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Automated Time Study of Forwarders using GPS and a vibration sensor

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Abstract

Manual time and motion studies are the most common method to collect forest harvesting machine performance data. However, manual methods require skilled observers and are generally limited in duration, making it difficult to obtain a sufficiently large sample for machines with long cycle times such as skidders and forwarders. Of the automated data capture techniques studied previously, few have the breadth and ease of application to conduct long term autonomous studies for a range of harvesting machines. Analysis of Global Positioning System (GPS) data has been successfully trialled previously to conduct time studies of comparable accuracy with skilled observers, however, these approaches have been limited by the need for a degree of manual data processing.

The current study trialled a fully automated system using analysis of GPS and vibration sensor data to estimate cycle times and time elements, and compare them with those determined using traditional time and motion studies for three forwarders at different sites. The mean difference between the cycle times estimated by the two methods was <1 second. This demonstrated the automated system's ability to accurately determine each log landing location and extent and each work cycle start and end points. The correspondence between time elements using each approach was poorer. This was mainly caused by mislabelling of brief periods by the automated system as loading events when the forwarder slowed to negotiate steep areas at one study site. These errors may be able to be addressed by adding further rules to the automated system.

Keywords: forwarder, global positioning system, multidat, automated time study, vibration sensor

1. Introduction

Time and motion studies of forest harvesting machines are an important component of forest operations research. In the last four years, over 20% of the articles published in the Croatian Journal of Forest Engineering and the International Journal of Forest Engineering were based on the results of time and motion studies. However, traditional manual time and motion studies of forest harvesting machines are typically time consuming, costly, limited in duration and involve potentially hazardous work in close proximity to heavy machinery. Direct observation of harvesting machines also requires skilled observers in order to minimise data collection errors (Nuutinen et al. 2008) and can bias study results by influencing the operator's performance (the »Hawthorne Effect« (Hogg 2009, Magagnotti and Spinelli 2012)).

Automated data capture approaches enable collection of long term, detailed machine performance data without bias caused by the presence of an observer. The difficulty in using an automated approach for forest harvesting time and motion studies lies in the variability in the number and type of work elements making up a work cycle. For example, a forwarder may load logs from several locations in the harvesting area, may commence at one landing and finish at another, and may unload logs onto a log stack or onto a waiting truck or a combination of these operations. In recent times, on board computers (OBC) collecting data to the StanForD standard (Skogforsk 2012) have become almost ubiquitous on forest harvesters and a number of studies have been published using harvester OBC data (e.g. Purfürst 2010, Strandgard et al. 2013). However, OBCs are still rarely installed on other harvesting machines. Other automated approaches that have been used to collect harvesting machine performance data include John Deere's TimberLink system (Gerasimov et al. 2012), CANBus (Controller Area Network) signal monitors (Nuutinen et al. 2008), dataloggers such as FPInnovation's MultiDat (Davis and Kellogg 2005), and Global Positioning System (GPS) data loggers (McDonald and Fulton 2005). McDonald and Fulton (2005) suggested that automated time study technology needs to meet a number of requirements before it can be used as a research tool. The technology must:

⇒ be simple to install to minimize downtime for participants in production studies;

⇒ be useful across the widest possible range of machinery systems without requiring extensive reconfiguration of the data collection system for every machine and site;

⇒ survive under harsh operating conditions;

⇒ produce data that duplicates that produced by a skilled field crew working on site.

Most automated data collection approaches fail to meet all the requirements: the TimberLink system is limited to late model John Deere machines; CANBus signal monitors need reconfiguration for different machine types, brands and models, and; to achieve its full potential, the Multidat needs to be hardwired into the machine and can require operator input. GPS data loggers are theoretically able to meet all the requirements (at least for skidders and forwarders). However, to meet the last requirement, requires development of methods to automatically interpret machine activities from the GPS data.

