# MONITORING PRODUCTIVITY AND UTILIZATION OF A FELLER-BUNCHER USING FPDAT SYSTEM


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MONITORING PRODUCTIVITY AND UTILIZATION OF A FELLER-BUNCHER USING FPDAT SYSTEM

by

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# A CAUTION TO THE READER

# ABSTRACT

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Keywords: feller-buncher, forest operations, FPDat, key performance indicator [KPI], On-Board Computer [OBC], operator, productivity, scheduled machine hours [SMH], shift, utilization

This thesis summarizes the process of equipping a Tigercat 870C feller-buncher with an FPDat on-board computer system. The harvest contractor participating in this study is based in northwestern Ontario. The purpose of this study was to compile and examine the data collected by the FPDat in order to identify operational implications of these data, to provide insight into the useful features of the FPDat, and to identify areas where it can be improved. Establishment of a machine utilization rate, comparison of operator work habits, and identification of factors influencing machine productivity were attributable to the data collected and examined. The utilization rate of the feller-buncher over the study period was 77.4%. A comparison of operator work habits was also carried out through the use of descriptive statistics. The data collected by the FPDat were used to compare descriptive statistics for key performance indicators according to various operators. A two-way ANOVA was completed to determine that the two operators compared exhibited a significant difference in productivity ($\alpha = 0.05$) with regard to the response variable, number of trees cut per scheduled machine hour. Experience with using the FPDat in this study allowed for recognition of the merits of the FPDat that make it a useful tool, as well as deficiencies with the current technology upon which recommendations for improvement are based. Further insight is provided into the operational importance of these results, and to how this technology can be better utilized to increase efficiency in harvest operations in northwestern Ontario. Of key importance in a successful implementation of an on-board computer system is diligence on behalf of the technology developer, forest products company, contractor, and operator.

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I would like to thank the contractor for their involvement in this study. In addition to working on my thesis studying this feller-buncher, owned by Raleigh Falls Timber, I am also a staff member of Raleigh Falls Timber, and in my role as an operations supervisor, the results obtained from my research had a direct relevance to me. A special thanks is directed to the owner of the company and the general manager. In addition, I must thank the operations supervisors who I work alongside for sharing their knowledge with me. I must also thank the various machine operators for their respective levels of tolerance throughout the study period.

I would like to thank FPInnovations for providing knowledge throughout the setup of this project and their continued interest throughout the project's progression. I would also like to thank the Domtar staff with whom I had initial contact with regard to this project, and the KBM Resources Group for providing technical support and performing the installation of the FPDat unit.

# 1. INTRODUCTION

The FPDat system is an on-board computer [OBC] developed by FPInnovations that is equipped for navigation and recording machine performance data in logging machinery. It is a new generation of data collection system following the MultiDat system, produced by FPInnovations in the early 2000's. The FPDat consists of a 10-inch touch screen with a navigation display that also displays key performance indicators [KPI] for the operator. The data collection system is wired into the machine's electronic system and collects data regarding the machine's utilization. These data are transferred through satellite to FPTrak, a data hosting service that is accessible online to users. The implementation of this system into logging machines as part of this study is the first incorporation of this technology in forest operations in northwestern Ontario.

The SFL holder taking part in the study is Domtar Inc., located in Dryden, Ontario. As part of the study, two of Domtar's forestlands contractors agreed to have FPDat units installed in one feller-buncher and one grapple skidder each. This thesis will focus on the data collected by the unit installed in a Tigercat 870C feller-buncher owned by Raleigh Falls Timber, the mills largest timber supplier. Throughout the study period, this feller-buncher operated on the Wabigoon Forest, shown in Figure 1.

Outlined in the Objective section of this report are the goals of the study, which will be elaborated upon both quantitatively and qualitatively through the data collected by the FPDat, as well as experience using the system. A null hypothesis is drawn which will provide the basis for the ANOVA test that will compare the effects of two factors on the productivity of the feller-buncher. The two factors that will be considered are part of the shift scheduling of the machine; operator and shift. The Literature Review will provide a background on machine tracking technology in Canada, as well as some of the factors which influence feller-buncher productivity. The setup of the experiment, including the features of the FPDat and process by which data were collected are described in detail in the Materials and Methods section. The results section displays descriptive statistics according to the operator for the KPIs selected. The findings of the two-way ANOVA will then be presented to show the significance of the two factors compared as they influence the productivity of the feller-buncher. The Discussion will examine the implications of the results presented, as well as challenges and potentials of the FPDat system, to offer feedback as to how this system can be more effectively used in forest operations in northwestern Ontario.

## 1.1. OBJECTIVE

The purpose of this thesis is to compile and examine the data collected by the FPDat to identify operational implications of the data, specific to the operation in which it has been implemented. Of particular interest are the machine's utilization rate and counts of trees harvested per unit time. The statistical analysis will compare work habits according to operators and further examine the components of shift scheduling that ultimately influence the productivity of the feller-buncher through analysis of variance. These factors are operator and shift (day or night). Based on this study, and the associated experience from working with this technology, the merits of the FPDat system will be indentified in order to promote and expand its use in northwestern Ontario. This thesis will provide insight into the features of this technology that make it a useful tool for decision making in the harvest block, and identify areas where the system should be improved to more effectively meet operator needs.

## 1.2. HYPOTHESIS

The null hypothesis for the two-way ANOVA is that there will be no statistically significant difference ($\alpha$=0.05) in productivity according to operator ($A_i$ , i = 1,2), shift ($B_j$ , j = 1,2), or the interaction between those factors.

$A_1\sigma = A_2\sigma$ Equation [1]

$B_1\sigma = B_2\sigma$ Equation [2]

$AB_{11}\sigma = AB_{12}\sigma = AB_{21}\sigma = AB_{22}\sigma$ Equation [3]

## 1.3. LITERATURE REVIEW

Specific data relating to machine productivity is somewhat lacking in forest operations, and this data is of utmost importance for making decisions in an efficient and feasible manner. Operating forest machines is expensive, and accurate tracking of economic variables is challenging (Holzleitner *et al.* 2012). Data collection in this regard is important to increase fuel economy, provide more detailed machine costing models, and identify operating methods that best utilize the machine. Uncertainty in the forest products industry is attributable to a lack of knowledge that would require a long-term dedication to data collection to achieve (Frayret *et al*. 2004). Castonguay and Gingras (2014) reported that monitoring of forest operations can be challenging because of the lack of cellular reception, which can increase difficulty in maintaining a flow of information and automation of processes. In addition, forest contractors are poorly equipped to collect data relating to productivity and performance of their machinery. This lack of data can create an unnecessary degree of uncertainty in rate negotiations, or scheduling of equipment. Accordingly, a technological solution which tracks and effectively communicates operational data would serve to increase productivity (Castonguay and Gingras 2014).

### 1.3.1. Use of OBCs in Canada

The Forest Engineering Research Institute of Canada [FERIC] (1996) identified new areas of innovation that were deemed as promising technological breakthroughs in forest operations. Use of GPS, computerized decision-support tools, data-acquisition and transfer systems, and operator-machine interface systems were identified as having great potential in the future of forest operations. All of these functions are currently met by on-board computers. In implementing these technologies, FERIC identifies the need for a collaborative approach between industries and enhanced training in forest operations. Of particular note is the inclusion of incentives for contractors as a means to expand the use of advanced technologies in forest operations. This is important, because successful use of advanced technologies could result in the forest company reducing the harvesting rates of the contractor, thus providing the contractor with no incentive to use the technology (FERIC 1996).

A FERIC study (1996) examined operator attitude towards advanced technology in logging machines. Diagnostic and monitoring systems were found to be the most helpful improvements suggested by the 106 operators interviewed, followed by navigation aids. Owners were more receptive to the inclusion of these advanced technologies in logging machines than were employees, though overall both parties had positive attitudes towards advanced technology. Positive outcomes were identified by operators, which included effects on the environment, the industry's image, safety, and quality of work. Negative attitudes raised concerns about job security, difficulty with training, and expense of incorporating these technologies (Courteau 1996).

Reynolds (2002) found that GPS units in felling equipment provided insufficiently accurate positioning to be relied upon for regulatory and reporting purposes. Accordingly, these systems could only be relied upon to provide an indication of the size and shape of the block, as well as monitoring the progress in harvesting the block. Since these findings, continuous refinement of technology has contributed to systems that can offer reliable positioning, though the tracking device, if mounted on the cab of the machine, cannot monitor the location of the felling head.

Strandgard *et al.*(2011) concluded that the installation of the OBCs themselves is a very minor component of the process of incorporating these systems in logging operations. The incorporation of these systems involves organizational changes. These changes must prepare the organization to effectively use the data collected by OBCs. Without this organizational framework, it is difficult to achieve productivity improvements that are possible from the implementation of these systems (Strandgard *et al.* 2011). Accordingly, there is an apparent obligation to diligence on behalf of supervisory staff if OBCs are to be fully utilized in forest operations.

Several forest products companies are exploring the potential of OBCs in contractor operations. Experience with OBCs in North America and Europe has identified that the effective use of an on-board computer in a harvesting machine can lead to increases of up to 30% in availability, utilization, and productivity (Jamieson 2004, Brown *et al.* 2012). Laforest (2012) performed a case study involving the predecessor to the FPDat, called the MultiDat. These systems were installed in a variety of contractor-owned equipment in northern Ontario. The study determined that improvements in productivity and other key performance indicators could result in a 105% return on investment [ROI] if 10 feller-bunchers were equipped with the technology. Tolko Industries is currently involved in forest operations research as part of their Innovative Phase Logging program. This program focuses on the capabilities of OBCs and how these operating systems can improve the efficiency of the operations in which they are involved (Sterling 2015). The MultiDat and FPDat are some of the OBCs being used in this study.

Advanteck Inc. (2015) designed and developed a sub-meter GPS navigation system for harvesting operations. This system uses a touch screen to display digital maps, high-resolution photography, and LiDar data. This system has been in use in forest operations since November 2012. The GPS tracking system is accurate to ± 30cm. The Advanteck system is able to identify unmapped sensitive areas based on imagery to avoid the possibility of damaging sensitive areas. The system is used in lieu of manual flagging of harvest compartment boundaries, and the maker identifies increased safety of forest workers and reduced cost as benefits of using this technology as opposed to using line runners, who are in short supply, to mark boundaries. There is no capital cost of this software, and Advanteck advertises that the charges for boundary control are applied based on the navigated kilometer and are less than that for manual boundary marking. Manual flagging can add up to 20% of the distance to the actual GIS-generated line because of irregular track lines. This technology is currently in use in contractor operations in Ontario, including some Resolute Forest Products harvest operations. Applications include regular harvesting operations and right-of-way clearing (Advanteck 2015).

Forest equipment manufacturers are now selling logging equipment with OBCs sold as optional equipment, that are able to perform various functions which are tailored to customer needs. John Deere has developed forest-specific technologies which are integrated with the feller-bunchers and skidders they currently manufacture (John Deere 2017). These machine optimization technologies are marketed under the name John Deere ForestSight™ suite of products. The JDLink™ machine monitoring system allows a supervisor to view maps, receive alerts, view engine hours for maintenance planning and enroll in a factory-suggested maintenance plan. Further options to the JDLink interface include a machine health prognostics ability, which detects low fluid levels, and a remote diagnostics and programming option which allows the user to remotely record machine performance data and remotely read and clear diagnostic codes. Data collected by this system are transmitted either via cellular service, or satellite, depending on user preference, and can be viewed on smartphones using an application, or a web interface on computers. TimberNavi™ is the name of John Deere's OBC mapping interface. It is available for late-model feller-bunchers and skidders. This system operates using ESRI ArcGIS™ to display digital maps and features a touch screen monitor (John Deere 2017).

### 1.3.2. FPSuite™

The FPSuite integrated monitoring platform is the most recent technological development from FPInnovations, created for use by contractors and forest companies in order to provide information that will help these clients boost profitability (Castonguay and Gingras 2014). The integrated monitoring platform consists of software and electronic tools, and has three main components; FPDat™, FPCom™, and FPTrak™. The FPDat system is designed for navigation and collection of data on performance and productivity of machinery. The components of the FPDat include a data acquisition system, navigation system, GPS receiver, and 10" touch screen that allows the operator to view and adjust a display consisting of a maps and key performance indicators. FPCom is the name of the satellite network that sends data collected from the machine in near-real time. The FPCom also allows for the transfer of GPS data between machines through a wireless network used to link the machines. FPTrak is the website and data hosting service that tracks and stores the data collected by the FPDat (Castonguay and Gingras 2014). There are currently about 800 FPDat units in use throughout Canada. Uptake in Ontario has been minimal to date (Caron 2016). Using FPTrak, a supervisor can view and generate reports on the activity of a machine, examine productivity and observe the machine's location and past movements.

1.3.3. Machine Utilization and Productivity

Holzleitner *et al.* (2012) identify the utilization rate of the machine as being one of the most important factors influencing a machine costing model. The utilization rate of a machine [MU] is the proportion of workplace time [WP] that the machine performs productive work [PW], the task for which the machine was designed (Richards *et al.* 1995). This relationship is expressed in Equation 4. It is important to understand that workplace time is often recorded in scheduled machine hours [SMH], and productive work is measured in productive machine hours [PMH].

$$\text{MU } (\%) = \frac{\text{PW}}{\text{WP}} \times 100 \qquad \text{Equation [4]}$$

The increasing complexity of equipment and harvesting standards will demand a reduction in poor utilization and poor harvesting practices, which result in higher environmental and production costs (Courteau 1996).

Productivity is recorded on a cubic metre per PMH basis, with Gingras (1988a) establishing values of 32 $m^3$/PMH for a non-levelling cab feller-buncher in favourable stand and terrain conditions, and 31 $m^3$/PMH for a levelling cab feller-buncher working in adverse stand conditions. This information highlights the influence of machine design and stand conditions on machine productivity.

## 1.3.4. Feller-Bunchers

The feller-buncher is a complex machine that is used to complete the rigorous task of felling multiple stems of standing timber and placing the full trees on the ground in bundles, to facilitate transport to roadside. The use of feller-bunchers has resulted in the increased popularity of mechanical felling with full-tree skidding in Canada (Gingras 1988a). The feller-buncher works fairly independently of the process that must follow to transport the wood to roadside (Gingras 1988b). With this being said, the feller-buncher has an important role in creating bundles of optimal size and placing them in such a manner so as not to cause hindrances while skidding the bundles to roadside. The technique of the feller-buncher operator is a key determinant of the grapple skidder's productivity (Gingras 1988b). Given this relationship, no component can be isolated from the logging system (Pulkki 2016).

