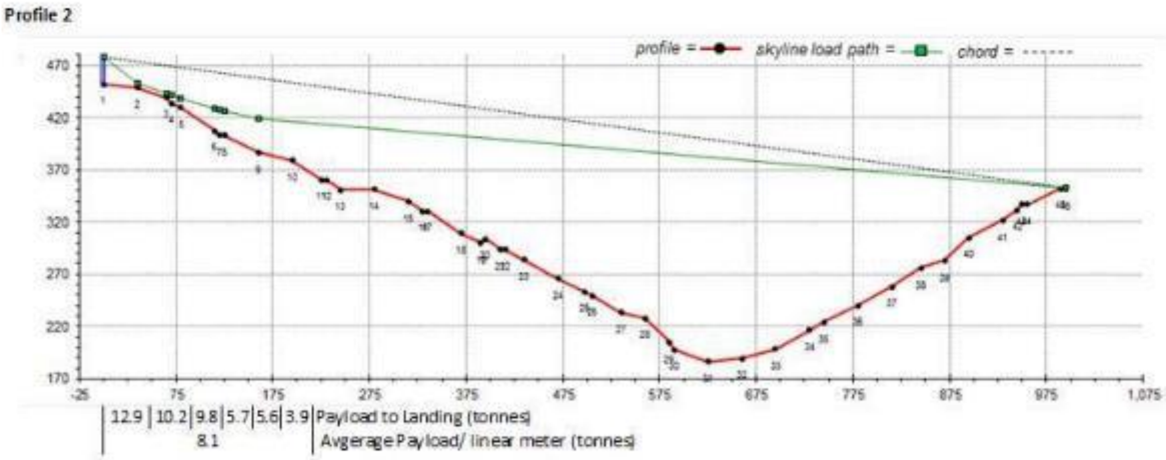


Figure 3: SkylineXL profile and payload analysis results for the North Bend and North Bend Bridled operations

Payload analysis indicated that the limiting payload for profile 1 was 1.4 tonnes and was located at mid-span, while the limiting payload for profile 2 was 3.9 tonnes, located at the extent of yarding distance (Figure 3). The yarder operator did not have a skyline tension monitor with display unit, and the safe working load (21.3 tonnes) was exceeded during 14 of the 19 cycles (74% frequency).

Cycles 1-9 were recorded on the first day of the operation, and were all from profile 1 while the North Bend configuration was used (Figure 4). Skyline tensions in this setup were relatively high in all elements of the cycle, and each of the nine cycles exceeded the safe working load of 21.3 tonnes (209 kN). The high pretention in the skyline (13-14 tonnes) was apparent by the minimum tension occurring during the unhook element. The high pretension was likely a function of the weight of the skyline and operating cables having to be suspended across the >900 metre span length, with the low associated deflection (5.2%).

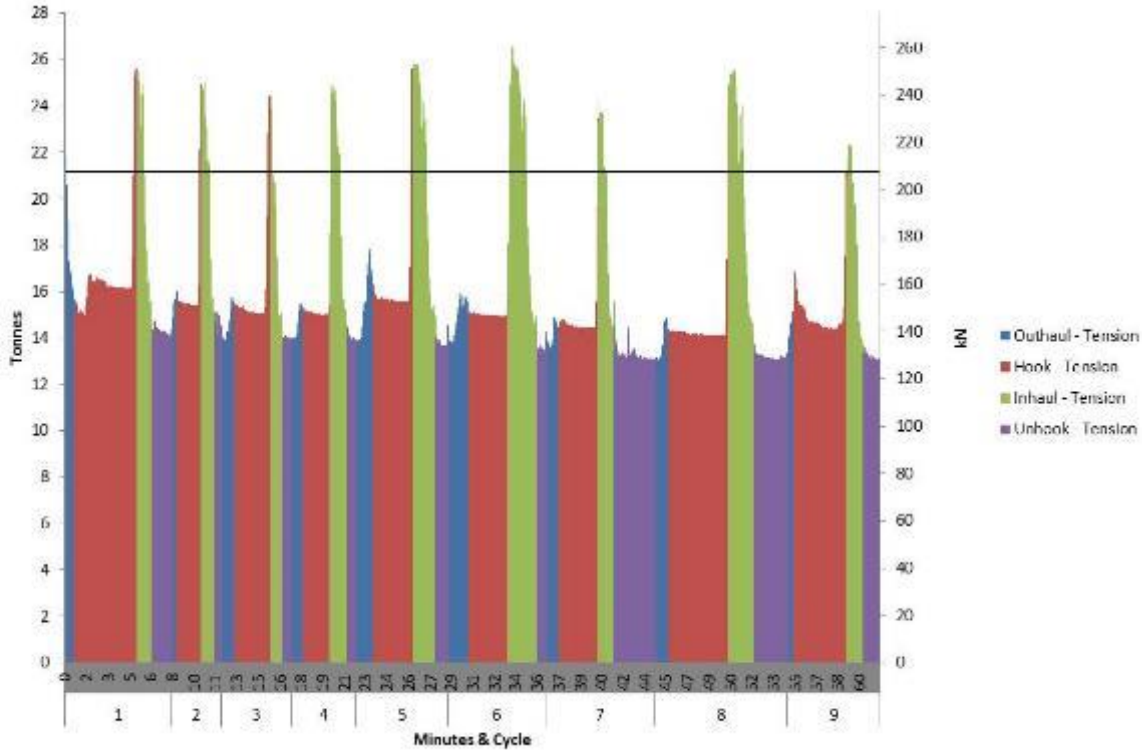


Figure 4: Skyline tensions for profile 1, cycles 1-9, North Bend configuration

Yarding resumed the following day across the first span, with cycles 10-14 (Figure 5). Peak tensions during inhaul exceeded the safe working load on four out of the five cycles. Low deflection and a blind lead area caused hang-ups during inhaul, where stems had to be unhooked, as indicated by the several minutes of delay in cycles 11 and 14. The hang-up in cycle 14 caused the mainline to disconnect from the carriage. A skyline shift to profile 2 occurred during this period of down time.

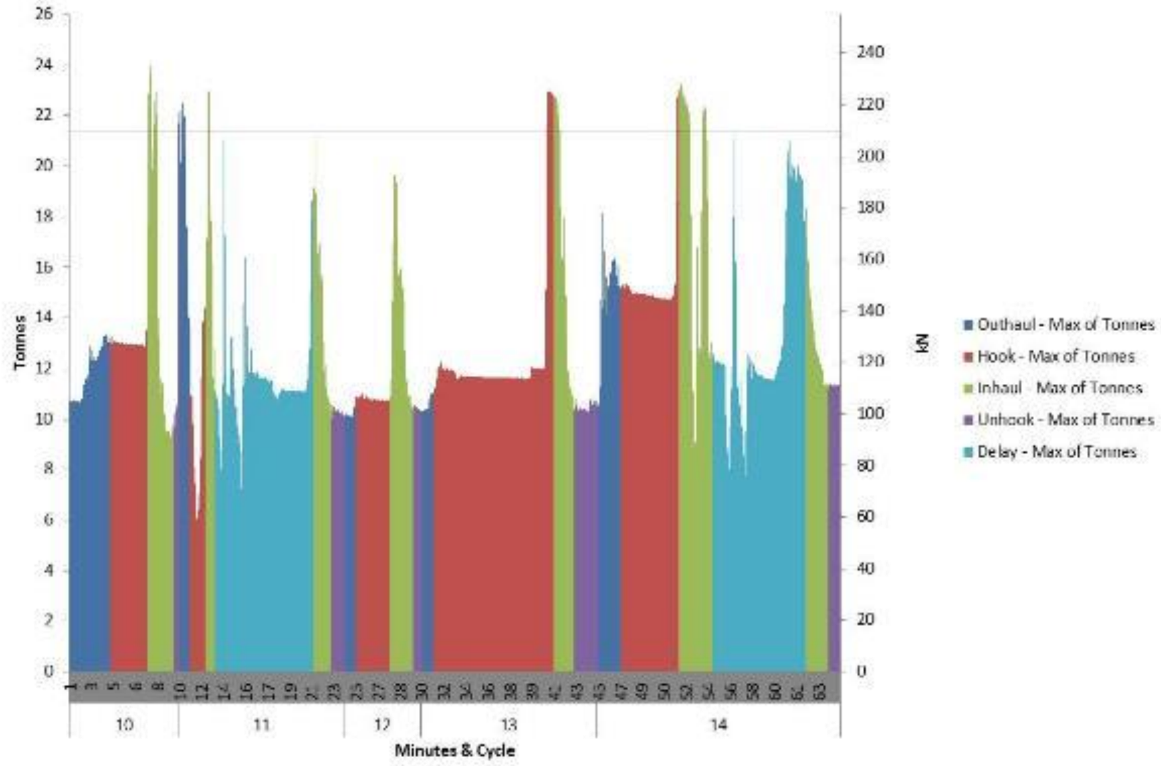


Figure 5: Skyline tensions for profile 1, cycles 10-14, North Bend configuration

After the skyline shift to profile 2 occurred, the configuration was changed to North Bend Bridled for cycles 15-19. The haul back blocks were placed just below the road due south of the yarder (as shown in Figure 2). Cycle 15 was the first using the North Bend Bridled configuration and although extraction was from a different location, a hang-up occurred during inhaul (Figure 6).

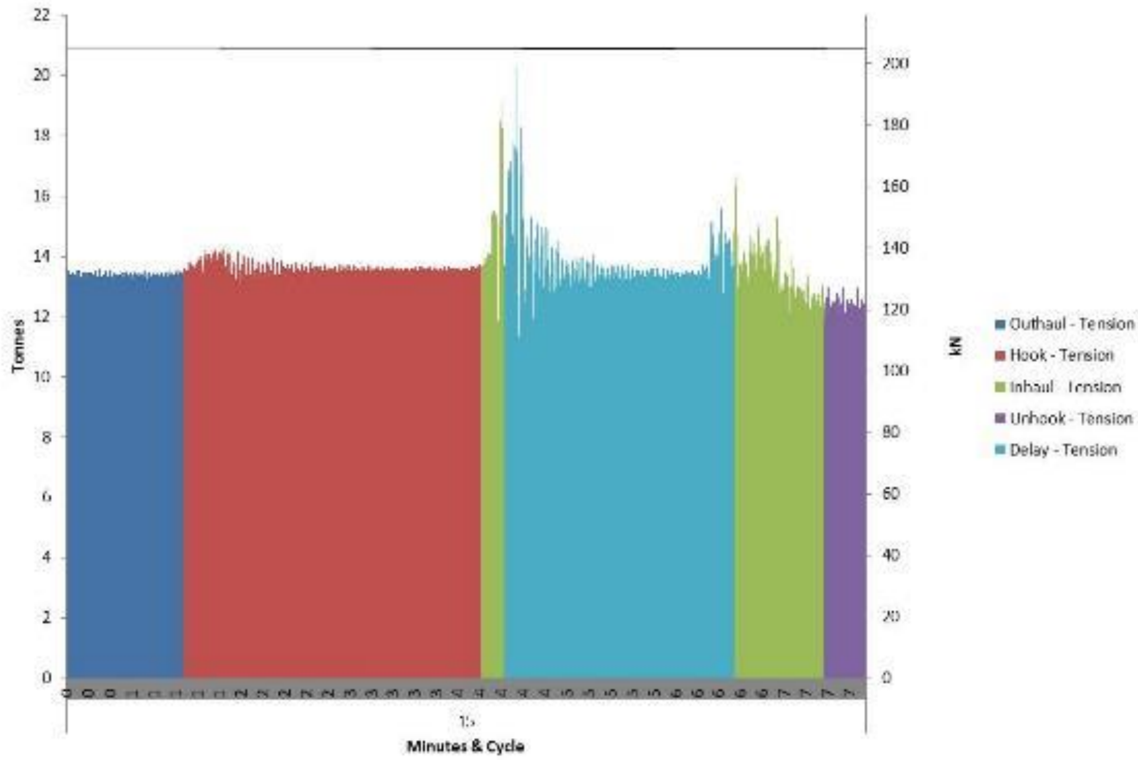


Figure 6

Figure 6: Skyline tensions for profile 2, cycle 15, North Bend Bridled configuration

The haul back block was moved again after cycle 15 to avoid the hang-up issue, and yarding resumed with cycles 16 through 19 (Figure 7). Cycle 16 was the only one of the five cycles using North Bend Bridled to exceed the safe working load. Note the effect on tension behaviour of off-setting the haul back blocks during the bridled cycles. There was little difference in tensions between the outhaul, hook and unhook elements as compared to cycles 1-14, achieving something of a dampening effect.

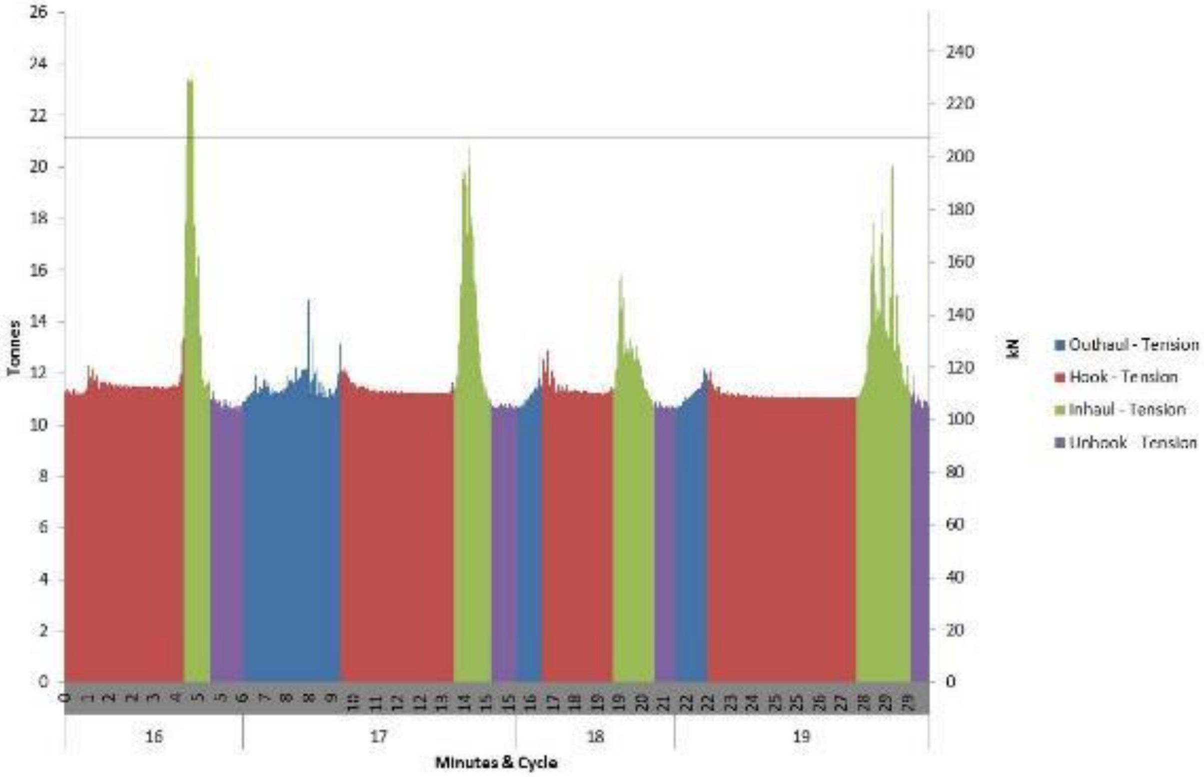


Figure 7: Skyline tensions for profile 2, cycles 16-19, North Bend Bridled configuration

APPENDIX 4

Study 4: Acme S28 motorised slack pulling carriage in a slackline configuration

The operation at Study Site 4 in Gisborne was a slackline configuration using an Acme S28 motorised slack pulling carriage (Figure 1). The operation was observed for one day across two spans.

