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MULTI-CAMERA SURVEILLANCE SYSTEM FOR TIME AND MOTION STUDIES OF TIMBER HARVESTING OPERATIONS

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MULTI-CAMERA SURVEILLANCE SYSTEM FOR TIME AND MOTION STUDIES
OF TIMBER HARVESTING OPERATIONS

THESIS

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in
Forest and Natural Resource Sciences in the
College of Agriculture, Food and Environment
at the University of Kentucky

By
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2019

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ABSTRACT OF THESIS

MULTI-CAMERA SURVEILLANCE SYSTEM FOR TIME AND MOTION STUDIES OF TIMBER HARVESTING OPERATIONS

Timber harvesting is an important activity in the state of Kentucky; however, there is still a lack of information about the procedure used by the local loggers. The stump to landing transport of logs with skidders is often the most expensive and time-consuming task in timber harvesting operations. This thesis evaluated the feasibility of using a multi-camera system for time and motion studies of timber harvesting operations. It was installed in 5 skidders in 3 different harvesting sites in Kentucky. The time stamped video provided accurate time consumption data for each work phase of the skidders, which was used to fit linear regressions and find the influence of skidding distance, skid-trail gradient, and load size on skidding time. The multi-camera systems were found to be a reliable tool for time and motion studies in timber harvesting sites. Six different time equations and two speed equations were fitted for skidding cycles and sections of skid-trails, for skidders that are both loaded and unloaded. Skid-trail gradient and load size did not have an influence on skidding time. There is a need for future studies of different variables that could affect skidding time and, consequently, cost.

KEYWORDS: Time and Motion Studies, Timber Harvesting, Skidding Time Models.

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MULTI-CAMERA SURVEILLANCE SYSTEM FOR TIME AND MOTION STUDIES OF TIMBER HARVESTING OPERATIONS

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DEDICATION

To my parents Maria Terezinha and Mauro for the unconditional love and support. To my grandfathers Ezequiel (in memoriam) and Jacinto (in memoriam), both whom I said goodbye when I left Brazil and I will never have a chance to see again. To my grandmothers Maria Zebina and Francisca for all the prayers they sent me. To my aunt Conceição for the guidance through the tough times of the academic life. To the rest of my family Uaná, Camila, Luiz, Marta, and Mariza for all the support. To the brothers that life presented me Marcelo, Sérgio and Vinicius.
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CHAPTER 1. INTRODUCTION

1.1 Timber Harvesting Practices in Kentucky

The consumption of solid wood timber products in the United States has been growing over the last years, and projections indicate that it will keep growing, due to the establishment of new housing, which increased in almost 10% in the last 5 years (Howard et al. 2017). Forested land covers nearly 50% of Kentucky (Kentucky State and Private Forestry Fact Sheet, 2017), and is responsible for providing economic and non-economic benefits throughout the state.

The forest sector employed 59,451 people in Kentucky in 2017, with 26,068 total direct employment, contributing to the economy with a total of $13.3 billion, $8.4 billion derived directly from timber harvesting and wood processing (Stringer et al., 2018). Logging alone employed 2,179 people last year in Kentucky and contributed $242 million to the economy. While paper converters are the largest sub-sector, timber harvesting is the most important forest sub-sector as it provides the raw material for all the other forest related business including milling, secondary industries, and residues (Stringer et al., 2018). Kentucky has an important and active logging sector. However, there is a lack of information about mechanized timber harvest operations as well as reliable information on the current productivity and costs of these operations.

The majority of timber harvesting in Kentucky is accomplished with ground-based operation. They require the construction of roads and skidder and forwarder trails in order to create pathways to extract wood and provide access for forest management (Sessions, 2007; Kellogg, 1992). Logging results in the loss of canopy cover and can cause soil compaction, changing the surface moisture content and causing runoff and erosion,
potentially having negative effects on the aquatic systems and terrestrial (Maigret et al., 2014; Bowker, 2013). The proper layout of the skidder and forwarder trails has an important role in decreasing logging disturbance and reducing skidding costs (Contreras et al., 2016; Stringer et al., 1998).

1.2 Timber Harvesting Operations

A successful timber harvesting should follow a harvest plan developed for each harvest area, considering the local forest composition, topography, machinery used, and harvest objective of the harvest (Odhiambo, 2010). The harvesting plan aims to describe clearly how to conduct each operation in order to increase productivity (Odhiambo, 2010; Frank, 1985). Harvesting timber consists of a series of operations. The present study is being conducted on ground-based operation consisting of: building forest roads and skid-trails using bulldozers; cutting trees (felling) with a feller-buncher; primary transport of logs from the cutting site to the landing using skidders; bucking and truck loading with loaders; and transporting the logs from the forest to the mill with trucks, including semi-tractor trailers.

1.2.1 Primary Transport

The primary transport of logs in ground-based operations is often the most time consuming operation and improving the cost efficiency of skidding can directly improve the efficiency of the entire operation. Primary transport, also called terrain transport, is the transport of trees or tree sections from the felling site to the landing, where they will be bucked and loaded for transport to the mill (Odhiambo 2010). The most common
machinery used for this operation are skidders and forwarders. The selection of which to use should be determined by site conditions and log length (Contreras et al. 2016; Kellogg et al., 1992).

The design of the primary transport network including either skid-trails or forwarder paths has a significant influence on the productivity of the machines, optimizing distances between log bunch locations and the landing is a way to reduce the time and costs of primary transport and as a result the cost of the entire operation (Contreras et al. 2016; Greulich 2003).

Primary transport is the most expensive operation in forestry (Behjou 2008 et al., Dvorak 2005). Time and motion studies have been used to calculate the productivity, measured by the speed that machines operate and the load they transport, and costs of primary transport. There are a number of methods to conduct these studies. Contreras et al. (2017) adapted surveillance cameras to work on skidders and determine the influence of skid-trail gradient on skidding time. Behjou et al. (2008), Gilanipoor et al. (2012) used traditional stopwatch methods to estimate production and costs of skidders. Strandgard et al. (2016) achieved satisfactory results using the Global Navigation Satellite System (GNSS) on time studies of forwarders.

1.3 Time and Motion Studies

Time and motion studies are valuable in determining productivity and costs of industrial operations and it has been widely applied in studies of forest machinery productivity (Nuutinen 2013; Behjou et al. 2008; Olsen et al. 1983; Worley et al. 1965). Forest harvesting is a significant cost operation that requires high investment in
machinery. To manage these operations to achieve maximum productivity and cut logging costs, managers need accurate productivity information (Hejazian et al. 2013, McDonald and Fulton 2005). This information can be obtained through time and motion studies.

The union of the time study work of Taylor with the motion study work of Gilbreth gave origin to modern time and motion studies (Nuutinen 2013; Niebel 1976). Time studies measure time consumption for a determined task, through repetitive work cycles. Motion studies work on the improvement of tasks through the elimination of unnecessary motions and the subsequent reduction in time (Niebel 1976).

The biggest challenge for conducting time and motion studies in forestry is the variability of environmental conditions in forests (Olsen et al. 1983; Worley et al. 1965). Niebel (1976) also noted the human factor as an influential variable in time and motion studies, causing deviations as great as 50%, by working either faster or more slowly than usual (Niebel 1976). Developing new technologies to address differing forest conditions is important to facilitate the applicability of such significant studies.

Several methods for conducting time and motion studies are currently in use, including both classic methods and new emerging technologic alternatives.

1.3.1 Security Camera Systems

Recent studies testing the feasibility of using security camera systems, commonly used for surveillance, adapted for use on skidders have proved useful for determining information on the primary transport of logs. Contreras et al. (2017) concluded, under
controlled circumstances, that security camera systems are reliable for conducting time and motion studies providing suitable levels of accuracy. The most relevant advantages of this method are quick and non-invasive installation, high storage capacity, unlimited battery life (assuming power is derived from the vehicle), weather resistance, capacity to capture multiple angles, high definition and detailed image, and software that provides option to watch time stamped footage in both fast-forward and slow motion speed (Contreras et al. 2017).

Using cameras for time and motion studies might offer an advantage over other methods because it is possible to identify the cause of possible delays on the performed tasks. Although regular video cameras have been used for similar purposes, they are usually limited by low storage capacity and short battery life (Parker et al. 2010). Low tolerance for high temperatures and fragility can also limit the use of regular video cameras on forestry heavy machinery, especially harvesting vehicles.

1.3.2 Global Positioning System (GPS)

Global Positioning System (GPS) are being widely employed to track a variery of vehicles associated with a number of differing military and private uses including agriculture (Dupre 2006). Although GPS is being applied on agricultural equipment, the use of this technology in logging operations is currently uncommon (Dupre 2006).

Several studies used GPS units to track the primary transport of the logs, made by skidders and forwarders, with the objective to create automated time study systems (Strandgard et al. 2016; McDonald and Fulton 2005). Dupre (2006) was able to identify and measure skid cycles using GPS tracking. McDonald and Fulton (2005) were able to
identify more than 90% of skid cycles in their experiment, and found a difference of about 2% between GPS and times, determined using a stopwatch.

