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Automated time study of skidders using global positioning system data

T.P. McDonald [a,*], J.P. Fulton [b]

[a] *Biosystems Engineering Department, Auburn University, 224 Corley Building, Auburn, AL 36849, USA*
[b] *Biosystems Engineering Department, Auburn University, 219 Corley Building, Auburn, AL 36849, USA*

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Abstract

Time study is an important research tool used in comparing productivity of forest harvesting systems across varying conditions. Unfortunately, it has been an expensive tool to apply, involving travel and fieldwork by a crew of technicians plus time in the office to reduce raw data to usable information. In the interests of safety and cost reduction, it would be preferable to have a means of performing autonomous time study that did not involve fieldwork and that produced detailed summaries of machine or system performance over long periods of time. Automated tracking of machine productivity is currently possible on advanced harvesting equipment, notably cut-to-length harvesters, but is not for the predominant tree-length logging systems used in the US south. This paper reports on a data acquisition system used to convert movement and positional data collected using a GPS receiver mounted on tree-length harvesting equipment, primarily skidders, into time study information. The conversion was performed in two stages: reduction of raw position data to a set of measurable, simple events; interpretation of sequences of simple events as machine functions. Simple events were extracted from the raw position data along with time and distance accumulated since the previously occurring event, then passed to the interpretive stage of processing. The stream of simple events was evaluated using a pattern-matching system that combined events into machine functions. Patterns were rules specified using a regular expression syntax that defined machine-specific operational characteristics. Field trials with the data acquisition system on skidders showed it was capable of reproducing measurements obtained from field crews. In two tests measuring total skid cycle time (46 cycles), the automated time study system missed identifying fewer than 10% of the cycles, and of those identified, the difference in cycle time averaged less than 2% (5 s). Although small, the bias was consistent (automated system shorter) and significantly different from 0. Elemental time study was also possible. A three-element

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[*] Corresponding author.
E-mail addresses: mcdontp@auburn.edu (T.P. McDonald), fultojp@auburn.edu (J.P. Fulton).

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cycle (travel empty, grapple, and travel loaded) was identified in 33 of the 36 cycles with differences in element times between clock and automated system measurements being generally less than 10%.

Keywords: Skidder; Global positioning system; Automated time study

1. Introduction

Field time study has been widely applied in evaluating logging production on tree-length harvesting systems prevalent in the US south. Kluender and Stokes (1994), for example, used time study in comparing harvest cost and production as a function of removal intensity in the Ouachita Mountains. About 30% of nearly 70 publications resulting from work at the USDA Forest Service Forest Operations Research Unit in Auburn, AL, over a recent 3-year period involved application of time study. Performing a time study typically involves a crew of field technicians working multiple days at logging sites located some distance from central offices. The commitment of resources to carry out such a study can be large, limiting their application to the most urgent, or perhaps most convenient, situations. The need for logging system productivity data, however, has not diminished. Forest practices are evolving under pressure from greater environmental concerns and globally depressed prices for wood products. Adapting existing logging equipment to implement new forest management prescriptions at acceptable cost to meet these challenges will require production information for many harvesting systems under a range of conditions. In order to cut logging costs, managers and loggers need a better understanding of how site characteristics affect logging productivity in order to plan future operations for the highest return and minimal impacts. Developing such an understanding of the interaction between local conditions and productivity for most logging systems necessitates an increased application of production studies to provide needed data. The development of automated time study systems would be a key factor in meeting this greater demand for harvest system productivity research. System production is calculated using data collected on two aspects of machine performance: time required to complete a function (time study), and the quantity of material handled during that function.

The development of automated systems for monitoring performance of harvest equipment originated on cut-to-length (CTL) equipment in Scandinavia. CTL harvesters use a boom-mounted harvesting head to cut and process timber in the stand. Thor et al. (1997) reported on a system for tracking removal intensity in thinnings with harvesters. The system allowed real-time feedback to the operator on compliance with silvicultural objectives for retained basal area, and also provided a means of mapping elevation changes. Application of the technology to tree-length harvest systems common in the US south has not proceeded at the same pace. Harvest, silvicultural, and regulatory systems in the region are very different from those found in Scandinavia. Tree-length harvesting systems are common in the region. In this type of harvesting, entire stems are cut using a wheeled, drive-to-tree feller-buncher, the tree is then skidded to a deck for delimbing, topping, and loading on a truck. The primary regeneration technique used in southern pine species is clearcutting prior to replanting, and timber is treated more as a commodity product rather than optimizing value of each stem. Feedback of detailed performance information while harvesting, therefore, is of limited value to logging contractors and they are not interested in paying for the technology. Techniques for performing real-time analysis of machine productivity in tree-length harvest systems have therefore not been developed. But from a research standpoint the need for automated production study is still pressing. The research reported in this paper was an attempt to create the time study portion of an automated production study system. A production study of logging equipment normally measures the rate at which material is handled and processed. To calculate this information, the time rate of performing work is measured (time study) along with some measure of the material quantity being handled. Time study is performed to establish norms for the duration required to complete a specific job or task. Time study data is one component in measuring production per unit time of a harvesting system, and consequently in identifying conditions under which the system can be applied most economically.

Automated time study technology will have to satisfy a number of requirements to be most useful as a research tool. First, the system must be simple to install to minimize downtime for loggers participating in production studies. Second, the technology must be useful across the widest possible range of machinery systems. Having to extensively reconfigure the data collection system for every machine and site would limit its utility. Third, survivability under harsh operating conditions will be essential. Finally, the data produced using the automated system must duplicate that produced by a skilled field crew working on-site.