Figure 1: Standing skyline using Acme motorised slack pulling carriage in a slackline configuration

The corridors were located next to one another with relatively smooth, but steep terrain that was concave in shape (Figure 2). Slackline was the only rigging configuration used at this study site, as it was a configuration with which the crew had the most experience.

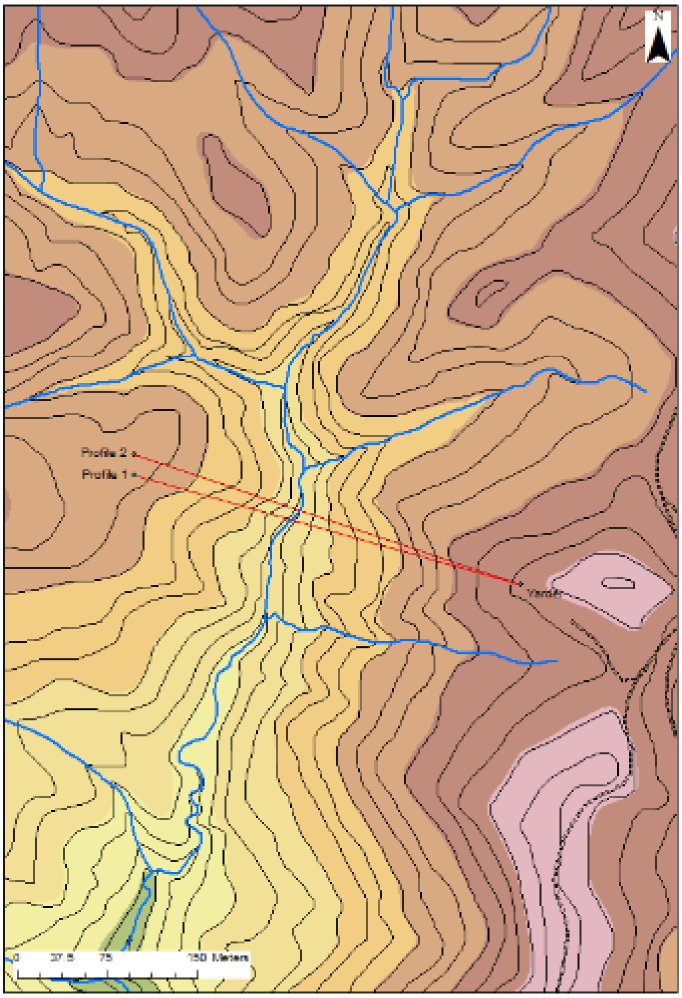


Figure 2: ArcMap 10-metre contour elevation showing profiles for payload analysis of each yarding corridor observed at Study Site 4 in Gisborne.

In total, only 22 hauler cycles were recorded (Table 1). The average cycle time was 7.44 minutes and average haul volume was 6.0 m³ resulting in average productivity of 48.8 m³/PMH for this configuration.

Table 1: Summary of the 22 observed cycle times and variables at Study Site 4 in Gisborne.

Cycle (#)	Corridor (#)	Outhaul (min)	Distance (m)	Hook (min)	Pieces (#)	CyclVol (m^3)	Inhaul (min)	Unhook (min)	Delays (min)	Cycle Time (min)	Productivity (m^3/PMH)
1	1	0.43	154	5.52	3	6.6	0.87	0.68	1.02	7.50	52.8
2	1	0.13	160	3.98	2	7.5	0.80	0.25	0.00	5.16	87.2
3	1	0.32	165	6.23	2	3.8	1.50	0.18	3.63	8.23	27.7
4	1	0.47	186	7.40	2	4.0	0.95	0.22	0.00	9.03	26.6
5	1	0.33	191	4.97	3	7.5	1.52	1.20	0.00	8.02	56.1
6	1	0.45	191	8.55	3	8.6	1.22	1.02	0.92	11.23	45.9
7	1	0.52	213	6.57	3	9.1	2.58	0.15	2.65	9.81	55.6
8	2	0.53	208	7.27	3	7.1	0.97	1.00	0.00	9.77	43.6
9	2	0.27	221	4.47	2	9.1	1.37	0.68	0.00	6.78	80.5
10	2	0.55	248	4.50	3	6.6	1.80	1.88	0.00	8.73	45.3
11	2	0.43	246	5.80	2	6.7	1.97	0.60	0.00	8.80	45.7
12	2	0.70	260	4.57	3	5.6	0.65	0.98	0.52	6.90	48.7
13	2	0.62	263	2.67	3	7.0	2.10	0.30	0.27	5.68	73.9
14	2	0.57	265	3.85	3	8.0	2.58	0.57	0.00	7.57	63.4
15	2	1.02	307	2.07	2	4.4	3.35	0.20	0.68	6.63	39.8
16	2	0.90	313	3.48	2	4.7	3.50	0.32	0.00	8.20	34.4
17	2	0.92	315	1.73	1	3.6	1.97	0.22	0.00	4.83	44.7
18	2	1.28	318	3.27	11	5.0	1.95	0.62	0.15	7.12	42.2
19	2	0.62	317	2.95	3	4.3	2.60	0.28	0.00	6.45	40.0
20	2	0.67	317	1.93	2	4.0	3.00	0.10	2.58	5.70	42.1
21	2	1.62	317	1.20	2	5.1	2.82	0.80	0.00	6.43	47.6
22	2	0.65	317	1.83	1	2.6	1.78	0.87	0.00	5.13	30.4
Min		**0.13**	**154**	**1.20**	**1.0**	**2.6**	**0.65**	**0.10**	**0.00**	**4.83**	**26.6**
Max		**1.62**	**318**	**8.55**	**11.0**	**9.1**	**3.50**	**1.88**	**3.63**	**11.23**	**87.2**
Avg		**0.64**	**250**	**4.31**	**2.8**	**6.0**	**1.90**	**0.60**	**0.56**	**7.44**	**48.8**
SD		**0.34**	**59**	**2.06**	**2.0**	**1.9**	**0.84**	**0.44**	**1.04**	**1.69**	**15.8**

Payload analysis indicated that the limiting payloads of 2.0 tonnes and 3.7 tonnes for profiles 1 and 2 respectively were located at mid-span (Figure 3). The yarder operator did not have a skyline tension monitor with display unit, and the safe working load (21.3 tonnes) was exceeded during 21 of the 22 cycles recorded (95% frequency).

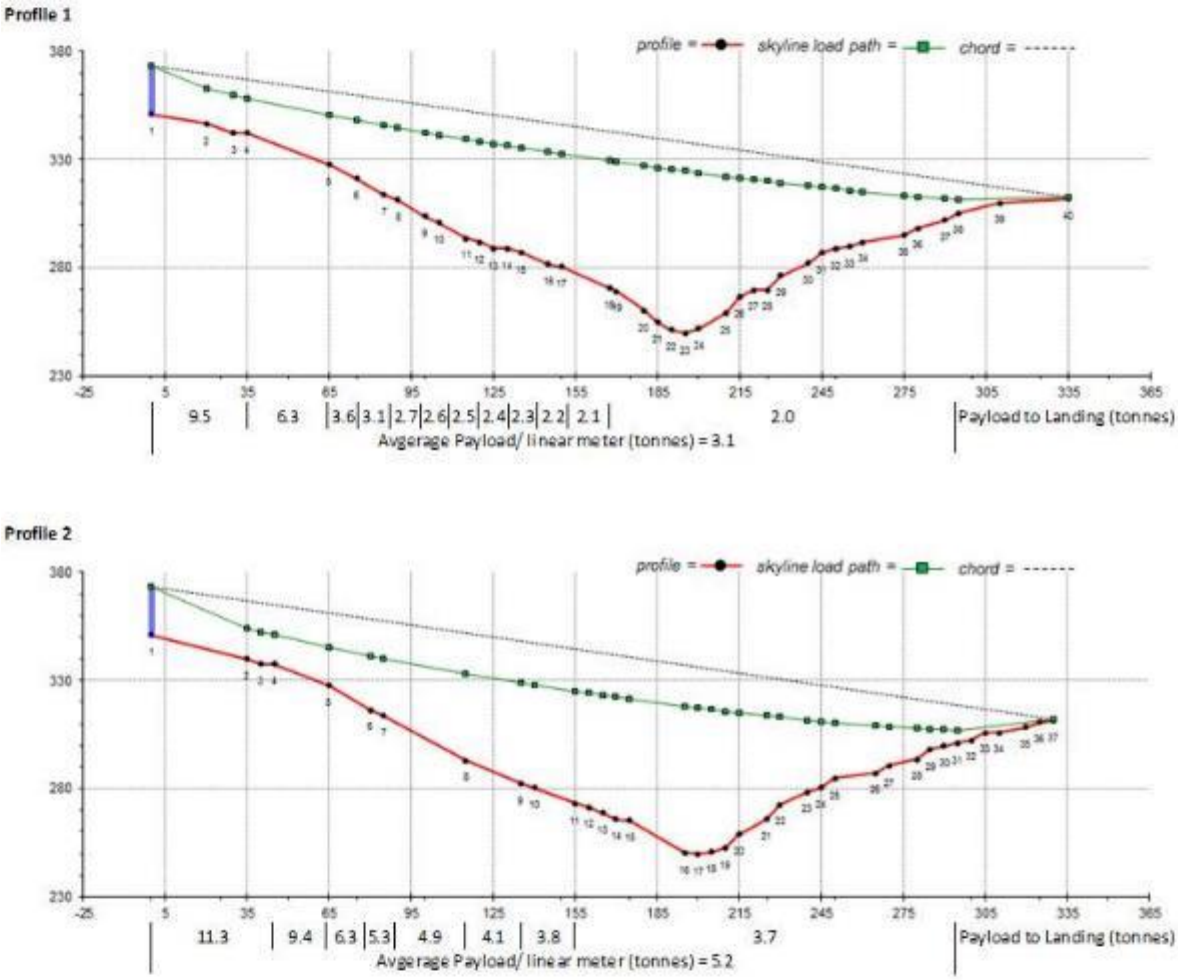


Figure 3: SkylineXL profile and payload analysis results for the Acme Slackline operation at Study Site 4 in Gisborne

Cycles 1-7 were recorded across profile 1, where every cycle exceeded the safe working load of 21.3 tonnes (209 kN), often by over 30% (Figures 4 and 5). One point to note is the effect of the carriage skyline clamp on tension behaviour, indicated by the peaks at the beginning and end of the hook element. The delays associated with cycle 1 were due to the loader having to clear the chute before stems could be landed, followed by having to re-land the stems so they rested properly on the landing before unhooking. Similar delays occurred on cycles 6 and 7 (Figure 5). The longer delay at the start of cycle 3 was due to a change of chokers on the carriage. Cycle 7 also had a hang-up during inhaul and one stem had to be unhooked before inhaul could resume.

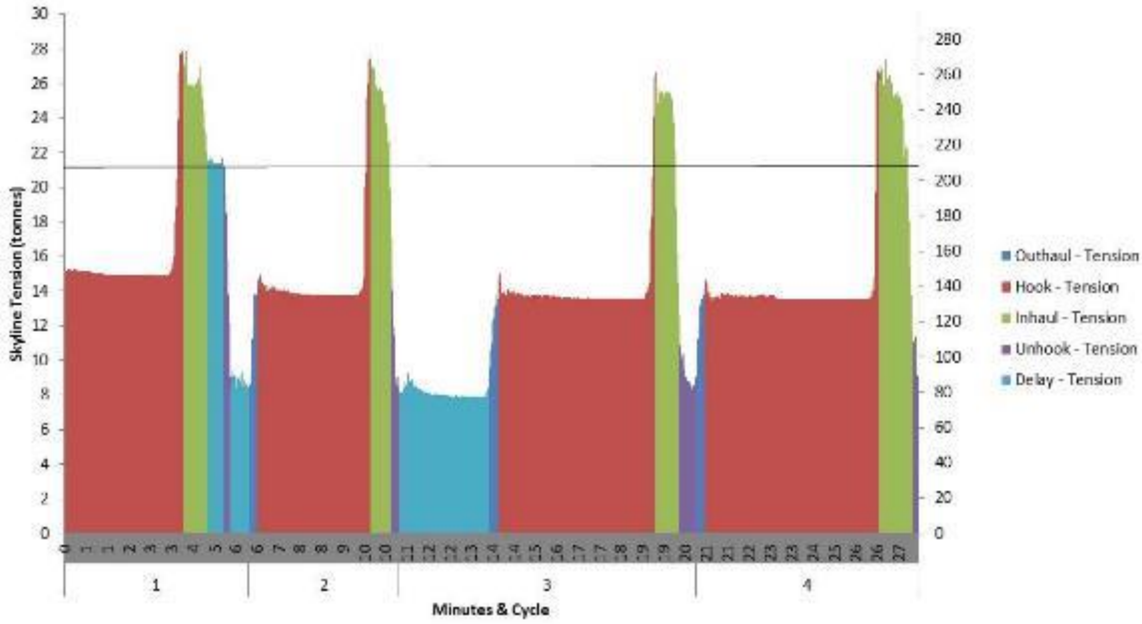


Figure 4: Skyline tensions for profile 1, cycles 1-4, Acme Slackline configuration

Cycles 8 to 14 were recorded across profile 2 where deflection had increased from 4.2 to 6.1%, but each cycle continued to exceed the safe working load (Figure 5). Interaction delays with the loader clearing the chute and having to re-land logs for stability issues persisted in cycles 10, 12 and 13.

