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Multi-camera surveillance systems for time and motion studies of timber harvesting equipment

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ABSTRACT

We evaluated the feasibility of using a multi-camera security system to conduct time and motion studies. It was installed on a John Deere 540G cable skidder and connected to the skidder's battery for continuous recording with minimal effort and intervention. After recording the skidder's work for eleven experimental skidding cycles, time stamped video footage was visually inspected to obtain time consumption of work tasks, which provided for accurate calculation of total cycle times and delays. Several advantages of the security camera system including quick and non-invasive installation, large memory storage, transferability, resistance to weather elements, and the capacity to capture different views, offer a great potential for this method to be adopted as a reliable approach to accurately conduct time and motion studies. Along with distance and gradient information for skid-trail segments, we also explored the influence of gradient on travel time for loaded and unloaded skidding. There is a need for future studies to formally explore this relationship and develop more detailed cycle time equations that explicitly take into account skid-trail gradient for individual segments.

1. Introduction

Time and motion studies are essential for determining machine cost and productivity of forest harvesting equipment. During the past several decades, numerous studies have been conducted for individual harvesting machines, harvesting methods, and harvesting systems (Kosir et al., 2015; Olsen and Kellogg, 1983; Worley et al., 1965). Data collected via traditional stopwatch methods have been useful for measuring time consumption of different work tasks and estimating productivity (LeDoux and Huyler, 1992; Olsen and Kellogg, 1983). However, these traditional methods are labor intensive and only sample work tasks (Nuutinen, 2013). Even with advances in video technology, manual methods are prone to observer error in recording work task time and require the presence of researchers on site, which can influence operator behavior (Parker et al., 2010; de Hoop and Dupre, 2006; Wang et al., 2003).

Recent developments in time and motion studies include the use of global positioning system (GPS) technology and automated methods to extract time consumption of individual work tasks (Strandgard and Mitchell, 2016; Hejazian et al., 2013; Odhiambo, 2010). Despite the perceived benefits of recording work tasks automatically, there are several limitations associated with the use of GPS-based approaches. Unreliable satellite signal strength is common, particularly in steep and dissected terrain often associated with forestry operations. Even in the absence of canopy cover, positional accuracy and time estimates can be impacted (McDonald and Fulton, 2005). Also, GPS-based approaches are not able to capture variables that have a significant impact in cycle time and productivity such as payload. Because of these shortcomings there is a need for alternative approaches. Although recognizing work tasks and measuring time consumption is possible with GPS data (de Hoop and Dupre, 2006; McDonald and Fulton, 2005), this process could likely be improved with the aid of cameras.

Limitations of manual and GPS-based data collection methods can potentially be addressed using video-based recording. Video technology has been used to address a number of aspects of forestry work including validation of advanced manual recording methods (Wang et al., 2003), quantification of productivity and worker exposure to hazards during manual felling activities (Parker et al., 2010), evaluating relationships between harvester felling time and tree diameter (Nakagawa et al., 2007), operator and equipment interactions (Gellerstedt, 2002), evaluating machine utilization rates (Wang and Haarlaa, 2002), and developing time and productivity models (Nurminen et al., 2006). These studies show that the use of video cameras can effectively minimize observer errors and their influence on operator behavior.

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They can be attached to individual workers and/or machines, eliminating the need for researchers to be present on site during data collection. The ability to pause and replay video recordings facilitates accurate identification of individual work tasks and precise timing (Parker et al., 2010; Gellerstedt, 2002; Ovaskainen et al., 2006).

Comparison of GPS and video-based approaches reveals distinct advantages of the latter. The most important is the ability to visualize and record individual work tasks that are not easily identifiable using GPS positional data (Nurminen et al., 2006; Wang and Haarlaa, 2002; Gellerstedt, 2002). Visualization may also provide for more accurate interpretation of movement patterns and recognition of work tasks that can create or contribute to variation in work times, for example irregular skidding cycles in timber harvesting operations (McDonald and Fulton, 2005). While video-based monitoring has been used in time and motion studies associated with forestry operations there was not a focus on describing and evaluating video capture methodologies. As a result there is little information on camera characteristics and video processing techniques, making replication difficult. Additionally, most previous studies used digital cameras which have limited storage capacity and battery life, effectively limiting the amount data collected (Parker et al., 2010).