From visual inspection of maps generated in earlier work using the global positioning system (GPS) to measure traffic intensity of harvesting equipment (McDonald et al., 2002), it was noted that, at least for skidders, function could be interpreted from location and movement of the machine relative to specific landmarks on the site. There were characteristic motions, for example stopping and reversing direction to grapple a load, that were obvious from the machine's path and were characteristic of specific portions of the skidding work cycle. This was exactly the type of information needed to create an automated time study system. Such a system, using only positional data, would satisfy portability and ease of installation requirements, but would require development of a method to automatically interpret a machine path in a fashion similar to a human observer. Grisso et al. (2002) used a similar approach in evaluating field efficiency in agricultural applications. Their work, however, relied on human interpretation of the GPS data to extract data required for time calculations.

This paper reports on the development of a system to infer time study data from maps of a skidder's movements. The system detected simple location-based events from the machine path, then used a pattern-matching tool to evaluate sequences of events, combining them into functional elements that could be used to describe and measure machine cycle time. It was intended for use in long-term performance monitoring of skidders and designed to work independently of operator, site, and harvest system variations. The automated data acquisition system was validated through comparison of results calculated using the system to those derived from using a field crew to measure skidder performance.

2. System implementation

Typical forest operations time study begins with identification of a set of functional elements comprising the work cycle of the machine being evaluated. Tree-length harvesting employs single-purpose machines to perform the main functions of cutting, collecting, processing and loading trees. The functions are repetitively performed by from one to several machines, and each machine work cycle can be broken up into distinct elements. In performing a time study, observers watch for these elements as the machine works and note the duration of the event (elemental time) and any other factors that influence the machine's performance (for example, distance covered, size of trees moved or cut, etc). The sequence or type of functional elements comprising the work cycle for any machine may vary across sites and operators. Time study element definitions must therefore be adapted to each set of circumstances.

Analysis of raw time study data involves combining elemental times into machine cycles, or fundamental units of production. As an example, a skidder typically leaves a landing (deck) area, proceeds into the stand and locates a bundle of cut trees, grabs the trees with its grapple, and returns to the landing. One simple set of elemental times selected to describe this work cycle might consist of 'travel empty', 'position and grapple', and 'travel loaded', but there are many alternate sets possible, and also many variations in practice. The skidder might sporadically pick up two bundles to make a full load, or use a gate to delimb stems while in transit to the deck. These types of variations happen routinely, with rarely two successive work cycles being exactly the same. Time study, therefore, consists of measuring durations and performance parameters (primarily distance covered in the case of skidders) for a sequence of work cycle elements selected based on the circumstances of the harvest system being evaluated, then distilling the results into information that can be used to improve efficiency. The automated time study system developed for this project implemented field measurement of time and location data using GPS, then reduced machine path data into elemental times.

Fig. 1 shows an example of a machine path recorded using a GPS mounted on a skidder operating in a clearcut harvest. The skidder was pulling tree bundles to a trailer-mounted grapple loader located on a cleared deck area. The skidder used a delimbing gate located next to the deck to reduce the volume of limbs hauled to the loading area requiring subsequent removal. The figure shows two work cycles for the skidder, each consisting of one round trip from the deck to a tree bundle, and return. In a typical field time study, work cycles would be broken down into several elements that would be timed individually: time spent on the deck; time to travel to a bundle (travel empty); time spent positioning and grappling the load; time to return to the deck (travel loaded); and any time spent delimbing using the gate, or other delays in the process. Persons familiar with tree-length harvesting operations, when given a map of some key landmarks (lines and polygons) and the path shown in Fig. 1, could readily identify starting and ending points of these time elements. The purpose of the automated system developed for this study was to duplicate the ability of humans observing this type of machine path data, extracting information on distance and time spent performing various tasks identified as important in performing the skidding function. Success of the system would be judged based on how closely the output of the system matched that of a field time study crew making independent observations of the skidder's performance.

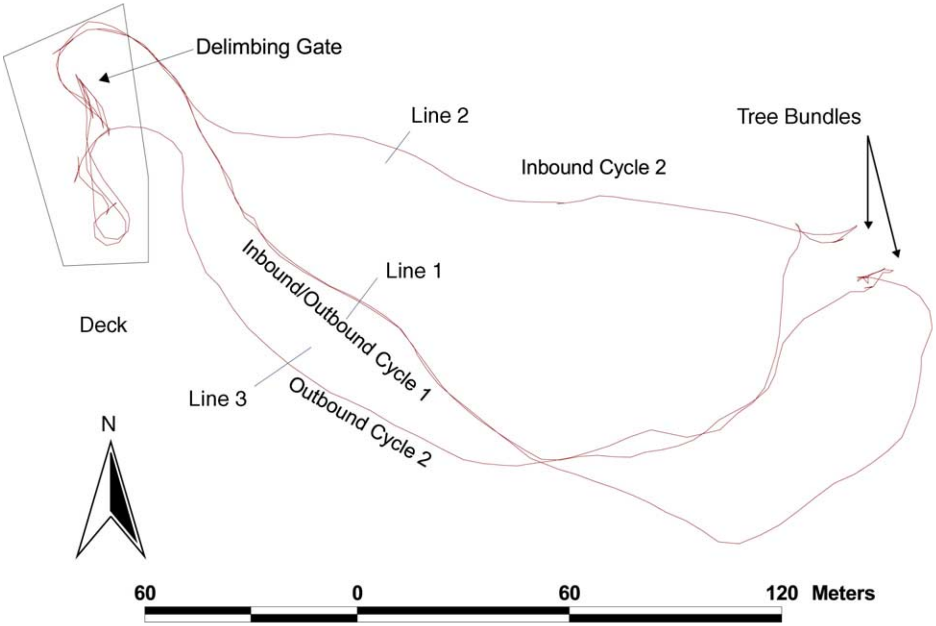

Fig. 1. An example of a path driven by a skidder while retrieving two tree bundles and delivering them to a deck for processing and loading.