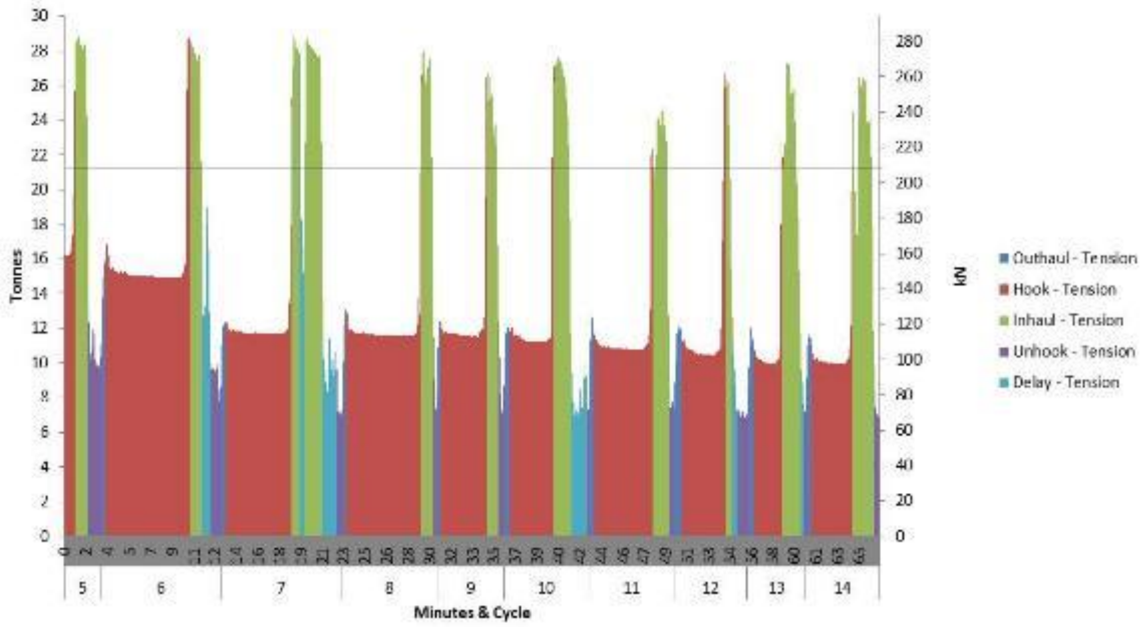


Figure 5: Skyline tensions for profile 1, cycles 5-7 and profile 2, cycles 8-14, Acme Slackline configuration

The final cycles (cycles 15-22) recorded along profile 2 were different in tension behaviour from the previous cycles (Figure 6). The stems were extracted from the back face of the canyon, out of a stockpile of stems just in front of the anchor machine. Points to note include the peaks in the outhaul tension as the carriage crossed mid-span, and the comparative reduction in hook tensions, since the carriage was not resting near mid-span during the hook element for cycles 15 to 22. One interesting behaviour noted in the final recorded cycles was the high cyclic loading compared to earlier cycles, which was due to a change in inhaul strategy. The operator was trying to drag the stems along the ground during inhaul from the back face, even though full suspension was achievable. There was a noticeable reduction in cyclic loading when the load was fully suspended during cycle 17; there was also a reduction in peak inhaul tension and inhaul element time. Compared to other configurations at other study sites, the peak tensions observed in this operation were relatively consistent but also high. Most tensions exceeded 26 tonnes (256 kN), which could be associated with the carriage skyline clamp.

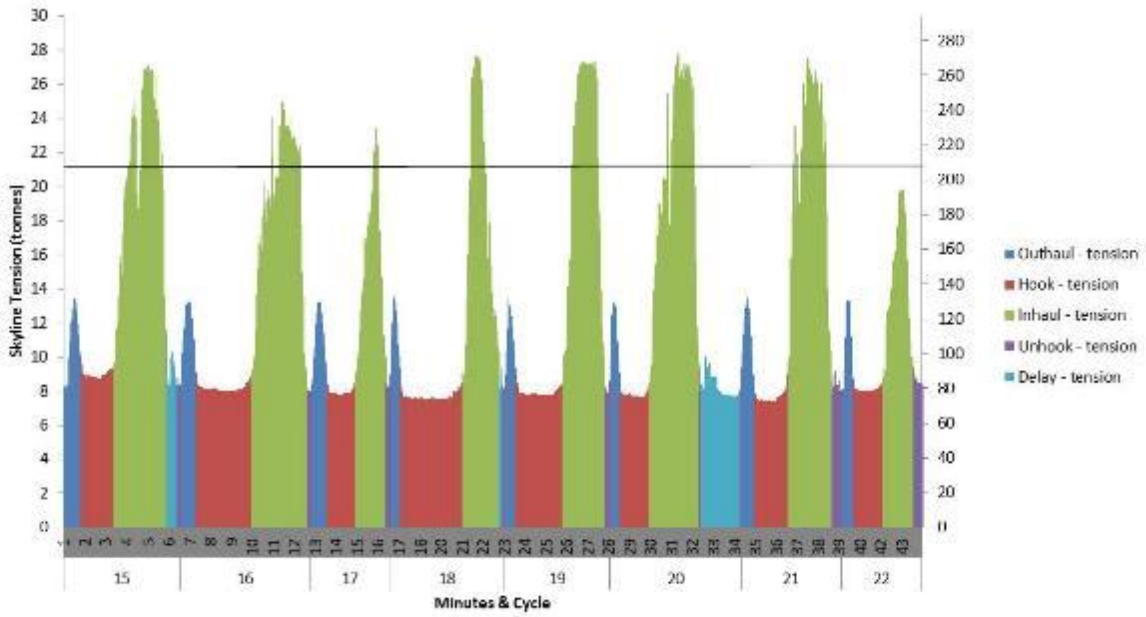


Figure 6: Skyline tensions for profile 2, cycles 15-22, Acme Slackline configuration

APPENDIX 5

Study 5: Falcon motorised grapple carriage in a shotgun configuration

The operation at study site 5 in Nelson was a live skyline using a Falcon motorised grapple carriage in a shotgun configuration (Figure 1). The operation was observed for one day across one long span (>600 m), however the maximum yarding distance measured was just over 250 m.

Figure 1: Live skyline using Falcon motorised grapple carriage in a shotgun configuration

The corridor had smooth terrain with a straight shape, which meant that the anchor had to be elevated on the other side of the valley to provide deflection (Figure 2).

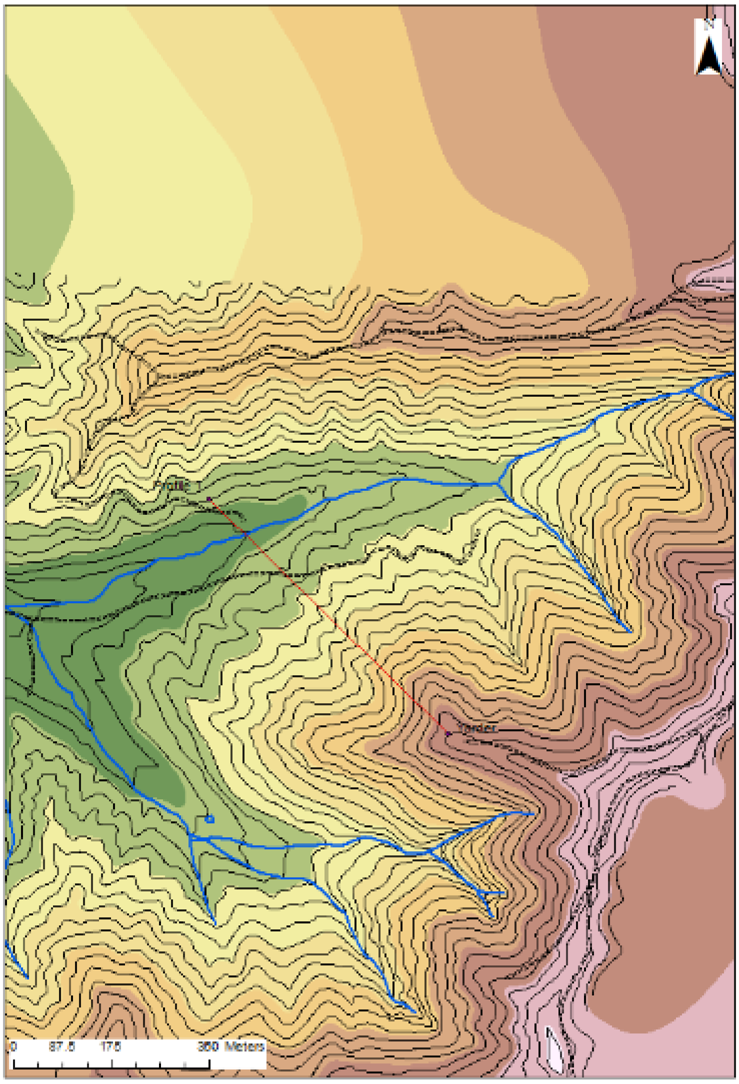


Figure 2: ArcMap 10-metre contour elevation showing profile for payload analysis of the single yarding corridor observed at Study Site 5 in Nelson

In total, 34 cycles were recorded (Table 1). An average cycle time of 2.84 minutes and average haul volume of 2.20 m³ resulted in average productivity rate of 47.7 m³/PMH.

Table 1: Summary of the 34 observed cycle times and variables at Study Site 5 in Nelson

Cycle (#)	Corridor (#)	Outhaul (min)	Distance (m)	Hook (min)	Pieces (#)	CyclVol (m^3)	Inhaul (min)	Unhook (min)	Delays (min)	Cycle Time (min)	Productivity (m^3/PMH)
1	1	0.45	123	0.72	1	1.4	0.65	0.37	0.65	2.19	39.0
2	1	0.82	118	1.18	2	2.3	0.83	0.20	0.00	3.03	45.4
3	1	0.43	127	1.37	1	0.3	0.43	0.33	0.00	2.57	6.6
4	1	0.50	132	0.90	2	4.4	0.57	0.28	0.00	2.25	117.1
5	1	0.58	137	0.93	1	1.4	0.73	0.57	0.00	2.82	29.8
6	1	0.43	141	1.38	2	3.9	1.00	0.57	0.00	3.38	69.1
7	1	0.58	154	0.63	1	2.1	0.73	0.75	0.67	2.70	47.6
8	1	0.38	160	0.62	1	3.1	0.72	0.32	0.00	2.03	91.8
9	1	0.45	166	1.02	2	2.7	1.67	0.30	0.75	3.43	47.3
10	1	0.35	173	0.55	1	2.1	0.52	0.53	0.00	1.95	64.4
11	1	0.37	171	0.73	2	3.3	0.92	0.48	0.00	2.50	78.2
12	1	0.37	178	0.43	1	1.5	0.77	0.52	0.00	2.08	44.0
13	1	0.43	177	0.73	2	3.5	1.07	0.63	0.00	2.87	72.6
14	1	0.40	186	0.37	2	2.5	1.45	0.35	4.42	2.57	58.4
15	1	0.40	186	0.42	2	1.7	1.10	0.48	0.00	2.40	43.1
16	1	0.53	194	0.73	2	3.2	1.15	0.30	0.38	2.72	69.7
17	1	0.52	198	0.30	3	1.9	1.17	0.53	0.00	2.52	44.4
18	1	0.42	205	0.97	1	1.2	0.90	0.50	0.47	2.78	25.7
19	1	0.72	204	0.53	1	1.0	1.08	0.52	0.00	2.85	22.0
20	1	0.52	207	1.18	1	3.5	1.20	0.22	0.30	3.12	67.5
21	1	0.90	217	0.48	1	2.1	1.47	0.50	1.27	3.35	37.4
22	1	0.52	222	1.15	1	2.9	1.57	0.50	0.77	3.73	47.3
23	1	0.43	209	1.05	1	0.8	1.73	0.23	2.55	3.45	13.4
24	1	0.42	222	0.68	1	3.7	1.38	0.43	0.00	2.92	76.6
25	1	0.50	220	0.98	1	1.3	1.20	0.63	0.00	3.32	23.3
26	1	0.40	219	1.35	1	0.2	1.63	0.22	0.60	3.60	3.7
27	1	0.55	226	0.42	1	4.7	1.55	0.52	0.00	3.03	92.0
28	1	0.50	235	0.53	1	2.8	1.43	0.47	0.00	2.93	57.9
29	1	0.37	252	0.73	1	2.8	1.72	0.78	0.00	3.60	47.2
30	1	0.25	130	1.28	1	1.8	0.67	0.57	0.00	2.77	38.2
31	1	0.27	144	1.13	1	0.7	0.80	0.45	0.00	2.65	15.2
32	1	0.42	152	0.42	2	0.8	0.68	0.32	0.00	1.83	24.7
33	1	0.45	245	1.25	1	1.6	1.42	0.45	0.57	3.57	26.1
34	1	0.77	239	0.85	1	1.8	1.35	0.20	0.85	3.17	35.0
Min		**0.25**	**118**	**0.30**	**1.0**	**0.2**	**0.43**	**0.20**	**0.00**	**1.83**	**3.7**
Max		**0.90**	**252**	**1.38**	**3.0**	**4.7**	**1.73**	**0.78**	**4.42**	**3.73**	**117.1**
Avg		**0.48**	**184**	**0.82**	**1.4**	**2.2**	**1.10**	**0.44**	**0.42**	**2.84**	**47.7**
SD		**0.14**	**39**	**0.33**	**0.5**	**1.2**	**0.38**	**0.15**	**0.88**	**0.51**	**26.0**

Payload analysis indicated that the limiting payload (5.1 tonnes) was located at the extent of the yarding distance for profile 1 (Figure 3). The yarder operator had a skyline tension monitor with display unit, and the safe working load (21.3 tonnes, or 209 kN) was exceeded during 15 of the 34 cycles (44% frequency).