Pulkki (2016) identifies that feller-bunchers can be tracked or wheeled, with tracked feller-bunchers being swing-to-tree bunchers that rely on a boom-mounted felling head. Tracked feller-bunchers are the most commonly used in Canada because of their enhanced ability to fell larger trees in sensitive sites, and ability to negotiate difficult terrain. Feller-bunchers can be equipped with shear, auger, cone, chainsaw, or circular saw heads. The continuous circular saw head is the most common of these designs in Canada. Referred to as a 'hot saw', this head configuration also has the most rapid cutting time, and is thus capable of the highest productivity among saw head types.

1.3.5. Factors Affecting Feller-Buncher Productivity

Predicting the productivity of feller-bunchers can be very difficult because of the extreme levels of variability in the areas that they are designed to operate. It is difficult to relate production to environmental variables because of differences between machines, data collection methods and operator quality (Gingras 1988a). It is important for forestlands workers and owner-operators to understand how variables such as slope, terrain, and tree size can effect costs and profits (Howard 1987). The most common method used by researchers to collect productivity data are detailed time studies and shift level-studies (Hossain *et al*. 1998). Pulkki (2016) describes the following steps in the completion of a feller-buncher's work cycle:

i) move or swing to tree

ii) cut and accumulate

iii) repeat i) and ii) until accumulator arms are full

iv) move or swing to bundle location

v) drop bunch

In completing this work, the aim of the operator is to minimize boom swing distance, extension and retraction, ground distance travelled, and number of settings, all while accumulating the greatest number of stems possible in each cycle (Pulkki 2016).

Gingras (1988a) examined feller-buncher productivity according to various stand conditions. These parameters included ground firmness, ground roughness, slope, sidehill, underbrush cover, tree branchiness, advance regeneration, density of unmerchantables, stand distribution and average tree diameter (DBH). These parameters were further expanded to include accumulated trees per cycle, trees per bunch, ratio of merchantable to unmerchantable stems, visibility, basal area, and tree volume. The most important factor affecting productivity on a $m^3$/PHM basis was found to be average DBH, followed by accumulated trees per felling cycle, ratio of merchantable to unmerchantable stems, stand density, and slope and sidehill. By having an understanding of these variables, a contractor can be better prepared to purchase equipment that is best suited for the anticipated conditions in the area they are situated. Examples could include purchasing a feller-buncher of larger size to accommodate more trees in a felling cycle, or purchasing a leveling cab feller-buncher to better negotiate terrain in areas of marginally operable slope.

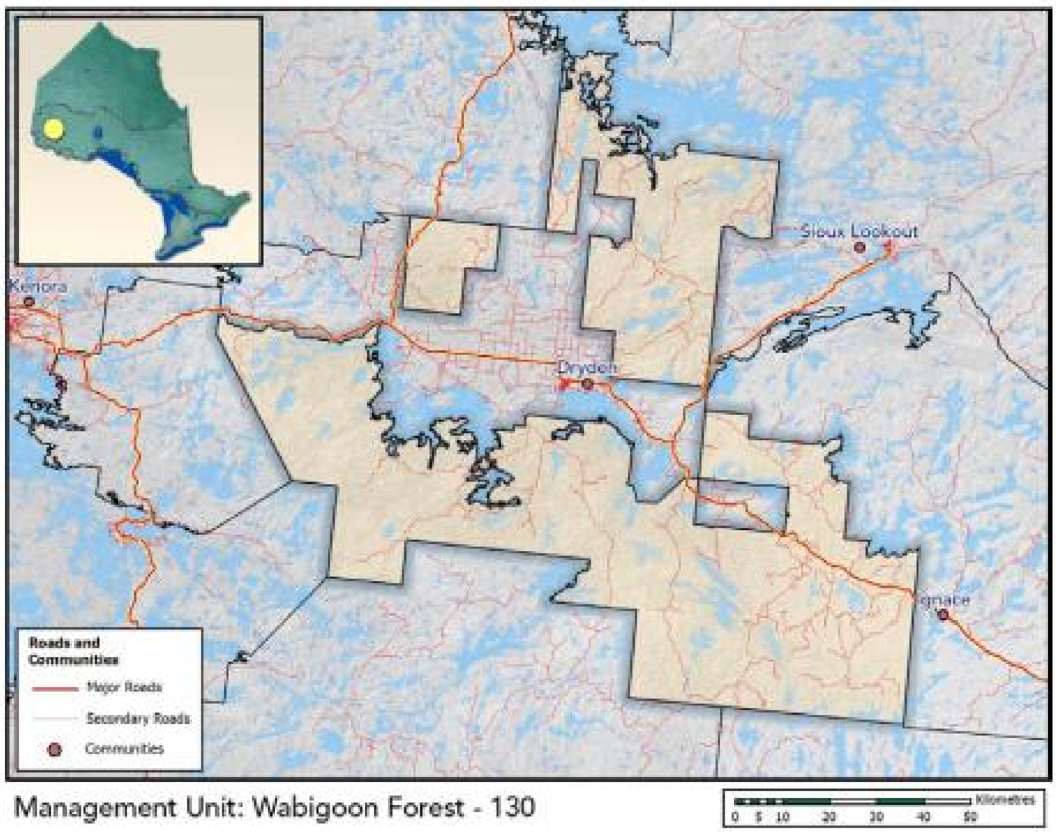
### 1.3.6. Cost Savings

Equipment monitoring can offer cost savings from increased productivity and increasing awareness of how equipment can be used in a more economical manner. In an Australian study, Brown *et al*. (2012) identify a widespread potential for use of onboard systems to identify areas in which inefficiencies exist in harvesting systems. The ability to effectively quantify and understand the performance of machinery is essential to developing efficient operations. Achieving a better understanding of performance would allow for a more accurate establishment of harvesting rates (Makkonen 2004).

Makkonen (2004) notes that continuous increases in fuel prices have raised operating costs for forestry equipment. A feller-buncher has the highest fuel consumption of off-road logging machines. The fuel consumption of a machine is dependent on the design of the machine, the engine technology, and the work methods of the operator. The work methods of the operator can account for a 20% variation in the fuel consumption of a logging machine. Off-road machines are most efficient when operating at an engine speed (rpm) that allows for the production of the most torque. Using a high engine speed with a low torque output increases the machine's fuel consumption. Operating forestry machines at moderate engine speeds is one technique that an operator can use to maintain torque and save fuel, while reducing maintenance and repair costs without a reduction in productivity. The use of multiple hydraulic functions simultaneously increases the load on the engine and allows work to be performed more rapidly. This practice also is identified as leading to increased fuel economy in equipment. Other practices to reduce fuel consumption include reducing idling time, keeping tracks and chains properly tensioned, and minimizing full boom extension (Makkonen 2004).

# 2. MATERIALS AND METHODS

## 2.1. SITE SELECTION AND TIME PERIOD




Source: Williams 2011

Figure 1. Reference map of Wabigoon Forest SFL.

This study took place on the Wabigoon Forest Sustainable Forest Licence [SFL]. Figure 1 displays the Wabigoon Forest SFL. The SFL holder is Domtar Inc., located in Dryden, Ontario. The contractor partaking in this study was Raleigh Falls Timber, also based in Dryden. The harvest blocks in which operations proceeded were a part of the Annual Work Schedule. The data collection began in June 2016 and was completed in November 2016. For the purposes of confidentiality, the operators of the machine are not identified.

## 2.2. MACHINE STUDIED


Figure 2. Tigercat 870C feller-buncher monitored in study.

The machine studied is a Tigercat 870C feller-buncher owned by Raleigh Falls Timber. The feller-buncher is known as RFT-9705 for identification purposes within the company and is shown in Figure 2. This feller-buncher is a tracked, swing-to-tree buncher equipped with a large, continuous disk saw head. According to the Tigercat machine guide, the 870C is a model designed to handle large timber in mixed natural stands with difficult and/or rocky terrain. These machines are designed for clear-felling applications. Dimensional specifications are provided in Table 1 and Figure 3. The saw on the felling head of this feller-buncher is shown in Figure 4.

Table 1. Specifications for Tigercat 870C feller-buncher.

| Specification | | |
|---|---|---|
| **Engine** | | |
| MAKE | Cummins | |
| MODEL | QSL9 | |
| GROSS POWER | 300 hp | 223.7 kw |
| POWER MEASURED @ | 1800 rpm | |
| **Operational** | | |
| OPERATING WEIGHT W/O ATTACHMENT | 66870 lb | 30331.7 kg |
| FUEL CAPACITY | 256.2 gal | 970 L |
| HYDRAULIC SYSTEM FLUID CAPACITY | 50.2 gal | 190 L |
| OPERATING VOLTAGE | 24 V | |
| ALTERNATOR SUPPLIED AMPERAGE | 110 amps | |
| **Undercarriage** | | |
| TRACK PITCH | 8.5 in | 215 mm |
| SHOE SIZE | 24 in | 610 mm |
| TRACTIVE EFFORT | 73000 lb | 33112.2 kg |
| NUMBER OF TRACK ROLLERS PER SIDE | 9 | |
| **Boom** | | |
| MAX CUT RADIUS | 27.8 ft in | 8460 mm |
| MIN CUT RADIUS | 15.7 ft in | 4800 mm |
| BARE PIN LIFT AT MAX REACH | 13315.9 lb | 6040 kg |
| **Dimensions** | | |
| OVERALL LENGTH | 18.2 ft in | 5540 mm |
| OVERALL WIDTH | 10.8 ft in | 3300 mm |
| HEIGHT TO TOP OF CAB | 10.8 ft in | 3300 mm |
| GROUND CLEARANCE | 2.3 ft in | 710 mm |
| TAIL SWING RADIUS | 4.7 ft in | 1420 mm |

Source: Ritchie Specs 2017

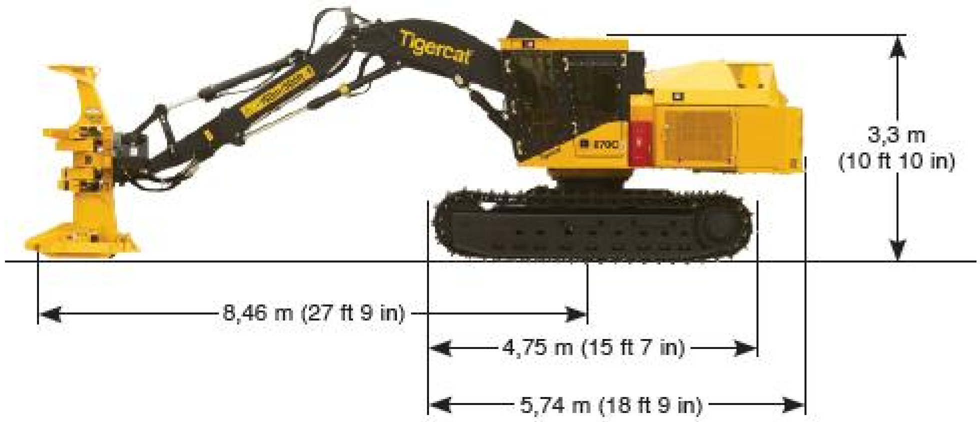



Figure 3. Dimensional specification diagram for Tigercat 870C feller-buncher.

Source: Tigercat 2015


Figure 4. Felling head and circular saw on Tigercat 870C feller-buncher.

While this study focuses on the previously indentified feller-buncher, the Domtar project saw a total of 4 machines equipped with the FPDat equipment, including 2 Tigercat 870 feller-bunchers and 2 John Deere 848 grapple skidders. One of each of these machines were owned by Raleigh Falls Timber, with the other two machines being owned by another contractor.

## 2.3. FPDAT

The main components of the FPDat system include a data collection system, a navigation system with key performance indicator display, a GPS receiver, and a 10" touch screen displaying KPIs and navigation. This touch screen also allows for operator input. The data collection system and touch screen are depicted in Figure 5. The software allows for monitoring of production activities of the machine using the FPTrak online data-hosting service.


Figure 5. FPDat unit and touch screen.

2.3.1. FPDat Installation

The initial installation of the FPDat took place in February 2016. This installation occurred in an operating area and took roughly 8 hours to complete. The process was made more difficult by poor weather and resulted in a shift of unplanned downtime for the feller-buncher. A welder was also required to be on site for the installation of the GPS receiver, which had to be placed on a part of the machine that had direct exposure but also would be somewhat protected from falling debris during harvesting. After the initial installation, the operators were shown how to use the system by the technician who performed the installation. The second phase of the installation occurred in June 2016, and consisted of the connection of a wire 'channel' connected to the electronic impulse generated by the utilization of the grab arms on the felling head of the machine. This resulted in the ability of the FPDat to collect a grab arm count, which can be used to represent the number of stems cut by the feller-buncher over a given time period. With additional data pertaining to scaled volume of trees, productivity estimates ($m^3$/SMH and $m^3$/PMH) can also be produced.

2.3.2. FPDat Capabilities

The FPDat has a motion sensor that is used to calculate productive machine hours. Input channels allow the system to record machine activities. For the feller-buncher being studied, the grab arm utilization was tracked by using this feature. The GPS receiver on the FPDat collects and displays GPS track logs, displaying these tracks on the navigation touch screen and uploading the tracks to FPTrak via satellite. Using a J1939 electric control unit, the system is capable of collecting machine data such as fuel consumption and rpm (Caron 2016). The operator of the machine is able to enter information, including operator ID, stop codes, and activities being performed using the machine. A KPI display on the screen allows an operator to see selected KPIs, such as machine utilization. The navigation system allows for the upload and generation of customizable maps using ESRI shapefiles and display of geo-referenced images, which can be uploaded to the system via USB. Boundary alarms can be set up to notify an operator that is approaching a harvest boundary or AOC. This feature is useful for carrying out ribbonless cutting, though the feature was not used, as this was not an objective of the trial.

FPCom operates using satellite or a combination of Wi-Fi and cellular service to transfer the data collected by the FPDat. Data can be transferred from one machine to the other when they are parked beside each other, and allows for the exchange of track logs between the machines. Data is also available through the FPTrak web interface (Caron 2016).

Each FPDat unit costs roughly $5,250.00 (all figures CAD) and the cost of installation is around $2,000.00 per unit. Additional costs include a monthly satellite communication fee of roughly $50.00 per month, and an FPTrak fee of around $25.00 per month per FPDat unit (Caron 2016).

## 2.4. SHIFT SCHEDULE

In order to effectively view data in FPTrak, the shift schedule of the machine must be entered online. This was completed throughout the study based on the hours that the machine worked. For the most part, the machine was operated for two 10-hour shifts from Monday to Thursday. Some overtime shifts occurred on Friday and Saturday, though not on a consistent basis. The same two operators spent the majority of the study period operating the machine. These two operators, hereafter referred to as 'Operator A' and 'Operator B', had enough time on the machine to produce sufficient replicates based on their number of shifts on the machine. A total of 7 operators had run the machine during the study period, mainly while the usual operators of the machine had taken vacation. Table 2 displays the generic shift schedule for the buncher, which consists of two 10-hour shifts, Monday to Thursday. The day shift runs from 6:00 AM to 4:00 PM, and the night shift runs from 4:00 PM to 2:00 AM the following morning.