The automated time study process was implemented as two transformations applied consecutively to the raw machine path data. The two steps differed in the degree of specificity relative to the machine being evaluated. The first step extracted from the path a sequence of ’primitive’ events. The primitive events were assumed to have two characteristics: they were stateless in the sense that they could be interpreted without any knowledge of what events had occurred either before or after; and event definition required no knowledge of what machine was traversing the path. The set of all ’primitive’ events used in this study were as follows:

enter or leave a polygon,
occupy a location (inside or outside a polygon),
cross a linear feature,
start or stop moving,
reverse direction.

Identifying these events within sets of position data taken for a particular study required some site-specific knowledge, typically a polygon defining the limits of a log deck, and any other features likely to be of use in interpreting machine function. These other types of features were helpful as landmarks and were typically lines, for example located perpendicular to a major skid trail, as illustrated by those seen in Fig. 1. These landmarks could be either surveyed on site or simply drawn in place using mapping software, depending on their intended use.

The second step used information specific to the machine being evaluated to interpret the output from the previous analysis, assigning functional significance to sequences of simpler events. This step incorporated domain-specific knowledge of characteristic movements or procedures of a given machine to measure details of its functional performance. For example, the travel empty phase of the skid cycle could be defined as that portion of time from when the skidder left the log deck to the point that it stopped just before reversing direction to back up to a bundle to grapple it. There could typically be slight variations in the process, but the basic steps of leaving the deck, proceeding out into the stand, and finally stopping and reversing direction were characteristic of this function and, when those primitive events were seen in that order with perhaps some other inconsequential events mixed in, it could be surmised with a degree of certainty that the function 'travel empty' had occurred. This qualitative analytical portion of the automated time study system was implemented as a computer program that interpreted a set of rules defining machine function as patterns of primitive event sequences, and then scanned a stream of events for sequences matching those rules. When a matching sequence was found, it was replaced with the left-hand-side (LHS) of the rule definition. All time and distance data of the events forming the matching sequence were accumulated into the output event.

To illustrate the process in more detail, suppose the data from Fig. 1 were to be evaluated for reduction to elemental times and associated distances. The first step in the process is to define landmarks that could be helpful in picking out events of note. In this example, there are two types of landmarks: the logging deck, plus three lines that were placed along the skid trails. The lines help in identifying which direction the skidder is moving, and, had there been more, could identify which trail among several along which the skidder is moving. Having established landmarks of interest, the next step is to define the set of primitive events to which the skidder path data are to be reduced. In this case, the group of observable primitive events most important in evaluating skidder performance would include: entering and leaving the deck; crossing one of the lines defined above; stop motion; and reverse direction.

This information, along with the skidder path recorded using a GPS, was evaluated using a program called *eventmap*. The *eventmap* program reads a description of the events of interest from a definition file then proceeds to scan the skidder path looking for those events. When one is encountered, its name is printed to standard output along with the accumulated time and distance traveled since the previous event. Listing 1 is an example of an event definitions file. A definitions file contains three types of objects: landmarks, event descriptors, and comments (lines beginning with '#'). Landmarks are specified by name and type of object (polygon or line), followed by a list of vertex nodes enclosed in parentheses. The vertex list is enclosed in square brackets and consists of easting, northing pairs, in our case in UTM coordinates. Once landmarks are defined they can be used as parameters in event descriptors. An event descriptor consists of keywords and landmark names followed by a colon, then an event name terminated with a semicolon. The keywords on the left-hand-side of the colon represent some combination of measurable features that define the event named on the right-hand-side of the colon. For example, the descriptor

$$reverse\ and\ not\ (inside\ Deck):\ rev;$$

```
line L1 [ (625175,3609487), (625166,3609475) ]
line L3 [ (625156,3609467), (625140,3609456) ]
Line L2 [ (625184,3609528), (625177,3609519) ]

# deck polygon
#
Polygon Deck [
    (625110,3609515),
    (625110,3609491),
    (625086,3609490),
    (625069,3609549),
    (625103,3609564) ]

stopwin 6 ;
stopdist 3.0 ;

cross L1: xl1 ;
cross L2: xl2 ;
cross L3: xl3 ;

reverse and not (inside Deck): rev ;
enter Deck: ondeck ;
leave Deck: offdeck ;
```

Listing 1. Event definition file used in time study analysis for the data in Fig. 1.

names an event, **rev**, that is defined as occurring whenever the path reversed, and the point at which the path reversed direction was not inside the feature (in this case a polygon) named **Deck**.

The term '**stop**', as applied in the *eventmap* program, refers to a pause in the progress of the path over some window of time. The window is defined using the term **stopwin**, in Listing 1 the value is 6 s. Since the path data were collected using a GPS, there is also a path variation parameter defined (**stopdist**) that specifies a radius (in meters) within which motion around a given point is considered to be noise rather than forward progress.

The program *eventmap* is invoked with two arguments: the event definition file specified as a command line argument, and the target machine path to be read from standard input. The program uses code from a custom library to read, write, and manipulate a general path. Event definition files are processed using a *yacc*-generated parser, which builds a decision tree based on the event specifications. For each point in the path, the decision tree is evaluated and, if a specified condition is met, the event type and accumulated distance and time since the end of the previous event are written to standard output. Listing 2 shows a representative subset of the output of *eventmap* when applying the event specification of Listing 1 to the two skid cycles mapped in Fig. 1. The 'xl1' and 'ondeck' events were detected as the skidder moved toward the logging deck with a load of trees. The 'offdeck' and 'xl3' events occurred as the skidder left the logging deck and returned into the stand for a load. The multiple 'rev' events were a result of the skidder stopping and grappling the load, and the 'xl2' event was detected as the skidder proceeded back towards the deck. These types of events were typical for a skid cycle.