Security camera systems commonly used for surveillance can be used to addresses these limitations. It is common for these systems to have a significant storage capacity, multiple channels (cameras), high-quality recording definition, and wireless capability. The most common systems have eight synchronized cameras, indicating usefulness in capturing multiple views and facilitating recognition of work tasks. They also have storage capacity sufficient for several weeks of continuous recording, are widely available and relatively inexpensive (400–1000 US $). This study was designed to determine the feasibility of using a readily available consumer grade, security camera system to conduct a skidding cycle time and motion study. In addition, we explored the influence of skid-trail gradient on skidding time using information along an existing 1.1 km skid trail.

2. Methods

2.1. Security camera system and installation

A Swann® 8-channel, 8-camera indoor/outdoor high-definition DVR surveillance system was used in this study. The system is manufactured for do-it-yourself installation and use in residential and business applications and is available through retail outlets making it widely available and relatively inexpensive. The system was installed on a John Deere 540 cable skidder. The 110-voltage, 42-watt potency system was coupled to a power inverter (Wagan 2016–6 700 W) connected to one of the two 12-volt batteries in the skidder. The inverter provided a potency of up to 700 W of alternating current that could be accessed by two outlets. Fig. 1 shows a diagram of the cameras-DVR-inverter-battery connections as well as the monitor used for adjusting camera angles during the installation process. Four cameras were attached to the external metal mesh of the skidder cab and were positioned to capture views on both sides of the machine, as well as the front and back (Fig. 2). To minimize obstructions in the operator's field of view, cables connecting cameras to the DVR were routed along the cab corners to a padded plastic box that was placed behind the operator's seat. The plastic box contained the DVR and the inverter, from which a connection was run to the battery enclosure outside the cab behind the operator. Prior to installation, in the desktop user interface the system was setup to record when power was available.

2.2. Skid-trail and loads description

We selected an existing 1.1 km constructed skid-trail at the University of Kentucky's Robinson Forest (37°28′23″N - 83°08′36″W), with elevation ranging from 419 to 465 m.a.s.l. laid out in an area with 45% average terrain slope (Fig. 3). We surveyed the skid-trail by measuring horizontal distance and gradient between 21 flags. Flags were placed at changes in gradient and/or direction along the skid-trail to examine the effect of skid-trail gradient on skidding travel time. Five logs of varying weight were used for the test (Table 1). These logs were cut two days before skidding near the existing skid-trail and their weight was estimated based on their dimensions and species using Timson (1972) study. In order to use the same logs for consecutive turn cycles and minimize unused time, a skidding cycle was defined as an empty trip from the landing (flag 1 in Fig. 3) along the looped skid-trail and back, followed by the loaded trip along the looped skid-trail. Skidding cycles were conducted with different load sizes starting with one cycle with five logs totaling 9.68 tons, followed by five cycles with four logs (7.59 tons), and five cycles with three logs (5.22 tons). The eleven cycles were determined as sufficient for evaluating the potential for security video systems to measure cycle times and the work tasks and variables that can affect cycle time.

2.3. Time consumption

The time stamped video-feed from the four cameras was visually inspected in the camera systems desktop user interface to measure time consumption for each work task with a precision of one second. We defined six work tasks and two delay elements for skidding cycles (Table 2). Time consumption for traveling unloaded and loaded was also recorded for each skid-trail segment. A segment was defined as the distance between successive flags (Fig. 3), and time consumption was measured when the flag was captured in either side camera. Fig. 4 shows the view from the four cameras and the moment when a flag comes into view on a side camera. Lastly, total cycle times were used to calculate skidder productivity in terms of scheduled machine hour, which considered delays, and productive machine hours, which omitted delays.

3. Results

The installation of the camera system, which ensures the positioning of the four cameras facilitated the identification of work tasks, required approximately 30 min. The skidder operator initiated recording with the inverters on/off switch. The camera system was able to continuously record uninterrupted video of the eleven skidding cycles totaling 7.83 h (7 h 49 min 29 s). Reviewing the video manually to identify individual work tasks and measure time consumption as well as measure travel time by skid-trail segment required 14.6 h.

Although the skidder's maximum drawbar pull at peak torque for first gear is almost 15 tons (Simonson and Horcher, 2002), the skidder was not able to pull the five-log load (9.68 ton) at flag 14 (Fig. 3). This was likely due to a combination of factors, including the presence of a sharp turn on the skid-trail, wet soils conditions, steep skid-trail gradient, and relatively low velocity, all of which resulted in tire slippage and halted the skidders forward movement. One of the logs was unhooked and the four remaining logs (7.59 ton) were used to complete the cycle. The four-log load was used for the next five cycles. During cycle six, a log slid off the skid-trail at Flag 4 and had to be unhooked. The skidder then continued with three logs (5.22 ton) and picked up the unhooked log