Use of GPS data in forest harvesting research is particularly suited to monitoring the activities of primary transport machines, such as skidders and forwarders, because their ability to move rapidly and cover large distances makes them difficult subjects for traditional time and motion study techniques and their movements, location and speed largely define the activities they perform. In addition, their long cycle times relative to harvesting machines requires a longer period of time to collect a statistically sufficient sample size, particularly for forwarders. A number of studies have used GPS data to interpret the activities of harvesting machines, primarily skidders (e.g. Veal et al. 2001, McDonald and Fulton 2005, Cordero et al. 2006, de Hoop and Dupré 2006). The major limitation of these studies is that they have required one or more manual steps to analyse the GPS data. de Hoop and Dupré (2006) conducted a GPS time and motion study on skidders that involved completely manual interpretation of the GPS data, whereas McDonald and Fulton (2005), in their time and motion study of skidders, manually defined site specific features, such as a polygon defining the log deck boundaries, as an initial step prior to automated extraction of machine activities from the GPS data. Manual entry of site specific features, such as used by McDonald and Fulton (2005), may require repeated site visits by the researcher or data collection by a member of the harvesting crew or a supervisor. Ideally, an automated time and motion study system would dispense with these manual components and extract details of machine activities directly from analysis of the GPS data.

The objective of the current study was to determine whether a fully automated time study system (ATSS) could be created to analyse GPS and vibration sensor data from a forwarder to accurately estimate the forwarder total cycle time and the type and duration of individual time elements.

2. Material and methods

Three sites were used in the study (Table 1). Two sites were in short rotation *Eucalyptus globulus* plantations being clearfelled for chiplogs (each studied for a part day) and one was in a thinned *Pinus radiata* plantation being clearfelled for sawlogs and pulplogs (studied over two consecutive days). Total observation time was 17.5 hours. The weather was fine and sunny for all four days. Different forwarders (Table 1) and operators were studied at each site. All the operators were experienced.

Cycle time started when the forwarder commenced travelling empty from a log landing, and ended when the forwarder had completed unloading and was about to start travelling empty. Cycles were divided into the following time elements: »Travel empty«, »Loading«, »Moving during loading«, »Travel loaded«, »Unloading«, »Movement during unloading« and »Delays« (Table 2).

2.1 Automated time study system

Multidat data loggers equipped with an internal GPS receiver (Garmin GPS 15 (12 parallel channels, accuracy <15m 95% of the time)) were installed in the cabin of each forwarder, with a magnetic base antenna on the cabin roof, to record GPS data. The GPS was set to record a point every 30 seconds and every 20 metres. During testing of the ATSS prior to the trial, it was found that the ATSS could not reliably detect delays

Table 1 Site and forwarder details

Location	Central Victoria	South-west, Western Australia	South-west, Western Australia
Species	Eucalyptus globulus	Eucalyptus globulus	Pinus radiata
Mean tree volume, m^3	0.16	0.14	1.4
Age	12	10	32
Slope, °	<5	<5	7–24
Forwarder	Valmet 890.2, >10.000 engine hours	Valmet 890.4, 3500 engine hours	Valmet 890.3, >9000 engine hours

Table 2 Forwarder time element definitions

»Travel empty«	Starts when forwarder commences travel into the harvest area from the log landing and ends with start of the first crane movement to collect logs
»Loading«	Starts with commencement of crane movement to collect logs and ends when the forwarder commences another element. Includes adjustments to the logs on the bunk
»Moving during loading«	Movement between log piles with no crane movement. Starts when the wheels begin to rotate and ends when crane recommences movement. Simultaneous crane and wheel movement is recorded as loading
»Travel loaded«	Starts when travel to the log landing with a load and ends when wheels cease to rotate or grapple commences to move at the log landing
»Unloading«	Starts with commencement of crane movement, with an empty grapple, towards the forwarder bunk and ends when the forwarder commences another element. Includes adjustments to the log stack
»Moving during unloading«	Movement between log stacks at the log landing with no crane movement. Starts when the wheels begin to rotate and ends when the crane recommences movement to the forwarder bunk. Simultaneous crane and wheel movement is recorded as unloading
»Delay«	Any interruption causing the forwarder to cease working during a shift

using only GPS data. To overcome this limitation, the output of the Multidat internal vibration sensor was used. For each forwarder, the duration of each work cycle and type, and duration of each work element were determined through analysis of the GPS and vibration sensor data by the ATSS.