The second processing phase, implemented as a program called *eventparse*, uses as input the stream of events, in the form of text strings, generated from the *eventmap* program and

```
xl1 80 184.24
ondeck 46 104.70
offdeck 78 164.19
xl3 28 83.77
rev 72 196.58
rev 12 15.77
rev 4 3.36
xl2 30 52.09
```

Listing 2. Output from the first processing stage: reduction to primitive events.

applies knowledge of how the machine operates to derive time study data. The machine operational knowledge is supplied to the program *eventparse* as a set of rules that match sequences of events to form elemental times defined as part of a production study. The rules are defined in the form of regular expressions. Regular expressions are pattern-matching operators that provide mechanisms for matching, alternation, completion, and recursion. Regular expression rules are best illustrated using file name completion features in a shell program. In the DOS shell, for example, one asks for all files ending in ".exe" by typing 'dir *.exe'—this is an example of the completion function meaning list all files ('*' = 0 or more) that have that specific ending. The alternation function allows one to ask for all files ending in one of a list of ways, for example, all files ending in .exe or .bat. The matching function is performed simply on text, and recursion is allowed by defining regular expressions that include previously defined expressions. Regular expressions are commonly implemented in programming languages (PERL being a notable example) and form the basis for many types of information processing analyses (see for example Clark and Cormack, 1997).

Listing 3 is an example of an *eventparse* rule used to interpret machine function from simpler events. In this example, the function **delimb** is defined (LHS of the rule, to the left of the ':'). Delimbing with a skidder is an activity performed using a steel grate with large openings (0.5 m on each side, referred to as a 'gate') standing perpendicularly to the ground. The skidder repeatedly backs the logs through the grate, knocking off the limbs. The function definition states that the delimbing function could be inferred from a sequence of at least two **cross_gate_line** events, separated by 0 or more (indicated by the completion operator, *) other occurrences of either (indicated by the alternate operator, |) the **cross_gate_line** or **reverse** functions. This definition encapsulates the motions of the skidder while gate delimbing. The skidder, in this instance, drives past the gate, stops, and repeatedly backs up to shove the stems through it. The **cross_gate_line** feature was located at a point on the trail just past the gate. If the skidder passes this line, then reverses direction, perhaps crossing the line again (even several times), before any other type of motion is detected, the skidder must have been delimbing. The parentheses in the definition indicate grouping, and the '\'

```
delimb: cross_gate_line \(\(reverse \)\| \(cross_gate_line
\)\)*cross_gate_line ;
```

Listing 3. Example of a rule to reduce primitive events to a delimbing event.

is used to indicate special meaning was attached to the following character and it should not be interpreted literally.

In operation, the *eventparse* program reads a set of rules from a file provided as a command line argument then applies the rules to a stream of events read from standard input. The *eventparse* program reads a stream of primitive events, for our purposes the output of the *eventmap* program, and applies rules to reduce the stream to compound events that had meaning with respect to some machine function. If no rules are matched, the input stream of events remains unchanged. As above, rules are generally formed to transform the input event stream into some production cycle, for example a skid cycle. In most cases, a time study is performed to examine variations in elemental times, or the times required for a set of tasks that make up the skid cycle. When the *eventparse* program rule set reduces primitive events to cycles, however, these elemental times are lost in the process, having been accumulated into the cycle times. One way to avoid this was to use multiple rule sets and do the analysis in stages, extracting individual time elements along the way, but this was found to be somewhat difficult to manage. A convenience operator was therefore added to the regular expression parser, the **%** symbol, that, when appended to the LHS of a rule, would output immediately the time and distance parameters of a matched rule. This modification allowed the analysis of elemental times in a single pass.

Prior to application in the field, the automated time study system was tested under controlled conditions using a GPS mounted on an automobile, primarily to assess accuracy of distance measurements. Three courses were laid out resembling a skid cycle, with a ‘deck’, and a simulated load and delimbing gate. Distances along the course were measured with a road wheel, ranging from 330 to 603 m in total length. The car was driven over the three courses, three times each, and the driven path recorded. These data were reduced using the same approach as in deriving time study data from skidders, and distances measured via GPS compared with those from the wheel. In eight of the nine cases, the GPS measurement of total cycle distance was longer. The average difference was 1.5% (7.3 m), and significantly different from 0 ($P < 0.04$). Although non-zero, the differences were small and considered acceptable over a range of total driven distance from 300 to 600 m.

The automated time study system was evaluated for its performance in

(a) gross time study, where the primary concern was variations in total skid cycle duration and length;
(b) elemental time study, in which individual times for cycle elements were of primary concern.

Both measures of system effectiveness were evaluated from data for skid cycles recorded over the course of 2 days on two different skidders: one operated in a tree-length clearcut (Timberjack 460C), and the other in a clean chipping (trees converted to pulp chips in the woods) clearcut operation (Timberjack 660). A Trimble model AgGPS 132 positioning system was installed in each. Table 1 shows a summary of GPS receiver parameters used in the study. The GPS sampled and recorded positions every 2 s. The OmniStar DGPS service was used in all tests. In all cases reported in this paper, the skidding operation was done without the presence of a tree canopy. Multipath errors attributable to a canopy could seriously impact the ability of the automated system to function with a high degree of accuracy.