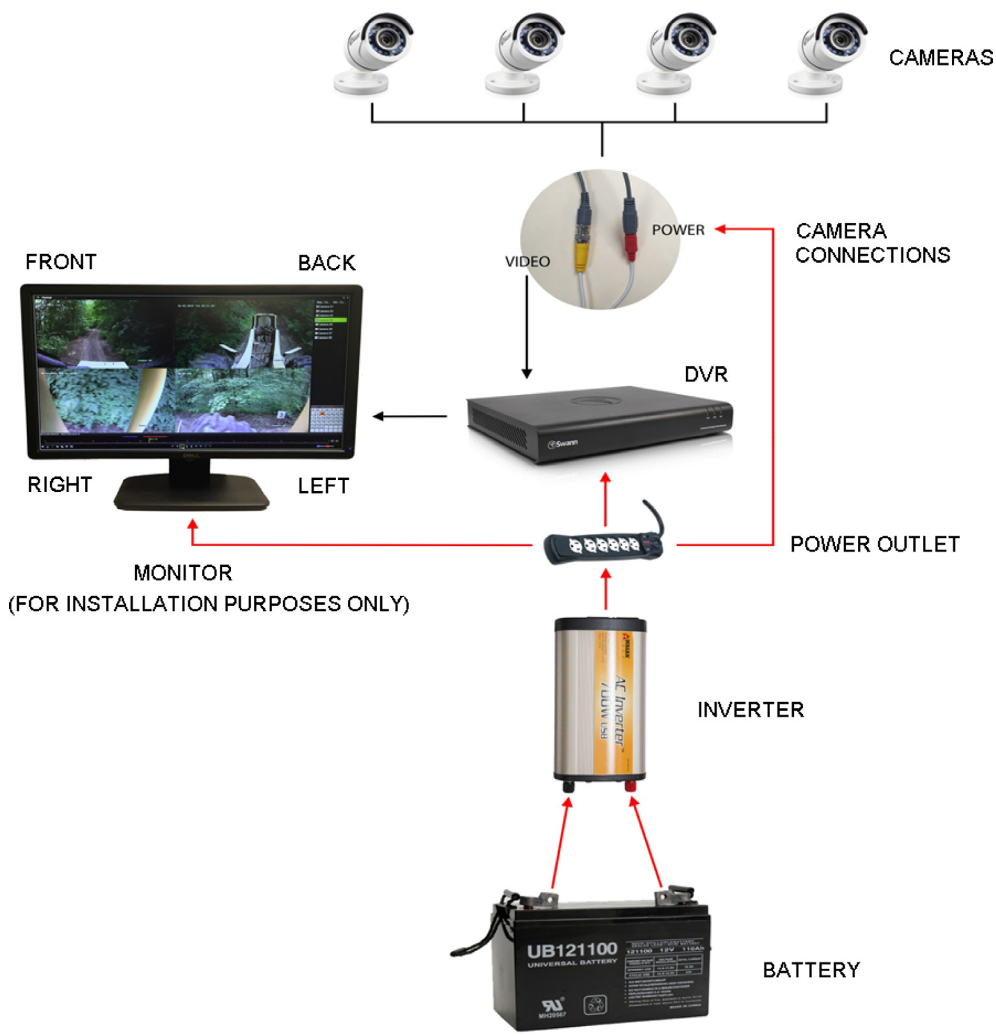

Fig. 1. Diagram of the connections for the battery-powered security camera system installed on the John Deere 540G cable skidder.

on its way back to the landing to finish the cycle with four logs. The remaining cycles were completed with a load size of three logs (5.22 ton).

Total cycle time varied widely across the eleven skidding cycles, from approximately 70 min to 20 min (Table 3). The relatively long cycle times of skidding cycles one and six (about 70 min) were due to the skidding delays involving dropping and re-hooking logs (Fig. 5). As expected, load size had an effect on total skidding cycle time. Even when ignoring the skidding delay in cycle one, elapsed time was longest for this cycle (44 min 25 sec). The average skidding times for cycles with loads of four and three logs were 39 min 55 s and 26 min 48 s, respectively. Total delays (skidder and other) accounted for 1 h 44 min 52 s, resulting in a machine utilization rate of 77.65%. On average, skidder productivity was 9.42 ton by scheduled machine hour and 12.1 ton by productive machine hour. Due to the relatively large delay during cycle six, productivity was similar between loads with four and three logs (11.4 and 11.7 ton SMH^{-1}). When considering delays however, productivity was higher for loads with four logs than those with three logs (15.2 vs 13.4 ton PMH^{-1}).