McDonald and Fulton (2005) also found some problems associated with the use of GPS in forests such as signal loss, difficulty in determining the exact position of the machine over time, and inaccurate determination of specific tasks involved in skidding operations.

1.3.3 Stopwatch Technique

Wang et al. (2003) identified stopwatch and paper as probably the most common method for time and motion studies in logging operations. This method requires two people, one operating the stopwatch and other recording the time and any other needed measurements (Wang et al. 2003; Olsen and Kellogg 1983). Olsen and Kellogg (1983) defined this process as tedious, expensive, and prone to a high probability of error. This method requires people working full time in the field carefully watching the operations, making it expensive, time consuming, and even dangerous as work conditions associated with timber harvesting can be hazardous.
CHAPTER 2. TIME AND MOTION STUDY

2.1 Introduction

Kentucky is one of the largest producers of hardwood sawlogs in the United States; however, there is still a lack of basic information about mechanized timber harvest productivity and operational costs for ground skidding operations common to Kentucky.

Timber harvesting machinery is expensive to acquire and operate, has high repair and maintenance cost and high fuel consumption, all of which tend to get higher as the machinery ages (Holzleitner et al., 2011). For several decades, utilizing time and motion studies to estimate machine productivity and costs for various harvesting systems has been essential (Nuutinen, 2013; Behjou et al., 2008; Olsen and Kellogg, 1983; Worley et al., 1965).

Traditionally, the stopwatch method was used to conduct time and motion studies in logging operations (Wang et al., 2003; Olsen and Kellogg, 1983). Despite its popularity, this method has a few important limitations including only sampling a subset of the work due to long work hours, requiring the presence of researchers on site, and high likelihood of altering operators’ behavior while being observed (Nuutinen, 2013; Parker et al., 2010; de Hoop and Dupre, 2006; Wang et al., 2003; Olsen and Kellogg, 1983). In recent years, global positioning system (GPS) technology has been introduced into time and motion studies with the hope of automating data collection and avoid some of the limitations of the stopwatch method (Strandgard et al. 2016; McDonald and Fulton 2005). Satisfactory results have been reported in agricultural operations (Grisso et al., 2012; Palasniswami et al., 2011), but its use in forest operations has been limited mainly because of the isolated areas with difficult terrain conditions often under canopy, that
leads to poor satellite reception (McDonald and Fulton, 2005). Another limitation is that individual work phases (e.g. unloaded travel, loading, loaded travel) cannot be identified from the spatial data alone (Dupre, 2006; McDonald and Fulton, 2005). Video cameras have also been introduced into time and motion studies to estimate the productivity of harvesters and forwarders (Nakagawa et al., 2010 and 2007; Nurminem et al., 2006). Security camera systems, commonly used for property surveillance, are a feasible option for conducting time and motion studies on forest harvesting equipment offering high storage capacity, multiple cameras recording simultaneously in high definition, and a low implementation cost (Contreras et al., 2017). Video footage from camera systems combined with GPS units have can be used to accurately determine time consumption of each work phase and extract machine movements, thus facilitating time and motion studies while avoiding the limitations of the traditional stopwatch method (Contreras et al., 2017; Nurminem et al., 2006; McDonald and Fulton, 2005).

Skidding is the highest cost component among all stump-to-landing harvesting activities and its efficiency is highly dependent on the location of skid-trails and landings (Lopes and Diniz, 2015; Behjou et al., 2008; Renzie and Han-Sup, 2008; Dvorak, 2005). In contrast, the efficiency of felling, processing, and loading is independent of the location of skid-trail and landings. Thus, numerous studies have used time and motion studies to estimate skidding productivity and develop cycle time equations (Strandgard et al., 2016; Contreras et al., 2016; Gilanipoor et al., 2012; Behjou et al., 2008).

Most of these studies have developed skidding cycle time equations as a function of skidding distance and load size (i.e. number of logs). Skidding cost for a tract is
typically calculated using the average skidding distance, average load size, and an estimated number of total skidding turns. Terrain steepness, which has been reported to affect skidder travel time (Proto et al., 2018; Contreras et al., 2017; Lopes and Diniz, 2015; Gilanipoor et al., 2012; Behjou et al., 2008; Heinimann, 1999), has rarely been incorporated directly in skidding cycle time equations. A common approach is to develop different equations for uphill and downhill skidding (Contreras et al., 2016; Han and Renzie, 2005). However, this approach only produces course cycle time estimates because terrain along a skid-trail often have sections with varying slopes and both uphill and downhill. Lopes et al. (2007) fitted different skidding time equations for different ranges of slope gradient, not considering complete skidding cycles, finding that slopes above 20% could impede wheeled skidders to operate due to the lack of attraction with the soil. The lack of field methods to collect efficiently terrain slope along skid-trails has been the main reason for not including terrain slope in cycle time models. With advances in geographic information system (GIS) technology, high-resolution digital elevations models are now readily available, from which terrain slope data can be derived across entire forest tracts and can be incorporated into the development of more accurate cycle time models. Recent models develop to find the optimal location of skid-trails, landing and access roads (Parsakhoo et al., 2017; Sterenczak and Moskalik, 2015; Akbarimehr and Naghdi, 2012) will greatly benefit from more accurate skidding cycle time models. 

Lastly, the state of Kentucky has an active logging industry and it is the second largest hardwood producer in the eastern United States. However, there is a lack of studies addressing productivity and costs of logging equipment in the state, which is much needed in the face of increased pressure to utilize forest resources sustainably. In
This work, we focus on conducting time and motion study for skidding operations and evaluating the effect on terrain slope in skidding productivity using data collected from logging sites in Kentucky. More formally, this work considered two main objectives: 1) conduct a time and motion study using a security camera system to automate data collection and accurately measure time consumption of different work phases, and 2) evaluate the effect of terrain slope (skid-trail gradient) on skidding productivity to develop more accurate skidding cycle time models.

2.2 Methods

2.2.1 Site description

In this study, data collection was performed from three active logging sites across the state of Kentucky. All sites employed fully mechanized harvesting operations. The majority of felling was conducted using tracked feller-bunchers with occasional manual felling in areas of difficult access. Bulldozers performed skid-trail construction and, occasionally, winched logs from the stump to the skid-trails. The primary transport from stump to landing in all sites was conducted using grapple skidders. Once the logs arrived at the landing, log loaders delimbed and bucked them into 8 feet logs.

2.2.1.1 Site 1

Site 1 was located at the University of Kentucky’s Robinson Forest (RF) in Clayhole, Kentucky (37°28’23”N – 83°08’36”W) in Perry, Knott and Breathitt counties (Figure 1).
Vegetation at Robinson Forest, located in the Cumberland Plateau physiographic region, is a mixed mesophytic forest characterized by high species diversity and complex structure. The most common harvested species were Tulip Poplar (*Liriodendron tulipifera*), Scarlet Oak (*Quercus coccinea*), Chestnut Oak (*Q. montana*), Black Oak (*Q. velutina*), Red Oak (*Q. rubra*), and White Oak (*Q. alba*). A total of 7135 feet of skid-trails were included in this study. The surveyed skid-trail length was 7135 feet, with an average gradient, measured by its slope percent, of 2.65%, ranging from 21 to -28% of slope percent gradient for unloaded travels. One Timbco 445 EXL feller-buncher performed the felling at assigned patches, assisted by two chainsaw operators who harvested trees where future skid trails were going to be built. One John Deere 850K bulldozer constructed the skid-trails, assisted by two John Deere 650 bulldozers, that also occasionally conducted the transport from the stump to the skid trails. The stump to landing transport was made by one John Deere 648G-II Grapple Skidder, driven by an operator with 10 years of experience, and one John Deere 648G-III Grapple Skidder, driven by an operator with 5 years of experience operator. At the landing, one John Deere 437E loader equipped with a delimber and a bucksaw, delimbed and bucked the logs into 8 feet long logs.

### 2.2.1.2 Site 2

The second site was located in a private property in Beaver Dam, Kentucky (37°24′33.313″N - 86°49′20.71″W), located in the Western Coal Fields region and covered by an Oak bottomland hardwood forest (Figure 1). Black Oak was the most
harvested species, followed by Yellow Poplar, Southern Red Oak (*Quercus falcata*), and White Oak. The surveyed skid trail length was 4166 feet, ranging from 350 to 550 feet of elevation with an average skid-trail gradient of -4.30%, ranging from 17 to -23% for unloaded travels. Only two workers were present, a Timbco T425-D Track feller-buncher performed all the felling and bunching of the logs to facilitate skidding. No skid-trails were built. Preexisting roads were used for the primary transport of the logs. One John Deere 648G-III Grapple Skidder, operated by a driver with 30 years of experience who did all the primary transport and arranged the logs into piles at the landing. No processing operations were performed during the time the researchers were present.