Table 1
Settings used for key GPS parameters

Parameter	Setting
Mode	Manual 3D
AMU (SNR) mask	6
Elevation mask	15°
PDOP mask	6
PV filter	Off
Dynamic mode	Land
DGPS mode	Auto on/off

Traditional time study was carried out on both systems using a 2-person crew, with one stationed at the deck and one positioned near the bundles to be skidded. Elements were timed using synchronized stopwatches with 1/1000th minute resolution. Cycle components tracked included travel empty, grappling and positioning, and travel loaded. A skidder is a wheeled, articulated machine with a large grapple on the back. This grapple is used to grab a bunch of trees laid down by a feller-buncher and pull them to a central decking location. The skidding work cycle normally involves travel to (travel loaded) and from (travel empty) the deck, plus time to grab the load (grappling), delimbing, and occasionally traveling between two bunches of trees to make a full load (intermediate travel). The operator of the 460C delimbed every load using a gate, but this element was not tracked separately and was included in travel loaded times. The other operator delimbed only occasionally, normally using standing dead or unmerchantable timber as an impromptu gate, and the element was not broken out in that case either. Total cycle time data were collected on 47 skid cycles, elemental times on 36 of those. Skid distances were measured on a sub-set of the cycles (total of 27). On one site, distances were measured using a laser rangefinder, and on the other a distance wheel was used. Clock times for skid cycles are shown in Table 2. Note that, although delimbing and intermediate travel (movement from the point of grappling the bundle to the delimbing gate) were not timed separately in the clock measurements, they were identifiable from the GPS data and values were included (for the cycles in which they occurred) in Table 2.

Reference to ‘cycle times’, for this study, was to time spent by the skidder operating off the landing area. This convention was used to reflect the typical application of time study by the authors, namely to investigate the effects on time efficiency of skid distance, operator training, stand conditions, or some other factor external to the landing. Although time spent on the landing does influence overall time efficiency of the machine, we do not ordinarily study those variations. Neither is it likely the ATS approach presented here would work well in partitioning time spent on the landing into meaningful categories.

3. Results and discussion

3.1. Gross time study

There were a total of 47 skid cycles timed using automated time study (ATS) and field crew measurements. Of that total, three cycles (6%) were not identified from ATS analysis:

Table 2
Measured and automated time study-derived estimates of elemental skid cycle times (min) and distances (m)

Cycle	Travel empty		Grapple		Travel loaded		Int travel ATS	Delimb ATS	Cycle		Skid distance	
	ATS	Clock	ATS	Clock	ATS	Clock			ATS	Clock	ATS	Measured
1	1.20	1.18	0.70	0.32	1.27	1.65			3.17	3.15	102.7	79.2
2	0.97	1.03	1.67	0.55	0.77	1.93			3.41	3.51	76.2	115.5
3	0.80	0.92	0.30	0.34	1.23	1.30			2.33	2.56	88.7	103.0
4	0.87	0.98	0.27	0.32	1.37	1.47			2.51	2.77	93.0	104.9
5	0.93	1.12	0.30	0.32	1.03	1.10			2.26	2.54	91.4	88.1
6	1.03	1.17	0.30	0.37	1.47	1.50			2.80	3.04	115.8	110.3
7	1.23	1.35	0.87	0.67	1.23	1.52			3.33	3.54	119.5	122.8
8	1.50	1.62	0.43	0.50	1.92	1.92			3.85	4.04	152.7	181.1
9	1.62	1.82	4.97	4.93	2.40	2.43			8.99	9.18	178.3	204.5
10	1.77	2.30	2.47	1.02	2.57	3.65			6.81	6.97	178.6	225.6
11	2.70	2.85	0.90	0.97	1.97	3.58	1.37	0.27	7.20	7.40	266.7	263.0
12	2.57	3.07	0.47	0.45	1.88	3.42	1.17	0.70	6.79	6.94	275.5	240.2
13	1.98	2.45	0.80	0.42	1.93	3.45	0.80	0.67	6.18	6.32	211.8	231.0
14	1.82	1.90	0.55	0.55	2.07	2.85	0.50	0.23	5.17	5.30	193.9	209.1
15	2.37	1.80	5.93	5.03	2.58	3.33			10.88	10.16	174.3	189.9
16	1.53	1.65	2.40	0.85	1.67	3.17			5.60	5.67	130.1	173.1
17	0.60	0.72	0.63	0.66	0.77	0.83			2.00	2.21	46.9	50.3
18	0.70	0.83	0.37	0.63	1.13	0.90			2.20	2.36	65.5	43.6
19	1.37	1.27	0.07	0.28	1.33	1.35			2.77	2.90	81.4	53.6
20	2.50	2.51	2.27	2.11	2.23	2.78	0.20	0.27	7.47	7.40	208.2	222.8
21	3.33	3.32	0.30	0.39	2.30	3.03	0.13	0.70	6.76	6.74		
22	2.17	2.17	0.70	0.70	2.37	2.84	0.17	0.33	5.74	5.71	209.4	212.1
23	2.13	2.11	0.43	0.46	2.23	2.84	0.13	0.53	5.45	5.41		
24	2.07	2.09	0.27	0.30	3.03	3.42	0.13	0.33	5.83	5.81		
25	2.10	2.10	0.17	0.22	2.13	2.84	0.13	0.30	4.83	5.16	206.7	212.1
26	2.03	2.04	0.23	0.27	2.13	2.50	0.13	0.30	4.82	4.81	209.4	213.4
27	2.13	2.15	(Missing)	0.33	2.67	2.50	0.17	0.30	5.27	4.98		
28	2.37	2.36	0.47	0.20	2.53	3.23	0.17	0.30	5.84	5.79	207.6	207.0
29	1.63	1.68	0.20	0.21	1.77	2.16	0.17	0.33	4.10	4.05	163.7	163.7
30	1.93	1.95	1.17	1.17	1.70	2.43	0.17	0.63	5.60	5.55		
31	1.83	1.84	0.80	0.75	1.47	2.45	0.13	0.83	5.06	5.04	156.1	175.9
32	1.70	1.71	0.50	0.52	1.90	3.03	0.17	1.03	5.30	5.26		
33	1.67	1.67	0.27	0.26	1.63	2.34	0.17	0.60	4.34	4.27	155.4	158.2
34									3.20	3.28		
35									3.50	3.66		
36									4.17	4.34		
37									2.80	3.04		
38									3.83	3.99		
39									4.57	4.70		
40									3.37	3.53		
41									3.10	3.28		
42									3.23	3.42		
43				‘					3.07	3.22		

Note that intermediate travel and delimbing time were not measured in the clock study, only in the automated analysis.