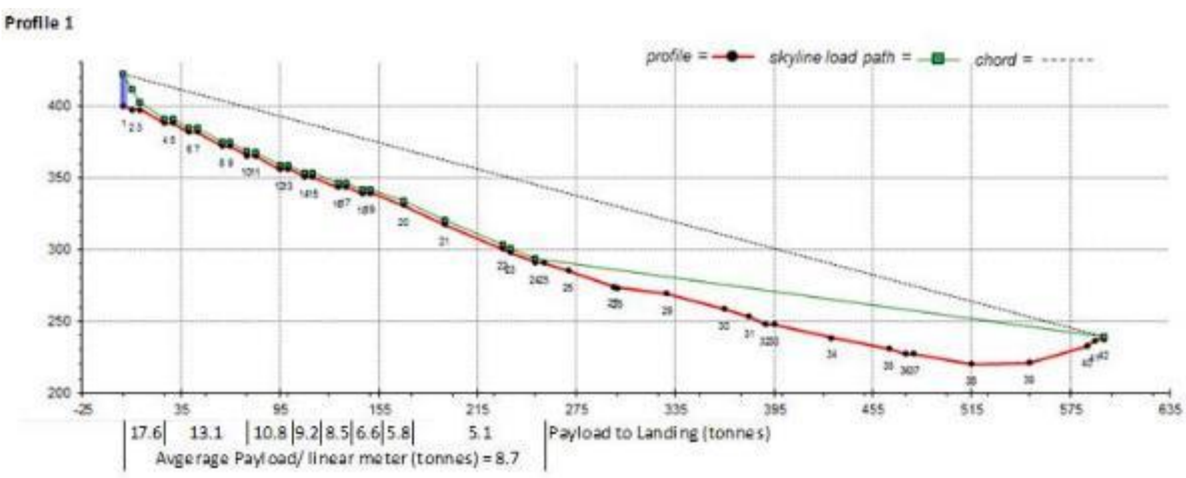


Figure 3: SkylineXL profile and payload analysis results for the Falcon Shotgun operation at Study Site 5 in Nelson.

Cycles 1-17 were recorded along profile 1 (Figure 4).

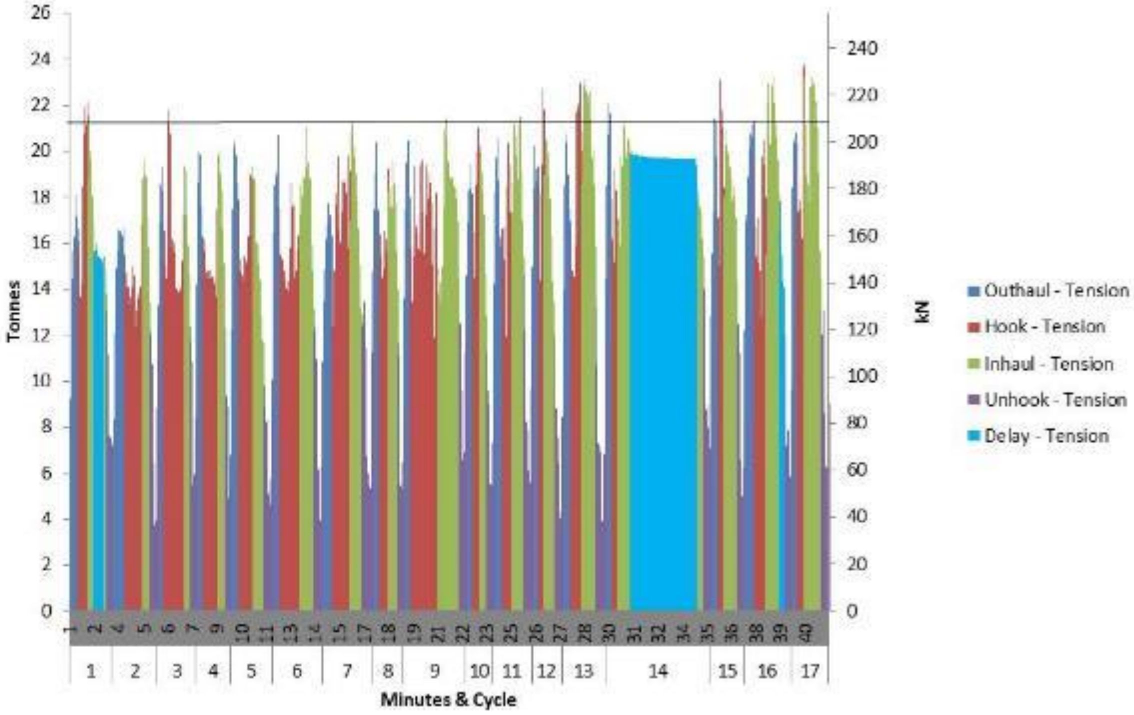


Figure 4: Skyline tensions for Study Site 5, profile 1, cycles 1-17, Falcon Shotgun configuration

Similar skyline tension behaviour existed as observed at Study Site 2, where a live skyline system with a Falcon grapple carriage in a shotgun configuration was also used and the carriage followed the ground slope during inhaul. However, the longer span at this study site (>600 m) and the relatively low deflection (6.1%) resulted in peak tensions of the outhaul, hook and inhaul elements that were very similar. The quick average cycle times (2.84 min) made it difficult for the loader operator to keep the landing clear, as indicated by the interaction delay (i.e. waiting for loader) in cycles 1, 14 and 16.

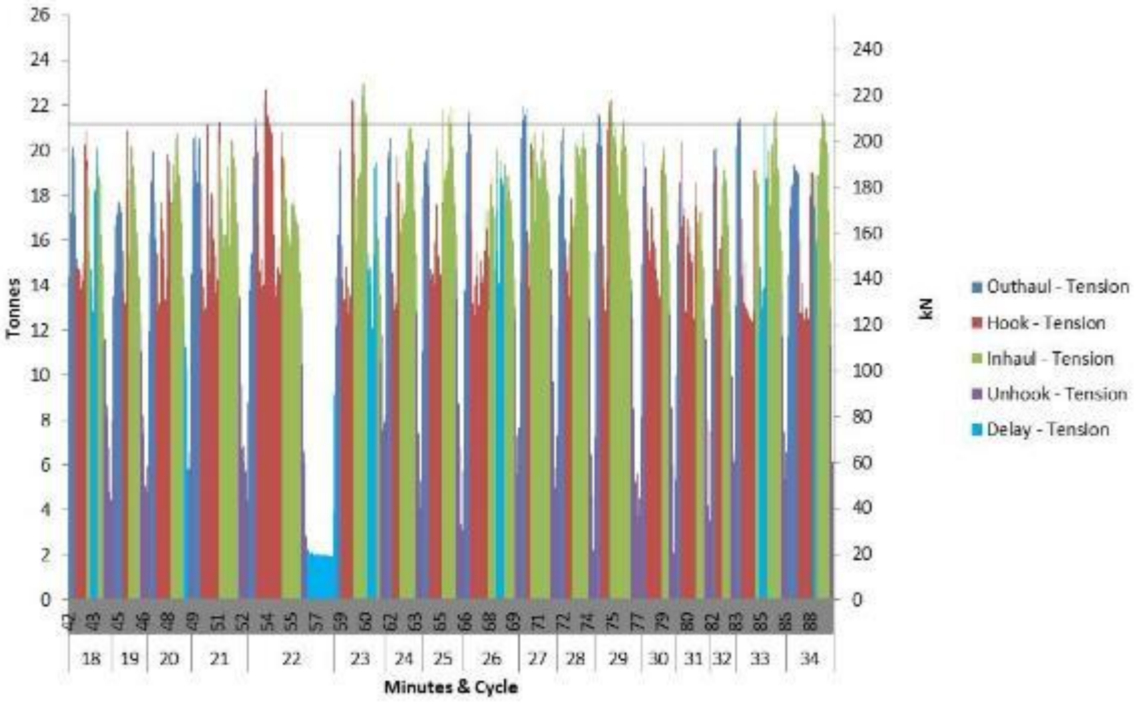


Figure 5: Skyline tensions for Study Site 5, profile 1, cycles 18-34, Falcon Shotgun configuration

Cycles 18-34 were also recorded along profile 1, of which six cycles exceeded the safe working load (Figure 5). Extraction distance continued to increase with each cycle towards mid-span but there was no apparent increase in peak tensions. Many delays occurred during these cycles, such as loader interaction (cycles 16 and 20), having to wait for a worker to move from under the skyline (cycle 22), and having to re-grapple stems broken or lost during inhaul (cycles 18, 23, 26 and 33). Compared to the other Falcon configurations studied, this study site had the highest peak tensions, which was likely due to the long span, low deflection, and carriage weight as previously discussed.

APPENDIX 6

Study 6: North Bend Bridled configuration

The operation at Study Site 6 in Marlborough was a North Bend Bridled configuration (Figure 1), which was observed for two days. The skyline extended across one long span (1,100 m), however during the study the maximum yarding distance observed was 473 m.

Figure 1: Standing skyline using North Bend Bridled configuration at Study Site 6 in Marlborough

The corridor had very steep and broken terrain, so the anchor had to be extended across the valley bottom to provide deflection (Figure 2). North Bend Bridled was the only configuration in use at this study site, and provided the means to yard trees laterally away from the native bush boundary and power lines.

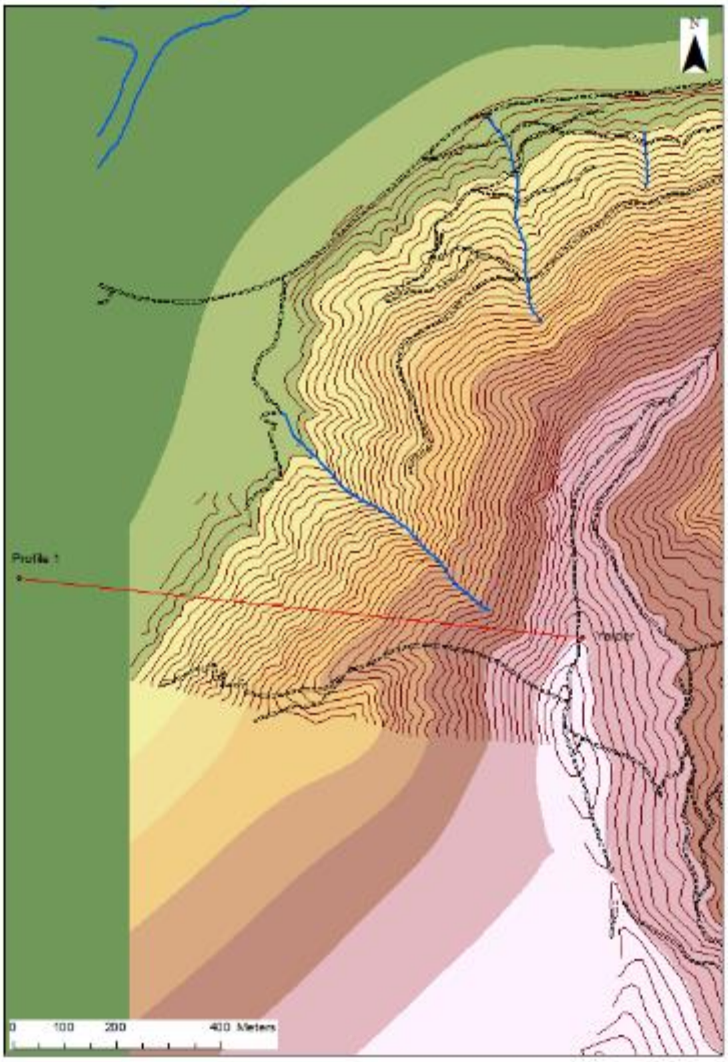


Figure 2: ArcMap 10-metre contour elevation showing the profile for payload analysis of the single yarding corridor at Study Site 6 in Marlborough

In total, 34 hauler cycles were recorded (Table 1). With an average cycle time of 9.26 minutes and average haul volume of 4.7 m³ this configuration resulted in average productivity of 32.2 m³/PMH.

Table 1: Summary of the 34 observed cycle times and variables at Study Site 6 in Marlborough

Cycle (#)	Corridor (#)	Outhaul (min)	Distance (m)	Hook (min)	Pieces (#)	CyclVol (m^3)	Inhaul (min)	Unhook (min)	Delays (min)	Cycle Time (min)	Productivity (m^3/PMH)
1	1	1.00	218	3.93	2	7.4	1.73	1.42	0.00	8.08	54.9
2	1	1.17	229	2.83	2	4.2	1.25	0.87	0.00	6.12	40.7
3	1	0.72	221	3.58	1	0.5	1.17	0.67	0.00	6.13	4.4
4	1	0.75	240	2.95	1	3.2	1.32	0.67	0.00	5.68	33.8
5	1	0.98	245	2.95	2	9.0	1.72	0.80	0.00	6.45	83.7
6	1	1.07	250	3.13	2	7.7	1.40	1.07	0.00	6.67	69.3
7	1	1.42	258	4.28	3	7.5	1.65	1.55	0.00	8.90	50.6
8	1	1.00	264	3.88	1	2.6	1.27	0.32	0.00	6.47	24.1
9	1	0.80	248	3.85	2	9.4	1.63	0.58	6.00	6.87	82.1
10	1	1.23	261	3.92	4	6.2	1.47	1.02	0.00	7.63	48.7
11	1	1.07	258	4.82	2	4.5	1.65	1.78	2.27	9.32	29.0
12	1	0.93	260	4.02	2	4.5	1.45	0.78	0.00	7.18	37.6
13	1	1.22	255	2.88	3	5.8	3.25	0.95	1.27	8.30	41.9
14	1	0.95	260	3.62	2	6.0	1.75	1.77	1.68	8.08	44.5
15	1	1.40	280	3.63	2	6.5	2.03	1.27	33.00	8.33	46.8
16	1	1.08	270	5.60	2	7.6	1.82	2.05	0.00	10.55	43.2
17	1	1.00	270	5.55	2	1.9	1.53	3.27	0.00	11.35	10.0
18	1	0.97	285	5.28	1	0.3	1.55	1.47	0.00	9.27	1.9
19	1	0.90	280	5.37	4	2.9	2.35	0.68	0.00	9.30	18.7
20	1	1.25	330	2.70	2	3.1	2.55	1.32	0.00	7.82	23.4
21	1	2.08	385	4.63	2	3.9	3.65	1.23	35.18	11.60	20.4
22	1	1.88	390	3.38	2	2.8	4.60	0.93	6.02	10.80	15.6
23	1	1.67	381	3.30	2	5.9	5.83	1.68	0.00	12.48	28.4
24	1	1.70	380	2.22	2	3.7	4.57	2.28	0.00	10.77	20.8
25	1	1.68	376	2.55	1	1.9	3.72	0.93	5.78	8.89	12.9
26	1	1.25	260	4.47	2	4.0	2.10	1.10	0.00	8.92	26.6
27	1	1.98	375	3.97	1	3.4	2.62	2.67	1.85	11.23	18.0
28	1	2.12	410	2.42	1	2.2	2.80	1.03	15.83	8.37	15.9
29	1	1.80	415	2.00	1	3.3	5.28	1.58	0.00	10.67	18.4
30	1	1.47	414	2.67	2	5.5	4.00	3.68	0.00	11.82	27.9
31	1	1.75	473	4.27	2	5.8	3.93	1.25	0.00	11.20	31.0
32	1	1.53	345	7.35	3	10.5	3.80	4.53	34.18	17.22	36.5
33	1	1.58	342	6.03	1	1.0	2.25	1.30	0.00	11.17	5.5
34	1	1.83	430	3.58	3	5.3	3.48	2.25	0.00	11.15	28.8
Min		**0.72**	**218**	**2.00**	**1.0**	**0.3**	**1.17**	**0.32**	**0.00**	**5.68**	**1.9**
Max		**2.12**	**473**	**7.35**	**4.0**	**10.5**	**5.83**	**4.53**	**35.18**	**17.22**	**83.7**
Avg		**1.33**	**311**	**3.87**	**2.0**	**4.7**	**2.56**	**1.49**	**4.21**	**9.26**	**32.2**
SD		**0.40**	**72**	**1.19**	**0.8**	**2.5**	**1.28**	**0.92**	**9.94**	**2.39**	**20.0**