Similar to total skidding time, the time consumption of all work tasks for loads with four logs was longer than that for loads with three logs (Table 3). However, the proportion of time by work task was similar (Fig. 6). As expected, traveling loaded and traveling unloaded were the most time consuming work tasks, while unhooking logs and maneuvering to leave the landing were the least time consuming. On average, travel loaded required 10 min 44 s, and traveling unloaded required 7 min 28 s. Time consumption for both tasks was longer for the 4-log loads as compared with the 3-log loads and in general, consecutive cycles became slightly shorter (Fig. 7). This is likely because the operator became more familiar with the skid-trail layout throughout the course of the project.

The gradient of skid-trail segments ranged from −15% to +15% with an average gradient of about 7.2%. Average skidding speed while unloaded was similar for downhill and uphill skidding (2.76 vs 2.72 m sec^{-1}, respectively; Fig. 8), with also similar standard deviation (0.65 vs 0.72 m sec^{-1}). A *t*-test also showed no significant differences in speed for downhill and uphill. These results indicate that skid-trail gradient did not influence unloaded travel speed. This was expected because the skidder engine (129 HP – 96 kW) can easily handle the relatively low gradient without a reduction in speed. In contrast, the average skidding speed for loaded travel was larger for downhill skidding (2.28 ± 0.68 m sec^{-1}) than for uphill skidding (1.76 ± 0.48 m sec^{-1}), with significantly different mean values as evidenced by a *t*-test. As expected, skid-trail gradient had an influence on skidding time for loaded travel and is a significant predictor (p-value < 0.001; Fig. 9). Loaded skidding speed ranged from about 0.5 to 3.5 m sec^{-1}, and was inversely related to gradient.

Fig. 2. Placement of the cameras on the back of the skidder cab for sides and rear view. (One more camera was placed in front the skidder cab to capture the front view).

4. Discussion

Single cameras have been used in previous studies to explore different aspects of forestry work (Odhiambo, 2010; Nuutinen, 2013), and their use will likely increase with technological improvements and lower costs. However, security camera systems offer several advantages over single cameras, which make them an efficient alternative tool for time and motion studies. These include continuous power supply when connected to the equipment battery, relatively large storage capacity for capturing entire work shifts (work census instead of work sampling), multiple cameras for facilitating recognition of individual work tasks, automatic synchronization of cameras, and a built-in software package for analyzing video footage. In addition, McDonald and Fulton (2005) mentioned several factors necessary for automated systems to be successfully used for conducting time and motion studies. These include easy/non-invasive set-up and operation (convenience to loggers), transferability to other equipment, durability, and consistency with field data. Installing the security camera system is relatively quick (~30 min) and once installed, the system does not interfere the operator's view and can be easily started by turning a switch. While the system was installed on a cable skidder in this study, it can be mounted on any machine with minor modification, making it possible to conduct time and motion studies for all harvesting, road construction, and transportation equipment. In terms of durability, these systems are manufactured for indoor and outdoor use, and are therefore resistant to harsh weather conditions such as dust, wind, and rain. A 15 min rain event during data collection and common equipment vibrations did not reduce the