Table 2. Generic shift schedule for RFT9705 feller-buncher.

| | | Day of Week | | | | |
|---|---|---|---|---|---|---|
| Shift | | Monday | Tuesday | Wednesday | Thursday | Friday |
| Day | Start | 6:00 AM | 6:00 AM | 6:00 AM | 6:00 AM | - |
| | End | 4:00 PM | 4:00 PM | 4:00 PM | 4:00 PM | - |
| | SMH | 10.00 | 10.00 | 10.00 | 10.00 | - |
| Night | End | - | 2:00 AM | 2:00 AM | 2:00 AM | 2:00 AM |
| | Start | 4:00 PM | 4:00 PM | 4:00 PM | 4:00 PM | - |
| | SMH | 10.00 | 10.00 | 10.00 | 10.00 | - |

## 2.5. DATA COLLECTED

Data collected and displayed in FPTrak were periodically reviewed throughout the study period. Data were downloaded from the data hosting service at the end of the study period and entered into Microsoft Excel. Daily records were matched according to the machine's operator. Processing of the data resulted in the statistical metrics used for the various displays, which are presented in the Results section. These results compare KPIs according to the operator of the machine. It is important to note that while the FPDat configurations allow the operator to select their name at the beginning of a shift, only the two operators regularly operating the machine were initially listed as operators in the settings files, which were uploaded to the machines. Additionally, there were also issues with the operator's willingness to use the technology. Accordingly, records of the operator were not provided on a daily basis through FPTrak, rather, they had to be recorded separately.

### 2.5.1. Selection of KPIs

In order for the data to be effective in providing useful results pertaining to operator and machine performance, key performance indicators were devised. Most of these indicators were recorded by the FPDat and displayed in the utilization reports available through FPTrak. Two additional KPIs were further developed using the raw data collected. The KPIs monitored directly by the FPDat that were used for this study were machine utilization, number of times the grab arms were activated during the shift, and fuel consumption.

Machine utilization is calculated by dividing the amount of productive work time by the amount of scheduled time as input in the shift schedule. It is expressed as a percentage. The number of times the accumulator arms are activated is an important parameter which makes measuring productivity possible. This is because the grab arms must be activated in order to secure each tree while it is being cut. Accordingly, grab arm counts can be used to provide an accurate estimate of the number of trees cut per shift, assuming that the operator is not activating the grab arms unnecessarily in an excessive manner. Fuel consumption is measured on a liters per productive hour [L/PMH] basis and records the rate at which the machine burns diesel fuel during the shift. This is an indicator on how hard the machine is being run by the operator.

The two KPIs that were further developed using the data downloaded from FPTrak were number of trees cut per scheduled machine hour and number of trees cut per productive machine hour. The number of trees cut per SMH was calculated for each shift by dividing the number of trees cut by the duration, in hours, of the shift. The number of trees cut per PMH was calculated by dividing the number of trees cut per SMH by the utilization rate expressed as a decimal.

The number of trees cut per SMH was chosen as the main indicator of operator performance. This may seem like an abnormal choice, because productivity is generally measured in the amount (volume) of timber harvested per PMH. The rationale for using trees cut per SMH as the key indicator is that it is an indicator that is influenced by the actual utilization rate of the machine, and the speed at which an operator is able to work. This indicator was also chosen, because by simply multiplying by the 10 scheduled machine hours that are generally in a shift, the expected number of trees per shift can be calculated from the number of trees cut per SMH.

### 2.5.2. Descriptive Statistics

Descriptive statistics were generated, and are provided to display KPIs attributable to all of the operators using the machine throughout the study period. These data are presented for all 7 operators who had used the machine, regardless of how many shifts they operated the machine. It is necessary to note that a statistically significant sample size consists of at least 30 replicates, and the measure of replicates for this study was the number of shifts that the operator ran the machine. The two regularly scheduled operators have 79 and 76 shifts, respectively, while the next most common operator on the study unit only operated it for 6 shifts. These statistics provide a comparison of productivity between operators to understand the work habits of these operators. It must be understood that some measures of spread will be larger for operators who do not have a significant number of replicates on the machine, and that their actual productivity may differ somewhat from the data pertaining to their limited time on the study unit. These results are presented in Section 3.1.

### 2.5.3. Two-way ANOVA

A two-way ANOVA statistical test was completed on the collected data using IBM SPSS computer software and quantified which of two factors were significant in determining the productivity of the feller-buncher. Productivity was measured by stems harvested per SMH, which was measured using the grab arm counts recorded by the FPDat for the shift, divided by the number of hours in the shift. The two factors that were considered were part of the shift scheduling of the machine; operator, and shift. Only the two main operators during the study period had sufficient replicates (shifts) on the machine to be compared in the ANOVA. These operators both had over 30 replicates for each day and night shift. In order for the dataset to yield meaningful results from an ANOVA, it had to meet certain criteria, including passing Levene's test for homogeneity of variances. The formulation and results of the two-way ANOVA are presented in Section 3.2.

# 3. RESULTS

This section contains both descriptive statistics pertaining to the performance of the various operators during the study period, and the results of a two-way ANOVA performed to determine whether any significant differences existed between the two regularly scheduled operators according to the two selected scheduling factors: operator and shift.

## 3.1. DESCRIPTIVE STATISTICS

In examining the descriptive statistics, it is apparent that there are two operators who have significantly more time on the machine than the other operators who had run the machine during the study period. These operators are identified as operators 'A' and 'B', and the data obtained while these operators were working are indicated in bold text. Table 4 provides the descriptive statistics of various KPIs pertaining to operator performance. These include number of scheduled shifts, total number of trees cut, total SMH, trees cut per SMH, trees cut per 10 hour shift, utilization, trees cut per PMH, and average fuel consumption. With the exception of operators A and B, who ran the machine for both day and night shift in roughly equal proportions, other operators ran the machine on less predictable shift patterns. Operators C and D ran the machine exclusively on day shift. Operator E ran the machine for night shift. Operator F worked

2 night shifts and 1 day shift. Operator G is not primarily a feller-buncher operator, but ran the machine on night shift when mechanical issues persisted on other machines, or when acting also as a mechanic. The data presented in Table 3 tracks the data obtained by the FPDat and made available via FPTrak for the 176 shifts for which the feller-buncher was used during the trial period.

Table 3. Performance statistics for operators on RFT 9705 feller-buncher.

| ID | Shifts | Total Trees Cut | Total SMH | Trees /SMH | Trees/ shift (10hr) | Utilization (%) | Trees /PMH | Average fuel consumption (L/hr) |
|---|---|---|---|---|---|---|---|---|
| **A** | **79** | **112406** | **784.5** | **143** | **1433** | **78.5** | **182** | **28.4** |
| **B** | **76** | **99159** | **755** | **131** | **1313** | **75.7** | **173** | **27.0** |
| C | 6 | 19850 | 60 | 331 | 3308 | 80.5 | 411 | 34.8 |
| D | 5 | 14752 | 44.5 | 332 | 3315 | 84.8 | 391 | 35.8 |
| E | 4 | 10258 | 40 | 256 | 2565 | 81.2 | 316 | 37.0 |
| F | 3 | 8518 | 30 | 284 | 2839 | 78.0 | 364 | 34.6 |
| G | 3 | 3852 | 24 | 161 | 1605 | 63.6 | 252 | 28.2 |
| Totals | 176 | 268795 | 1738 | 155 | 1547 | 77.4 | 200 | 28.5 |

As presented in Table 3, there appears to be a considerable difference in productivity, measured in trees cut per SMH, between the regularly scheduled operators and the other operators. Table 4 displays both the weighted average, which is weighted according to the number of SMH that each operator ran the machine and reflects the actual production of the machine over the trial period; and the unweighted average that would have resulted from each of the operators in Table 3 running the machine for an equal number of SMH. While the assumption of the unweighted average does not reflect the actual production of this machine, it is a useful comparison to show long-term production capabilities among various operators, assuming that operators C to G are able to consistently produce at the same rate at which they were monitored by the FPDat.

Table 4. Comparison of weighted and unweighted averages of KPIs among operators.

| ID | Trees /SMH | Trees/shift (10hr) | Utilization (%) | Trees /PMH | Average fuel consumption (L/hr) |
|---|---|---|---|---|---|
| **Weighted Average** | **154.7** | **1547** | **77.4** | **199.8** | **28.7** |
| Unweighted Average | 234.0 | 2340 | 77.5 | 298.7 | 32.3 |

Using Table 4, comparisons can be made for individual operators to the averages presented. These comparisons are made in Tables 5 and 6, with Table 5 displaying the comparison of KPI levels to the weighted average, and Table 6 displaying the comparison of KPI levels to the unweighted average. Operators exceeding the 100% mark demonstrate a higher-than-average level for that particular parameter as compared to the averages established in Table 4. The percentage of shifts attributed to each operator is also displayed. Table 5 reflects the comparison of KPIs according to averages established using the actual proportion of shifts that each operator spent on the machine. Table 6 assumes an idealized situation by which all operators operated the machine for an equal portion of time and performed at the levels indicated in Table 3. This situation can be used to simulate the performance of all of the feller-buncher operators within the company, of which the 7 operators tracked during the trial period comprise a more reasonable sample than just the two regularly scheduled operators.

Table 5. Comparison of operator performance to weighted average.

| ID | Shifts (% of Total) | Trees /SMH | Trees/shift (10hr) | Utilization (%) | Trees /PMH | Average fuel consumption (L/hr) |
|---|---|---|---|---|---|---|
| **A** | **44.9%** | **93%** | **93%** | **101%** | **91%** | **100%** |
| **B** | **43.2%** | **85%** | **85%** | **98%** | **87%** | **95%** |
| C | 3.4% | 214% | 214% | 104% | 206% | 122% |
| D | 2.8% | 214% | 214% | 110% | 196% | 126% |
| E | 2.3% | 166% | 166% | 105% | 158% | 130% |
| F | 1.7% | 184% | 184% | 101% | 182% | 121% |
| G | 1.7% | 104% | 104% | 82% | 126% | 99% |

Table 6. Comparison of operator performance to unweighted average.

| ID | Shifts (% of Total) | Trees /SMH | Trees/shift (10hr) | Utilization (%) | Trees /PMH | Average fuel consumption (L/hr) |
|---|---|---|---|---|---|---|
| **A** | **14.3%** | **61%** | **61%** | **101%** | **61%** | **88%** |
| **B** | **14.3%** | **56%** | **56%** | **98%** | **58%** | **84%** |
| C | 14.3% | 141% | 141% | 104% | 138% | 108% |
| D | 14.3% | 142% | 142% | 109% | 131% | 111% |
| E | 14.3% | 110% | 110% | 105% | 106% | 115% |
| F | 14.3% | 121% | 121% | 101% | 122% | 107% |
| G | 14.3% | 69% | 69% | 82% | 85% | 87% |

Table 7 groups the two main operators of the feller-buncher and the other operators that have operated the machine during the trial period. By reviewing the data in the previous tables, it is apparent that operators A and B exhibit similar levels for the KPIs measured in this study, and that these levels are lower than the levels achieved by the other operators throughout the study period.

Table 7. Comparison of main operators vs. other operators on RFT 9705 feller-buncher.

| ID | Total SMH | SMH (% of Total) | Trees /SMH | Trees/shift (10hr) | Utilization (%) | Trees /PMH | Average fuel consumption (L/hr) |
|---|---|---|---|---|---|---|---|
| **Main** | **1539.5** | **88.6%** | **137** | **1374** | **77.2** | **178** | **27.7** |
| Other | 198.5 | 11.4% | 288 | 2883 | 78.9 | 366 | 34.5 |

While utilization numbers are similar between the main operators and the other operators, there are large differences in productivity, with the other operators felling trees at more than double the rate of the main operators. The fuel consumption level for the other operators is also higher than that of the main operators.

The standard deviation is a measure of spread that can be used to make inferences pertaining to operator consistency. Values of the standard deviation according to operator, for the respective KPI, are displayed in Table 8.

Table 8. Standard deviation values for KPIs monitored among operators.

| ID | Shifts | Trees/ SMH | STDEV (Trees/ SMH) | Utilization (%) | STDEV Utilization (%) | Trees/ PMH | STDEV (Trees/ PMH) |
|---|---|---|---|---|---|---|---|
| **A** | **79** | **143.0** | **40.9** | **78.5** | **7.0** | **181.5** | **48.0** |
| **B** | **76** | **131.2** | **34.9** | **75.7** | **10.0** | **171.7** | **34.4** |
| C | 6 | 330.8 | 60.2 | 80.5 | 8.6 | 408.3 | 40.7 |
| D | 5 | 326.8 | 76.2 | 84.8 | 8.6 | 383.9 | 71.4 |
| E | 4 | 256.5 | 23.5 | 81.2 | 3.1 | 316.8 | 38.3 |
| F | 3 | 283.9 | 58.4 | 78.0 | 7.8 | 361.9 | 43.5 |
| G | 3 | 161.2 | 44.0 | 63.6 | 3.3 | 254.7 | 76.2 |

Based on sample size alone, it would be expected that those operators with more replicates in this study (shifts), would have lower values for standard deviation than the other operators. One must also consider that this may not be the case because the regularly scheduled operators are more likely to be operating the machine when it experiences downtime due to mechanical issues, supervisor visits, or scheduled maintenance, and equipment moves. According to the data in Table 8, operator E was very consistent over the 4 shifts that this operator was on the machine, with a low standard deviation for all 3 KPIs. The standard deviation for percent utilization for the two main operators appears to be somewhat high, but given their time on the machine those standard deviation levels might be more reflective of the actual levels of downtime that operators regularly experience during their shift.

Table 9 presents the productivity estimates that would be expected of these employees from the data collected by the FPDat. The number of trees per 10 hour shift is what the operator could be expected to fell on average, per shift. This value is accompanied by the standard deviation for trees cut in a shift, as well as the standard error of the mean. Using the standard error of the mean and a desired confidence level, upper and lower confidence limits can be generated. At a 95% confidence level, upper and lower confidence limits are ± 1.96 times the value of the standard error of the mean.

Table 9. Standard deviation, standard error and confidence limits for trees cut per 10 hour shift among operators.

| ID | Trees/10hr shift | STDEV (Trees/10hr shift) | STD ERROR | LOWER C.L | UPPER C.L |
|---|---|---|---|---|---|
| **A** | **1430** | **409** | **46** | **1340** | **1521** |
| **B** | **1312** | **349** | **40** | **1233** | **1390** |
| C | 3308 | 602 | 246 | 2827 | 3790 |
| D | 3268 | 762 | 341 | 2599 | 3936 |
| E | 2565 | 235 | 118 | 2334 | 2795 |
| F | 2839 | 584 | 337 | 2178 | 3500 |
| G | 1612 | 440 | 254 | 1114 | 2109 |

The standard error is understandably much smaller for those operators who have a higher number of replicates, because data that exist as part of a larger sample size is more likely to establish a mean that would have a higher tendency to be more closely replicated among repeated measures than data with fewer replicates. Accordingly, operators A and B have low values for this parameter because they have significantly more replicates than other operators. With 95% confidence, it can be expected that repeated measures of this trial would result in an operators mean production level for trees felled in a shift to fall between the lower and upper confidence levels for that respective operator as presented in Table 9. Figure 6 provides a column chart displaying tree counts from Table 9 according to operator, with error bars representing the confidence intervals. Figure 7 features fuel consumption per engine hour according to trees cut per PMH for each operator over the study period.