2.2.1.3 Site 3

The third harvesting site was located in Middlesboro, Kentucky (36°40'54.279"N - 83°44'22.521"W), also located on the Cumberland Plateau physiographic region, covered by a mixed mesophytic forest (Figure 1). Logs brought to the landing were Red Maple (*Acer rubrum*), followed by Chestnut Oak, Yellow Poplar, and Hickory (*Carya spp.*). The surveyed skid-trail length was 4919 feet, ranging from 1800 to 2000 feet in elevation with a 6.76% average skid-trail gradient, ranging from 30 to -12% for unloaded travel. One Timbco T425-D track feller-buncher performed all the felling, and bunching of logs adjacent to the skid-trails. No skid-trails were built during while the research was conducted. Two Prentice® 2432 skidders performed the stump to landing transport; the operators had 2 and 3 years of experience. On the landing, two Barko® loaders model 495ML were delimming, bucking, and loading the trucks.
Figure 1. Skid-trail layout of sites 1 (A), 2 (B), and 3 (C).

2.2.2 Field data collection

The on-site data collection occurred between October 12th and November 2nd of 2017 on site 1, July 25th to August 1st of 2018 for site 2, and August 23rd to September 4th of 2018 on site 3.
2.2.2.1 Skid-trail

To understand the effects of skidding distance and skid-trail gradient on skidding time, we surveyed existing skid-trails prior skidding operations at the three sites. Numbered flags were placed at changes of gradient and direction along skid-trail, and slope distance, horizontal distance, and gradient in between adjacent flags were measured using a True Pulse® 200L laser rangefinder with the precision of one foot for distance and a tenth of a degree for gradient. Flags were made from laminated paper sheets attached to wooden sticks and placed about 3 feet above the ground. For better identification on the video footage, flags were colored coded by skid-trail.

2.2.2.2 Security camera systems

The Swann® 8-channel indoor/outdoor digital video recorder (DVR) with high definition wide-angled cameras were used to collect data at all three sites. For each skidder, four cameras were positioned outside the cabin to capture images from the front, back, and both sides, providing a near 360° field of view (Figure 2). Power inverters were used to power the 110w DVRs from the 12V system on the skidders. Several inverters were used including the EverStart Plus 750W, Power Bright® ML900-24 900W (2 pieces), Schumacher models XI75B 750W and EverStart Plus 750W, and Wagan 2016–6 700W.

Each skidder was outfitted with four cameras, one DVR, and one power inverter. The 12V inverters were connected directly to one of the two skidder batteries, providing an alternating current that could be accessed by regular power outlets, feeding the DVR
and the cameras. Video cables connected the cameras to the DVR, running along edges of the cabin to a plastic box containing the DVR, the power inverter, and power strip (Figure 3). Figure 4 shows the connections between the camera set, DVR, inverter, and power supply. The plastic boxes were positioned outside the skidder, in front of the windshield to minimize the impact to the operator’s field of view, firmly fixed using bungee cords.

Once the installation was complete, the skidder drivers committed to turn the power inverter on at the beginning of each day of work, providing power for the whole system and automatically starting the video recording.
Figure 3. Plastic box containing the DVR and power inverter after a day of work.
Figure 4. Scheme of the installation of the battery-powered security camera system.

2.2.2.3 Load measurement

Data were recorded for each load in a skidding cycle, including the number of logs and species, diameter outside bark at 5 feet increments, and length were recorded for each log. The length and diameter were measured using respectively a measuring tape,
with the precision of a tenth of a foot, and a tree caliper, with the precision of a tenth of an inch. The weight of each log was estimated by its dimensions and specie, following the procedure explained by Timson (1972). The sum of the weights of all the logs brought to the landing by the end of each skidding cycle were considered the total load size of the cycle.

2.2.3 Time consumption

Time was recorded for the installation of each video system. The time stamped video footage from the cameras was visually analyzed directly from the DVR software to measure both the loaded and unloaded skidder travel time for each flagged section and summed to estimate total skidding travel time. To define a skidding cycle, we considered five work tasks: 1) unloaded travel; 2) maneuvering to grapple logs; 3) loaded travel; 4) maneuvering to drop the logs; and 5) log arrangement at the landing. An additional work task was included for sites 2 and 3, where skidder operators also arranged logs to keep the landing clear while the processing and loading were not active. All delays were also recorded and classified as bottleneck, maintenance due to breakdown, extra maneuvering, stuck skidder, waiting for logs, and waiting for researchers to finish log measurements.

Skidding time for travel between adjacent flags and any unproductive time between flags was obtained from the time stamp in the DVR video footage. The colors and numbers on the flags, positioned besides the skid-trails indicated the location of the skidders at the time of travel, providing accurate distance crossed by the skidders in between two adjacent flags. Complete skidding cycle time was calculated by summing up unloaded travel, maneuvering to grapple the logs besides the skid-trail, loaded travel, and
maneuvering to drop the logs at the landing. The average skid-trail gradient for unloaded and loaded travel for each skidding cycle was also determined considering gradient between all skid-trail sections along a skid-trail. The time required to review the video footage to extract time consumption for all work tasks by skidding cycle was calculated.

2.2.4 Data analysis

Time consumption data on skid-trail sections was analyzed to determine correlations between skid-trail gradient, total load weight, length of the longest log, and number of logs in the skidding time of each cycle as well as differences between unloaded and loaded travel.

Linear regressions tested, at 95% of confidence, the influence of skidding distance, skid-trail gradient (average slope for unloaded and loaded travel), total load weight, number of logs, and length of the longest log on skidding time, as well as the interaction between them. Eight regressions were fitted to predict delay-free cycle time, total skidding travel time, unloaded travel time, loaded travel time, unloaded section time, loaded section time, unloaded section speed, and loaded section speed.

The regressions that best fit each of the five models were found using the dredge function on the software R. There were no control samples, each skidding cycle counted as a repetition and the difference on distance and gradient between each pair of flags were the sampling units.
2.3 Results

2.3.1 Security Camera Systems

The first installation of the security camera system on each skidder required approximately 1 hour. The most time-consuming tasks were to build appropriate power cables and connect them to the battery of the skidder, connect them securely to the battery of the skidders, and safely attach the plastic box outside the cabin. Installation time was reduced to approximately 30 minutes on all following installations on a same machine. Once the installation was complete, the skidder operators committed to turn on the power inverter on at the beginning of each day of work, providing power for the whole system and automatically starting the video recording.

The security camera systems performed successfully, the high definition video footage allowed the researchers to see clearly the flags placed beside the skid-trails and to distinguish easily the different skidding tasks, and to identify the causes of any delays or breaks during the skidding cycles. Three different researchers manually reviewed the video footage to identify and measure the time consumption of all individual work tasks. In one hour of work in the lab, 1.04 hours of footage were reviewed for site 1, 0.75 hours for site 2, and 0.8 hours for site 3.

Although the cameras resisted well the hard environment of logging operations and provided high quality footage, there was loss of video footage during some skidding cycles due to unidentified technical failures. We measured the load size of 139 cycles on site 1. However, the cameras properly captured only 92 complete skidding cycles. On site 2, 115 out of 135 measured cycles were recorded, and on site 3, 104 cycles were recorded
out of the 142 measured cycles. In summary, 74.76% of all the field work was successfully recorded by the camera system. While the DVR software reports a log of possible failures, the software did not accuse overheating or any other issues, which suggests that the power supply was interrupted during the missing or incomplete cycles.

Sixteen cameras were used for this study; one camera was knocked off a skidder and lost, and five other cameras sustained mounting damage. However, all of them were capable of recording video at full quality (Figure 5). One camera was severely damaged resulting in loss of the recording capacity. The cables used to connect the cameras to the DVR and the inverter to the battery were not damaged indicating that the cables were robust enough and their installation, being taped safely to the machines in order to keep them out of the operators’ field of view, was sufficient to maintain their integrity. The plastic boxes used to store the DVRs and the power inverters kept all the equipment safe from rain, water and dust. Holes drilled in the side of the boxes to fit all the connection cables may have provided enough ventilation to avoid system overheating.
After extensive use, the oldest DVR, acquired in 2015, experienced a hardware failure, making it impossible to watch the videos directly from its native software. In order to preserve the footage saved on its hard drive, all the videos were backed up to an external hard drive, then put together and synchronized on the computer software Adobe Premiere Pro® CC 2018. Out of the 6 power inverters used for this study, the one model EverStart Plus 750W resulted in fuse failures. Four other inverters, Power Bright® ML900-24 900W (2 pieces), Schumacher XI75B 750W, and Wagan 2016–6 700W, stopped working with no apparent signs of damage. The only power inverter that did not exhibit any problems was the Schumacher model X175DU 750W, which was the last one to be purchased and less used.
2.3.2 Skidding Productivity

2.3.2.1 Site 1 – Skidders 1 and 2

Total cycle time and skidding distance varied widely across the 92 skidding cycles captured on site 1 (Table 1). Total cycle time varied from approximately 5 minutes to 75 minutes, including delays, while the skid-trail distance varied from 1,088 to 5,096 feet. The terrain slope gradient varied from -28 to 21%. Total load weight for site 1 ranged from 5,076 to 23,867 pounds, and log length ranged from 33 to 113 feet. The skidders carried from 1 to 6 logs per cycle. The average productivity per scheduled machine hour was 15.9 2 ton/h for skidder 1 and 14 ton/h for skidder 2.