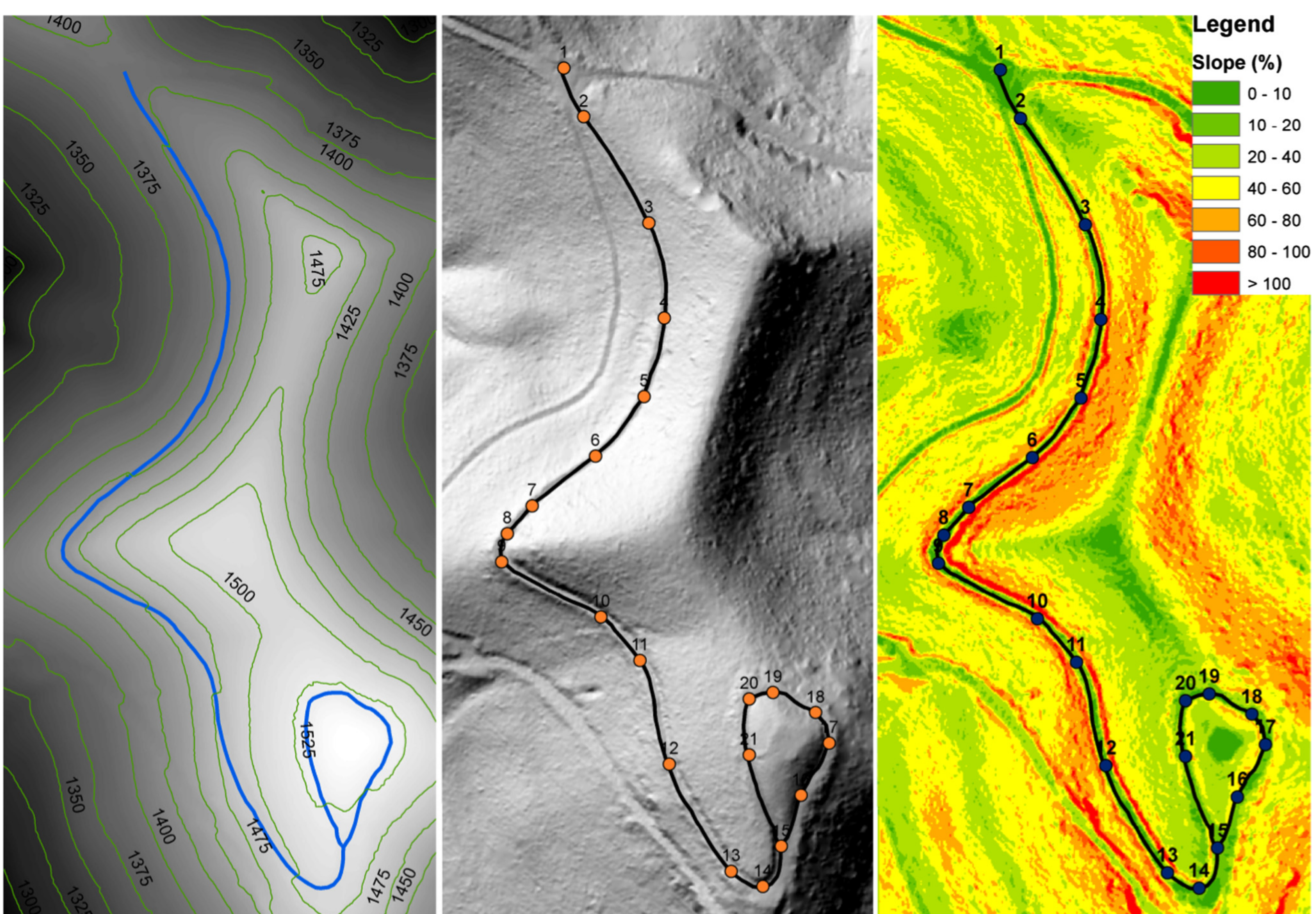

Fig. 3. Terrain elevation, relief, and slope of the area where the skid-trail was laid out.

Table 1
Dimensions of the five logs forming the different loads.

Log Id	Species	Large-end diameter (cm)	Small-end diameter (cm)	Length (m)	Weight (ton)
1	Chestnut Oak	55.6	22.9	15.7	2.09
2	Chestnut Oak	55.6	38.1	10.8	1.81
3	Chestnut Oak	71.1	40.6	11.8	2.89
4	Scarlet Oak	66.0	53.3	8.5	2.37
5	Chestnut Oak	38.1	22.9	7.2	0.52

Table 2
Definition of work tasks forming skidding cycles.

Work task	Description
Traveling unloaded	Driving unloaded from the landing along the looped skid-trail length and back
Maneuvering to hook logs	Turning the skidder around at the landing and positioning it in front of logs prior to hooking
Hooking and winching logs	Extending the winch cable and chockers by hand from the skidder, setting chockers, and winching logs to the skidder
Traveling loaded	Driving loaded from the landing along the looped skid-trail length and back
Unhooking logs	Unhooking chockers from logs and winching chockers and cable back skidder
Maneuvering to leaving landing	Turning the skidder around at the landing
Skidding delays	Delays during driving loaded such as re-choke logs and maneuvering the skidder to reduce tire skipping
Other delays	All other unproductive time such as refueling, bathroom breaks and communication with other chockers, among others

video quality. The study's short duration and use of a constructed skid trail, that in all probability limited vibration and shock compared to off-trail usage, did not allow us to assess the camera system stability over a full range of possible skidding conditions.

The camera system offers a semi-automated approach in that after installation, data can be collected autonomously without the presence of a researcher on site, but measurement of time consumption is obtained manually from the video feed. These advantages can effectively enhance the accuracy of time and motion studies.