(1) because of a failure in the cycle parsing system; (2) because of a loss in GPS signal. In a subsequent study, 48 skid cycles were correctly discerned out of 51 observed, again a 6% error rate (McDonald and Rummer, 2002). Based on these results, it was felt that the automated system could correctly identify at least 90% of total skid cycles with a minimal set of cycle parsing rules and in operating conditions not differing greatly from those in these studies.

Correspondence of total cycle time from ATS and clock measurements in the remaining 44 cycles was very good, the difference averaging less than 2% (about 5 s), but was statistically different from 0 ($P = 0.0043$). Average clock-measured cycle time was 4.72 min, while for the automated system it was 4.64 min. The difference was probably due to the landmarks (in this case, the deck boundary) used in deriving ATS cycle time not corresponding to those used in the clock time study, and illustrated the sensitivity of the ATS measurements to placement of some landmarks. These differences might have been eliminated had the deck boundary been established using GPS, rather than drawing it in based on a map of the site. The difference could also have been due partly to the manner in which event times were assigned in the analysis. Detecting an event such as entering a deck meant that the skidder path crossed a polygon edge, but when that crossing actually occurred was indeterminate because of the finite sampling rate. In the analysis, the crossing time was defined to be identical to the observed time of the point just outside the polygon, slightly shortening the measured event duration.

The lack of identification of cycles in two cases was because of a loss in GPS signal for a significant period of time during which some key event occurred. The one cycle not identified because of a specific failure of the automated time study system was a result of the operator stopping to talk with a crewmember. The location the skidder stopped happened to be inside the area designated as the delimbing zone in the site-mapping phase of the analysis, resulting in a delimbing event being identified at the beginning of the cycle. Such uncharacteristic cycles can be reduced, but would require writing a special-case parsing rule to handle the situation.

ATS-estimated skid distances differed significantly from those measured on the ground ($P < 0.005$). On average, the ATS estimate was 12 m longer (13%, $N = 27$) than direct observation. This was as expected since ground measurements do not typically account for movement during delimbing or while grappling the load. Half the total travel empty plus travel loaded distance (removed travel associated with grappling load and delimbing then averaged) was, therefore, compared with one-way ground-measured skid distances. In that case, the ATS-derived distances were 5% less (7.2 m), on average, than direct measurements, again probably due to differences in landmark locations, and also to some minor flaws in the calculations of the cycle parsing system (rounding errors and ignoring of some distance elements). This difference was not statistically significant ($P = 0.076$).

The relationship between skid distance and cycle time was estimated using both the ATS-derived and clock-measured data. Fig. 2 is a graph of one-way skid distance as a function of total cycle time, along with fitted linear regressions. The model, in both cases, was significant ($P > F = 0.0001$) with adjusted R^2 being 0.51 and 0.63 for the ATS and clock data, respectively. Estimates of the slopes were similar, with the ATS-derived model being 19.9 and 24.3 m/min for the clock data.

3.2. Elemental time study

Elemental time study data were available for a total of 36 skidder cycles, a subset of the cycles used in the gross time study analysis. Elements measured included travel empty, grappling, and travel loaded. Of the 36 cycles, the parsing rules reduced to elemental times in all but 3 cases. One instance was mentioned above (pausing to talk inside the delimbing area), while the other two resulted from similar circumstances. In one case, there was only one reversal of direction noted during the grappling phase, essentially folding the grappling

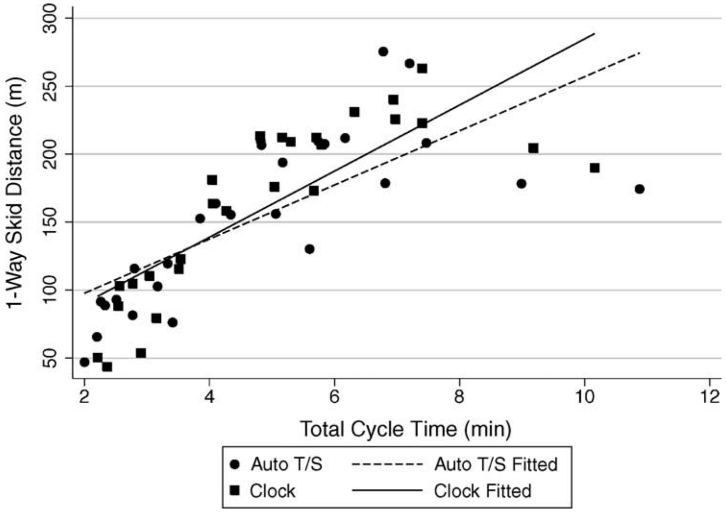

Fig. 2. One-way cycle distance as a function of total skid cycle time. Data represent cycles derived from automated and manual time study.

time into travel loaded. In the second, there was a tree bundle located in the delimbing area and no cycle was detected. In each of these failures, a rule (or rules) to handle the unusual circumstances could have been added and the cycles reduced, but this was felt to violate the premise that a general set of simple rules could be developed that would be effective in unsupervised time study analysis. It was felt that most unusual cycles that did not reduce would require some attention from a human observer anyway, so the fact that they were not correctly identified would serve as a means of flagging those cycles that were not typical.