Approximately 40 hours and 38 minutes of work footage was captured on site 1, with 9 hours and 59 was unproductive time resulting in 75.42% of time spent on productive tasks. The major causes of delay on site 1 were bottlenecks and the skidders being stuck on the wet skid-trail, corresponding to respectively 1 hour and 46 minutes and 50 minutes (Figure 6). The productive task that consumed more time in site 1 were the loaded travels (Figure 7).

2.3.2.2 Site 2 – Skidder 3

115 cycles were recorded on site 2, with total cycle time ranging from 2 to 36 minutes, and the skid-trail distance ranged from 186 to 5,084 feet (Table 1). The gradient ranged from -23 to 17%. Total load weight for site 2 ranged from 2,003 to 14,604
pounds, and log length ranged from 26.7 to 75.1 feet. The skidder 3 carried from 1 to 5 logs per cycle with a productivity per scheduled machine hour of 21.4 ton/h.

Approximately 17 hours and 15 minutes of work were recorded on site 2, with 5 hours and 33 minutes of unproductive time. The percentage of time spent on productive tasks was 67.83%. The major cause of delay on site 2 was waiting for the feller-buncher to finish cutting and processing the logs, corresponding to 3 hours and 46 minutes (Figure 6). The productive task that consumed more time in site 2 were the loaded travels (Figure 7).

2.3.2.3 Site 3 – Skidders 4 and 5

104 cycles were recorded on site 3, with total cycle time ranging from 4 to 119 minutes, the skid-trail distance varied from 1,400 to 4,006 feet (Table 1). The gradient ranged from -12 to 30%. Total load weight for site 2 ranged from 6,119 to 23,650 pounds, with log length ranging from 31 to 110 feet. The skidders carried from 1 to 7 logs per cycle. The productivity per scheduled machine hour of skidder 4 was 20.4 ton/h and of skidder 5 was 19.7 ton/h.

The cameras recorded approximately 33 hours and 12 minutes of work footage for site 2, with 8 hours and 8 minutes of unproductive time. The percentage of time spent on productive tasks was 75.43%. The major causes of delay on site 3 were machinery breakdown and the skidders being stuck on mud, corresponding to respectively 1 hour and 44 minutes and 1 hour and 27 minutes (Figure 6). The productive task that consumed more time in site 3 was the maneuvering to grapple the logs (Figure 7).
Table 1. Work details of the skidders.

<table>
<thead>
<tr>
<th></th>
<th>Site 1</th>
<th>Site 2</th>
<th>Site 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Skidder 1</td>
<td>Skidder 2</td>
<td>Skidder 3</td>
</tr>
<tr>
<td>Mean</td>
<td>Min.</td>
<td>Max.</td>
<td>Mean</td>
</tr>
<tr>
<td>Skidding distance (ft)</td>
<td>3073.5</td>
<td>1088.0</td>
<td>5096.0</td>
</tr>
<tr>
<td>Load weight (lbs)</td>
<td>14665.5</td>
<td>5075.8</td>
<td>21623.4</td>
</tr>
<tr>
<td>Number of logs</td>
<td>3.3</td>
<td>1.0</td>
<td>6.0</td>
</tr>
<tr>
<td>Length of the longest log (ft)</td>
<td>69.9</td>
<td>41.6</td>
<td>102.3</td>
</tr>
<tr>
<td>Total cycle time (min)</td>
<td>25.1</td>
<td>6.5</td>
<td>74.5</td>
</tr>
<tr>
<td>Delay-free cycle time (min)</td>
<td>18.1</td>
<td>6.5</td>
<td>30.7</td>
</tr>
</tbody>
</table>
Figure 6. Delay time distribution

Figure 7. Time distribution of the skidding tasks in sites 1 (A), 2 (B), and 3 (C).
2.3.3 Skidding Time Models

With the purpose of modeling skidding time based on skidding distance, skid-trail gradient, load weight, number of logs, and length of the longest log, we only considered unloaded and loaded travel times. Linear correlations between each of the five different independent variables and delay-free skidding time yielded the highest coefficients of determination ($R^2$). To find the most appropriate model for skidding time, five different linear regressions were fitted to delay-free times of skidding cycles and skid-trail sections. Skidding cycles cannot determine the effect of gradient once the average gradient is zero, therefore cycles were divided into unloaded and loaded travels to find the average gradient of each unloaded and loaded travel. Loaded travels also considered all variables related to load size. In order to incorporate more precisely the effect of skid-trail gradient skid-trail sections were used as sample units, fitting one regression for unloaded travels and other for loaded travels.

The best-suited models for each scenario were selected based on the Akaike information criterion (AIC). The analysis of complete cycles included 307 sampling units, using the position on the AIC rank to find the most well fitted model. The section models have over 8500 sampling units and they were ranked by the AICc.

2.3.3.1 Delay-free Skidding cycles

The variables that best explained the delay-free skidding cycle time were total skidding distance, total load weight, number of logs, and maximum log length (Table 2). The best-fit model (Equation 1) resulted in an $R^2$ of 0.723. Although this model has shown to be suitable for estimating delay-free skidding cycle time, it is not sensitive to
skid-trail gradient, which we believed had a significant influence on loaded travel time.

All independent variables showed a positive correlation to skidding time (Table 3). Skidding distance and total load weight showed the strongest correlations to skidding time.

\[
Y = -41.59 + 3.69\beta_1 - 3.03\beta_2 + 0.13\beta_3 + 0.004\beta_4 - 0.01\beta_2\beta_3 + 0.005\beta_2\beta_4 
\]  

(1)

Where \(Y\): estimated skidding time

\(\beta_1\): maximum log length

\(\beta_2\): number of logs

\(\beta_3\): total skidding distance

\(\beta_4\): total load weight

| Variables             | Estimate | Std. Error | t value | Pr(>|t|) |
|-----------------------|----------|------------|---------|----------|
| Intercept             | -41.590  | 85.946     | -0.484  | 0.629    |
| Maximum length        | 3.688    | 1.025      | 3.597   | 0.0004 ***|
| Number of logs        | -3.034   | 29.378     | -0.103  | 0.918    |
| Total distance        | 0.133    | 0.015      | 8.966   | < 2e-16 ***|
| Total load weight     | 0.004    | 0.009      | 0.477   | 0.634    |
| Num. logs : distance  | -0.010   | 0.005      | -2.001  | 0.046 *  |
| Num. logs : weight    | 0.005    | 0.003      | 1.835   | 0.067 .  |

Signif. codes: 0 *** 0.001 ** 0.01 * 0.05 .

Residual standard error: 244.9 on 300 degrees of freedom
Multiple R-squared: 0.7227, Adjusted R-squared: 0.7172
F-statistic: 130.3 on 6 and 300 DF, p-value: < 2.2e-16
2.3.3.2 Skidding Travel Time

This model considers skidding travel time only, unloaded and loaded without including the remaining three work tasks. The variables retained in the model were distance, total load weight, and maximum log length (Table 4). The best-fit model (Equation 2) resulted in an $R^2$ of 0.959. Although this model has shown to be suitable for estimating delay-free skidding travel time, it was not sensitive to skid-trail gradient. All independent variables showed a positive correlation to skidding time (Table 5). Skidding distance had a stronger correlation to skidding time than the other independent variables (0.98).

$$Y = -18.11 + 0.71\beta_1 + 0.11\beta_2 + 0.0005\beta_3 + 1.27\times10^{-6}\beta_1\beta_3$$  \hspace{1cm} (2)
Where Y: estimated skidding time

$\beta_1$: maximum log length

$\beta_2$: total skidding distance

$\beta_3$: total load weight

### Table 4. Total travel time model coefficients:

| Variables            | Estimate | Std. Error | t value | Pr(>|t|) |
|----------------------|----------|------------|---------|----------|
| Intercept            | -18.1100 | 17.5700    | -1.0310 | 0.30     |
| Maximum length       | 0.7102   | 0.3092     | 2.2960  | 0.022 *  |
| Total distance       | 0.1062   | 0.0052     | 20.6070 | < 2e-16 *** |
| Total load weight    | -0.0005  | 0.0016     | -0.2780 | 0.782    |
| Distance : weight    | 1.27x10^-6 | 3.66x10^-7 | 3.4600  | 0.0006 *** |

Signif. codes: 0 *** 0.001 ** 0.01 * 0.05 .