Although we reported total cycle times and time consumption of individual work tasks as well as skidder productivity, these results were derived from only eleven experimental skidding cycles. However, the eleven cycles were adequate to meet the studies primary objective of determining the feasibility of using a security video camera system to accurately measure time consumption for skidding cycles. For this purpose, the eleven skidding cycles were sufficient to determine the successful use of this technology. The video footage from the security camera system was used in conjunction with field measurements along the skid-trail to explore the relationship between skidding travel speed and skid-trail gradient. Other studies have sought to understand this relationship and have incorporated a gradient component in cycle time equations (Gilanipoor et al., 2012; Behjou et al., 2008). However, these studies describe gradient as the average of the entire skid-trail length between the log-bunch and the extraction point (landing or road size), which does not capture the gradient variability along the skid trail. Future studies can use security camera systems along with measurements of skid-trail gradient to formally explore this relationship and develop more detailed cycle time equations that explicitly take into account skid-trail gradient for individual segments. Such equations are needed to aid models that seek to identify optimal skid-trail networks (Contreras et al., 2016). Although we demonstrated the utility of the camera system to accurately measure time consumption of individual works tasks as well as total skidding cycle time, future studies should also focus

Fig. 4. View from the four cameras installed on the John Deere 540G cable skidder used for visual inspection and measuring time consumption.

Table 3
Summary of time consumption by work task for all eleven skidding cycles.

Skidding cycle	Load size		Time consumption (hr:min:sec) by work task									
	Number of logs	Weight (tons)	Traveling unloaded	Maneuvering to hook logs	Hooking and winching logs	Traveling loaded	Unhooking logs	Maneuvering to leave landing	Skidding delays	Other Delays	Total cycle	Total cycle without delays
1	5–4	9.68	0:08:15	0:02:11	0:10:45	0:20:52	0:01:28	0:00:54	0:24:46	0:00:00	1:09:11	0:44:25
2	4	7.59	0:09:43	0:01:24	0:04:15	0:13:33	0:00:38	0:00:48	0:01:06	0:00:00	0:31:27	0:30:21
3	4	7.59	0:07:28	0:01:23	0:15:36	0:10:54	0:04:00	0:00:32	0:00:00	0:01:02	0:40:55	0:39:53
4	4	7.59	0:07:24	0:01:21	0:04:46	0:10:08	0:00:40	0:00:38	0:00:46	0:00:31	0:26:14	0:24:57
5	4	7.59	0:07:41	0:01:17	0:06:02	0:10:47	0:01:32	0:00:34	0:01:21	0:00:00	0:29:14	0:27:53
6	4–3–4	7.59	0:07:06	0:01:25	0:06:39	0:09:34	0:01:23	0:00:39	0:42:40	0:02:19	1:11:45	0:26:46
7	3	5.22	0:07:56	0:01:10	0:05:00	0:09:27	0:00:51	0:00:41	0:01:07	0:02:32	0:28:44	0:25:05
8	3	5.22	0:07:03	0:01:12	0:02:11	0:09:04	0:00:49	0:00:28	0:00:39	0:11:25	0:32:51	0:20:47
9	3	5.22	0:06:18	0:01:01	0:02:46	0:08:30	0:00:29	0:00:30	0:00:47	0:00:00	0:20:21	0:19:34
10	3	5.22	0:06:51	0:01:04	0:13:25	0:08:33	0:00:32	0:00:30	0:00:30	0:00:00	0:31:25	0:30:55
11	3	5.22	0:06:32	0:01:05	0:03:31	0:08:28	0:00:45	0:00:18	0:00:00	0:00:00	0:20:39	0:20:39
Average with 4 logs (cycles 2–6)			0:07:52	0:01:22	0:07:28	0:10:59	0:01:39	0:00:38	0:09:11	0:00:46	0:39:55	0:29:58
Average with 3 logs (cycles 7–11)			0:06:56	0:01:06	0:05:23	0:08:48	0:00:41	0:00:29	0:00:37	0:02:47	0:26:48	0:23:24

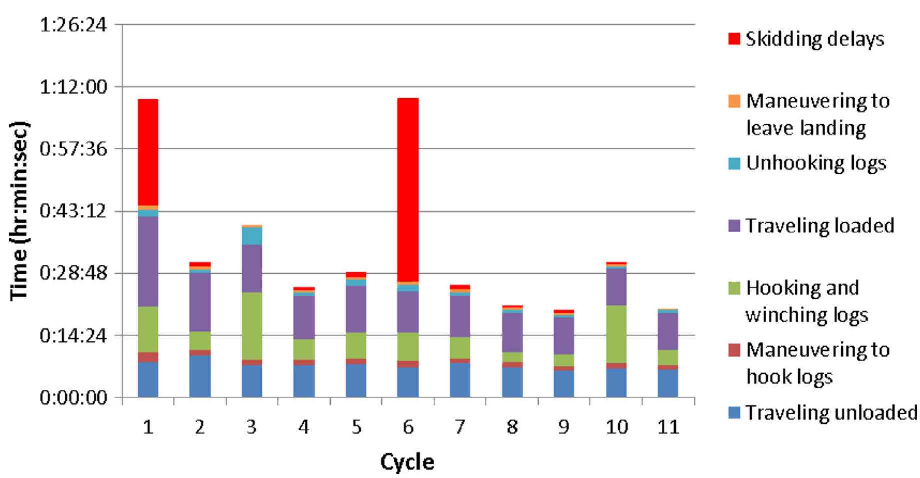

Fig. 5. Time consumption by work task for all eleven skidding cycles.