The methodology used by the ATSS to analyse the GPS and vibration sensor data was as follows:

Step 1 (Determine the location and extent of each log landing)

The GPS used in the study recorded data to 5 decimal places – equivalent to an on-ground resolution of approximately 1 metre. The ATSS tallied the number of times each pair of GPS coordinates was recorded within a GPS dataset. GPS points with a high tally count relative to the remainder of the harvesting area were primarily log landings or log pickup areas. The ATSS labelled GPS points as part of a log landing if their tally count exceeded a user defined limit. Adjacent log landing GPS points were flagged as part of the same log landing. The boundary of each log landing was defined by a four sided polygon generated by the ATSS to encompass each region of high GPS point density. Polygon boundaries were extended by 5 m to allow for noise in the GPS data.

Step 2 (Find start of first work cycle)

The forwarder was defined as being at a landing if its GPS coordinates were within one of the log landing polygons defined in »Step« 1 and its speed and distance travelled between consecutive GPS points fell below the user defined thresholds (1 kmh^{-1} and 8 m, respectively). This definition allowed for occasions when the forwarder travelled through log landings without stopping. Cycles began and ended at a log landing so the ATSS detected the start of the first work cycle as the first instance when the forwarder was at a log landing at a GPS point and then travelling at the next GPS point.

Step 3 (Identify forwarder work elements)

»Travel empty/loaded« and »Moving during unloading/loading« were identified when the forwarder speed and distance travelled between GPS points exceeded user defined thresholds. »Travel empty« and

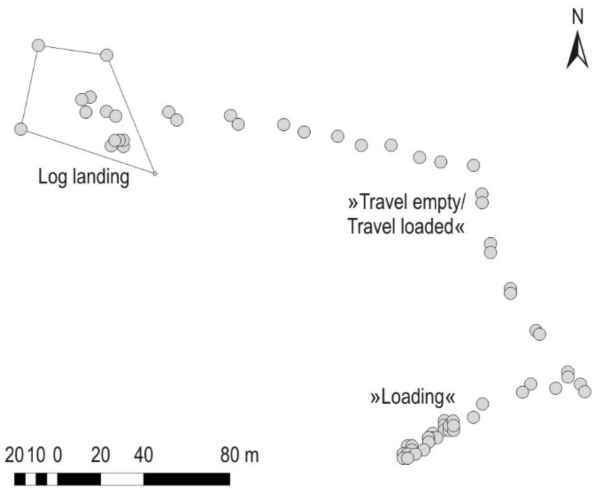

Fig. 1 Example of GPS points representing a forwarder cycle showing »Travel empty«, »Loading«, »Travel loaded« and »Unloading« elements and a log landing

»Travel loaded« were distinguished by whether the forwarder had been identified as »Loading« since it was last at a log landing. »Moving during unloading« or loading was determined as travel between »Loading« or »Unloading« occasions, respectively. »Loading« was identified as periods when the forwarder was not at a landing and its speed and distance travelled fell below user defined thresholds. »Unloading« was identified as periods when the forwarder was within a log landing polygon and its speed and distance travelled between GPS points were below user defined thresholds. »Delays« were identified as periods when the Multidat vibration sensor recorded that the vibration had dropped below the user defined threshold for working.

The key to the operation of the ATSS is accurate identification of the location and extent of each log landing. As the ATSS was designed for long observation periods, the observation periods for the study may have been too short to accurately identify all the log landings. Therefore, data from a longer time period than that used for the manual time and motion (T&M) studies at each site were analysed by the ATSS and the results corresponding to each T&M study period were extracted. Fig. 1 shows an example of the GPS points representing a forwarder cycle and a log landing.

Extraction distance in each cycle was also estimated by the ATSS by adding the estimated distance between consecutive GPS point coordinates (Mean extraction distance = 359 m, Range = 152–868 m). A comparison with manual distance estimation approaches was not made in this study.