Residual standard error: 75.15 on 302 degrees of freedom
Multiple R-squared: 0.9585, Adjusted R-squared: 0.958
F-statistic: 1746 on 4 and 302 DF, p-value: < 2.2e-16

### Table 5. Correlation between all variables for complete skidding travels.

<table>
<thead>
<tr>
<th></th>
<th>Total load weight</th>
<th>Number of logs</th>
<th>Maximum log length</th>
<th>Skidding distance</th>
<th>Time spent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total load weight</td>
<td>1.00</td>
<td>0.3798</td>
<td>0.6658</td>
<td>0.4524</td>
<td>0.4900</td>
</tr>
<tr>
<td>Number of logs</td>
<td></td>
<td>1.00</td>
<td>0.2624</td>
<td>-0.0019</td>
<td>0.0260</td>
</tr>
<tr>
<td>Maximum log length</td>
<td></td>
<td></td>
<td>1.00</td>
<td>0.3495</td>
<td>0.3887</td>
</tr>
<tr>
<td>Distance</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>0.9765</td>
</tr>
<tr>
<td>Time spent</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.00</td>
</tr>
</tbody>
</table>
2.3.3.3 Unloaded Skidding Travel Time

To test the influence of skid-trail gradient on skidding time, we also modeled unloaded skidding travel time. The best model to predict unloaded skidding travel time retained average skid-trail gradient, skidding distance, and the interaction between them (Table 6). The $R^2$ of this model is 0.920 (Equation 3). Travel distance and skid-trail gradient showed a negative correlation to skidding time for unloaded travels (Table 7). However, both presented weak correlations.

$$Y = 2.92 + 0.11\beta_1 - 1.10\beta_2 + 0.007\beta_1\beta_2$$ (3)

Where $Y$: estimated unloaded travel time

$\beta_1$: distance of unloaded travel

$\beta_2$: average skid-trail gradient for unloaded travel

| Variables           | Estimate | Std. Error | t value | Pr(>|t|) |
|---------------------|----------|------------|---------|----------|
| Intercept           | 2.915    | 4.924      | 0.592   | 0.554    |
| Unloaded distance   | 0.114    | 0.003      | 34.101  | < 2e-16 *** |
| Unloaded gradient   | -1.097   | 1.154      | -0.951  | 0.342    |
| Distance : gradient | 0.007    | 0.001      | 6.441   | 4.65e-10 *** |

Signif. codes: 0 *** 0.001 ** 0.01 * 0.05 .

Residual standard error: 38.66 on 303 degrees of freedom
Multiple R-squared: 0.9199, Adjusted R-squared: 0.9191
F-statistic: 1160 on 3 and 303 DF, p-value: < 2.2e-16
Table 7. Correlation between the independent variables on complete unloaded travels.

<table>
<thead>
<tr>
<th></th>
<th>Distance</th>
<th>Gradient</th>
<th>Time spent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance</td>
<td>1.00</td>
<td>0.9427</td>
<td>-0.3767</td>
</tr>
<tr>
<td>Gradient</td>
<td>1.00</td>
<td></td>
<td>-0.2235</td>
</tr>
<tr>
<td>Time spent</td>
<td></td>
<td>1.00</td>
<td></td>
</tr>
</tbody>
</table>

2.3.3.4 Loaded Skidding Travel Time

The influence of skid-trail gradient on skidding time was also modeled for loaded skidding travel time. The best-fit model retained skidding distance, average gradient, and total weight as the independent variables (Table 8), resulting in an $R^2$ of 0.950. In this case, skid-trail gradient did have an influence (Equation 4). The independent variable that showed the strongest correlation to skidding time was skidding distance (Table 9). The other variables showed weak correlations to skidding time.

$$Y = 17.40 + 0.10\beta_1 - 4.51\beta_2 + 0.003\beta_3 + 0.004\beta_1\beta_2 + 3.74\times10^{-6}\beta_1\beta_3$$  (4)

Where $Y$: estimated loaded travel time

$\beta_1$: loaded travel distance

$\beta_2$: average skid-trail gradient for loaded travel

$\beta_3$: total load weight
Table 8. Loaded travel time model coefficients:

| Variables          | Estimate | Std. Error | t value | Pr(>|t|) |
|--------------------|----------|------------|---------|----------|
| Intercept          | 17.400   | 11.840     | 1.470   | 0.14265  |
| Loaded distance    | 0.102    | 0.008      | 12.819  | < 2e-16 *** |
| Loaded gradient    | -4.511   | 1.625      | -2.776  | 0.00585 ** |
| Total load weight  | -0.003   | 0.001      | -2.160  | 0.03154 * |
| Distance : gradient| 0.004    | 0.002      | 2.432   | 0.01560 * |
| Distance : weight  | 3.74x10^-6 | 5.77x10^-7 | 6.486   | 3.62e-10*** |

Signif. codes: 0 *** 0.001 ** 0.01 * 0.05 

Residual standard error: 53.86 on 301 degrees of freedom
Multiple R-squared: 0.9495, Adjusted R-squared: 0.9487
F-statistic: 1132 on 5 and 301 DF, p-value: < 2.2e-16

Table 9. Correlation between all variables on complete loaded travels.

<table>
<thead>
<tr>
<th>Total load weight</th>
<th>Number of logs</th>
<th>Maximum log length</th>
<th>Distance</th>
<th>Time spent</th>
<th>Gradient</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total load weight</td>
<td>1.00</td>
<td>0.3798</td>
<td>0.6658</td>
<td>0.4558</td>
<td>0.4744</td>
</tr>
<tr>
<td>Number of logs</td>
<td>1.00</td>
<td>0.2624</td>
<td>0.0002</td>
<td>-0.0095</td>
<td>-0.4537</td>
</tr>
<tr>
<td>Maximum log length</td>
<td>1.00</td>
<td>0.3538</td>
<td>0.3633</td>
<td>-0.2337</td>
<td></td>
</tr>
<tr>
<td>Distance</td>
<td>1.00</td>
<td>0.9683</td>
<td>0.3580</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time spent</td>
<td></td>
<td></td>
<td>1.00</td>
<td>0.3395</td>
<td></td>
</tr>
<tr>
<td>Gradient</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.00</td>
</tr>
</tbody>
</table>

2.3.3.5 Unloaded Skidding Travel Time on Skid-trail Sections

To further explore the influence of skid-trail gradient on skidding time, this model considered unloaded skidding travel time on individual skid-trail sections. As flags were
placed on every change of skid-trail gradient along the skid-trails, each individual section
represents more accurately the terrain influence on skidding travel time. The fitted linear
model shows that skid-trail gradient did not significantly influence unloaded skidding
time (Equation 5, $R^2 = 0.196$). However, skidding distance and the interaction between
skidding distance and skid-trail gradient have a significant positive effect on the unloaded
skidding time (Table 10). The low $R^2$ indicated a lack of usefulness of these variables and
the high variability in the skidding time data. Section travel distance and gradient showed
positive correlation to skidding time (Table 11). However, neither of the independent
variables sowed a strong correlation to skidding time.

$$ Y = 1.23 + 0.09\beta_1 + 0.02\beta_2 + 0.02\beta_1\beta_2 $$  \hspace{1cm} (5)

Where $Y$: estimated unloaded travel time

$\beta_1$: distance of unloaded travel

$\beta_2$: skid-trail gradient for unloaded travel

| Variables          | Estimate | Std. Error | t value | Pr(>|t|)       |
|--------------------|----------|------------|---------|---------------|
| Intercept          | 1.228    | 0.151      | 8.142   | 4.42e-16 ***  |
| Unloaded distance  | 0.092    | 0.002      | 40.916  | < 2e-16 ***   |
| Unloaded gradient  | 0.018    | 0.030      | 0.598   | 0.55          |
| Distance : gradient| 0.002    | 4.82x10^-4 | 4.065   | 4.84e-05 ***  |

Signif. codes: 0 *** 0.001 ** 0.01 * 0.05 .

Table 10. Unloaded section time model coefficients:

Residual standard error: 4.677 on 8584 degrees of freedom
Multiple R-squared: 0.1962, Adjusted R-squared: 0.1959
F-statistic: 698.4 on 3 and 8584 DF, p-value: < 2.2e-16
Table 11. Correlation between the independent variables on unloaded travels for skid-trail sections.

<table>
<thead>
<tr>
<th></th>
<th>Distance</th>
<th>Gradient</th>
<th>Time spent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distance</td>
<td>1.00</td>
<td>0.1259</td>
<td>0.4163</td>
</tr>
<tr>
<td>Gradient</td>
<td>1.00</td>
<td>0.1976</td>
<td></td>
</tr>
<tr>
<td>Time spent</td>
<td></td>
<td>1.00</td>
<td></td>
</tr>
</tbody>
</table>

2.3.3.6 Loaded Skidding Travel Time on Skid-trail Sections

Similarly, we modeled loaded skidding travel time on individual skid-trail sections to test the influence of skid-trail gradient. The best-fitted model retained skidding distance, gradient, number of logs, total load weight, and maximum log length (Table 12). The $R^2$ for this model is 0.236, higher than for unloaded travels yet neither gradient nor load size alone are the best predictors for skidding time. Equation 6 shows the best predicted skidding time for loaded skidding travels. All independent variables showed positive correlation to skidding time (Table 13). However, the strongest correlation, which was between section travel distance and skidding time, was not strong (0.34).

$$Y = 3.49 + 0.04\beta_1 + 0.25\beta_2 - 0.005\beta_3 + 0.22\beta_4 - 1.16\times10^{-4}\beta_5 - 0.002\beta_1\beta_2 + 0.001\beta_1\beta_3 + 2.53\times10^{-6}\beta_1\beta_5 - 0.06\beta_2\beta_4 + 2.93\times10^{-5}\beta_2\beta_5 - 0.007\beta_3\beta_4 + 2.74\times10^{-5}\beta_4\beta_5$$ (6)
Where Y: estimated loaded travel time