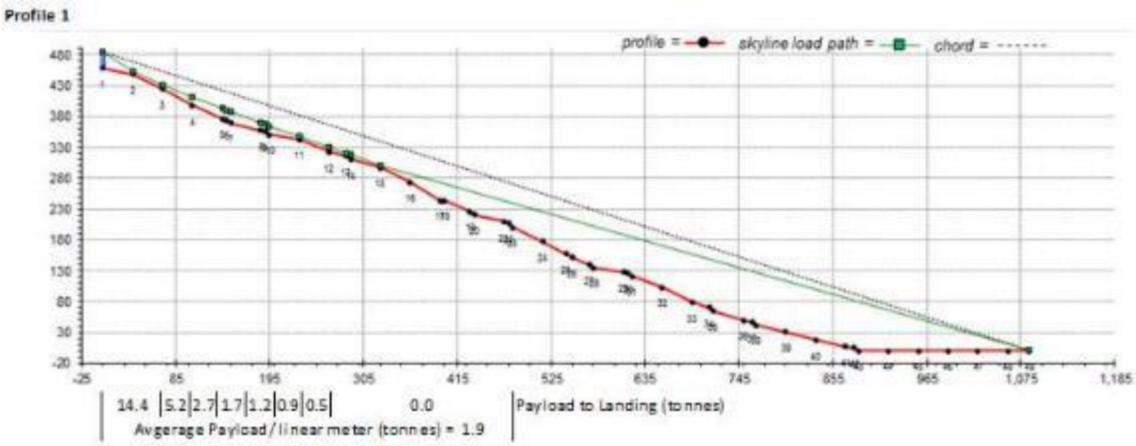


Figure 3: SkylineXL profile and payload analysis results for the North Bend Bridled operation

Payload analysis indicated that the limiting payload (0.0 tonnes) was located at approximately 300 metres from the yarder, where a blind lead resulted in insufficient carriage clearance (Figure 3). The yarder operator did not have a skyline tension monitor with display unit, and the safe working load (21.3 tonnes) was exceeded during 22 of the 34 cycles (65% frequency).

Cycles 1-14 exceeded the safe working load (21.3 tonnes, 209 kN) on four of the cycles (Figure 4). A delay of more than five minutes was observed between cycles 8 and 9, due to a rope wrap issue that had to be resolved before outhaul on cycle 9. That is, the rigging was sent out part way and then brought back to the landing to untangle the ropes. Delays associated with cycles 11, 13 and 14 were due to difficulty in landing the rigging at the end of the outhaul component. The difficulty was due to the fact that the crew was reaching the limits of their setup, and eventually shifted the haul back blocks after cycle 14.

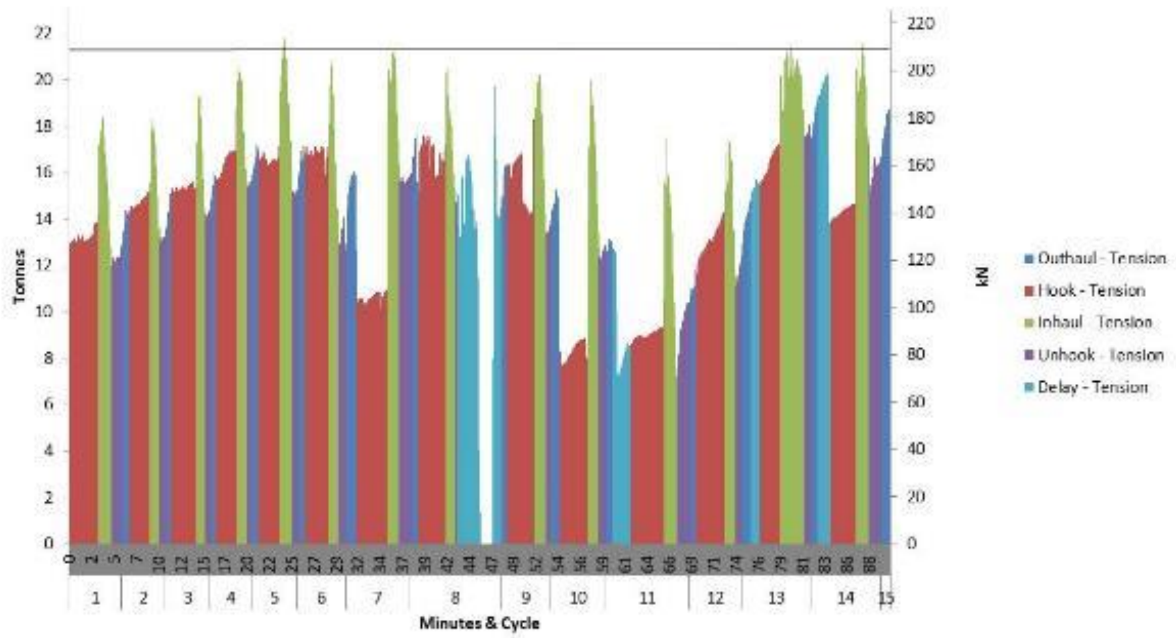


Figure 4: Skyline tensions for profile 1, cycles 1-14, North Bend Bridled configuration

During cycles 15-19, skyline tension increased for all elements of the cycles compared to earlier cycles, where all except for cycle 15 exceeded the safe working load (Figure 5). The extraction distance was gradually increasing as it approached mid-span; so too was the lateral offset due to bridling. The hook element time and tensions increased as a result of the increased lateral yarding distance. Breakout appeared to be getting more difficult and so were issues during inhaul with a blind lead area that wasn't yarded across in prior cycles. The skyline drum slipped at a tension of 27 tonnes, during inhaul of cycle 19, which generated enough of a shock load (8 tonnes) to knock the tension monitor off the skyline.

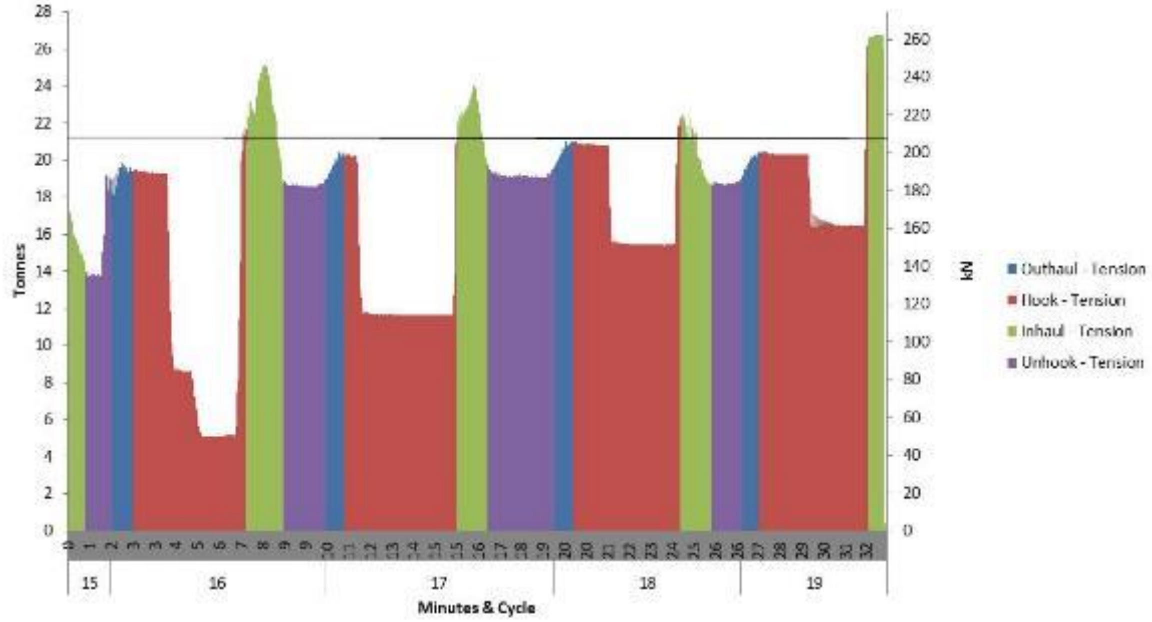


Figure 5: Skyline tensions for profile 1, cycles 15-19, North Bend Bridled configuration

Yarding resumed on the second day of observation with cycles 20 and 21 (Figure 6). The long delay associated with the start of cycle 21 was due to shifting haul back blocks to again extend the yarding and lateral yarding distances.

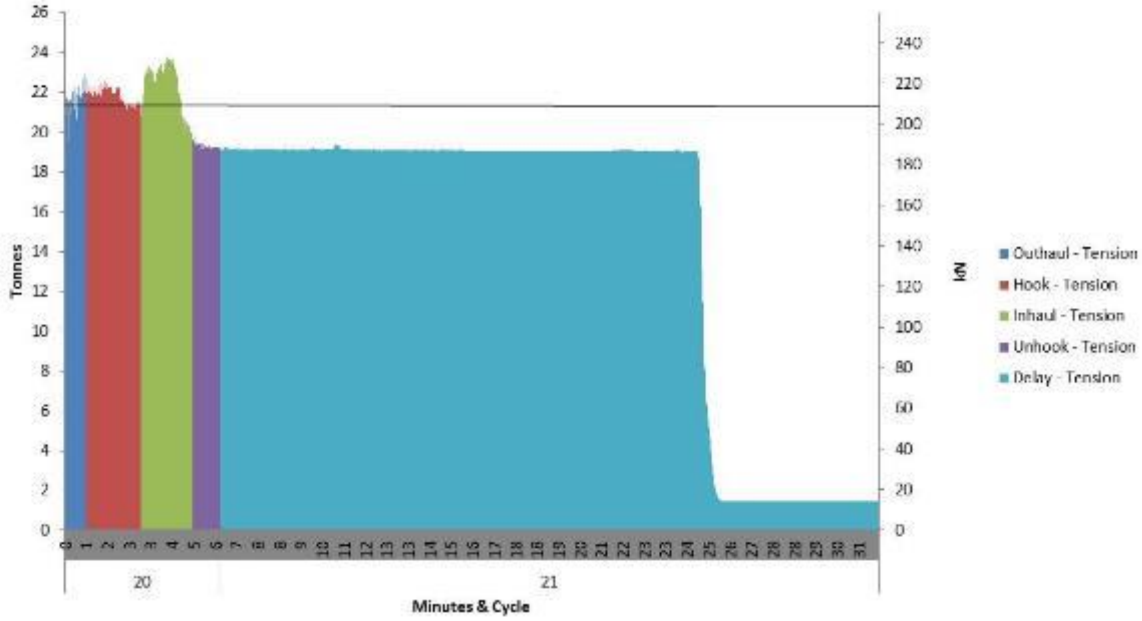


Figure 6: Skyline tensions for profile 1, cycles 20-21, North Bend Bridled configuration

The five-minute delay at end of cycle 21 was due to researchers reconnecting the carriage-mounted GPS unit which was knocked off during inhaul due to the carriage collision with the ground in the blind lead area of the profile (Figure 7). Delays associated with cycles 22 and 25 occurred during inhaul, when again there was poor clearance over the blind lead and drags became stuck. One stem had to be unhooked during cycle 25. The delay at the end of cycle 26 was due to changing chokers on the butt-rigging at the landing. The delay before outhaul of cycle 28 was due to shifting the haul back blocks.

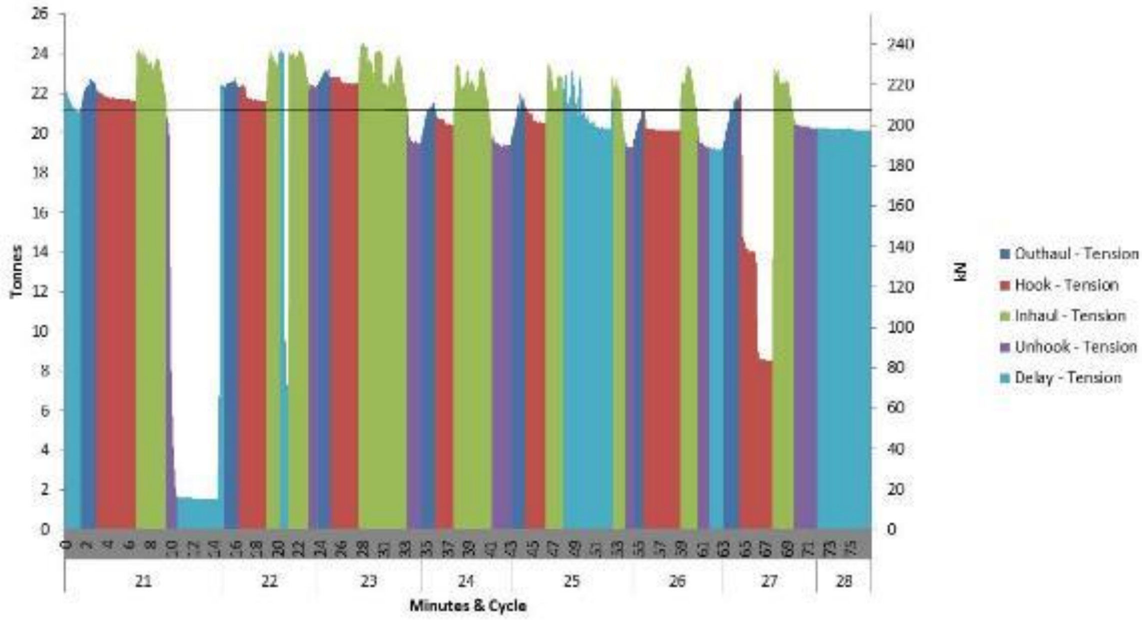


Figure 7: Skyline tensions for profile 1, cycles 21-28, North Bend Bridled configuration

The delay in cycle 32 (Figure 8) was due to a 30-minute lunch break initiated after stems were hooked. Maximum tensions during inhaul again continued to exceed the safe working load each cycle (100% frequency).