2.2 Time and motion studies

At the two *Eucalyptus globulus* sites, forwarder elemental times (Table 2) were recorded by single observers using the TimerPro Professional software (www.acsco.com) installed on a Personal Digital Assistant (PDA). At the *Pinus radiata* site, the forwarder activities were captured using a digital video camera and elemental times were later recorded from the video recordings using the TimerPro Professional software.

2.3 Data analysis

The ATSS and T&M data for forwarder cycle times and »Loading«, »Unloading«, »Travel empty«, »Travel loaded« and »Delay« elemental times were compared using the Bland Altman Method (Bland and Altman 1986). Mean bias (mean difference between the T&M and ATSS values), limits of agreement (bias ±1.96 x standard deviation of the bias (*SD*)) and percentage error (1.96 x *SD* divided by the mean ATSS and T&M cycle or elemental times) were calculated for cycle and elemental times. The acceptable percentage error limit was set at ±30% (Critchley and Critchley 1999). Root Mean Square Errors (RMSE) were also calculated. »Moving« during loading and »Moving« during unloading elements were excluded from the analysis as they were minor components of the forwarder work cycles and did not occur in every cycle.

3. Results

3.1 Cycle times

Thirty one forwarder cycles were recorded by the ATSS and manual T&M (8 per *Eucalyptus globulus* site, 15 at the *Pinus radiata* site). At the *Pinus radiata* site, the GPS signal was lost for periods of approximately 5 hours on each study day (study data was collected prior to GPS signal loss on each day). Analysis using Trimble's mission planning software (http://ww2.trimble.com/planningsoftware_ts.asp) suggested the signal was lost due to occlusion of several GPS satellites by the hill the forwarder was working on. When the GPS signal was available, the ATSS was able to detect 100% of the forwarder cycles.

Individual forwarder cycle times estimated from the ATSS and T&M were very close with a mean difference of less than one second (Fig. 2 and Table 3). The percentage error for the ATSS and T&M cycle time differences was well within the limit of acceptability.

3.2 Elemental time

»Unloading« times and »Delay« times were the most consistent elemental times between the ATSS and