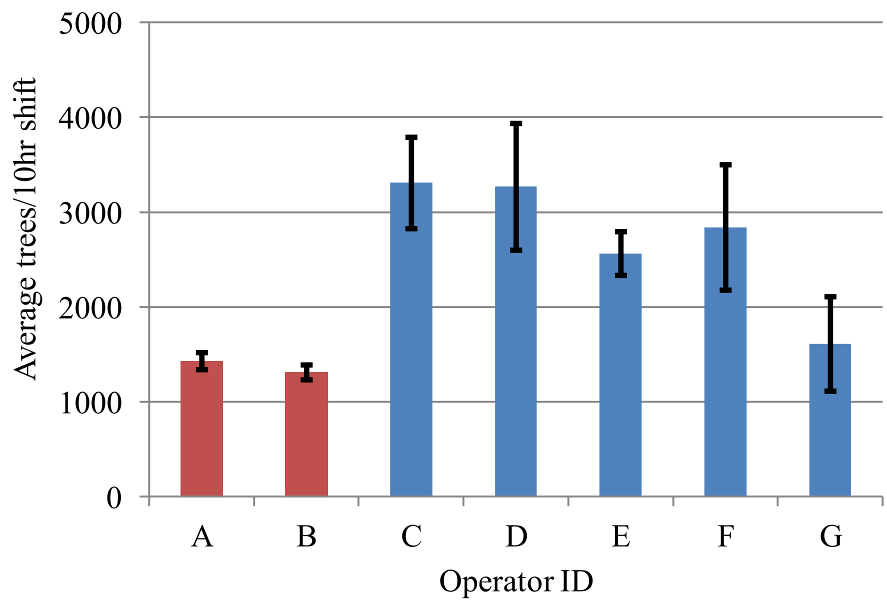



Figure 6. Mean production levels for trees felled per 10 hour shift according to operator.

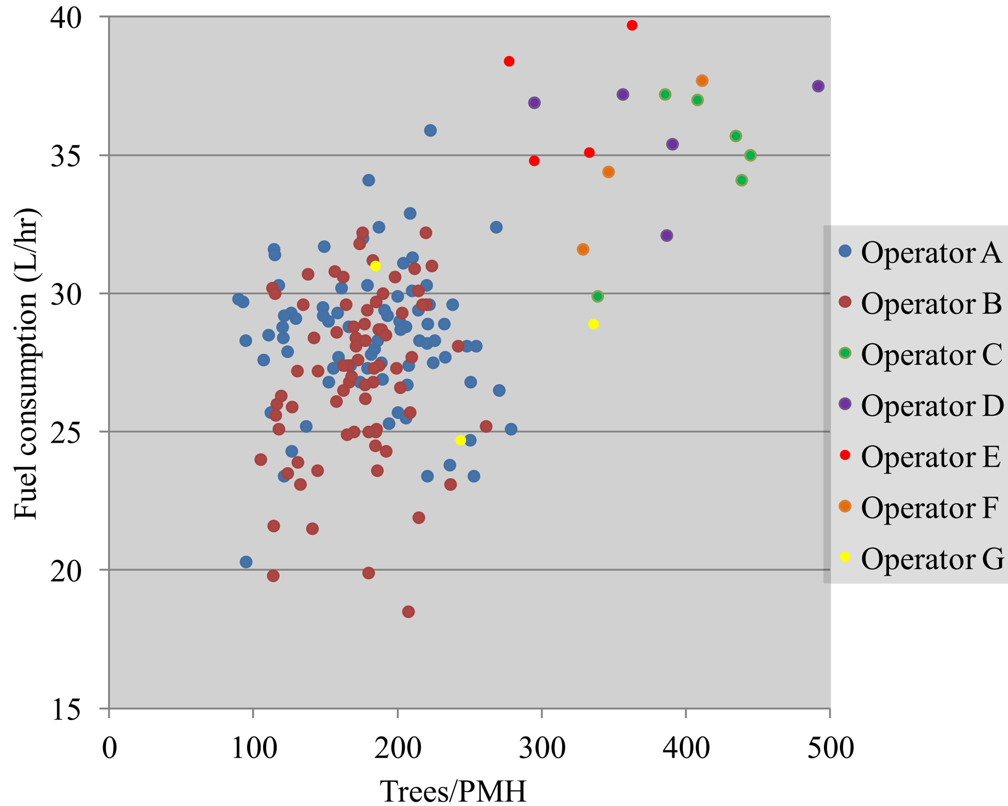



Figure 7. Fuel consumption vs. productivity according to operator.

Figure 7 shows that on a shift-by-shift basis, when the machine is operated to perform at higher levels of production, more fuel is consumed. While this is understandable because the hydraulics are being used to a higher extent as production increases, producing at double the rate per PMH does not double fuel consumption per engine hour. Accordingly, the average cost of fuel in $/tree decreases as machine production increases.

## 3.2. ANOVA

A two-way ANOVA compares the mean differences between groups that have been split into two dependent variables, called factors. The purpose of the ANOVA is to determine if there is an interaction between the two factors as they relate to the dependent variable (Laerd Statistics 2013). The dependent variable may also be referred to as the response variable. Using the same raw data that were used to generate the tables in section 3.1., data were isolated to include only that which pertained to the performance of operators A and B. Using these data, which included the operator ID, shift, and number of trees cut in that shift, a meaningful analysis could be completed to examine which of the two factors, if any; between operator and shift, or an interaction of the two factors; was responsible for a significant difference in productivity. The response variable used for this analysis was trees cut per SMH. The ANOVA provides an analysis of variance for the two factors being examined: the operator and shift. Each of these factors are fixed factors and have two levels as specified in Table 10. The confidence level of this ANOVA is 95% ($\alpha=0.05$).

Table 10. Factors and levels used for two-way ANOVA.

| Factor | Fixed/Random | Number of Levels | Level 1 | Level 2 |
|---|---|---|---|---|
| Operator | Fixed | 2 | Operator A | Operator B |
| Shift | Fixed | 2 | Day shift | Night shift |

The linear model for this ANOVA is as follows:

$$Y_{ijk} = \mu + A_i + B_j + AB_{ij} + \varepsilon_{(ij)k} \qquad \text{Equation [5]}$$

where:

$Y_{ijk}$ = the measured response of the $k^{th}$ replicate of the $j^{th}$ level of factor B with the $i^{th}$ level of factor A.

$\mu$ = the overall mean

$A_i$ = the fixed effect of the $i^{th}$ of 2 levels of factor A (operator)

$B_j$ = the fixed effect of the $j^{th}$ of 2 levels of factor B (shift)

$AB_{ij}$ = the fixed effect of the $i^{th}$ level of factor A with the $j^{th}$ level of factor B

$\varepsilon_{(ij)k}$ = the random effects of the $k^{th}$ of replicates in the $ij^{th}$ treatment combination. The $\varepsilon_{(ij)k}$ are assumed to be IIDN $(0, \sigma^2)$

In order to determine that the two-way ANOVA was the appropriate statistical test for this analysis, six assumptions were met. These assumptions are provided in Table 11, and are accompanied by the rationale for the conclusion that the assumption was met by the data set. By ensuring the assumptions were met, a valid result for the two-way ANOVA could be achieved (Laerd Statistics 2013).

Table 11. Assumptions and validation for ANOVA data.

| Assumption* # | Description | Met? (Y/N) | Rationale |
|---|---|---|---|
| 1 | Dependent variable should be measured at continuous level (ratio or interval variable). | Y | Number of trees cut per SMH is ratio data. |
| 2 | Two independent variables should each consist of two or more independent, categorical levels. | Y | Operator: 2 independent, categorical groups (Operator A, Operator B); Shift: 2 independent, categorical groups (Day shift, Night shift). |
| 3 | Data should exhibit independence of observations. | Y | No relationship between observations in each group, or between the groups themselves. Both factors mutually exclusive. |
| 4 | There should be no significant outliers. | Y | No outliers present in data used for ANOVA. |
| 5 | Dependent variable should be approximately normally distributed for each combination of the groups of the two independent variables. | Y | Data approximately normally distributed for each combination of the two factors. Sufficient number of replicates for each interaction. |
| 6 | Data should have homogeneity of variances for each combination of the groups of the two independent variables. | Y | Homogeneity of variances exists in this dataset. Verified using Levene's test for homogeneity of variances. |

*Source: Laerd Statistics 2013

Using Levene's test on the input data provided a significance level of .426. Because this result is higher than the critical significance level of 0.05, there is no significant difference in error variances at the 95% probability level. Accordingly, each combination of groups of the two independent variables exhibit homogeneity of variances to pass criterion 6 of Table 11. Table 12 displays the results of Levene's test.

Table 12. Results of Levene's test of equality of error variances.

Dependent Variable: TreesPerSMH

| F | df1 | df2 | Sig. |
|---|---|---|---|
| .934 | 3 | 151 | .426 |

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept + Operator + Shift + Operator * Shift

Tables 13 and 14 display the distribution of shifts on the machine throughout the study period. Each operator had over 30 replicates for each day and night shift. This represents a statistically valid sample size for this study. Data from a total of 155 shifts were analyzed for the ANOVA. These data represent 1539.5 scheduled machine hours for the feller-buncher.

Table 13. Distribution of replicates for factors over 155 shifts studied.

| | | Value Label | N |
|---|---|---|---|
| Operator | 1.00 | A | 79 |
| | 2.00 | B | 76 |
| Shift | 1.00 | Day | 81 |
| | 2.00 | Night | 74 |

Table 14. Descriptive statistics and number of replicates for between-factor variables.

Dependent Variable: TreesPerSMH

| Operator | Shift | Mean | Std. Deviation | N |
|---|---|---|---|---|
| A | Day | 148.0981 | 40.77355 | 36 |
| | Night | 138.7857 | 41.05661 | 43 |
| | Total | 143.0293 | 40.93198 | 79 |
| B | Day | 132.3000 | 37.11881 | 45 |
| | Night | 129.5071 | 32.00153 | 31 |
| | Total | 131.1608 | 34.92651 | 76 |
| Total | Day | 139.3214 | 39.33859 | 81 |
| | Night | 134.8987 | 37.57565 | 74 |
| | Total | 137.2099 | 38.44622 | 155 |

The null hypothesis for this ANOVA was that there would be no significant difference in the number of trees cut per SMH according to the operator, shift, or the interaction between operator and shift. Because the significance level used in the test is 95%, the significance (Sig.) level must be less than 0.05 in order to reject the null hypothesis for that attribute. The calculated significance levels for this ANOVA are presented in Table 15.

Table 15. Tests of between-subjects effects with significance levels.

Dependent Variable: TreesPerSMH

| Source | Type III Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|
| Corrected Model | 7298.809[a] | 3 | 2432.936 | 1.667 | .176 |
| Intercept | 2853290.178 | 1 | 2853290.178 | 1955.458 | .000 |
| Operator | 5959.763 | 1 | 5959.763 | 4.084 | .045 |
| Shift | 1388.806 | 1 | 1388.806 | .952 | .331 |
| Operator * Shift | 402.836 | 1 | 402.836 | .276 | .600 |
| Error | 220330.402 | 151 | 1459.142 | | |
| Total | 3145746.099 | 155 | | | |
| Corrected Total | 227629.211 | 154 | | | |

a. R Squared = .032 (Adjusted R Squared = .013)

Using the value of 0.05 to compare to the significance values displayed for the factors in Table 15 determines whether any of these factors is significant in determining productivity of the feller-buncher. Because the 'Operator' factor has a significance value of 0.045, there is a significant difference in productivity between operators A and B. Therefore, the null hypothesis that there is no significant difference between operators is rejected. This is the only null hypothesis that is rejected, as the significance levels for the shift factor and the operator-shift interaction are higher than 0.05, meaning these parameters did not significantly affect machine productivity in this study.

# 4. DISCUSSION

The results presented have a number of implications for each of the parties involved in the development and implementation of this technology. A major outcome of the data collected over the study period is the establishment of a utilization rate for the RFT 9705 feller-buncher. The utilization rate for the machine over the 5-month study period was 77.4%. These data are important because they are experimental data, which can be used in machine costing models and rate models in lieu of expected utilization rates. Having the actual utilization rate adds a higher degree of reliability to models attempting to predict costs based on estimated data. With further data collection relating to scaled volume of the timber harvested, productivity can be easily determined. These data would also be imperative to improving the certainty of machine and rate models and provide an accurate cost for the felling phase of a harvesting operation. Together with fuel consumption data, these variables add a level of legitimacy that is often uncommon in forest operations.

The descriptive statistics presented demonstrate vast differences in the feller-buncher's production levels according to the operator of the machine. The two regularly scheduled operators exhibited a significant difference in productivity when compared using the ANOVA test. These two operators, operators A and B, are on the low-productivity end according to the descriptive statistics which offer a comparison to some of the other operators within the company. While operators A and B exhibit similar levels of productivity, there is still a significant difference between operator A and B, with operator A having a higher productivity, by an average of 118 trees per shift. There was no significant difference between day shift and night shift. While there is poorer visibility on night shift as compared to day shift, operators will generally cut more sensitive areas with rougher ground on day shift so as to reduce the likelihood of operating in potentially hazardous conditions on night shift. This habit can explain the result that there is no significant difference in productivity between day and night shift, as the more adverse ground conditions operated in on day shift seem to offset the effect of poor visibility on night shift.

This section will discuss the significance of the results obtained through this study. Of particular importance is the significance to a supervisor. A system review will be provided for the FPDat platform, outlining the strengths and weaknesses of the technology. In addition, considerations will be made with intent to provide a greater understanding of the responsibilities of the various parties involved in the implementation of advanced technologies in forest operations. These recommendations are made from experience with this project in order to make the implementation and use of these technologies more successful in future applications.

## 4.1. SIGNIFICANCE TO A SUPERVISOR

The reports generated through FPTrak from the data collected by the FPDat allow the supervisor to have accurate information pertaining to operator performance in their operation. This gives the supervisor the ability to identify the work habits of their operators. Having an in-depth knowledge of operator performance gives the supervisor a greater capacity to make operational decisions with a higher degree of certainty. The speed at which a certain feller-buncher operator cuts is important for a supervisor to understand in providing timing estimates in an operational setting where all other forest machines rely on feller-buncher productivity to remain productive.