Fig. 3 shows path data collected on 28 skidder cycles, as well as a series of line and polygon features used to define events for the ATS analysis. Some of the feature and event definitions used as input to the *eventmap* program are in Listing 4. Those definitions left out were to establish the other features in Fig. 3 (for example, polygon **DelimbPoly**, or line **Road**). The rules used to infer skidder time study elements are in Listing 5. Note that the rules used in the analysis included several that defined the same event in different ways, and that the final reduction to cycles used a rule defining a standard cycle (travel empty, grappling, travel loaded), and two special cases. One such case was to catch skid turns that were in a different part of the stand (**cycle_thin**), and one was to reduce cycles in which a grappling event was not detected (**cycle_2**). The data in the figure, and inputs in Listings 4 and 5, represented a complete application of the ATS system on skidder path data collected over a single day and was representative of the system's use in the entire study. For the particular data in Fig. 3, all cycles but one, including elemental times, were correctly identified, representing the most successful application of the system. Elemental time study was only performed on a subset of cycles (16) because we did not have clock data for comparison. Of those 16, there was 1 cycle in which grappling was not detected and was reduced using the **cycle_2** rule.

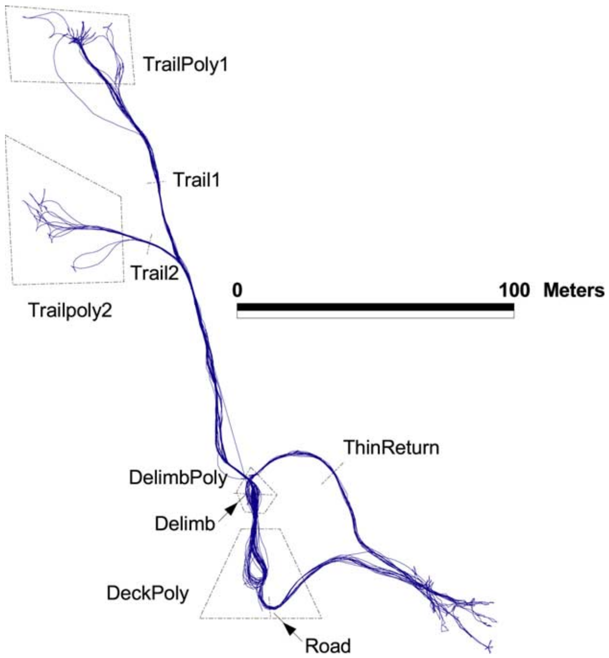

Fig. 3. GPS data obtained for 28 skid cycles, or about 4 h of data collection. The map includes lines and polygons used in the analysis. Feature names are as found in Listing 6.

```
LINE Delimb [
    (648033,3627540),
    (648058,3627539) ]

POLYGON DeckPoly [
    (648038,3627517),
    (648063,3627517),
    (648090,3627459),
    (648011,3627459) ]

enter DeckPoly: enter_deck ;
leave DeckPoly: leave_deck ;

cross Delimb: x_delimb ;
cross Road: x_road ;
cross ThinReturn: x_thr ;
cross Trail1: x_t1 ;
cross Trail2: x_t2 ;

reverse and (inside DelimbPoly): rev_delimb ;
reverse and ((inside TrailPoly1) or (inside TrailPoly2)): rev_grapple ;
```

Listing 4. Event definition file used to analyze the path in Fig. 3.

```
travel_empty: leave_deck^ {x_delimb }*{{x_t1 },{x_t2 }}?rev_grapple ;
grApple: travel_empty^ {rev_grapple }+x_t1$ ;
grApple: travel_empty^ {rev_grapple }+x_t2$ ;

travel_loaded: grApple^ x_t1 x_delimb ;
travel_loaded: grApple^ x_t2 x_delimb ;
delImb: travel_loaded^ {{x_delimb },{rev_delimb }} ;
delImb: x_thr^ {{x_delimb },{rev_delimb }} ;
delImb: delImb x_delimb+ ;
delImb: delImb rev_delimb+ ;
delImb: delImb delImb+ ;

cycle: travel_empty grapple travel_loaded delimb enter_deck ;
cycle_2: travel_empty travel_loaded delimb enter_deck ;
cycle_thin: leave_deck^ x_thr delimb enter_deck ;
```

Listing 5. Skidder elemental time study definitions used when analyzing the path in Fig. 4.

The most consistent correspondence between measured elemental times and ATS-derived times was that of the travel empty component. On average, the difference between ATS and clock measurements of travel empty was 4.3% (4.7 s, $N = 33$). Clock times were significantly longer than those estimated using the ATS system (1.81 min clock, 1.73 min ATS, $P = 0.02$). ATS grappling times were 20% greater, on average, than clock values (10 s). There was a higher degree of variation in the grapple time data but the difference was still significantly greater than 0 ($P = 0.04$). ATS-measured travel loaded time estimates averaged 5.5% less than clock times (8 s). Again, however, the differences showed higher variability and, in this case, the mean difference was not significantly different from 0 at the $\alpha = 0.05$ level ($P = 0.08$).

Fig. 4 included plots of ATS- and clock-derived elemental times for grappling (4a), travel empty (4b), and travel loaded (4c). Travel loaded times for the ATS included intermediate travel and delimbing in those cases when the clock measurements also included them. The largest variability in estimates was found in the travel loaded and grappling elements, while ATS estimates of travel empty were fairly consistent with clock values. The higher degree of inaccuracy for grappling and travel loaded illustrated the unpredictable nature of applying an autonomous monitor in evaluating a complex and variable system. The greater variation reflected a higher probability of something unusual happening. Travel from the deck to a tree bundle (travel empty) was straightforward to estimate, having a well-defined start and end. Any errors beyond that point, however, got propagated to later events. Since cycle start and end times were well defined, over-estimation of an intermediate element such as grappling time would lead to under-estimation of the element that followed it.