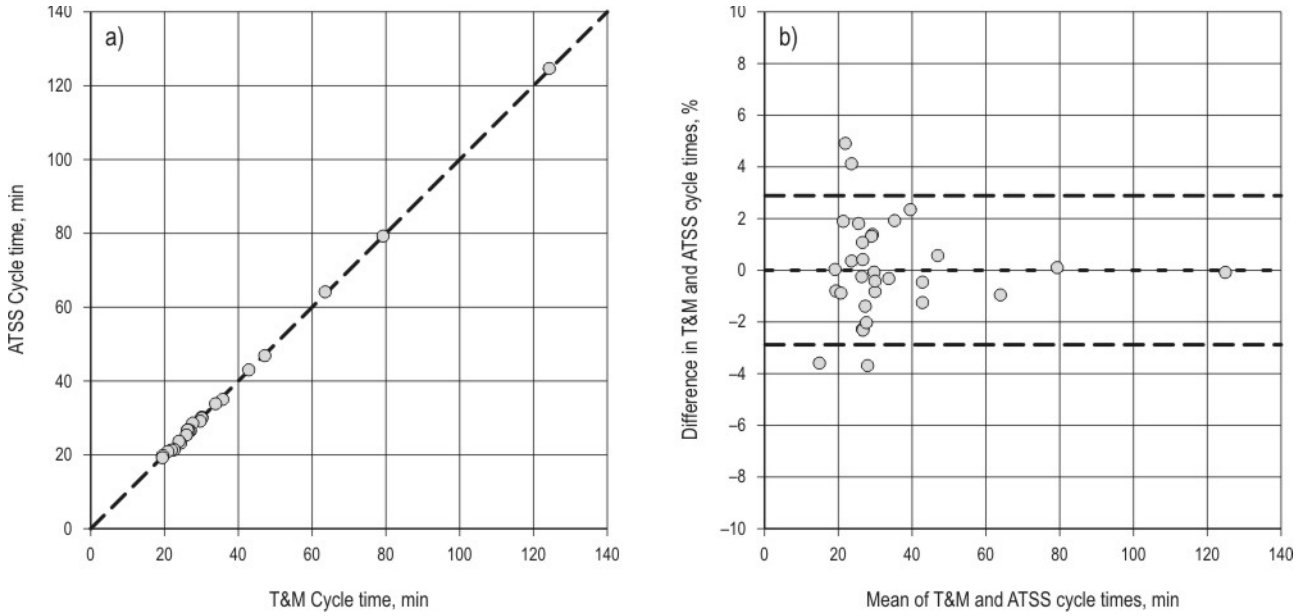

Fig. 2 a) Plot comparing ATSS and T&M cycle times (1:1 line shown); b) Difference in cycle times (T&M–ATSS) (%) against the mean of ATSS and T&M cycle times with mean difference (short dashes) and limits of agreement (long dashes)

T&M estimates (Fig. 3a, Fig. 3e, Fig. 4a and Fig. 4e) and »Travel empty« and »Travel loaded« times (Fig. 3b, Fig. 3c, Fig. 4b and Fig. 4c) were the least consistent. Percentage error values reflected the differences in consistency, with the percentage error values for »Unloading« and »Delay« times being within the limit of acceptability, whereas those for the »Travel empty« and »Travel loaded« times were well outside the limit of acceptability (Table 3). The major cause of the variation between the ATSS and T&M travel times were instances when the operator stopped or slowed the forwarder while travelling, which were interpreted by the ATSS as a Loading event, which caused the mislabelling of subsequent travel times. Although »Loading« times (Fig. 3d and Fig. 4d) were reasonably consistent between the ATSS and T&M times, the percentage error for this element was outside the limit of acceptability. The outliers resulted from a number of »Movement« during loading events that were recorded in the T&M study, but was just below the ATSS speed threshold used in the study (1 km h^{-1}).

4. Discussion

The ATSS analysis detected all 31 forwarder cycles observed during the corresponding traditional T&M studies and accurately estimated cycle times compared with the results of the T&M studies, however the correspondence between individual time elements was poorer. This is comparable to the findings of Mc-

Table 3 Mean, limits of agreement, percentage error and RMSE of cycle times and elemental times for travel empty, loading, travel loaded, unloading and delays (minutes)

Cycle or elemental time	Mean (ATSS)	Mean (T&M)	Limits of agreement	% error	RMSE
»Cycle time«	34.2	34.2	–1.0 to 1.0	2.9	0.48
»Travel empty«	2.9	3.5	–2.2 to 3.4	86.4	1.5
»Loading«	11.0	10.4	–4.9 to 2.16	39.4	2.2
»Travel loaded«	2.6	3.0	–3.4 to 4.2	130.8	1.9
»Unloading«	9.8	9.2	–3.2 to 2.2	27.9	1.4
»Delay«	5.6	5.9	–1.3 to 2.1	29.2	0.96