For example, in an operational setting where the feller-buncher must quickly down wood in order to stay ahead of the remainder of the operation, the supervisor would not want to rely solely on lower-producing operators to avoid creating a bottleneck in the productivity of their operation. Additionally, a supervisor would be interested in making sure that the highest-producing operators are assigned to a machine capable of the highest levels of production as compared to other machines. In this regard, operators who are more productive should be assigned to the larger feller-bunchers equipped with a more powerful saw head with a higher accumulating ability. Some of the operators in this study, notably operators C, E, and F regularly ran a Tigercat 845C feller-buncher, a less-powerful machine equipped with a smaller felling head as compared to the large Tigercat 870C which was assigned to operators A and B.

Because operators A and B are on the lower-productivity end of the operators monitored by the FPDat over the study period, these operators would be most ideal for operating in areas where their slower operating habits would not hinder subsequent operations. Accordingly, it may be more feasible for this machine to be assigned to fell smaller-sized harvest compartments well in advance of a chipping operation moving into the compartment. Another possible application for this machine with these operators is in roadline clearing applications for road construction, where even a lower level of productivity is enough to stay ahead of a backhoe during road construction. A supervisor should be wary of this information and look for ways to match crews in a manner that maximizes the productivity of the business as a whole. In keeping mindful to this, there are many considerations for management to make, aside from operator productivity, when assigning crews to a harvest area.

Where possible, scheduling of overtime in accordance with production capabilities would also be important to an operations supervisor, whose constant responsibility is to be mindful of the costs of their operation and how to maximize productivity at minimal cost. If operators must be relied upon for overtime work, they are paid at a rate of 1.5 times their regular hourly rate. Because operator wage is one of the most significant components of a machine's hourly operating cost, the cost of felling in $/m$^3$ is higher for any given operator when they are on overtime. Accordingly, productivity of the operator is important to reducing felling costs. With the data presented in the results section, it becomes apparent that the more productive operators would be the ideal candidates for overtime work, and their productivity is worth the added cost, even at 1.5 times the rate of pay when compared to the productivity of operators A and B on regularly scheduled time.

### 4.1.1. The Dilemma

The tables presented in the Results section demonstrate that the regularly scheduled operators on the feller-buncher are less productive than the other operators that have operated the machine. In this particular case, the feller-buncher which is the focus of this study is one of the newest in the fleet of feller-bunchers owned by the company. The regularly scheduled operators on the machine are the two most senior feller-buncher operators within the company, which is a full-book union operation. When the feller-buncher was purchased, the three most senior operators were scheduled to run the machine on a triple shift (day shift, night shift, split shift). Before the trial began when the FPDat was programmed with the tree count feature, one of the operators had retired, leaving the remaining two operators to run the machine on a double shift (each operator would alternate between day shift and night shift on a weekly basis).

The statistics presented in the Results tables do not tell the entire story. Based on the information presented in the tables, one might draw conclusions about the quality of the two main operators in the study by comparing them with the limited statistics from other operators. While the two main operators of the feller-buncher cut less wood per unit time than other operators who had run the machine over the trial period, it would be a mistake to call the operators poor operators based on this information alone. Effective operators are careful operators who are environmentally cautious and do not operate the equipment in such a manner as to cause excessive wear or damage. In this regard, maintenance costs and environmental performance of operators should be incorporated in productivity studies. The two main operators who ran this feller-buncher were selected by the general manager of the company to run this machine because they are highly regarded, responsible and experienced operators, who are easy on equipment and always perform regular maintenance on the machine.

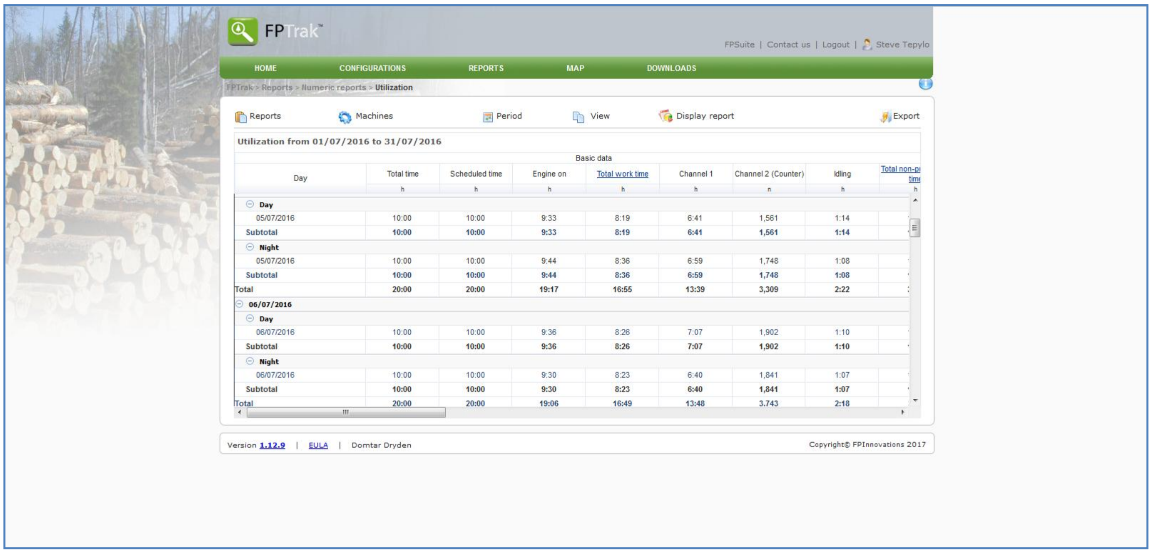
With regard to productivity and operating costs, it is clear that the higher the productivity of the machine, the lower the operating costs in $\$/m^3$ of wood cut. Accordingly, operators who cut more wood per unit of time are able to generate more profit for the company, even after the costs of additional fuel and minor repairs that are required as the result of increased demand on the machine. Thus, it is more feasible to offer overtime shifts as a reward to operators who are able to cut the most wood. This practice would be in violation of the collective agreement under which the employees of this company are managed. The collective agreement dictates that overtime shifts must be offered to members in order according to their seniority. Accordingly, it is difficult to use overtime as an incentive to reward junior unionized employees who are high-producers under a collective agreement with such a rule.

## 4.2. SYSTEM REVIEW

### 4.2.1. User's Review of FPTrak

The FPTrak interface allows the user to effectively generate reports to display the intended information regarding machine performance. By toggling through the report menus, the user is able to select the machine(s) for which the data will be displayed, select the time period for which data is shown, group the data according to a number of characteristics (ex. day, shift, machine, operator, etc.), and select to view work ratios such as utilization. Productivity and fuel consumption data are also available for viewing, as well as any stop codes that operators may enter when the machine is not performing productive work. Data can be displayed in and out of scheduled time if so desired by the viewer. The degree to which the user is able to select the data to be used in the report is important, because it allows for generation of reports that provide meaningful information to the viewer.

The setup on the FPTrak website could be improved to become more user-friendly. Figure 8 displays the screen on FPTrak once a report is generated. In order to generate a report, the "Report" button must be selected from the menu contained within the green bar. After selecting this, there are 4 options as to types of reports which can be displayed. The report shown in Figure 8 is a utilization report. After the report type is selected, the user must go through an additional 5 menus in order to create the desired report containing the selected information. While the level of complexity of the reports that the user can generate is indicative that there would understandably be a large number of options, the use of 6 drop-menus to generate a report is unnecessary. Additionally, once generated, the report is only displayed in the center of the screen and must be scrolled through in 2 directions (up/down and left/right) in order to view the contents of the entire report. Only about half of the screen area is utilized when the report is displayed, with the remainder of the screen area being blank. Within the report area, the column width is too wide and cannot be adjusted, so that only a few parameters are visible without scrolling, and that the vast majority of the report area is blank space. A suggested improvement to the aforementioned setup would see the report occupy a greater area of the screen. The left portion of the screen could be used to contain one large menu in which the contents of the drop menus could be listed and boxes checked to allow the user to view the parameters they desire.




| | Basic data | | | | | | |
|---|---|---|---|---|---|---|---|
| Day | Total time | Scheduled time | Engine on | Total work time | Channel 1 | Channel 2 (Counter) | Idling |
| | h | h | h | h | h | n | h |
| Day | | | | | | | |
| 05/07/2016 | 10:00 | 10:00 | 9:33 | 8:19 | 6:41 | 1,561 | 1:14 |
| Subtotal | 10:00 | 10:00 | 9:33 | 8:19 | 6:41 | 1,561 | 1:14 |
| Night | | | | | | | |
| 05/07/2016 | 10:00 | 10:00 | 9:44 | 8:36 | 6:59 | 1,748 | 1:08 |
| Subtotal | 10:00 | 10:00 | 9:44 | 8:36 | 6:59 | 1,748 | 1:08 |
| Total | 20:00 | 20:00 | 19:17 | 16:55 | 13:39 | 3,309 | 2:22 |
| 06/07/2016 | | | | | | | |
| Day | | | | | | | |
| 06/07/2016 | 10:00 | 10:00 | 9:36 | 8:26 | 7:07 | 1,902 | 1:10 |
| Subtotal | 10:00 | 10:00 | 9:36 | 8:26 | 7:07 | 1,902 | 1:10 |
| Night | | | | | | | |
| 06/07/2016 | 10:00 | 10:00 | 9:30 | 8:23 | 6:40 | 1,841 | 1:07 |
| Subtotal | 10:00 | 10:00 | 9:30 | 8:23 | 6:40 | 1,841 | 1:07 |
| Total | 20:00 | 20:00 | 19:06 | 16:49 | 13:48 | 3.743 | 2:18 |

Figure 8. FPTrak utilization report.

Another aspect of the FPTrak program is the mapping interface. When the 'Map' option is selected from the green menu in Figure 8, the map is generated in a new internet window. The map is able to show the most recently updated position of the machine, as well as its previous tracks (Figure 9). This is a useful tool for supervisors who are unable to check progress daily within the operating area and allows supervisors to see progress and determine approximate timelines for completion of harvest in an area. This display would also allow the supervisor to see if one of their roadlines has been cut, when more roadline within a block needs to be located, and to determine rough estimates of wood inventories to aid in operational decisions.

While the map interface does have some basic tools that would allow the user to measure distance and import shapefiles, and is user friendly with respect to these features, there are few tools available and this program cannot be used as a substitute for a reliable mapping program because it does not allow for a high degree of flexibility and customization required to generate high-quality maps of operating areas. Another deficiency of the mapping interface is the poor responsiveness and slow loading time associated with making adjustments, such as increasing or decreasing zoom levels, which can be done rapidly using many open-source online mapping interfaces which are more customizable and detailed, even allowing the user to display imagery with minimal loading delays.

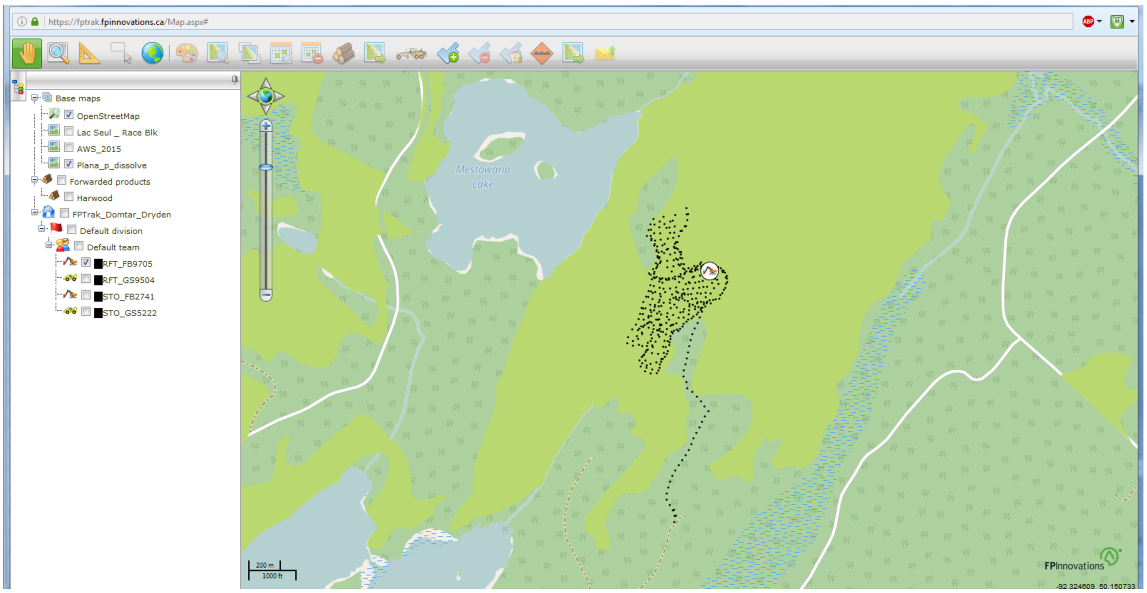



Figure 9. Map interface in FPTrak.

## 4.2.2. User's Review of FPDat

The general attitudes of machine operators towards the installation of the FPDat in the feller-buncher were poor. One of the regularly scheduled operators on the machine refused to use the FPDat system because this operator felt it was an unnecessary device within the machine, which was also equipped with another GPS unit. The main operator feedback pertaining to their preference not to use the FPDat mainly related to deficiencies they identified in its design features, which included but were not limited to;

poor responsiveness of the touch screen, placement within the machine, size of the screen and inability of the FPDat unit to provide the operator with meaningful data. The lack of meaningful data displayed on the screen is reflective of communication, collaboration, and follow-through complications with the SFL holder, specifically in the provision of updating the FPDat to display detailed maps. The FPDat computer must have maps and settings uploaded to it by connecting a USB drive to the unit and copying the data contained on the USB. Due to the limited memory space on the FPDat unit, it was only able to display a map of one operating area at a time. Unless the maps were changed, the operator would not be able to see anything but a blank screen when beginning work in a new operating area. This was perhaps the most significant factor that limited the effectiveness of using the FPDat as a navigational tool, which was the primary reason an operator would find it useful. The modification of the FPDat to include a larger memory capacity is a recommendation that will increase its utility for use in forest operations, which are fast paced and dynamic. Tablets are fairly inexpensive and robust, with a more responsive touch screen and significantly higher memory capacities than the FPDat system's current configuration.

## 4.3. EFFECTIVE IMPLEMENTATION OF A MONITORING PROGRAM

In order to successfully implement equipment monitoring technology in a mechanized harvesting operation, it must be demonstrated that cost savings are realized as a result of investing in and using the technology. There are 4 distinct roles to be played in the successful implementation, and these roles are fulfilled by the technology developer, the company, the contractor, and the operator. Each must play their part in putting forth an effort to adapt and accept change in order to remain innovative. A major interaction is that between the company and the contractor. If a forest products company wants to implement advanced technology such as OBCs into harvesting operations, they must be willing to work hand-in-hand with the contractor.