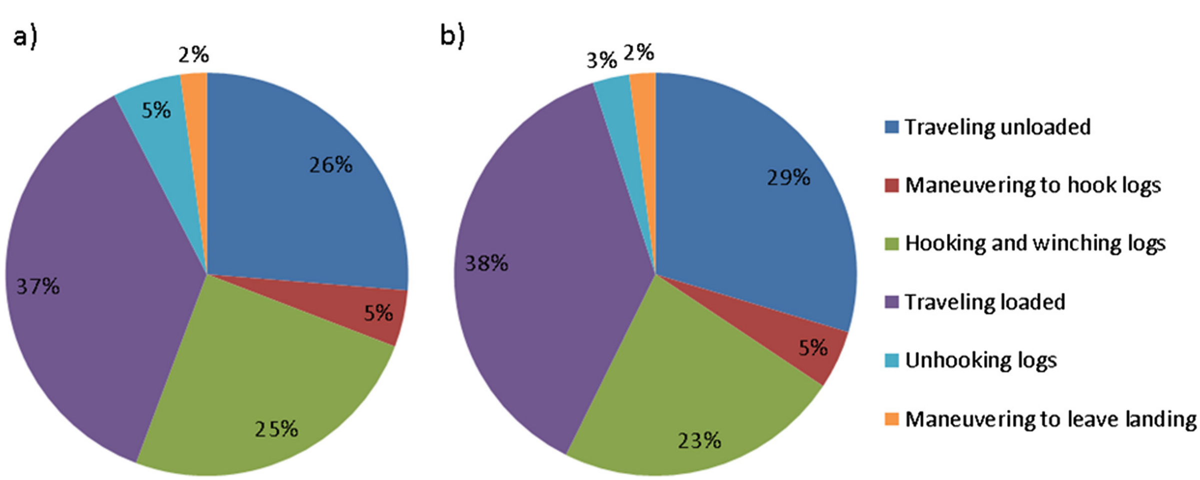

Fig. 6. Proportion of time consumption by work task for skidding cycles (excluding delays) for loads with four logs (a) 7.59 ton) and loads with three logs (b) 5.22 ton).

on developing accurate predictive models of cycle time. For such purposes, additional load size information is needed, which can be obtained via field measurements or potentially through a more challenging approach that utilizes multiple camera views to obtain measurements (i.e., log dimensions) from the video footage.

5. Conclusions

We evaluated the feasibility of using an alternative method, a multi-camera security system that can effectively address the limitations of existing methods. The four-camera security system was

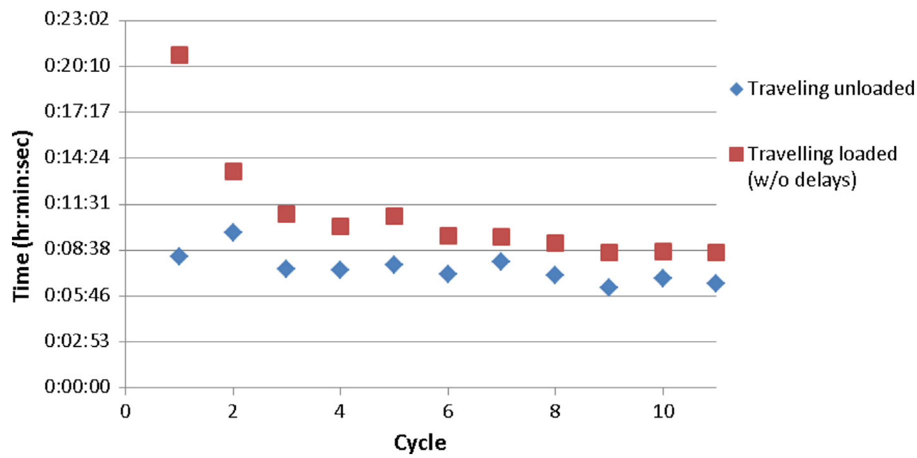

Fig. 7. Time consumption for traveling loaded and unloaded of all skidding cycles.