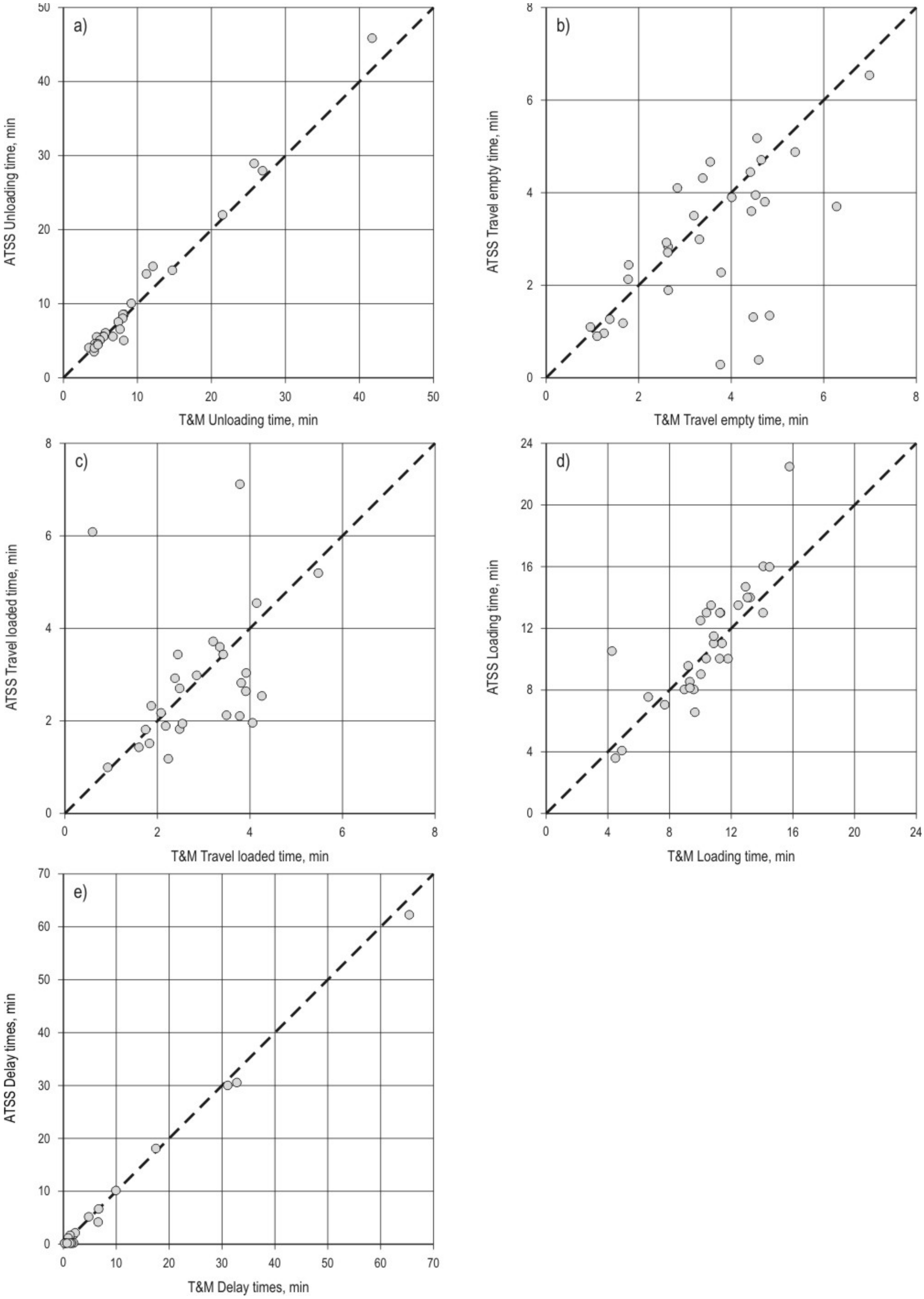

Fig. 3 Plots comparing ATSS and T&M elemental times a) »Unloading time«; b) »Travel empty time«; c) »Travel loaded time«; d) »Loading time«; e) »Delays«