### 4.3.1. The Technology Developer

The technology developer has the ultimate responsibility of ensuring that their product meets the needs of the customer. This begins in the development phase, which may take years. The technology should be developed to fulfill a need in forest operations. Since increased integration and desire for optimization are current objectives in forest operations, technology developers must continually develop their products in order to remain competitive in the marketplace. In order for the product to meet the needs of the customer, the product must be attractive to, or provide benefits to those using it. In this particular case, the focus on developing the technology should be primarily on the machine operators, who will be the ultimate users of the technology. All efforts should be taken to market the technology as an operator tool, as opposed to a tracking tool for management. By making the technology operator-friendly, the perception of the device as primarily a monitoring tool will be reduced as operators realize how the technology applies to them, by helping them work more safely and efficiently. In this respect, the ability to perform machine diagnostics and offer a user-friendly navigational interface is of utmost importance in order to appeal to operators.

4.3.2. The Company

The forest products company wishing to implement advanced technologies in their contractor operations must go above and beyond to ensure that their involvement in the effort does not cause unnecessary inconvenience for the contractor. In this regard, opportunities for cost savings must be identified and an agreement must be made with the contractor as to how these benefits will be shared. Gains in efficiency and subsequent reductions in cost should be shared equally between the two parties so that there is a joint incentive for successful implementation. The company must understand that benefits must exist for both the management of the contractor as well as for the operator. A training program should be developed that prepares both operators and management to work with the technology and that time and productivity lost for the installation, training and maintenance for the technology is remunerated to the contractor.

If the company is to receive data collected from the OBC, they must put forth an effort in ensuring that the settings within the data hosting service are updated when required. In addition, the company should be in contact with the contractor to ensure that the operating areas and shift scheduling of the machine is maintained in the data hosting service. In order to not be intrusive, excessive involvement with the machine in its operating state should be avoided so that results obtained are truly reflective of the actual operating conditions in which the machine is working. Delays and incurred costs should be borne by the company to ensure full participation and understanding of the complexity of the task.

4.3.3. The Contractor

The contractor has the role of encouraging operators to use the technology to its full potential. In this regard they also have a role to play in ensuring that their operators are comfortable with using the technology. The management must emphasize to the operators that the technology does not exist to force operators to work harder or produce at higher levels. This being said, the development of an incentive program for operators would be helpful in creating an atmosphere that encourages the use of the technology to better manage production and work habits. Machine utilization would be an ideal KPI because it does not discriminate against lower-producing operators who might be otherwise discouraged from using the equipment. Machine utilization is an indicator of operator diligence, rather than ability.

The contractor should be willing to share their experiences using the technology with both the company and the technology developer. Feedback based on use in actual field operations is valuable for both the company and technology developer. By effectively communicating challenges and potentials, the contractor provides these two parties with the ability to improve the technology or modify the monitoring and training programs so that OBCs can provide the highest level of utility to the operator and be used to effectively generate key information for the contractor.

### 4.3.4. The Operator

The operator must be willing to use the technology and enter required inputs so that data can be properly recorded. This shows transparency on behalf of the operator, who is essentially allowing the management to have access to the detailed timeline of their daily activities. While this may seem like an intrusion to the operator's privacy, the operator must understand that all parties can benefit from acquiring high-quality data from logging equipment. Benefits to the operator can include a bonus from effectively using the OBC to increase production, increased confidence attributable to high-quality maps and imagery that can be displayed on the OBC, and the potential for certain OBCs to provide machine diagnostics. The operator is the most important link to convey information that can be used to further develop the technology.

## 4.4. FURTHER STUDY OPPORTUNITIES

In order to effectively and accurately attribute the effects of operators on the felling costs of an operation, more detailed information is needed. While the number of trees harvested per SMH is a preliminary indicator or operator productivity, volume estimates are better indicators, because the number of trees cut does not provide any accurate insight into the actual volume harvested. This study was designed to capture a more complete and integrated dataset, including the incorporation of scaled bundles in the study.  Unfortunately, due to some of the challenges outlined in section 4.3, this was not accomplished, somewhat limiting the effectiveness and comprehensiveness of this study.

In order to truly understand the machine costs that result from operator habits, there are a number of additional considerations. These include fuel consumption, wear on equipment and damage to the machine. Downtime is detrimental to any harvesting operation, and effects of downtime can also be quantifiable. An operator is able to have an impact on reducing downtime by operating the machine safely and performing regular maintenance. It is certainly understandable that operating the machine at higher speeds is necessary to produce at higher levels. A further study could also examine the effects of increased levels of productivity on a machine costing model, based on the effects of a higher degree of repairs needed as a result of the machine being forced to work harder. Attempting to determine an optimal performance threshold for machine productivity, availability and longevity would prove valuable in this regard. This could be accomplished through long-term, careful accounting of parts and downtime.

## 4.5. APPLICABILITY

It should be noted that while the statistics and findings generated through this study offer an operations supervisor a basic estimation of feller-buncher operator productivity, a degree of individual knowledge must be used in addition to the knowledge attained through this study to make these results most applicable to individual operations.

While these data were produced strictly for one feller-buncher used as part of a conventional full-tree chipping operation, the results attained from this study are not limited to this type of operation. These results can be applied to gain an understanding of production levels for any harvesting operation relying on feller-bunchers. Additionally, variability in operator work habits is a reality that will exist in any mechanized harvesting operation. When studying a group of machine operators with controlled variables, some operators will be able to produce at higher levels. In this regard, the results of this study are applicable to gain an understanding in forest operations that extends beyond the individual operation from which these results were obtained. A higher amount of repetitions of operators and geographic extent would make results more transferrable, reflecting a wider variety of operating conditions.

# 5. CONCLUSION

These results are a showcase as to what can be accomplished using this new technology with the objective of increasing efficiency in harvest operations through provision of meaningful data. This study determined that the utilization of the feller-buncher during a 5-month period was 77.4%. Additionally, the data collected by the FPDat OBC and made available through the FPTrak data hosting service were used to generate and display KPIs relating to operator performance for the 7 operators who had run the machine during the study period, and identify operating habits of the individual operators. Using a two-way ANOVA comparing the productivity between 2 operators on day and night shift, it was determined that a significant difference ($\alpha = 0.05$) existed in the machine's productivity according to the operator of the machine, but there was no significant difference in the response variable between day and night shift, or the operator-shift interaction.

Experience with using the FPDat system for this study allowed for the provision of insight into the features of this technology that make it a useful tool for decision making in the harvest block. Additionally, areas where the system should be improved to more effectively meet operator needs were identified. Collaboration between parties involved in this project was poor and significantly limited the comprehensiveness of the data that could be produced as a result of using the FPDat OBC. Additionally, the poor degree of collaboration resulted in the operators not finding the technology useful, because they were not properly trained on how to use the system, and could rarely rely on the system to display harvest block maps and detailed imagery. A reasonable potential exists for the use of the FPDat in forest operations, provided there is a genuine willingness of all parties to develop and maintain an effective program for the use of this technology. Additionally, the technology developer should be continually refining their product based on operational observations to effectively meet the needs of the customer. In this regard, using modern hardware such as tablets as part of the system is advisable.

The factors that influence feller-buncher productivity are inter-related. The most effective utilization of a feller-buncher comes as a result of an experienced operator working on a machine that is well-maintained and has features that are suitable for the conditions in which the machine is operating. By understanding operator factors that contribute to the productive use of a feller-buncher, forest operations supervisors can be better prepared to manage their operations effectively. An effective OBC implementation in a mechanized harvesting operation would increase efficiency by providing the forest products company, the contractor staff, and the machine operator with the ability to make more informed operational decisions. This will allow these parties to increase operational efficiency, resulting in savings of cost, time, and waste.

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# APPENDICES

# APPENDIX I: DATASET FOR DESCRIPTIVE STATISTICS

| Op. ID | Op. Code | Day | Shift | SMH | Engine on | Total work time | Tree Count | Idling | Utilization (%) | Idling / Engine on | Engine on / Schedule d time | Fuel consump tion (L) | Fuel consumpt ion / Engine on (L/hr) | Trees /SMH |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A | 1 | 6-Jun-16 | 1 | 10.0 | 9:22 | 8:06 | 1,470 | 1:16 | 81 | 13.6 | 93.7 | 260.2 | 27.8 | 147.0 |
| A | 1 | 7-Jun-16 | 1 | 10.0 | 9:27 | 8:17 | 1,659 | 1:09 | 82.9 | 12.2 | 94.4 | 243.1 | 25.7 | 165.9 |
| A | 1 | 8-Jun-16 | 1 | 10.0 | 9:17 | 7:07 | 1,568 | 2:10 | 71.1 | 23.4 | 92.8 | 217.5 | 23.4 | 156.8 |
| A | 1 | 9-Jun-16 | 1 | 10.0 | 9:25 | 8:12 | 1,763 | 1:13 | 82 | 13 | 94.2 | 266.6 | 28.3 | 176.3 |
| A | 1 | 13-Jun-16 | 2 | 10.0 | 8:46 | 7:38 | 1,405 | 1:07 | 76.4 | 12.8 | 87.6 | 245.6 | 28 | 140.5 |
| A | 1 | 14-Jun-16 | 2 | 8.0 | 6:11 | 5:31 | 1,109 | 0:41 | 68.9 | 10.9 | 77.3 | 179.5 | 29 | 138.6 |
| A | 1 | 15-Jun-16 | 2 | 10.0 | 9:07 | 8:12 | 1,912 | 0:55 | 82.1 | 10 | 91.2 | 252.1 | 27.7 | 191.2 |
| A | 1 | 16-Jun-16 | 2 | 10.0 | 9:02 | 8:08 | 1,744 | 0:54 | 81.4 | 9.9 | 90.4 | 265.7 | 29.4 | 174.4 |
| A | 1 | 20-Jun-16 | 1 | 10.0 | 9:14 | 7:56 | 1,475 | 1:18 | 79.3 | 14.1 | 92.3 | 261.4 | 28.3 | 147.5 |
| A | 1 | 21-Jun-16 | 1 | 10.0 | 9:06 | 8:11 | 1,802 | 0:56 | 81.8 | 10.2 | 91 | 256.4 | 28.2 | 180.2 |
| A | 1 | 22-Jun-16 | 1 | 10.0 | 8:18 | 6:46 | 1,694 | 1:31 | 67.7 | 18.4 | 83 | 205.3 | 24.7 | 169.4 |
| A | 1 | 23-Jun-16 | 1 | 10.0 | 9:32 | 7:25 | 1,873 | 2:07 | 74.1 | 22.2 | 95.3 | 222.8 | 23.4 | 187.3 |
| A | 1 | 27-Jun-16 | 2 | 10.0 | 9:10 | 7:18 | 1,721 | 1:53 | 72.9 | 20.5 | 91.7 | 218 | 23.8 | 172.1 |
| A | 1 | 28-Jun-16 | 2 | 10.0 | 9:08 | 8:00 | 1,543 | 1:07 | 80.0 | 12.3 | 91.3 | 266.3 | 29.2 | 154.3 |
| A | 1 | 29-Jun-16 | 2 | 10.0 | 9:15 | 8:29 | 2,157 | 0:46 | 84.8 | 8.3 | 92.5 | 259.6 | 28.1 | 215.7 |
| A | 1 | 30-Jun-16 | 2 | 10.0 | 9:03 | 7:50 | 2,184 | 1:13 | 78.4 | 13.4 | 90.6 | 227.7 | 25.1 | 218.4 |
| A | 1 | 4-Jul-16 | 1 | 10.0 | 9:09 | 7:35 | 1,899 | 1:35 | 75.8 | 17.2 | 91.5 | 245.0 | 26.8 | 189.9 |
| A | 1 | 5-Jul-16 | 1 | 10.0 | 9:33 | 8:19 | 1,561 | 1:14 | 83.2 | 13.0 | 95.6 | 274.1 | 28.7 | 156.1 |
| A | 1 | 6-Jul-16 | 1 | 10.0 | 9:36 | 8:26 | 1,902 | 1:10 | 84.3 | 12.2 | 96.0 | 271.8 | 28.3 | 190.2 |
| A | 1 | 7-Jul-16 | 1 | 10.0 | 9:10 | 8:12 | 1,702 | 0:58 | 82.0 | 10.6 | 91.7 | 251.2 | 27.4 | 170.2 |
| A | 1 | 11-Jul-16 | 2 | 10.0 | 8:39 | 7:27 | 1,333 | 1:12 | 74.5 | 13.9 | 86.5 | 262.4 | 30.3 | 133.3 |
| A | 1 | 12-Jul-16 | 2 | 10.0 | 9:29 | 8:18 | 1,842 | 1:11 | 83.0 | 12.5 | 94.8 | 280.7 | 29.6 | 184.2 |
| A | 1 | 13-Jul-16 | 2 | 10.0 | 9:21 | 8:00 | 1,794 | 1:22 | 79.9 | 14.6 | 93.6 | 257.3 | 27.5 | 179.4 |
| A | 1 | 14-Jul-16 | 2 | 10.0 | 9:41 | 7:36 | 1,561 | 2:06 | 75.9 | 21.7 | 96.9 | 247.6 | 25.5 | 156.1 |
| A | 1 | 18-Jul-16 | 1 | 10.0 | 9:29 | 7:57 | 1,382 | 1:32 | 79.5 | 16.1 | 94.8 | 253.8 | 26.8 | 138.2 |
| A | 1 | 19-Jul-16 | 1 | 10.0 | 9:47 | 8:38 | 1,389 | 1:09 | 86.3 | 11.7 | 97.8 | 295.5 | 30.2 | 138.9 |
| A | 1 | 20-Jul-16 | 1 | 10.0 | 9:11 | 8:22 | 1,595 | 0:49 | 83.6 | 9.0 | 91.9 | 270.4 | 29.4 | 159.5 |
| A | 1 | 21-Jul-16 | 1 | 10.0 | 9:31 | 9:01 | 1,801 | 0:30 | 90.1 | 5.2 | 95.1 | 284.4 | 29.9 | 180.1 |
| A | 1 | 3-Aug-16 | 1 | 10.0 | 9:33 | 8:24 | 1,848 | 1:09 | 84.0 | 12.0 | 95.5 | 289.5 | 30.3 | 184.8 |
| A | 1 | 4-Aug-16 | 1 | 10.0 | 8:38 | 7:41 | 1,579 | 0:57 | 76.8 | 11.1 | 86.4 | 248.4 | 28.8 | 157.9 |
| A | 1 | 5-Aug-16 | 1 | 10.0 | 9:25 | 8:00 | 2,160 | 1:25 | 79.9 | 15.1 | 94.1 | 249.3 | 26.5 | 216.0 |
| A | 1 | 8-Aug-16 | 2 | 10.0 | 7:56 | 7:00 | 1,318 | 0:56 | 69.9 | 11.8 | 79.3 | 217.8 | 27.5 | 131.8 |
| A | 1 | 9-Aug-16 | 2 | 10.0 | 9:10 | 7:42 | 1,491 | 1:28 | 76.9 | 16.1 | 91.7 | 231.9 | 25.3 | 149.1 |
| A | 1 | 10-Aug-16 | 2 | 10.0 | 8:24 | 7:12 | 1,204 | 1:12 | 72.0 | 14.3 | 84.0 | 230.2 | 27.4 | 120.4 |
| A | 1 | 11-Aug-16 | 2 | 10.0 | 8:38 | 7:39 | 1,270 | 0:59 | 76.5 | 11.3 | 86.3 | 248.2 | 28.8 | 127.0 |
| A | 1 | 12-Aug-16 | 2 | 10.0 | 9:03 | 7:59 | 1,981 | 1:04 | 79.9 | 11.8 | 90.6 | 254.8 | 28.1 | 198.1 |
| A | 1 | 15-Aug-16 | 1 | 10.0 | 8:59 | 8:16 | 1,826 | 0:43 | 82.7 | 8.0 | 89.9 | 259.5 | 28.9 | 182.6 |
| A | 1 | 18-Aug-16 | 1 | 10.0 | 8:27 | 7:41 | 1,215 | 0:46 | 76.8 | 9.0 | 84.5 | 247.2 | 29.3 | 121.5 |
| A | 1 | 22-Aug-16 | 2 | 10.0 | 9:19 | 7:43 | 1,460 | 1:37 | 77.1 | 17.3 | 93.2 | 251.2 | 26.9 | 146.0 |
| A | 1 | 23-Aug-16 | 2 | 10.0 | 9:15 | 8:24 | 1,475 | 0:51 | 83.9 | 9.2 | 92.4 | 295.5 | 32.0 | 147.5 |
| A | 1 | 24-Aug-16 | 2 | 10.0 | 9:22 | 8:51 | 1,860 | 0:32 | 88.5 | 5.6 | 93.7 | 293.2 | 31.3 | 186.0 |
| A | 1 | 25-Aug-16 | 2 | 10.0 | 9:17 | 8:06 | 1,232 | 1:11 | 81.0 | 12.7 | 92.8 | 248.3 | 26.8 | 123.2 |
| A | 1 | 6-Sep-16 | 2 | 10.0 | 6:42 | 6:03 | 961 | 0:39 | 60.5 | 9.7 | 67.0 | 185.2 | 27.7 | 96.1 |
| A | 1 | 7-Sep-16 | 2 | 10.0 | 9:19 | 7:38 | 921 | 1:41 | 76.4 | 18.0 | 93.1 | 264.7 | 28.4 | 92.1 |
| A | 1 | 8-Sep-16 | 2 | 10.0 | 8:36 | 6:37 | 837 | 1:58 | 66.2 | 22.9 | 85.9 | 208.5 | 24.3 | 83.7 |
| A | 1 | 9-Sep-16 | 2 | 10.0 | 9:31 | 8:55 | 1,124 | 0:36 | 89.2 | 6.2 | 95.2 | 278.8 | 29.3 | 112.4 |
| A | 1 | 13-Sep-16 | 1 | 10.0 | 9:36 | 8:00 | 988 | 1:36 | 80.0 | 16.7 | 96.0 | 267.8 | 27.9 | 98.8 |
| A | 1 | 16-Sep-16 | 1 | 10.0 | 9:37 | 8:29 | 1,263 | 1:08 | 84.8 | 11.8 | 96.2 | 304.5 | 31.7 | 126.3 |
| A | 1 | 19-Sep-16 | 2 | 10.0 | 9:26 | 7:41 | 1,551 | 1:45 | 76.8 | 18.5 | 94.3 | 271.0 | 28.7 | 155.1 |