Delimbing time was not measured as part of the clock time study, but delimbing did occur and it was detectable from the cycle parsing system. Delimbing was recognized in all cycles in which it was performed (total of 20), but required additional information from the user. Both grappling and delimbing were detected based on reversals in travel direction, but distinguishing one reversal from the other required some contextual knowledge. This generally meant that the two actions were physically separated in space. Since delimbing happened in a particular place, distinguishing the two events was possible by defining a

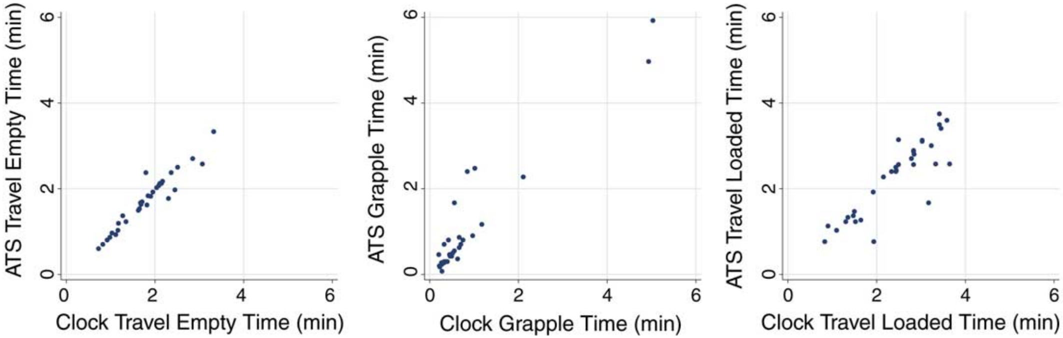

Fig. 4. Plots of automated times study-system estimates compared to clock estimates of travel empty time (a), grappling time (b), and travel loaded time (c).

polygon around the delimbing zone and looking for those reversals inside and outside that polygon.

4. Discussion

In general, the cycle parsing system worked very well in evaluating time performance of skidders. Defining the parser rule set to perform the cycle reduction was complicated, but, once established, the system was robust and capable of recognizing most operational events. Performance in gross time study was quite good, with better than 90% recognition rate. Correspondence with clock time study was also good, although there were biases apparent in some cases that were probably caused by different definitions of cycle starting and ending points between the clock and ATS analyses. The close correspondence of the regressions of total cycle time and distance measured using the clock and automated systems indicated that similar conclusions about system cycle times could be derived from analysis based on either system.

Elemental time study was also possible with the system, although correspondence with clock times was less precise. Travel empty and travel loaded times were close to clock values, but grappling times were subject to large errors. In about 20% of the cycles, grappling times differed from clock-estimated values by 100%, normally over predicting the amount of time required to grapple the load. It was not obvious what caused the errors, but the accuracy of the automated time study system could likely be enhanced with the addition of other sensors tracking, for example, grapple status. This type of modification to the system, although feasible, would require additional equipment to be installed on the skidder, increasing setup time and decreasing reliability.

Although grapple times were the least accurate elemental component from the GPS-based automated time study, they were the most interesting. Travel empty and travel loaded times were fairly consistent throughout most of the experiment, but grapple times varied quite a bit, in most cases representing about 10–15% of the total cycle time, but in a few cases the portion increased to nearly half. There was no obvious difference in the bundles in the cases of high grappling times, but perhaps a limit on bundle size had been exceeded that could have been detected with an automated production monitoring system on the feller-buncher. Given that this type of problem happened, although infrequently, it illustrated the potential for increasing cycle time efficiency using continuous monitoring systems on logging equipment.

Widespread application of this system for measuring performance of forest harvesting machinery is unlikely. The complexity of generating the sequences of rules and landmarks made it too difficult to use in every day practice, but it functioned well as a research tool to suit our particular needs. There were also many minor flaws in the system, including inconsistency in syntax for the rule parsers, and some annoying problems with handling of white space in the input definition files. The biggest drawback to the system, however, was that it was almost too flexible. Rules could be written in any number of ways that, at first glance, would match the same behavior. When used in the ATS, however, subtle differences would become apparent, making development of a robust set of parsing rules a time consuming and, sometimes, frustrating process. Although one goal in developing the automated system was keeping it flexible enough to handle any situation, that level of flexibility resulted in a high degree of difficulty in getting the desired output. Once understood, however, the user could adapt the system to monitoring just about any type of harvesting machine, for example a drive-to-tree feller-buncher with the addition of some simple electronics to track the state of control arms on the felling head (McDonald et al., 2001).

5. Conclusions

This study demonstrated the feasibility of an automated system for performing time study on forest harvesting equipment using primarily positional information. Because it required only a GPS to function, the time study system was both simple to install and rugged. It was also acceptably accurate in reproducing time study data collected using standard techniques, particularly when applied in evaluating gross time study. More than 90% of cycles measured in the clock study were identified from GPS information using the automated time study system. Of the cycles identified, the difference between clock and ATS cycle times was about 2%. Differences between measured and GPS-derived skid cycle distances were somewhat higher, averaging about 5%. Elemental time study was also possible, but required greater analysis time and was subject to larger errors when compared to clock studies.

The time study analysis system was intended to gain the maximum amount of useful information from positional data alone. To be truly effective, any automated time study system must require little or no modification to the contractor's equipment, be robust enough to withstand harsh operating conditions, flexible enough to handle many different silvicultural prescriptions, and not require any interaction with the machine operator. The developed system met these criteria and should be applicable for continuous automated time study in skidders, at least in a post-processing mode. Real-time evaluation of production required information (mainly the 'landmark' data) that was not known a priori. Overcoming this limitation will require some intervention on the part of an operator, or addition of instrumentation to detect events that would otherwise be recognized by spatial patterns. Adding instrumentation, however, would complicate the installation of the system and potentially reduce reliability.

Achieving fully automated productivity tracking will require further development of the time study system. Reliability of the data collection components and a means of accessing them remotely will have to be addressed. The parsing system needs further verification to ensure that results are completely accurate. Finally, the system will also require a means of measuring load size to perform true production studies.

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