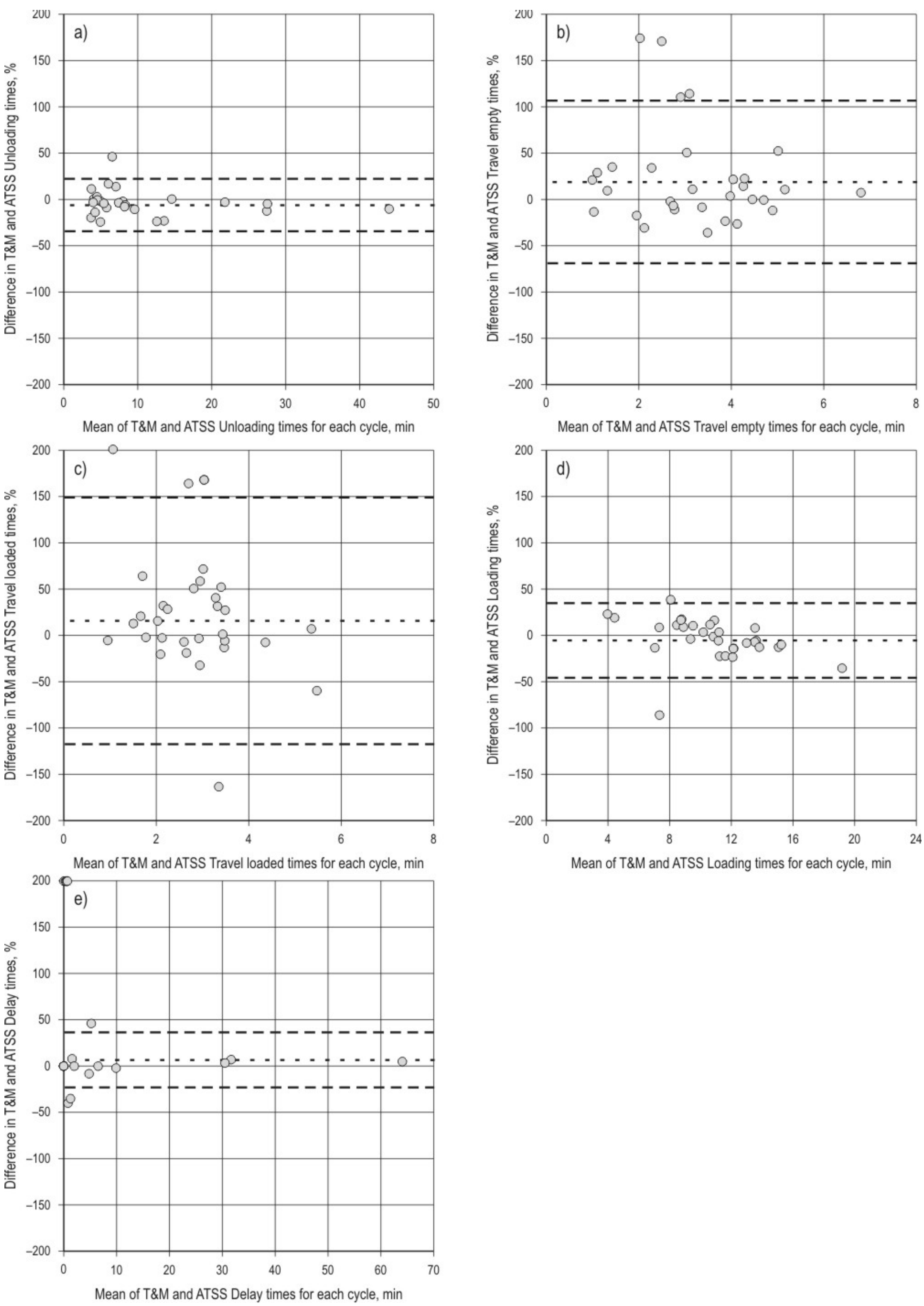

Fig. 4 Difference in elemental times (T&M–ATSS) (%) against the mean of ATSS and T&M elemental times with mean difference (short dashes) and limits of agreement (long dashes) a) »Unloading time«; b) »Travel empty time«; c) »Travel loaded time«; d) »Loading time«; e) »Delays«

Donald and Fulton (2005) in their GPS based automated time study of skidders. The good correspondence between the ATSS and T&M cycle times in the current study probably reflected the well-defined cycle start/end point, which has a strong contrast in activity when the forwarder finishes unloading at a log landing and commences travelling empty (typically operating at its highest travel speed (Stankić et al. 2012)).

The good correspondence between the ATSS and T&M cycle times also suggested the ATSS was able to accurately identify the location and extent of the log landings at the three sites. As mentioned previously, this step is critical to the operation of the ATSS. Potential log landing identification errors are:

⇒ erroneously labelling an area as a log landing (false positive);

⇒ failing to detect a log landing (false negative).