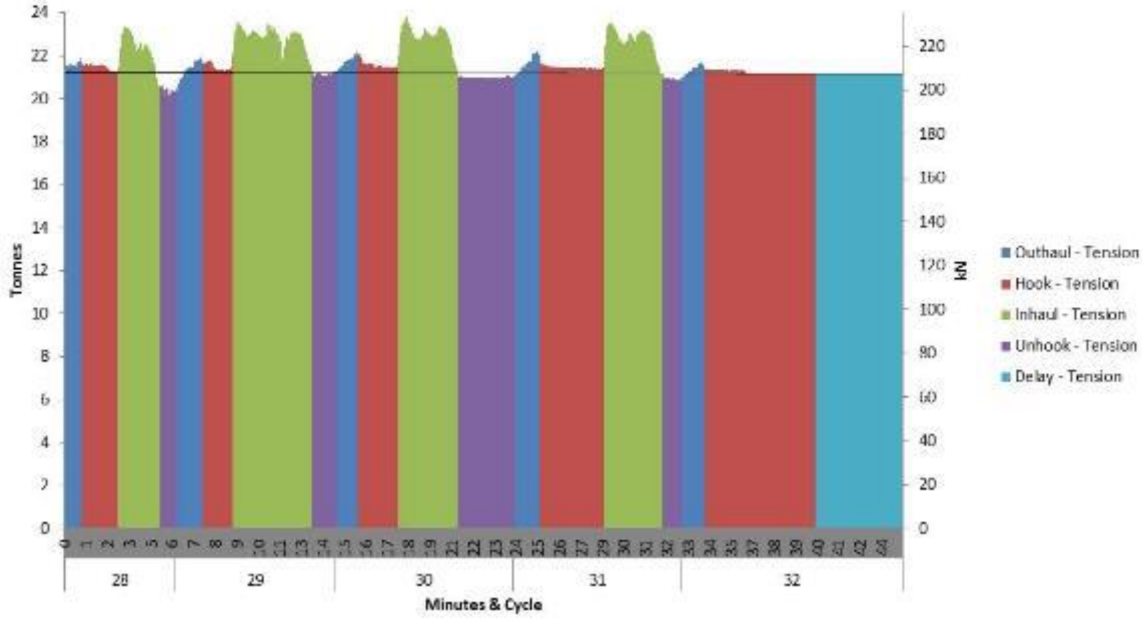


Figure 8: Skyline tensions for profile 1, cycles 28-32, North Bend Bridled configuration

The last cycles observed in this study had high skyline pretension which were nearly equal to the safe working load, apparent by the unhook tensions (Figure 9). It is interesting to note that there is little difference in tension due to different elements of the cycle, and very little variation in tension. These variable but high tensions can be attributed to the force generated by the off-setting of haul back blocks, which are pulling the carriage and skyline to the side. The tensions were very different in behaviour from the first cycles observed, which was likely due to the shifting of tail blocks (further out the span) after cycle 28 in combination with the poor deflection in this setup (3.8%).

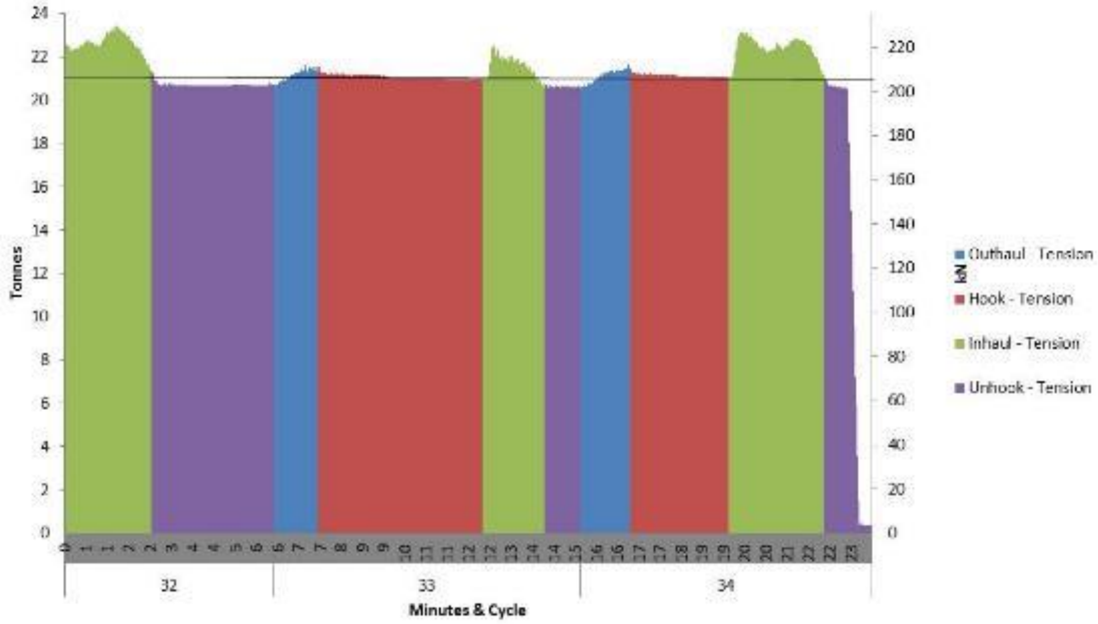


Figure 9: Skyline tensions for profile 1, cycles 32-34, North Bend Bridled configuration

APPENDIX 7

Study 7: North Bend configuration

The operation at Study Site 7 in Nelson was a North Bend configuration (Figure 1) providing the necessary lift over the incised gulley located at mid-span. The operation was observed for one day across two spans.

Figure 1: Standing skyline using North Bend configuration at Study Site 7 in Nelson

The corridors were located next to one another with relatively smooth terrain that was concave in shape (Figure 2).

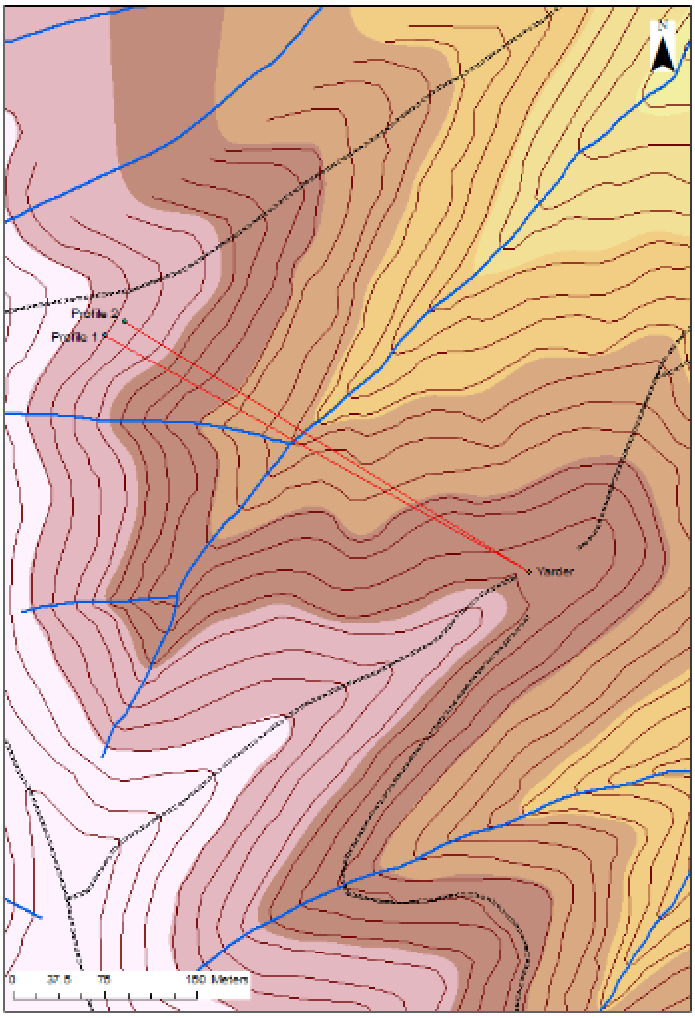


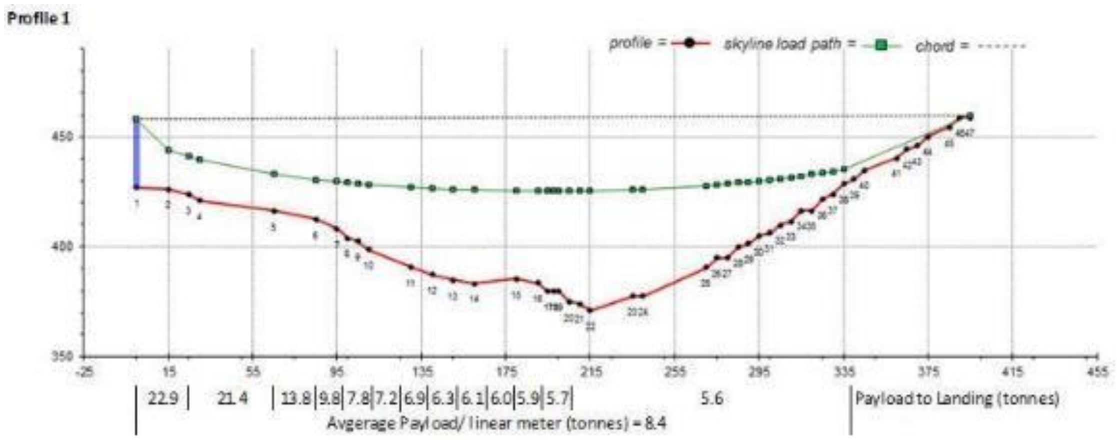
Figure 2: ArcMap 10-metre contour elevation showing profiles for payload analysis of each yarding corridor at Study Site 7 in Nelson

A total of 23 cycles were recorded (Table 1). With average cycle time of 7.70 minutes and average haul volume of 5.4 m³, this configuration had an average production rate of 43.9 m³/PMH.

Table 1: Summary of the 23 observed cycle times and variables at Study Site 7 in Nelson

Cycle (#)	Outhaul (min)	Distance (m)	Hook (min)	Pieces (#)	CyclVol (m³)	AvgVol (m³)	PayloadE	Inhaul (min)	Unhook (min)	Delays (min)	Cycle Time (min)	Productivity (m³/PMH)
1	0.77	308	3.90	5	4.9	2.7	1.82	2.20	1.85	0.00	8.72	33.7
2	1.05	319	2.42	5	5.7	2.7	2.11	2.05	2.18	0.00	7.70	44.4
3	0.77	308	2.02	3	4.6	2.7	1.70	1.88	2.05	0.00	6.72	41.1
4	0.95	324	3.50	5	4.0	2.7	1.48	1.75	2.87	0.00	9.07	26.5
5	0.65	330	4.82	5	4.6	2.7	1.70	2.25	2.60	0.00	10.32	26.8
6	0.90	342	3.28	5	6.1	2.7	2.26	2.10	1.55	0.00	7.83	46.7
7	0.90	349	1.82	5	7.0	2.7	2.59	2.15	1.57	0.00	6.43	65.3
8	0.90	348	1.92	3	4.8	2.7	1.78	1.82	1.58	0.00	6.22	46.3
9	0.97	364	2.72	4	5.4	2.7	2.00	1.98	2.93	0.00	8.60	37.7
10	1.05	374	1.88	5	5.9	2.7	2.19	2.42	1.50	0.00	6.85	51.7
11	1.12	202	4.37	3	2.9	7.3	0.40	1.35	2.22	45.72	9.05	19.2
12	0.65	195	4.98	5	5.2	7.3	0.71	1.68	1.40	1.33	8.72	35.8
13	0.68	216	6.30	6	4.9	7.3	0.67	1.63	3.90	0.00	12.52	23.5
14	0.75	223	2.92	5	4.3	7.3	0.59	1.45	1.35	0.00	6.47	39.9
15	0.53	233	2.85	5	5.3	7.3	0.73	1.27	1.18	0.00	5.83	54.5
16	0.87	246	3.15	5	5.1	7.3	0.70	1.90	1.38	1.65	7.30	41.9
17	0.67	252	3.37	6	8.4	7.3	1.15	2.05	0.83	1.05	6.92	72.9
18	0.72	262	2.45	5	7.3	7.3	1.00	2.27	1.80	0.00	7.23	60.6
19	0.67	267	2.55	4	5.1	7.3	0.70	1.78	1.40	0.00	6.40	47.8
20	0.70	272	3.18	4	4.9	7.3	0.67	1.22	2.58	0.00	7.68	38.3
21	0.70	285	3.98	5	7.0	7.3	0.96	1.42	1.38	0.00	7.48	56.1
22	0.75	285	3.00	5	5.5	7.3	0.76	1.83	1.35	0.00	6.93	47.6
23	0.62	291	2.67	5	5.4	7.3	0.74	1.65	1.25	0.00	6.18	52.4
Min	**0.53**	**195**	**1.82**	**3.0**	**2.9**	**2.7**	**0.40**	**1.22**	**0.83**	**0.00**	**5.83**	**19.2**
Max	**1.12**	**374**	**6.30**	**6.0**	**8.4**	**7.3**	**2.59**	**2.42**	**3.90**	**45.72**	**12.52**	**72.9**
Avg	**0.80**	**287**	**3.22**	**4.7**	**5.4**	**5.3**	**1.28**	**1.83**	**1.86**	**2.16**	**7.70**	**43.9**
SD	**0.16**	**53**	**1.11**	**0.8**	**1.2**	**2.3**	**0.66**	**0.34**	**0.72**	**9.51**	**1.55**	**13.3**

Payload analysis indicated that the limiting payloads of 5.6 and 6.7 tonnes for profiles 1 and 2, respectively were located at mid-span (Figure 3).



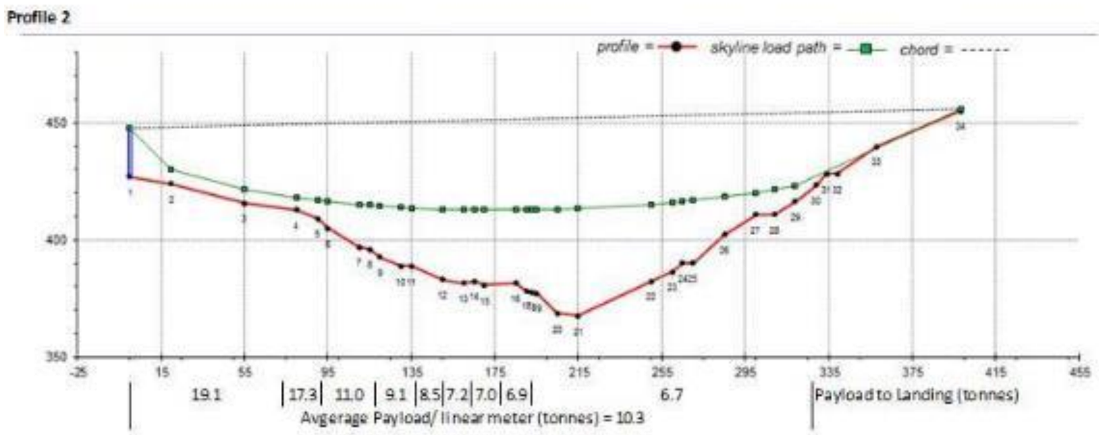


Figure 3: SkylineXL profile and payload analysis results for the North Bend operation at Study Site 7

Cycles 1-10 were recorded in just over an hour and all took place along profile 1 (Figure 4).