\( \beta_1 \): loaded skidding distance

\( \beta_2 \): skid-trail gradient for loaded travel

\( \beta_3 \): maximum log length

\( \beta_4 \): number of logs

\( \beta_5 \): total load weight

| Table 12. Loaded section time model coefficients: |
|-----------------|-----------|-----------|-----------|-------------|
| Variables        | Estimate  | Std. Error| t value   | Pr(>│t│)    |
| Intercept        | 3.494     | 0.950     | 3.680     | 0.000235 ***|
| Loaded distance  | 0.040     | 0.010     | 4.012     | 6.07e-05 ***|
| Loaded gradient  | 0.247     | 0.057     | 4.312     | 1.63e-05 ***|
| Maximum length   | -0.005    | 0.015     | -0.341    | 0.733       |
| Number of logs   | 0.224     | 0.214     | 1.051     | 0.293       |
| Total load weight| -1.16x10^{-4} | 6.31x10^{-5} | -1.837    | 0.066313 .   |
| Distance : gradient| -0.002   | 0.001     | -3.440    | 0.000585 ***|
| Distance : length | 0.001    | 1.85x10^{-4} | 2.940    | 0.003295 **  |
| Distance : weight | 2.53x10^{-6} | 7.60x10^{-7} | 3.323    | 0.000894 *** |
| Gradient : num. logs | -0.055   | 0.008     | -6.705    | 2.15e-11 ***|
| Gradient : weight | 2.93x10^{-5} | 2.83x10^{-6} | 10.366   | < 2e-16 ***  |
| Max. length : num. | -0.007   | 0.003     | -2.365    | 0.018030 *   |
| Num. logs : weight | 2.74x10^{-5} | 1.42x10^{-5} | 1.929    | 0.053787 .    |

Signif. codes: 0 *** 0.001 ** 0.01 * 0.05 .

Residual standard error: 5.641 on 8387 degrees of freedom
Multiple R-squared: 0.2362, Adjusted R-squared: 0.2351
F-statistic: 216.1 on 12 and 8387 DF, p-value: < 2.2e-16
Table 13. Correlation between all variables on loaded travels for skid-trail sections.

<table>
<thead>
<tr>
<th></th>
<th>Total load weight</th>
<th>Number of logs</th>
<th>Maximum log length</th>
<th>Distance</th>
<th>Gradient</th>
<th>Time spent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total load weight</td>
<td>1.00</td>
<td>0.1933</td>
<td>0.4922</td>
<td>-0.1072</td>
<td>0.02124</td>
<td>0.0722</td>
</tr>
<tr>
<td>Number of logs</td>
<td>1.00</td>
<td>0.2869</td>
<td>0.0545</td>
<td>-0.2116</td>
<td>0.0162</td>
<td></td>
</tr>
<tr>
<td>Maximum log length</td>
<td>1.00</td>
<td></td>
<td>-0.0664</td>
<td>-0.0004</td>
<td>0.0438</td>
<td></td>
</tr>
<tr>
<td>Distance</td>
<td>1.00</td>
<td></td>
<td></td>
<td>-0.0965</td>
<td></td>
<td>0.3382</td>
</tr>
<tr>
<td>Gradient</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.00</td>
<td>0.2631</td>
</tr>
<tr>
<td>Time spent</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.00</td>
</tr>
</tbody>
</table>

2.3.3.7 Unloaded Skidding Speed on Skid-trail Sections

To normalize for skidding distance of the different skid-trail sections, we also used skidding speed (ft/sec) instead of skidding time. In this case, when modeling unloaded skidding speed, the best-fit model showed that skid-trail gradient has a significant influence on skidding speed (Table 14). However, the $R^2$ was the lowest if compared to the other models (0.039), that suggests that it is a weak model to predict skidding speed, and thus productivity. Gradient showed a negative effect on skidding speed (Table 15), suggesting that skidder operators drive slower on uphill sections.

$$Y = 10.70 - 0.147\beta_1$$  \hspace{1cm} (7)

Where $Y$: estimated unloaded travel speed

$\beta_1$: slope gradient for the unloaded travel
Table 14. Unloaded section speed model coefficients:

| Variables       | Estimate | Std. Error | t value | Pr(> | t |)  |
|-----------------|----------|------------|---------|-------|------|
| Intercept       | 10.702   | 0.043      | 246.900 | <2e-16*** |
| Unloaded gradient | -0.142   | 0.008      | -18.640 | <2e-16*** |

Signif. codes: 0 *** 0.001 ** 0.01 * 0.05 .

Residual standard error: 3.97 on 8586 degrees of freedom
Multiple R-squared: 0.03891, Adjusted R-squared: 0.03879
F-statistic: 347.6 on 1 and 8586 DF, p-value: < 2.2e-16

Table 15. Correlation between gradient and speed on unloaded travels for skid-trail sections.

<table>
<thead>
<tr>
<th>Gradient</th>
<th>Skidding speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gradient</td>
<td>1.00</td>
</tr>
<tr>
<td>Skidding speed</td>
<td>-0.1972</td>
</tr>
</tbody>
</table>

2.3.3.8 Loaded Skid-trail Sections Speed

For the case of skidding speed for loaded travel, the model retained skid-trail gradient, length of the longest log, number of logs, and total load weight (Table 16). However, the low $R^2$ (0.151) suggests that it is also a weak model to predict skidding. Total load weight was the only variable that showed a negative correlation to loaded skidding section speed (Table 17). The strongest positive correlation occurred between maximum log length and loaded skidding speed.

\[
Y = 10.67 - 0.17\beta_1 - 0.023\beta_2 + 0.010\beta_3 - 2.56\times10^{-5}\beta_4 + 0.05\beta_1\beta_3 - 1.78\times10^{-5}\beta_1\beta_4 + 0.006\beta_2\beta_3 - 3.06\times10^{-5}\beta_2\beta_4
\]  (8)
Where \( Y \): estimated loaded travel speed

\( \beta_1 \): skid-trail gradient for the loaded travel

\( \beta_2 \): maximum log length

\( \beta_3 \): number of logs

\( \beta_4 \): total load weight

| Variables               | Estimate | Std. Error | t value | Pr(>|t|) |
|-------------------------|----------|------------|---------|----------|
| Intercept               | 10.670   | 0.460      | 23.225  | < 2e-16 *** |
| Loaded gradient         | -0.170   | 0.031      | -5.404  | 6.71e-08 *** |
| Maximum length          | -0.023   | 0.007      | -3.275  | 0.00106 ** |
| Number of logs          | 0.010    | 0.150      | 0.067   | 0.947    |
| Total load weight       | -2.56x10^{-5} | 2.94x10^{-5} | -0.871  | 0.384    |
| Gradient : # logs       | 0.046    | 0.006      | 8.013   | 1.27e-15 *** |
| Gradient : weight       | -1.78x10^{-5} | 1.97x10^{-6} | -9.054  | < 2e-16 *** |
| Max. length : # logs    | 0.006    | 0.002      | 2.664   | 0.00773 ** |
| # logs : weight         | -3.06x10^{-5} | 9.95x10^{-6} | -3.077  | 0.00210 ** |

Signif. codes: 0 *** 0.001 ** 0.01 * 0.05 .

Residual standard error: 3.959 on 8391 degrees of freedom
Multiple R-squared: 0.1512, Adjusted R-squared: 0.1504
F-statistic: 186.9 on 8 and 8391 DF, p-value: < 2.2e-16
### Table 17. Correlation between all variables on loaded travels for skid-trail sections.

<table>
<thead>
<tr>
<th></th>
<th>Total load weight</th>
<th>Number of logs</th>
<th>Maximum log length</th>
<th>Gradient</th>
<th>Skidding speed</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total load weight</td>
<td>1.00</td>
<td>0.1933</td>
<td>0.4922</td>
<td>0.02124</td>
<td>-0.1328</td>
</tr>
<tr>
<td>Number of logs</td>
<td>1.00</td>
<td>0.2869</td>
<td>-0.2116</td>
<td>0.2198</td>
<td></td>
</tr>
<tr>
<td>Maximum log length</td>
<td></td>
<td>1.00</td>
<td>-0.0004</td>
<td>0.7625</td>
<td></td>
</tr>
<tr>
<td>Gradient</td>
<td></td>
<td></td>
<td>1.00</td>
<td>0.3478</td>
<td></td>
</tr>
<tr>
<td>Skidding speed</td>
<td></td>
<td></td>
<td></td>
<td>1.00</td>
<td></td>
</tr>
</tbody>
</table>

#### 2.3.3.9 Comparing skidding time equations

The delay-free skidding cycle equation and the skidding travel times (loaded and unloaded) have significantly higher coefficients of determination and considerably lower sample size than models developed by skid-trail sections. Each skid-trail travelled through in a skidding cycle contains numerous skid-trail sections with high deviation in distance and gradient (Figure 8). In general, skid-trail sections are relatively short, ranging from 21 to 129 feet with an average of 62.9 feet, suggesting that any minimal change on the skidder speed would increase the deviation on the time spent among all sections.
The average skid-trail gradient for an entire skidding cycle is not an ideal variable to use to predict skidding time due to the high degree of variation in gradient along a skid-trail (Figure 9). Skid-trail gradient does not show stronger correlation with skidding time for neither the complete skidding cycles nor skidding travel models. Thus, skidding distance and load size were the best predictors of total delay-free skidding cycle time.