However, for a false positive to impact the analysis, the forwarder speed and distance, when travelling through an incorrectly labelled area, would need to be below the threshold values. This is likely to be a rare occurrence, although it is theoretically possible that a terrain feature could concentrate the forwarder activity in an area, and slow it sufficiently for it to be both incorrectly labelled as a log landing and for travel to be recorded as unloading. A false negative could occur when a log landing is used infrequently or the GPS data were collected over part of the harvesting operation. For the latter reason, GPS data collected over a period greater than that for the T&M study were used to generate the ATSS results. There was no evidence of false positives or false negatives occurring during the study.

As noted above, the primary cause of the large percentage errors for the differences between the ATSS and T&M »Travel empty« and »Travel loaded« elemental times was the forwarder stopping or slowing during travel. This was interpreted by the ATSS as loading, resulting in mislabelling of subsequent travel as »Moving during loading or unloading«. These errors mainly occurred during the *Pinus radiata* study and were the result of the forwarder manoeuvring carefully on steep areas. Reanalysing the data without the *Pinus radiata* site results, reduced the »Travel empty« and »Travel loaded« RMSE values to 1.08 minutes and 1.1 minutes, respectively, and reduced the percentage error values, however they were still outside the limit of acceptability. McDonald and Fulton (2005) similarly found in their study that unusual events caused the poor correspondence between automated and manual time estimates for some skidder work elements. They suggested implementing additional rules to detect these unusual events, which may be a possible solution for the ATSS.

Although the percentage error for the differences in the ATSS and T&M »Delay« times was within the limit of acceptability, the mean T&M delay time was slightly higher than the mean ATSS delay time. This was caused by the Multidat being set to record delays of one minute or greater, which resulted in a number of minor delays being included in the T&M data but not the ATSS data. In future studies, the Multidat minimum delay length could be set to a smaller value to examine the impact on mean delay values.

The main deficiency of using GPS data analysis for automated productivity studies is that there is no means of determining the product types and load weight or volume being carried by the forwarder. However, the use of a forwarder equipped with a set of grapple or bunk load scales could address this issue for single product harvest operations. Long term automated productivity studies using GPS can reveal trends that are not apparent in typical short term time and motion studies, such as the differences in productivity between days of the week noted by Cordero et al. (2006) and the potential areas for harvest system improvement suggested by McDonald and Rummer (2002). Absence of an observer, when using automated time study technology, is assumed to overcome the »Hawthorne Effect«, however, there may still be an effect on machine operator performance from the presence of the data collection technology, especially if it has been temporarily installed for the duration of a study.

GPS signal loss has been reported from a number of machine tracking studies (McDonald et al. 2000, Veal et al. 2001, McDonald and Fulton 2005, Hejazian et al. 2013), although only Veal et al. (2001) found a cause to the signal loss in their study (tree canopy). The GPS signal loss that occurred on the *Pinus radiata* site in the current study was believed to result from the occlusion of satellites close to the horizon caused by the hill the forwarder was working on. Use of Global Navigation Satellite System (GNSS) receivers that combine signals from both the GPS and GLONASS constellations is likely to significantly reduce instances of signal loss and also to improve the positional accuracy as they can access signals from over 50 satellites. However, as mentioned previously, the GNSS data would need to be combined with a means of detecting delays, such as the Multidat vibration sensor or a link to the engine management system to record engine rpm and/or load.

5. Conclusion

Time and motion studies of forest harvesting machines are an important component of forest operations research. However, traditional time and motion studies are generally impractical for long term studies. In the current study, the mean forwarder cycle time estimated using automated analysis of GPS and vibration sensor data was less than 1 second from the mean cycle time determined from traditional time and motion studies. The percentage error was also well within the limit of acceptability. For harvest areas producing a single product, combining the cycle times estimated from the GPS and vibration sensor data with output from a forwarder grapple or bunk load scale could be used to conduct long term, autonomous forwarder productivity studies which would allow examination of long term trends in forwarder productivity. However, results for individual time elements were poorer, mainly due to mislabelling of brief periods, when the forwarder stopped or travelled slowly manoeuvring on a steep slope. Inclusion of additional rules in the automated GPS data analysis may address this issue.

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