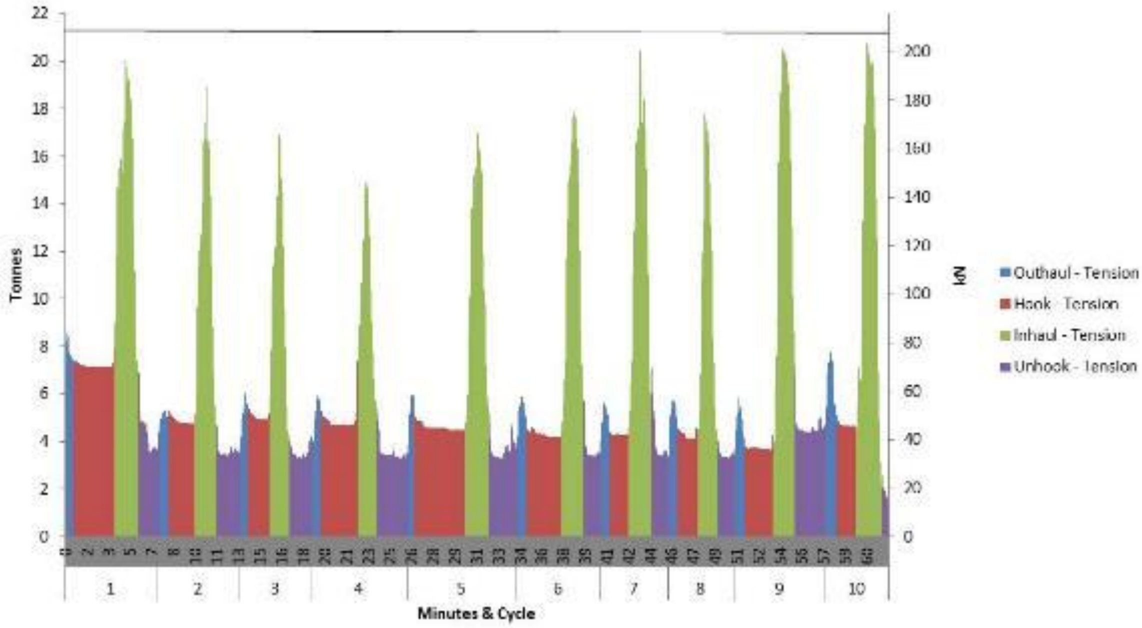


Figure 4: Skyline tensions for profile 1, cycles 1-10, North Bend configuration

Safe working load for the skyline (21.3 tonnes, 209 kN) was not exceeded, as maximum skyline tension of 20.8 tonnes occurred during inhaul of cycle 10, and pretension in the skyline (noted from the unhook component) was approximately 3 tonnes for this setting. The 10 cycles were all pulled from the back face with the latter ones close to the tail hold where the tension monitor was located, which may explain the higher tensions.

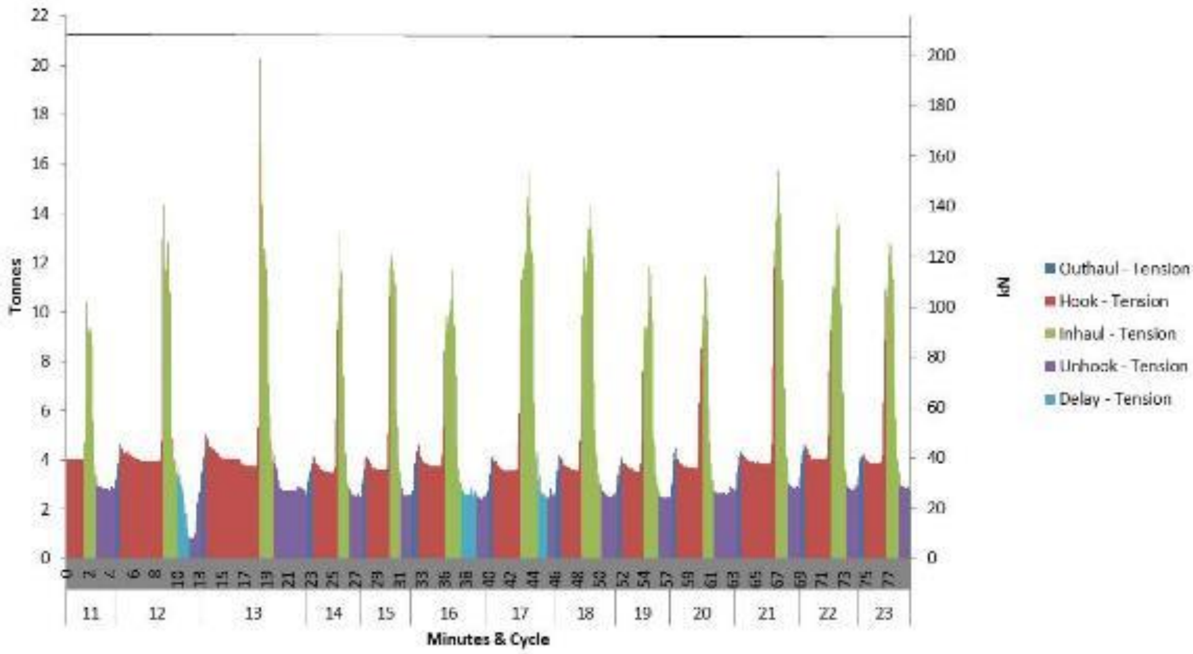


Figure 5: Skyline tensions for profile 2, cycles 11-23, North Bend configuration

Cycles 11-23 were all observed along profile 2 (Figure 5). These cycles were also pulled from the back face as in corridor 1, but yarding started from the incised gulley around mid-span (cycles 11-

14) and worked progressively further toward the tail hold. Note the longer hook time associated with these first cycles as the breaker-outs had to climb in an out of the gulley to attach chokers.

Also of interest (highlighting the difficulty of yarding from the 2-m incised gulley), cycle 13 had a peak tension that was 4 tonnes greater than other cycles in the profile, due to a hang-up during breakout. However, the safe working load was not exceeded and the peak tensions were much lower than the first span, most likely because deflection increased (from 8.4 to 10.1%).

Delays shown in cycles 12, 16 and 17 which occurred at the end of inhaul before unhooking, were 1.3 min, 1.6 min and 1.1 min respectively. These delays were associated with the difficulty of landing or having to re-land the stems before unhooking; the yarder operator claimed the weight of haul back was trying to pull stems back over the edge of the landing, which is a common issue associated with the North Bend configuration.

APPENDIX 8

Study 8: Acme S28 motorised slack pulling carriage in slackline and shotgun configurations

The operation at Study Site 8 in Otago used the Acme S28 motorised slack pulling carriage mainly in a slackline configuration, and where the chord slope was steep enough, the shotgun configuration was employed (Figure 1). The operation was observed for two days across three skyline spans.

Figure 1: Standing skyline using the Acme S28 motorised slack pulling carriage in both slackline and shotgun configurations

The corridors were located next to one another (Figure 2) and were all concave in shape, but due to occasional rock bluffs, terrain was broken.

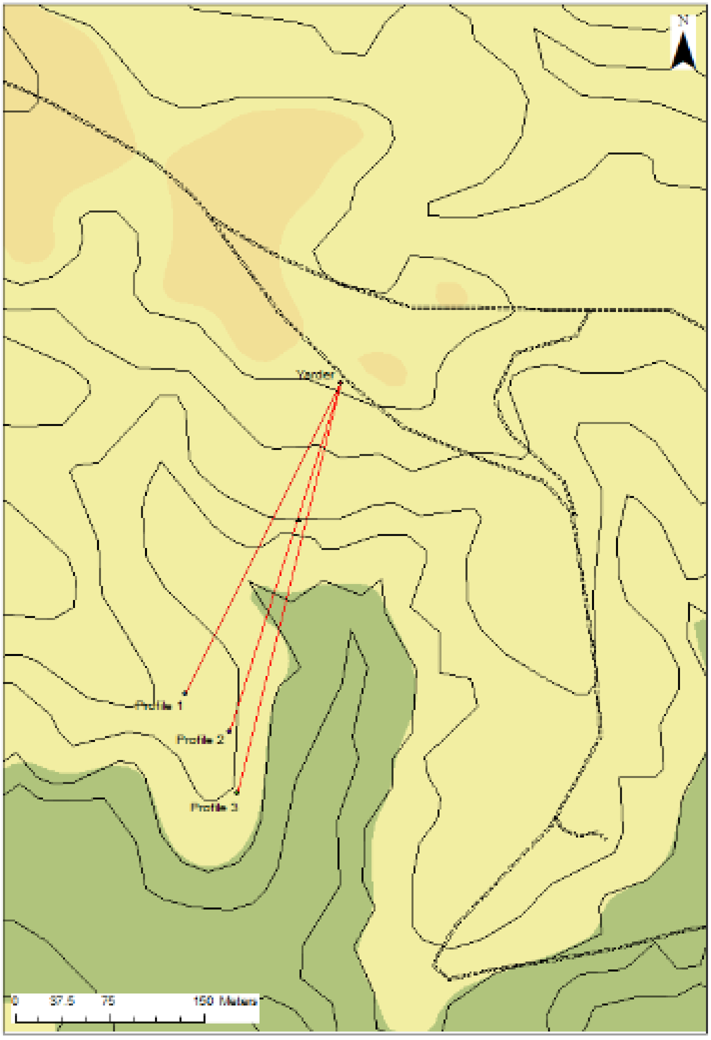


Figure 2: ArcMap 20-metre contour elevation showing profiles for payload analysis of each yarding corridor at Study Site 8 in Otago

A total of 42 hauler cycles were recorded (Table 1). The average cycle time of 5.57 minutes and haul volume of 3.2 m³ resulted in average productivity of 36.1 m³/PMH.

Table 1: Summary of the 42 observed cycle times and variables at Study Site 8 in Otago

Cycle (#)	Corridor (#)	Outhaul (min)	Distance (m)	Hook (min)	Pieces (#)	CyclVol (m³)	Inhaul (min)	Unhook (min)	Delays (min)	Cycle Time (min)	Productivity (m³/PMH)
1	1	0.58	223	2.08	2	4.9	1.33	0.37	1.97	4.37	67.7
2	1	0.62	227	2.87	2	2.4	1.43	0.47	1.20	5.38	26.4
3	1	0.67	232	1.55	2	4.2	1.73	0.58	0.67	4.53	55.8
4	1	0.72	237	1.77	2	3.4	1.57	0.45	0.00	4.50	44.9
5	1	0.72	249	3.33	2	1.4	1.85	0.78	1.20	6.68	12.7
6	1	0.59	284	2.52	2	0.7	1.32	0.57	11.88	5.00	8.0
7	1	0.40	284	2.97	2	2.7	1.07	0.63	5.55	5.08	32.1
8	1	0.53	184	6.45	2	1.9	1.30	0.78	0.00	9.07	12.3
9	1	0.60	189	3.45	2	3.7	1.42	0.45	0.00	5.92	37.0
10	1	0.55	212	2.38	2	3.1	1.65	0.77	0.00	5.35	35.2
11	1	0.52	212	3.03	2	3.1	1.58	0.43	0.00	5.57	33.4
12	1	0.63	223	2.85	2	2.0	1.43	0.65	0.00	5.57	21.6
13	1	0.62	230	5.38	2	3.3	1.08	0.67	0.00	7.75	25.9
14	2	0.53	159	2.62	3	1.8	1.35	0.57	0.00	5.07	21.6
15	2	0.53	166	4.05	3	3.1	1.65	0.40	0.00	6.63	27.6
16	2	0.50	175	2.60	2	2.5	1.12	0.52	0.00	4.73	32.1
17	2	0.57	179	3.73	3	3.6	1.23	0.73	0.00	6.27	34.2
18	2	0.58	184	2.77	2	3.3	1.15	0.40	0.00	4.90	40.2
19	2	0.87	183	3.07	2	1.8	1.07	0.58	0.00	5.58	19.6
20	2	0.53	187	2.35	2	5.1	1.55	0.35	0.00	4.78	64.5
21	2	0.55	198	5.48	2	3.9	1.50	0.30	0.00	7.83	29.9
22	2	0.52	197	3.45	2	4.4	1.45	0.37	0.00	5.78	45.5
23	2	0.55	192	5.30	2	0.7	1.28	0.32	0.00	7.45	6.0
24	2	0.63	207	2.17	2	3.0	1.40	0.37	0.00	4.57	39.4
25	2	0.62	209	3.40	2	3.0	1.35	0.32	0.00	5.68	31.2
26	2	0.72	217	4.62	3	3.2	1.58	0.45	3.18	7.37	26.2
27	2	0.72	227	3.07	2	3.4	1.78	0.33	0.00	5.90	34.6
28	3	0.47	122	3.53	2	5.0	1.50	0.32	0.20	5.82	51.5
29	3	0.27	124	3.15	2	2.4	1.45	0.12	0.52	4.98	28.5
30	3	0.18	127	5.18	3	4.8	1.48	1.02	0.00	7.87	36.2
31	3	0.20	132	2.62	3	2.5	1.08	0.67	0.18	4.57	32.8
32	3	0.30	130	1.97	2	4.0	1.12	0.35	0.13	3.74	64.1
33	3	0.27	141	2.83	2	3.9	1.57	0.45	0.15	5.12	45.5
34	3	0.23	146	2.55	2	4.2	1.37	0.52	0.15	4.67	53.5
35	3	0.27	144	3.10	2	3.0	1.17	0.48	0.17	5.02	35.6
36	3	0.25	146	4.57	1	2.5	0.97	0.82	0.15	6.61	22.4
37	3	0.37	155	2.38	2	4.1	1.20	0.38	0.15	4.33	57.0
38	3	0.22	153	2.98	2	4.1	1.30	0.48	0.08	4.98	49.5
39	3	0.33	162	3.95	2	2.3	1.07	0.40	0.17	5.75	24.2
40	3	0.32	160	2.47	2	3.8	1.77	0.52	0.13	5.07	44.5
41	3	0.25	165	2.33	2	4.1	1.42	0.43	6.85	4.43	54.9
42	3	0.33	170	1.57	2	3.0	1.17	0.42	0.17	3.49	51.6
Min		**0.18**	**122**	**1.55**	**1.0**	**0.7**	**0.97**	**0.12**	**0.00**	**3.49**	**6.0**
Max		**0.87**	**284**	**6.45**	**3.0**	**5.1**	**1.85**	**1.02**	**11.88**	**9.07**	**67.7**
Avg		**0.49**	**187**	**3.20**	**2.1**	**3.2**	**1.38**	**0.50**	**0.83**	**5.57**	**36.1**
SD		**0.17**	**41**	**1.13**	**0.4**	**1.1**	**0.22**	**0.18**	**2.25**	**1.21**	**15.2**

Payload analysis indicated that the limiting payloads (3.1 tonnes, 2.4 tonnes and 2.4 tonnes for profiles 1-3 respectively) were located at mid-span for each profile (Figure 3). The yarder operator had a skyline tension monitor with display unit, and the safe working load (21.3 tonnes) was exceeded during 24 of the 42 cycles (57% frequency). Slackline was the configuration in use over profiles 1 and 2.