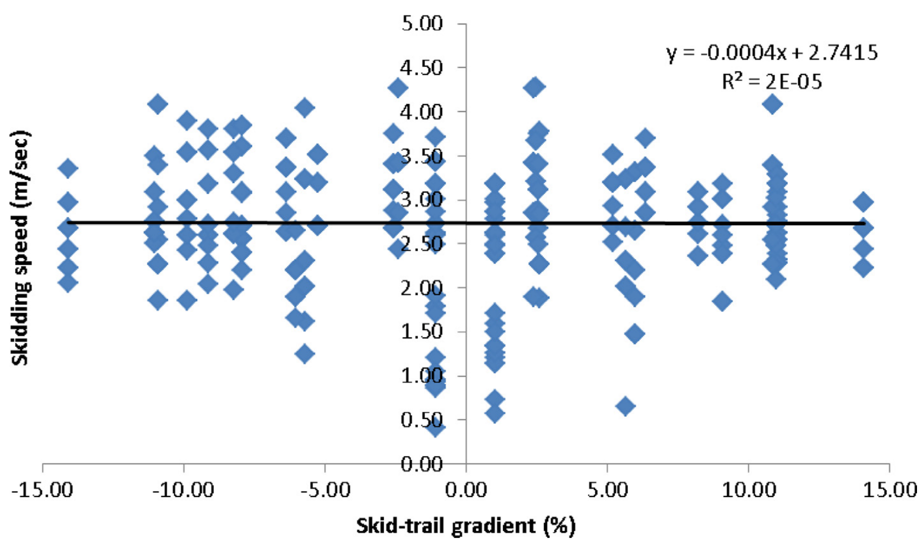

Fig. 8. Unloaded skidding speed as a function of skid-trail segment gradient.

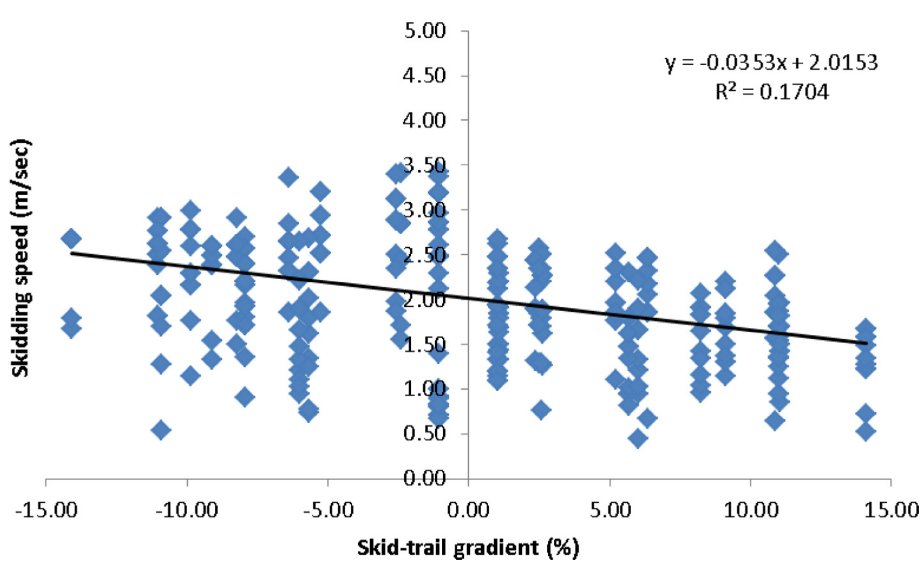

Fig. 9. Loaded skidding speed as a function of skid-trail segment gradient.

successfully installed on a John Deere 540G cable skidder and connected to the skidder's battery for continuous recording with minimal effort and intervention. Detailed and continuous time consumption provided for accurate calculation of total cycle times and delays. Several advantages of the security camera system offer a great potential for this method to be adopted as a reliable approach to accurately conduct time and motion studies. These advantages include: quick and non-invasive installation with minimal effort to operate the system, large memory storage that allows for continuous recording of the entire work shift, transferability to any battery-operated harvesting equipment, resistance to weather elements (i.e., dust and rain), and the capacity to capture different views to facilitate recognition and identification of individual work tasks. Further investigate is needed to determine the usefulness of this consumer.

Along with distance and gradient information for segments along the skid-trail, we explored the influence of gradient on travel time for loaded and unloaded skidding. Future studies should formally test this relationship to develop detailed cycle time equations that explicitly incorporate skid-trail gradient. Such equations are essential for recent models developed to determine optimal skid-trail networks that minimize total skidding costs.

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