As skidding distance is the main factor that influences travel time, speed was used as the dependent variable to test the effect of gradient and load size in skid-trail section time. In this case, the only independent variable that showed a significant influence on skidding speed were gradient and length of the longest log. However, the $R^2$ for these two models were the smallest of the five models.

Figure 8. Time spent to cover the length of complete skid-trails (A) and each of its sections (B).
2.4 Discussion

Video cameras have been used to record forest operations and estimate machine productivity, and advances in technology are providing equipment with better video quality, more power autonomy, and high storage capacity, with small increases in prices (Contreras et al., 2017; Nuutinen, 2013; Odhiambo, 2010). Newer security cameras systems are offering wireless cameras that can be monitored remotely only requiring access to the Internet. However, due to the lack of Internet connection on most timber harvesting sites, older wired models can perform in those locations, requiring a lower investment while still providing the same high video quality and high storage capacity. The Swann® security camera systems used on this study provided eight full high definition cameras and a 1 gigabyte storage DVR for roughly the same price as one sports camera manufactured by well-known brands (i.e. GoPro® Hero 7 and Sony® FDRX3000/W), with battery autonomy only up to 90 minutes and no memory card.
included. In addition to the native storage capacity, it is possible to replace the internal hard drive with minimum effort, storing as much footage as needed. The security camera systems performed satisfactorily for conducting time and motion studies of skidders and offered several of the advantages listed by Contreras et al. (2017) in a pilot study. These include quick and non-invasive installation, a hard drive large enough to store video of several weeks of work, transferability to any 12 or 24V battery-operated equipment, and weather resistance (i.e., rain, dust, and temperature changes). To ensure the best performance of the system, the cameras needed to be firmly tied to the machinery and the DVRs placed inside a sealed case, providing protection against the weather while not restricting the ventilation of the equipment. Any equipment on a skidder will be subjected to significant vibration and the use of foam inside the case is essential to keep the DVRs protected.

Zhang et al. (2010) stated that among the main challenges of using video for surveillance are the recognition of events under motion clutter, ability to interpret complex scenes, and putting events in context when recording multiple angles. As a result of the recording rate of 24 frames per second in this study, the motion of the machinery frequently captured blurry images on the video, which was exacerbated due to low natural light conditions. Whenever this clutter occurred, the researchers needed to pause the video and watch the same part in slow motion to be able to identify the number on the flags. Parker et al. (2010) mentioned the ability of watching the footage as many times as needed as another advantage of using video for productivity studies. Although the watching process was time consuming, and responsible for decreasing the productivity of the researchers, the researchers quickly gained experience in identifying
objects in the blurred video and playback time diminished. Security cameras provided video footage with enough quality to recognize and interpret all events related to the work tasks of the skidders. The DVR software automatically synchronized the footage of all four cameras, showing them side-by-side, enabling an easy understanding of the events surrounding the machine. A hardware failure in one of the DVRs made it impossible to watch the videos directly from its software, it took approximately 2 hours and 30 minutes to transfer the video files to the computer and synchronize them in a video editing software.

Video footage provide an accurate interpretation of tall tasks performed during a skidding cycle, allowing a highly specific partitioning of the work elements (Garcia-Sanchez et al., 2011; Wang and Haarlaa, 2002). Furthermore, the video enabled us to identify the reason of every interruption of working tasks, as well as to record the time spent on breaks, machinery maintenance, and refueling. The time stamps on the video footage made it possible to calculate the time spent in each work task, as well as the time spent to cover the path in between two flags, with the precision of one second. In the case of this study, flags beside the skid-trails were shown on video in intervals that varied from 1 to 253 seconds. To properly see the time from the video and record it on a spreadsheet, researchers needed to pause the video frequently. However, no video playback is needed when studying more time-consuming work tasks.
Additional positive points about the use of cameras for productivity studies are the potential reduction of field work, eliminating the pressure on the operators, and collecting information in a way that does not impede the studied machinery to perform their ordinary work (Parker et al., 2010). Wang et al (2003) stated that there is no need for people taking notes in the field when using video for time studies. If the study does not require the measurements of factors other than time (i.e. log sizes), researchers are only required to be in the field to install the equipment and collect the DVRs with the videos by the end of each day of work. The cameras are barely detectable by the skidder operators, which added to the absence of researchers on the field and reduced pressure over the operators. After flipping the switch to provide power to the camera system, the operators quickly forget that their work is being recorded. Once all camera equipment is
installed on the machines and all cables are taped away from the reach of operators and tree branches, the skidders can perform their work with no restrictions.

Garcia-Sanchez (2011) and Parker et al. (2010) observed the low energy efficiency of cameras as a disadvantage for their use on the field. This studied overcame this limitation by obtaining energy directly from the machine batteries. Battery power inverters are commonly used in recreational vehicles and trucks; they can efficiently provide electricity for any cameras systems mounted on the vehicles. The main concern about this method is that the inverters needed to be unplugged from the vehicles batteries at the end of the day; otherwise, they can keep recording overnight, possibly draining the batteries and preventing the vehicle from working until it is recharged from an external source. Industrial power inverters are expensive and hard to find, however they are a simple way to improve the system by being less susceptible to failure. Furthermore, the power inverter can be connected directly to the ignition switch of the machine to automatically turn the whole camera set on and off when the machine engine starts. Garcia-Sanchez (2011) also mentioned the loss of footage as an important concern about the use of cameras. It has also shown to be a problem in the present research as we lost over 25% of the video footage.

Wang et al. (2003) observed that camera and computer-based time studies are not completely autonomous as there is still a need for collecting data on the field. In the present study, the collection of skid-trail and load size data was time consuming and risky. The researchers were exposed to unsafe situations when flagging skid-trails while trees were being harvested in the surroundings. Furthermore, the landing is a hazardous
place to measure the logs brought by the skidders. These measurements needed to happen quickly in order not to delay the work of the skidders, exposing the researchers to the traffic of heavy machinery and to the wood debris thrown by the loaders. As an alternative for making the system more autonomous, modern remote sensing technology can be applied to get the measurements of the skid-trails, and portable scales can be a better tool for measuring load weight. On the other hand, video footage has great potential for educational purposes (Parker et al., 2010), and in helping to promote the awareness of the importance of personal protection equipment and enforcement of the best management practices in logging operations.

From the data collected by the security camera systems, it was possible to identify the duration of each skidding task. On sites 1 and 2, the most time consuming task was the loaded travel. Skidder operators on site 1 spent less time maneuvering to grapple the logs because of additional space at the landing and start of the main skid-trail, where to reverse the skidders. Once the skidder’s grapple was already facing the bunch of logs, it took less time to get the logs. Operators on site 3 spent the most percentage of their work time maneuvering to get the logs. They were the two less experienced operators and this lack of experience resulted in slower maneuvering and the need for more attempts to complete full loads. Operators on site 1 spent the most time maneuvering to drop the logs because the landing had a heavier traffic of equipment, slowing down the skidders. Skidders on site 2 and 3 had one extra task, which was to arrange the logs on the landing; it happened because there was no loader on site 2 to arrange the logs, and the loaders on site 3 were working slower than the skidders, accumulating logs on the landing.
Furthermore, it was possible to identify and measure the time of the delays that happened during the work tasks. The main reason for delays on site 1 were the bottlenecks that happened because both skidders were often working along the same skid-trails. Only one feller-buncher was working on site 1, requiring both skidders to take the logs in the same place, causing bottlenecks. The second main reason for delays on site 1 was the slippery ground along skid-trails after raining. Skidders were often stuck in uphill sections of the while traveling loaded. No delay due to stuck skidders was recorded for downhill sections or unloaded travel. On site 2, the main reason for delays was also bottlenecks, but this time was waiting for logs at the stump. Only one feller-buncher was operating and it was not able work fast enough to keep up with the skidder. On site 3, most delays were caused by machinery breakdown. To keep the working speed, the unexperienced operators demanded more power from the skidders, which may have caused the highest number of breakdowns between the three sites. Usually, almost the entire operation stopped when one skidder broke down on this site. Both skidder operators, the operations manager, and occasionally the loader operators stopped working to help fixing the broken down skidder. The second main reason for delays on site 3 was due to slippery ground on the skid-trails, similarly to site 1, which caused the skidders to get stuck while traveling loaded over wet soil.

Data collected for complete skidding cycles was sufficient to fit regressions to predict skidding cycle time based on skidding distance and load weight. To incorporate the effects of terrain on skidding time, smaller sections of the skid-trails provided the gradient. The large variability of gradients along a skid trail cause it to be weakly correlated with skidding time. The models for skidding cycle time are feasible to be used
to automatically design optimal skid-trials networks to reduce skidding time such as those developed by Contreras et al. (2016). These models differ from the ones fitted in previous studies by also including the average slope of the skid-trails, instead of considering merely up or downhill skidding. As skidding travel time and distance are expected to be directly correlated, an analysis with skidding speed was done for skid-trail sections, with the purpose of better understanding the effects of gradient. However, speed models did not show to have a strong coefficient of determination with gradient.