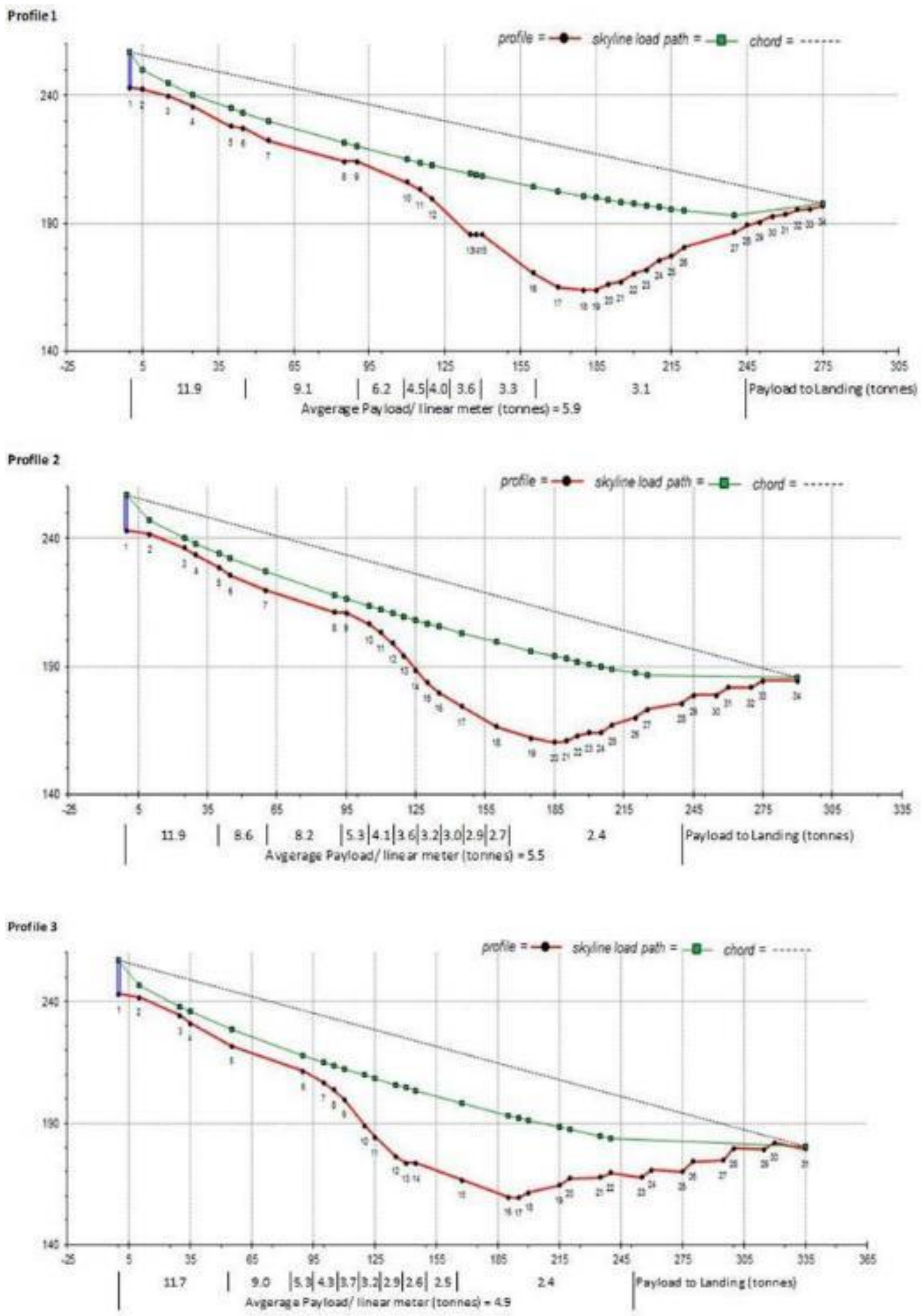


Figure 3: SkylineXL profile and payload analysis results for the Acme Slackline and Acme Shotgun operation at Study Site 8 in Otago

In the first profile (Figure 4), cycles 1, 3, 5 and 10 had delays during inhaul due to insufficient log clearance (difficult rock bluff). High tensions were generated during these delays as the carriage has to be stopped and clamped to the skyline, while the mainline was pulled through the carriage to raise the logs. After the logs had reached the desired height the carriage clamped the mainline and unclamped the skyline, and inhaul resumed. Cycles 6 and 7 had large delays associated with transporting fuel and other equipment along the corridor to assist in starting the tail hold machine, which had mechanical problems but was required for an upcoming line shift to skyline corridor 2. The skyline was adjusted during these cycles which is why there was a noticeable tension incease (especially during the hook element) for the remaining cycles. The skyline safe working load (18.6 tonnes, 182.3 kN) was exceeded during nine of the 13 cycles.

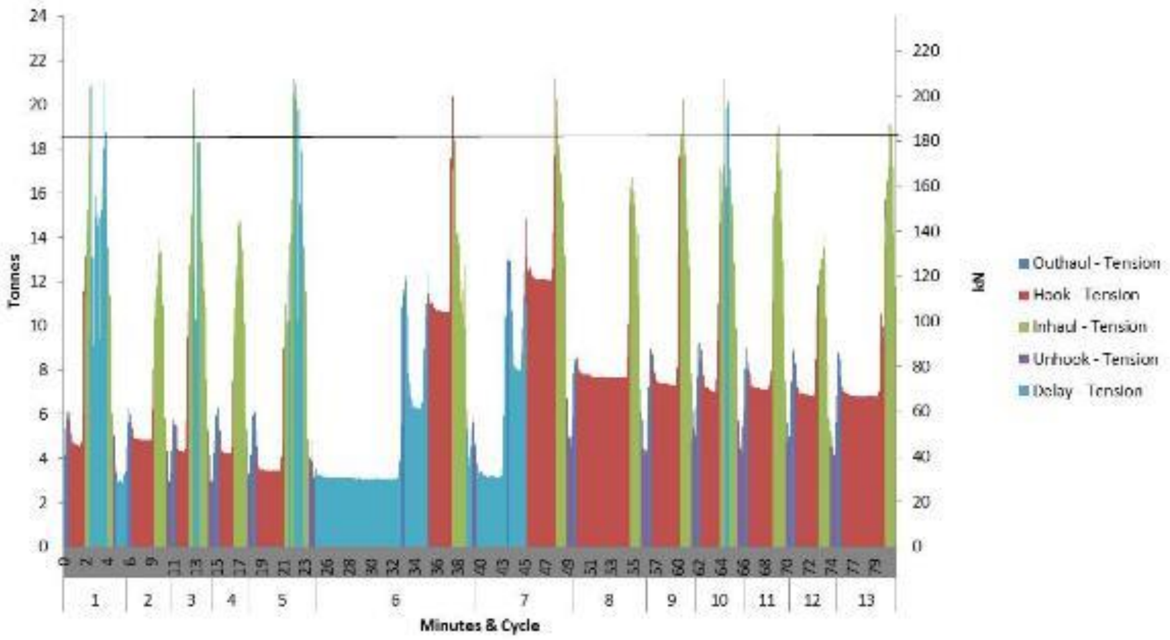


Figure 4: Skyline tensions for profile 1, cycles 1-13, Acme Slackline configuration

Over the second profile during cycles 14-27 (Figure 5), better log clearance due to topography resulted in fewer delays during inhaul.

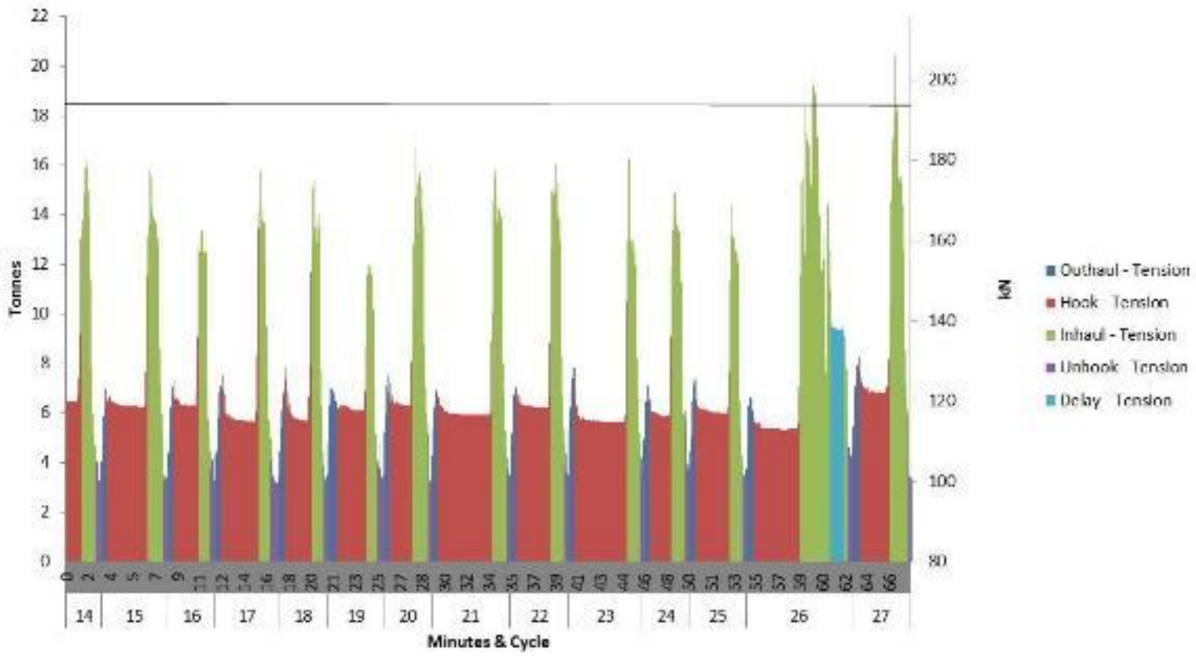


Figure 5: Skyline tensions for profile 2, cycles 14-27, Acme Slackline configuration

Cycle 26 included a personal delay where the yarder operator had to stop the carriage during inhaul to move a vehicle on the landing. In profile 2, the safe working load was exceeded during only two of the 14 cycles (14% frequency).

In the third span (cycles 28-42) a steep enough chord slope allowed for the shotgun configuration to be employed. In profile 3 (Figure 6), deflection was reduced to 6.2% as each cycle was extracted in close proximity to mid-span. The combination of reduced deflection and carriage position caused the safe working load to be exceeded in 13 of the 15 cycles (87% frequency).

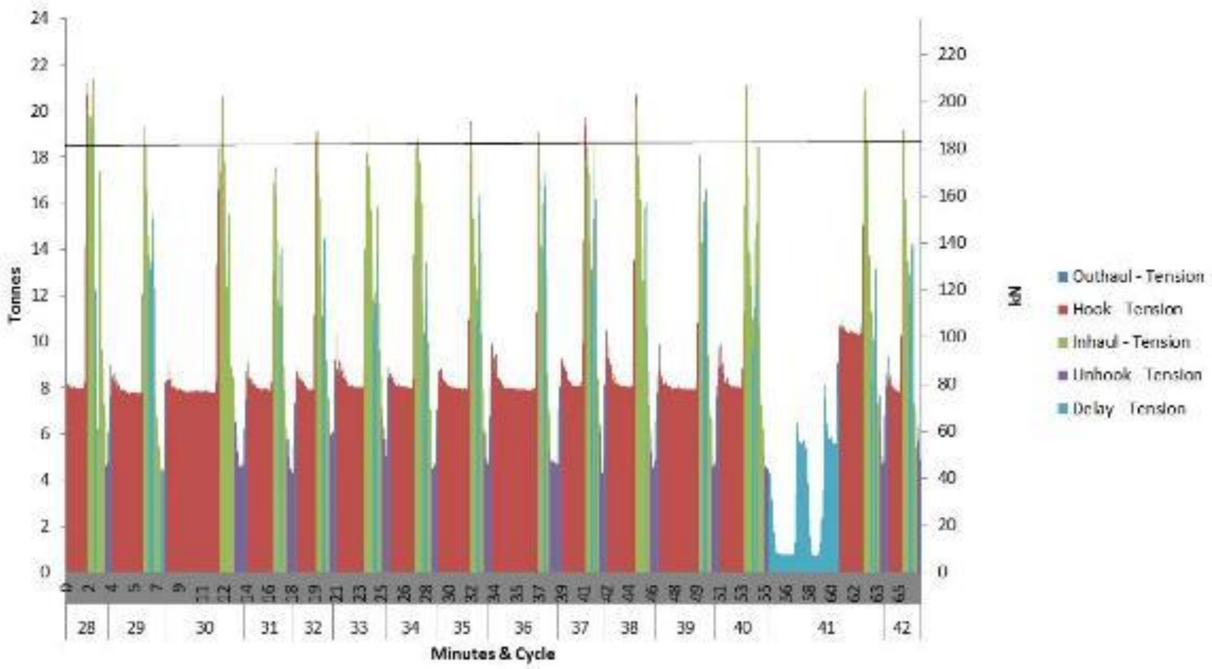


Figure 6: Skyline tensions for profile 3, cycles 28-42, Acme Shotgun configuration

Another rock bluff caused similar delays as observed during profile 1, but these delays occurred nearly every cycle. However, a difference in outhaul time was noticeable (as indicated by the dark blue shaded area) due to the shotgun configuration. The delay during cycle 41 was due to adjusting guy line tensions.