| Op. ID | Op. Code | Day | Shift | SMH | Engine on | Total work time | Tree Count | Idling | Utilization (%) | Idling / Engine on | Engine on / Schedule d time | Fuel consump tion (L) | Fuel consumpt ion / Engine on (L/hr) | Trees /SMH |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| A | 1 | 20-Sep-16 | 2 | 10.0 | 8:12 | 7:00 | 1,628 | 1:12 | 70.1 | 14.7 | 82.1 | 237.3 | 28.9 | 162.8 |
| A | 1 | 21-Sep-16 | 2 | 10.0 | 9:18 | 8:31 | 2,028 | 0:47 | 85.2 | 8.5 | 93.1 | 275.0 | 29.6 | 202.8 |
| A | 1 | 22-Sep-16 | 2 | 10.0 | 10:00 | 9:00 | 1,889 | 1:00 | 90.0 | 10.0 | 100.0 | 301.4 | 30.1 | 188.9 |
| A | 1 | 23-Sep-16 | 2 | 10.0 | 8:58 | 8:04 | 1,645 | 0:54 | 80.7 | 10.0 | 89.7 | 278.7 | 31.1 | 164.5 |
| A | 1 | 26-Sep-16 | 1 | 10.0 | 9:12 | 8:20 | 2,235 | 0:52 | 83.3 | 9.4 | 92.0 | 297.8 | 32.4 | 223.5 |
| A | 1 | 27-Sep-16 | 1 | 10.0 | 9:25 | 7:28 | 1,541 | 1:57 | 74.6 | 20.7 | 94.2 | 251.4 | 26.7 | 154.1 |
| A | 1 | 28-Sep-16 | 1 | 10.0 | 8:57 | 8:06 | 1,687 | 0:51 | 80.9 | 9.6 | 89.5 | 294.3 | 32.9 | 168.7 |
| A | 1 | 29-Sep-16 | 1 | 10.0 | 9:22 | 8:28 | 1,523 | 0:53 | 84.7 | 9.5 | 93.6 | 319.3 | 34.1 | 152.3 |
| A | 1 | 30-Sep-16 | 1 | 10.0 | 8:31 | 7:50 | 1,743 | 0:41 | 78.3 | 8.0 | 85.1 | 305.3 | 35.9 | 174.3 |
| A | 1 | 3-Oct-16 | 2 | 10.0 | 9:31 | 8:28 | 1,581 | 1:04 | 84.6 | 11.1 | 95.2 | 308.5 | 32.4 | 158.1 |
| A | 1 | 4-Oct-16 | 2 | 10.0 | 9:45 | 9:08 | 1,387 | 0:37 | 91.3 | 6.3 | 97.5 | 282.4 | 29.0 | 138.7 |
| A | 1 | 5-Oct-16 | 2 | 10.0 | 9:07 | 7:20 | 1,312 | 1:47 | 73.3 | 19.6 | 91.2 | 248.7 | 27.3 | 131.2 |
| A | 1 | 6-Oct-16 | 2 | 10.0 | 9:15 | 7:27 | 1,157 | 1:48 | 74.5 | 19.4 | 92.5 | 252.9 | 27.3 | 115.7 |
| A | 1 | 7-Oct-16 | 2 | 10.0 | 9:13 | 8:07 | 983 | 1:06 | 81.1 | 12.0 | 92.2 | 268.8 | 29.2 | 98.3 |
| A | 1 | 12-Oct-16 | 1 | 10.0 | 9:38 | 8:09 | 1,208 | 1:29 | 81.6 | 15.4 | 96.4 | 284.2 | 29.5 | 120.8 |
| A | 1 | 13-Oct-16 | 1 | 10.0 | 8:26 | 5:32 | 524 | 2:54 | 55.3 | 34.4 | 84.4 | 171.0 | 20.3 | 52.4 |
| A | 1 | 14-Oct-16 | 1 | 10.0 | 9:33 | 8:08 | 752 | 1:25 | 81.2 | 14.9 | 95.5 | 283.7 | 29.7 | 75.2 |
| A | 1 | 15-Oct-16 | 1 | 10.0 | 9:34 | 8:34 | 978 | 0:59 | 85.7 | 10.3 | 95.6 | 301.7 | 31.6 | 97.8 |
| A | 1 | 17-Oct-16 | 2 | 10.0 | 9:31 | 7:40 | 819 | 1:51 | 76.6 | 19.5 | 95.1 | 262.9 | 27.6 | 81.9 |
| A | 1 | 18-Oct-16 | 2 | 10.0 | 9:33 | 8:00 | 1,034 | 1:33 | 80.0 | 16.2 | 95.4 | 278.0 | 29.1 | 103.4 |
| A | 1 | 19-Oct-16 | 2 | 10.0 | 9:29 | 7:12 | 807 | 2:17 | 72.1 | 24.1 | 94.9 | 244.3 | 25.7 | 80.7 |
| A | 1 | 20-Oct-16 | 2 | 6.7 | 6:04 | 4:16 | 583 | 1:48 | 64.1 | 29.6 | 91.0 | 153.1 | 25.2 | 87.5 |
| A | 1 | 24-Oct-16 | 1 | 10.0 | 9:22 | 7:06 | 1,051 | 2:17 | 70.9 | 24.3 | 93.7 | 274.1 | 29.2 | 105.1 |
| A | 1 | 25-Oct-16 | 1 | 9.8 | 4:07 | 8:10 | 981 | 0:00 | 83.2 | 0.0 | 41.9 | 282.6 | 28.8 | 99.9 |
| A | 1 | 26-Oct-16 | 1 | 10.0 | 8:43 | 5:35 | 677 | 3:07 | 55.9 | 35.9 | 87.1 | 203.9 | 23.4 | 67.7 |
| A | 1 | 28-Oct-16 | 1 | 10.0 | 9:30 | 8:34 | 983 | 0:56 | 85.7 | 9.8 | 95.0 | 298.3 | 31.4 | 98.3 |
| A | 1 | 31-Oct-16 | 2 | 10.0 | 9:32 | 8:03 | 945 | 1:29 | 80.5 | 15.5 | 95.3 | 288.6 | 30.3 | 94.5 |
| A | 1 | 1-Nov-16 | 2 | 10.0 | 9:32 | 8:13 | 777 | 1:19 | 82.2 | 13.8 | 95.4 | 269.7 | 28.3 | 77.7 |
| A | 1 | 2-Nov-16 | 2 | 10.0 | 9:35 | 7:38 | 683 | 1:57 | 76.3 | 20.4 | 95.8 | 285.7 | 29.8 | 68.3 |
| A | 1 | 3-Nov-16 | 2 | 10.0 | 9:27 | 7:48 | 861 | 1:39 | 78.0 | 17.4 | 94.5 | 268.9 | 28.5 | 86.1 |
| B | 2 | 2-Jun-16 | 1 | 10.0 | 9:18 | 6:42 | 762 | 2:36 | 67.1 | 27.9 | 93.1 | 184.2 | 19.8 | 76.2 |
| B | 2 | 6-Jun-16 | 2 | 10.0 | 9:38 | 7:23 | 1,252 | 2:15 | 73.8 | 23.4 | 96.3 | 241.2 | 25.0 | 125.2 |
| B | 2 | 7-Jun-16 | 2 | 10.0 | 8:39 | 7:19 | 1,369 | 1:19 | 73.2 | 15.3 | 86.4 | 237.1 | 27.4 | 136.9 |
| B | 2 | 8-Jun-16 | 2 | 10.0 | 9:01 | 7:26 | 1,941 | 1:35 | 74.3 | 17.6 | 90.2 | 227.2 | 25.2 | 194.1 |
| B | 2 | 9-Jun-16 | 2 | 10.0 | 9:24 | 7:47 | 1,493 | 1:37 | 77.8 | 17.3 | 94.0 | 228.3 | 24.3 | 149.3 |
| B | 2 | 13-Jun-16 | 1 | 10.0 | 9:52 | 8:32 | 1,560 | 1:20 | 85.3 | 13.6 | 98.7 | 264.9 | 26.8 | 156.0 |
| B | 2 | 14-Jun-16 | 1 | 10.0 | 9:54 | 8:17 | 1,736 | 1:37 | 82.8 | 16.4 | 99.1 | 274.5 | 27.7 | 173.6 |
| B | 2 | 15-Jun-16 | 1 | 10.0 | 9:22 | 7:28 | 1,376 | 1:55 | 74.6 | 20.4 | 93.7 | 229.5 | 24.5 | 137.6 |
| B | 2 | 16-Jun-16 | 1 | 10.0 | 9:43 | 8:49 | 1,507 | 0:54 | 88.2 | 9.3 | 97.2 | 276.3 | 28.4 | 150.7 |
| B | 2 | 20-Jun-16 | 2 | 10.0 | 9:15 | 8:47 | 1,452 | 0:28 | 87.8 | 5.1 | 92.5 | 253.6 | 27.4 | 145.2 |
| B | 2 | 21-Jun-16 | 2 | 10.0 | 9:12 | 6:10 | 1,109 | 3:01 | 61.7 | 32.9 | 91.9 | 183.2 | 19.9 | 110.9 |
| B | 2 | 22-Jun-16 | 2 | 6.0 | 5:19 | 2:54 | 601 | 2:25 | 48.3 | 45.5 | 88.7 | 98.3 | 18.5 | 100.2 |
| B | 2 | 24-Jun-16 | 2 | 11.0 | 10:36 | 9:06 | 1,897 | 1:30 | 82.7 | 14.2 | 96.4 | 272.0 | 25.7 | 172.5 |
| B | 2 | 25-Jun-16 | 2 | 8.0 | 6:48 | 5:51 | 1,180 | 0:57 | 73.1 | 13.9 | 84.9 | 180.4 | 26.6 | 147.5 |
| B | 2 | 27-Jun-16 | 1 | 10.0 | 9:40 | 8:22 | 1,441 | 1:18 | 83.6 | 13.5 | 96.6 | 266.5 | 27.6 | 144.1 |
| B | 2 | 28-Jun-16 | 1 | 10.0 | 8:21 | 6:08 | 801 | 2:14 | 61.3 | 26.7 | 83.6 | 199.6 | 23.9 | 80.1 |
| B | 2 | 29-Jun-16 | 1 | 10.0 | 9:52 | 7:20 | 1,734 | 2:32 | 73.3 | 25.7 | 98.7 | 228.2 | 23.1 | 173.4 |
| B | 2 | 30-Jun-16 | 1 | 10.0 | 9:40 | 7:26 | 1,594 | 2:14 | 74.3 | 23.2 | 96.7 | 212.0 | 21.9 | 159.4 |
| B | 2 | 4-Jul-16 | 2 | 10.0 | 9:34 | 7:06 | 1,319 | 2:28 | 71.0 | 25.8 | 95.6 | 225.4 | 23.6 | 131.9 |
| B | 2 | 5-Jul-16 | 2 | 10.0 | 9:44 | 8:36 | 1,748 | 1:08 | 86.1 | 11.6 | 97.3 | 284.9 | 29.3 | 174.8 |
| B | 2 | 6-Jul-16 | 2 | 10.0 | 9:30 | 8:23 | 1,841 | 1:07 | 83.8 | 11.8 | 95.0 | 280.7 | 29.6 | 184.1 |
| B | 2 | 7-Jul-16 | 2 | 10.0 | 9:23 | 8:07 | 1,502 | 1:16 | 81.2 | 13.5 | 93.8 | 278.7 | 29.7 | 150.2 |
| B | 2 | 12-Jul-16 | 1 | 10.0 | 9:44 | 8:26 | 1,885 | 1:19 | 84.3 | 13.5 | 97.4 | 302.2 | 31.0 | 188.5 |
| B | 2 | 13-Jul-16 | 1 | 10.0 | 9:38 | 7:44 | 1,418 | 1:54 | 77.3 | 19.8 | 96.4 | 263.3 | 27.3 | 141.8 |
| B | 2 | 14-Jul-16 | 1 | 10.0 | 9:36 | 8:51 | 1,871 | 0:46 | 88.4 | 7.9 | 96.0 | 296.7 | 30.9 | 187.1 |
| B | 2 | 15-Jul-16 | 1 | 10.0 | 8:31 | 7:15 | 1,356 | 1:16 | 72.6 | 14.8 | 85.2 | 244.1 | 28.7 | 135.6 |
| B | 2 | 18-Jul-16 | 2 | 10.0 | 9:41 | 8:25 | 1,130 | 1:17 | 84.1 | 13.2 | 96.8 | 287.1 | 29.6 | 113.0 |
| B | 2 | 19-Jul-16 | 2 | 10.0 | 9:29 | 6:58 | 1,291 | 2:31 | 69.7 | 26.5 | 94.9 | 238.1 | 25.1 | 129.1 |
| B | 2 | 20-Jul-16 | 2 | 10.0 | 9:50 | 7:11 | 1,012 | 2:38 | 71.9 | 26.8 | 98.3 | 211.7 | 21.5 | 101.2 |