Skidder number 3, located in site 2, presented the highest productivity among the 5 skidders. The most experienced driver operated skidder 3, that also it covered the shortest average skidding distance, carried the lowest number of logs and the lowest total weight, and presented the lowest average skidding time. However, it had the longest average log length and the trails have neither the highest nor the lowest average slope. Gilianpoor et al. (2012) and Renzie and Han-sup (2008) found that skidding productivity is higher in shorter skid trials and in more gentle slope. The time models created in this study confirmed the effects of skid-trial length have effect over skidding time, however, the slope gradient did not show any strong effect over the studied machinery.

Skidder number 3 in site 2, presented the highest productivity among the five skidders because its operator was the most experienced, had the shortest average skidding distance, carried the lowest number of logs and lowest total weight, resulting in the lowest average skidding time. Gilianpoor et al. (2012) and Renzie and Han-sup (2008) found that skidding productivity is higher over shorter skid-trials and in gentler terrain. As expected, the results of this study confirmed the effects of skidding distance
have effect on skidding time; however, the slope gradient did not show a significant effect.

Among the five skidder operators, the more experienced presented the higher productivity and no delays caused by machinery breakdown. Gellerstedt (2002) stated that experienced operators have acquired field information that is used as their only guidance about what to do and how perform their work. All operators in this study affirmed that they are skilled enough to provide the best performance and that terrain and load size influence did not influence productivity. The small correlation between the independent variables and skidding time suggests that the operator’s skills, experience, and most importantly behavior, play an important role on skidding productivity, which were not properly captured in this study. Skidders hourly operating cost is relatively high, thus, decreasing skidding time is an obvious way to reduce the costs. However, skidding time along might not be the best alternative because, in order to keep productivity high, operators likely demand more from the machinery, thus consuming more fuel and wearing out the machinery at a faster rate. Previous studies considered fuel and lubricant consumption, repair and maintenance cost, and tires lifespan to estimate skidding costs (Norizah et al., 2016; Gilanipoor et al., 2012; Mousavi 2012). Due to the variability in terrain, forest composition, and machinery used, to correctly estimate the operational costs for forestry machinery it was necessary to have data from the specific location harvesting (Lopes and Diniz, 2015). Therefore, to find the effects of terrain and load size on skidders, and survey their influence on skidding costs in Kentucky, future studies should consider the fuel consumption and depreciation of the machinery working in the local forests in addition to skidding time.
2.5 Conclusions

We evaluated the performance of security camera systems for conducting time and motion studies of timber harvesting machinery using three live logging operations in Kentucky. The installation of the system was successfully installed on five different skidders. Continuous recording camera footage and measurements of skidder loads provided satisfactory data for a productivity study, even with a 25% loss of data. For the purpose of this study, the use of cameras did not exempt the full-time presence of researchers on the field, sharing some disadvantages with the traditional stopwatch technique. However, the cameras allow the researchers to watch and identify every work task performed by the skidders, and all footage is available for being revisited anytime on the future.

The security cameras used for this study have shown to be durable, resisting water, dust, and constant shocks against tree branches. The digital video recorders that come with the systems are not designed to work outdoors, thus it is essential to mount them inside a sealed case, using of foam inside the case to keep the DVRs protected against eventual shocks and the vibration of the skidders. The power inverters, that provided electricity to the system via the machinery 12V batteries, have shown failures as they stopped working frequently.

Skidding distance was the variable that showed the strongest correlation to skidding time, suggesting that the number and location of the landings have major importance to the layout of skid-trails, once shorter travels consumes less time. Skid-trail gradient showed influence on skidding time for loaded travels and on skidding speed for
both unloaded and loaded travels. Although higher skid-trail gradient have shown to increase skidding time and decrease skidding speed on short sections, the higher average gradient of skid-trails reduced the time spent on complete loaded travels. Total load weight and number of logs did not show to be significant in most of the models, suggesting that the operators have experience enough to discern how many logs they can get before slowing down. The length of the maximum log showed to increase skidding time of delay-free skidding cycles and complete travels, in addition to decrease skidding speed in between skid-trail sections. Long logs makes it difficult for the operators to make the sharper turns of the skid-trails, reducing the skidding speed. With the purpose of working as fast as possible, operators could demand more power from the machines. Future studies should focus on other variables such as fuel consumption and machinery depreciation as an alternative to measure what affects skidding time and, consequently, cost.
CHAPTER 3. RECOMMENDATIONS

3.1 Security camera systems installation and maintenance

The security camera systems used for this study have shown to be a good alternative for time and motion studies in forest harvesting machinery; however, some points must be considered prior the application of such method. If there is a need for knowing the load sizes of every skid cycle, as is was the case of this study, researchers must be full time on the field doing the load measurements, paying for the extra work would increase the expenses of the study. The presence of researchers on the landing also require more caution with the safety of the crew as it is a place with traffic of heavy machinery, tree branches are often being thrown out by the loaders, and venomous animals are often present. Every person present in the site must wear the full Individual Protection Equipment (IPE), including a high quality hard hat, gaiters, and gloves, to ensure no physical damage during the procedure. If the study only requires the measurement of the time spent on the work, researchers are only needed before the day of work starts to install the system, and after the work is done to collect the cases with the DVRs. It is recommended to collect the DVRs after every day of work to make the back up the video and to insure that the equipment will not be stolen.

In order to prevent damage to the equipment, the cameras must be installed firmly and with caution in a manner that tree branches would not hit them or knock them out of the machinery. The DVR and the power inverter must be fixed inside a hard shell case to be protected from shocks, rain, and dust. Although there is a need for drilling holes for ventilation of the system, these holes must never be facing the top of the case to prevent
rain water to get inside of it. The case containing the DVR and the power inverter should be installed in a safe place on the machine, preferably away from heating sources and in a place that would not block the operator’s field of view.

All the cables used on this system should be safely taped to the body of the machines. Loose cables easily get caught by tree branches and get torn apart. The cables that link the battery to the power inverter are an essential and fragile part of the system, they need to be well built and connected with caution to avoid an interruption of the power supply and further damage to the battery of the vehicles. Furthermore, conventional vehicle power inverters could be substituted for industrial power inverters, those are built to work on heavy machinery and can perform better under the study conditions.

3.2 Skidding

Although the terrain and load variables have not shown influence on skidding time, the work of the machinery presented many delays, decreasing the amount of wood brought to the landing at the end of the day. There were two main reasons for the delays, machinery breakdown and sliding on raining days. This study only collected data on raining days in one harvesting site (site 1), more data of work under these conditions are needed to study the effects of rain on skidding time, but the skidder operators should be aware of the soil moisture and grab less logs when skidding over a wet surface.

Machinery breakdown caused delays on the broken skidders and on other operations. In all visited sites, other workers were often required to stop performing their tasks to help fix the broken machinery. Furthermore, skidders broken in the trails
blocked the path for other machines, causing delays in larger scales. All studied skidders showed heavy wear and tear all over the machines as well as dust and dirt clogged on their moving parts. Investing more on preventive maintenance would make the skidding operations less expensive for the machine owners, the skidders would work with fewer delays, other workers on the site would not need to stop working to help fixing machines, and the price of maintenance would decrease significantly. Taking better care of the machinery, especially cleaning, lubricating, and mechanical maintenance would prevent delays due to breakdown and extend the lifespan of the skidders.

Furthermore, the maneuvering tasks can be done shortly. The skidders often take extended time to grapple the logs because the feller-buncher did not arranged them in a proper way. When the feller-buncher puts the logs parallel to the skid trail and closer to the trail, the skidders took substantially less time to grapple the logs, making the cycles shorter.

3.3 Future studies

The regressions fitted on this study have shown low correlation between skidding time and road gradient or load size, suggesting that the experienced operators how to drive efficiently over the change on the terrain. This lack of correlation however suggests that the operators might have been requiring too much of the machines. Delays on the work due to machinery breakdown were seen very often. In order to research about the factor that might affect skidding costs other variables should be chosen, including the machine depreciation and fuel cost. Skidder operators demand different amounts of power from the machines under different circumstances, if this demand is too high and
the machine breaks there is a loss of working time as well as the cost of repairing the machine. Knowing the skidding maintenance cost and fuel consumption for different terrains it would be possible to fit the skid trails in a way that, even if the skidding speed do not increase, the costs will decrease, making this activity more efficient and less expensive.
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VITA

Rafael Freitas is a Forest Engineer graduated from the Federal University of Viçosa (Minas Gerais state, Brazil). During his undergraduate program, Rafael worked in a Eucalyptus clonal garden, researched about physical properties of wooden panels, and helped to develop a study about productivity of skidders at the University of Kentucky. Currently, Rafael is a Master’s student at the Department of Forestry and Natural Resources of the University of Kentucky. His research is aims to develop and evaluate a new method for estimation of productivity of forest harvesting machinery.