| Op. ID | Op. Code | Day | Shift | SMH | Engine on | Total work time | Tree Count | Idling | Utilization (%) | Idling / Engine on | Engine on / Schedule d time | Fuel consump tion (L) | Fuel consumpt ion / Engine on (L/hr) | Trees /SMH |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| B | 2 | 21-Jul-16 | 2 | 10.0 | 8:34 | 7:46 | 1,474 | 0:48 | 77.7 | 9.3 | 85.7 | 257.2 | 30.0 | 147.4 |
| B | 2 | 2-Aug-16 | 2 | 10.0 | 9:35 | 8:33 | 1,854 | 1:03 | 85.4 | 10.9 | 95.9 | 283.7 | 29.6 | 185.4 |
| B | 2 | 3-Aug-16 | 2 | 10.0 | 9:34 | 7:41 | 1,279 | 1:52 | 76.9 | 19.6 | 95.6 | 255.9 | 26.8 | 127.9 |
| B | 2 | 4-Aug-16 | 2 | 10.0 | 9:40 | 8:18 | 1,392 | 1:23 | 82.9 | 14.2 | 96.7 | 260.9 | 27.0 | 139.2 |
| B | 2 | 8-Aug-16 | 1 | 10.0 | 9:16 | 8:18 | 1,646 | 0:57 | 83.1 | 10.3 | 92.6 | 283.8 | 30.6 | 164.6 |
| B | 2 | 9-Aug-16 | 1 | 10.0 | 9:20 | 8:50 | 1,940 | 0:29 | 88.4 | 5.3 | 93.3 | 300.0 | 32.2 | 194.0 |
| B | 2 | 10-Aug-16 | 1 | 10.0 | 5:13 | 4:19 | 680 | 0:54 | 43.2 | 17.2 | 52.2 | 136.1 | 26.1 | 68.0 |
| B | 2 | 11-Aug-16 | 1 | 10.0 | 9:41 | 8:00 | 1,935 | 1:41 | 80.0 | 17.3 | 96.8 | 272.1 | 28.1 | 193.5 |
| B | 2 | 19-Aug-16 | 1 | 10.0 | 8:48 | 8:19 | 1,781 | 0:29 | 83.1 | 5.5 | 88.0 | 265.2 | 30.1 | 178.1 |
| B | 2 | 20-Aug-16 | 1 | 10.0 | 9:14 | 8:35 | 1,467 | 0:39 | 85.8 | 7.0 | 92.3 | 259.0 | 28.1 | 146.7 |
| B | 2 | 22-Aug-16 | 1 | 10.0 | 8:38 | 7:42 | 1,304 | 0:56 | 77.0 | 10.8 | 86.3 | 248.8 | 28.8 | 130.4 |
| B | 2 | 23-Aug-16 | 1 | 10.0 | 8:42 | 7:44 | 1,382 | 0:58 | 77.3 | 11.1 | 87.0 | 255.5 | 29.4 | 138.2 |
| B | 2 | 24-Aug-16 | 1 | 10.0 | 8:48 | 7:44 | 1,459 | 1:05 | 77.3 | 12.2 | 88.0 | 252.4 | 28.7 | 145.9 |
| B | 2 | 25-Aug-16 | 1 | 10.0 | 8:34 | 7:29 | 1,329 | 1:05 | 74.9 | 12.7 | 85.7 | 242.3 | 28.3 | 132.9 |
| B | 2 | 5-Sep-16 | 1 | 10.0 | 10:00 | 8:28 | 1,686 | 1:32 | 84.7 | 15.3 | 100.0 | 272.8 | 27.3 | 168.6 |
| B | 2 | 6-Sep-16 | 1 | 10.0 | 7:46 | 6:25 | 1,184 | 1:21 | 64.1 | 17.5 | 77.6 | 194.4 | 25.0 | 118.4 |
| B | 2 | 7-Sep-16 | 1 | 10.0 | 7:21 | 5:45 | 663 | 1:36 | 57.5 | 21.9 | 73.6 | 188.6 | 25.6 | 66.3 |
| B | 2 | 8-Sep-16 | 1 | 10.0 | 7:46 | 6:24 | 927 | 1:22 | 64.1 | 17.5 | 77.7 | 211.4 | 27.2 | 92.7 |
| B | 2 | 12-Sep-16 | 2 | 10.0 | 9:33 | 8:23 | 1,360 | 1:10 | 83.8 | 12.2 | 95.5 | 253.3 | 26.5 | 136.0 |
| B | 2 | 13-Sep-16 | 2 | 10.0 | 8:45 | 6:38 | 878 | 2:07 | 66.3 | 24.2 | 87.5 | 202.3 | 23.1 | 87.8 |
| B | 2 | 15-Sep-16 | 2 | 10.0 | 8:27 | 6:51 | 817 | 1:36 | 68.6 | 18.9 | 84.5 | 222.5 | 26.3 | 81.7 |
| B | 2 | 16-Sep-16 | 2 | 10.0 | 9:31 | 8:26 | 1,496 | 1:05 | 84.3 | 11.4 | 95.2 | 249.1 | 26.2 | 149.6 |
| B | 2 | 19-Sep-16 | 1 | 10.0 | 7:24 | 5:33 | 913 | 1:52 | 55.4 | 25.1 | 74.0 | 184.3 | 24.9 | 91.3 |
| B | 2 | 20-Sep-16 | 1 | 10.0 | 9:20 | 6:56 | 1,246 | 2:24 | 69.3 | 25.8 | 93.3 | 233.1 | 25.0 | 124.6 |
| B | 2 | 21-Sep-16 | 1 | 10.0 | 9:18 | 8:29 | 1,549 | 0:49 | 84.8 | 8.8 | 93.0 | 290.1 | 31.2 | 154.9 |
| B | 2 | 22-Sep-16 | 1 | 10.0 | 9:59 | 9:04 | 1,572 | 0:55 | 90.6 | 9.2 | 99.8 | 317.7 | 31.8 | 157.2 |
| B | 2 | 23-Sep-16 | 1 | 10.0 | 8:51 | 7:06 | 1,361 | 1:45 | 71.0 | 19.7 | 88.4 | 251.8 | 28.5 | 136.1 |
| B | 2 | 26-Sep-16 | 2 | 10.0 | 7:53 | 6:50 | 1,121 | 1:03 | 68.3 | 13.4 | 78.8 | 233.7 | 29.6 | 112.1 |
| B | 2 | 27-Sep-16 | 2 | 10.0 | 7:52 | 7:02 | 997 | 0:50 | 70.3 | 10.7 | 78.6 | 223.0 | 28.4 | 99.7 |
| B | 2 | 28-Sep-16 | 2 | 10.0 | 7:55 | 7:04 | 1,105 | 0:51 | 70.7 | 10.7 | 79.2 | 244.1 | 30.8 | 110.5 |
| B | 2 | 3-Oct-16 | 1 | 10.0 | 9:55 | 9:06 | 1,596 | 0:50 | 90.9 | 8.4 | 99.2 | 319.2 | 32.2 | 159.6 |
| B | 2 | 4-Oct-16 | 1 | 10.0 | 9:55 | 8:37 | 1,396 | 1:19 | 86.1 | 13.2 | 99.2 | 303.6 | 30.6 | 139.6 |
| B | 2 | 5-Oct-16 | 1 | 10.0 | 7:29 | 5:42 | 722 | 1:47 | 57.0 | 23.8 | 74.8 | 193.5 | 25.9 | 72.2 |
| B | 2 | 6-Oct-16 | 1 | 10.0 | 9:44 | 7:53 | 1,394 | 1:51 | 78.8 | 19.0 | 97.3 | 281.6 | 28.9 | 139.4 |
| B | 2 | 7-Oct-16 | 1 | 10.0 | 9:42 | 9:02 | 1,423 | 0:40 | 90.3 | 7.0 | 97.1 | 277.9 | 28.6 | 142.3 |
| B | 2 | 11-Oct-16 | 2 | 10.0 | 9:28 | 6:40 | 700 | 2:48 | 66.7 | 29.6 | 94.7 | 227.7 | 24.0 | 70.0 |
| B | 2 | 12-Oct-16 | 2 | 10.0 | 9:32 | 7:35 | 1,094 | 1:57 | 75.8 | 20.5 | 95.3 | 224.9 | 23.6 | 109.4 |
| B | 2 | 13-Oct-16 | 2 | 10.0 | 9:36 | 7:29 | 868 | 2:07 | 74.8 | 22.0 | 95.9 | 249.1 | 26.0 | 86.8 |
| B | 2 | 14-Oct-16 | 2 | 10.0 | 9:35 | 8:04 | 1,052 | 1:31 | 80.7 | 15.8 | 95.8 | 260.9 | 27.2 | 105.2 |
| B | 2 | 17-Oct-16 | 1 | 10.0 | 9:29 | 6:31 | 806 | 2:58 | 65.2 | 31.2 | 94.9 | 222.9 | 23.5 | 80.6 |
| B | 2 | 18-Oct-16 | 1 | 10.0 | 9:26 | 7:57 | 1,289 | 1:29 | 79.4 | 15.7 | 94.3 | 258.6 | 27.4 | 128.9 |
| B | 2 | 19-Oct-16 | 1 | 10.0 | 7:07 | 5:36 | 658 | 1:32 | 56.0 | 21.4 | 71.2 | 178.4 | 25.1 | 65.8 |
| B | 2 | 20-Oct-16 | 1 | 10.0 | 9:53 | 7:24 | 844 | 2:28 | 74.1 | 25.0 | 98.8 | 213.5 | 21.6 | 84.4 |
| B | 2 | 31-Oct-16 | 1 | 10.0 | 9:54 | 7:49 | 1,386 | 2:05 | 78.2 | 21.0 | 99.0 | 264.3 | 26.7 | 138.6 |
| B | 2 | 1-Nov-16 | 1 | 10.0 | 9:10 | 7:53 | 891 | 1:18 | 78.8 | 14.1 | 91.7 | 277.2 | 30.2 | 89.1 |
| B | 2 | 2-Nov-16 | 1 | 10.0 | 9:45 | 8:13 | 944 | 1:32 | 82.2 | 15.7 | 97.5 | 292.7 | 30.0 | 94.4 |
| B | 2 | 3-Nov-16 | 1 | 10.0 | 9:15 | 8:08 | 1,121 | 1:07 | 81.4 | 12.0 | 92.5 | 284.5 | 30.7 | 112.1 |
| C | | 25-Jul-16 | 1 | 10.0 | 9:17 | 7:59 | 3,467 | 1:18 | 79.8 | 14.0 | 92.8 | 331.6 | 35.7 | 346.7 |
| C | | 26-Jul-16 | 1 | 10.0 | 9:47 | 8:43 | 3,824 | 1:04 | 87.2 | 10.9 | 97.9 | 334.2 | 34.1 | 382.4 |
| C | | 27-Jul-16 | 1 | 10.0 | 9:30 | 8:20 | 3,708 | 1:10 | 83.4 | 12.3 | 95.0 | 333.0 | 35.0 | 370.8 |
| C | | 28-Jul-16 | 1 | 10.0 | 8:03 | 6:22 | 2,154 | 1:42 | 63.6 | 21.0 | 80.5 | 240.6 | 29.9 | 215.4 |
| C | | 29-Jul-16 | 1 | 10.0 | 9:01 | 8:23 | 3,234 | 0:38 | 83.9 | 7.0 | 90.2 | 335.6 | 37.2 | 323.4 |
| C | | 2-Aug-16 | 1 | 10.0 | 9:13 | 8:30 | 3,463 | 0:44 | 84.9 | 7.9 | 92.2 | 340.9 | 37.0 | 346.3 |
| D | | 29-Aug-16 | 2 | 9.0 | 8:43 | 8:20 | 2,971 | 0:22 | 92.7 | 4.3 | 96.8 | 324.5 | 37.2 | 330.1 |
| D | | 30-Aug-16 | 1 | 10.0 | 8:34 | 7:59 | 2,352 | 0:35 | 79.8 | 6.8 | 85.6 | 315.6 | 36.9 | 235.2 |
| D | | 31-Aug-16 | 1 | 10.0 | 9:56 | 8:52 | 4,356 | 1:04 | 88.6 | 10.8 | 99.3 | 372.3 | 37.5 | 435.6 |
| D | | 1-Sep-16 | 1 | 10.0 | 9:54 | 9:04 | 3,538 | 0:51 | 90.6 | 8.6 | 99.1 | 350.5 | 35.4 | 353.8 |
| D | | 2-Sep-16 | 1 | 5.5 | 4:57 | 3:58 | 1,535 | 0:58 | 72.2 | 19.7 | 89.9 | 158.8 | 32.1 | 279.1 |
| E | | 24-Oct-16 | 2 | 10.0 | 8:46 | 8:11 | 2,726 | 0:35 | 81.9 | 6.6 | 87.7 | 308.0 | 35.1 | 272.6 |

| Op. ID | Op. Code | Day | Shift | SMH | Engine on | Total work time | Tree Count | Idling | Utilization (%) | Idling / Engine on | Engine on / Scheduled time | Fuel consumption (L) | Fuel consumption / Engine on (L/hr) | Trees /SMH |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| E | | 25-Oct-16 | 2 | 10.0 | 9:20 | 8:24 | 2,472 | 0:56 | 83.9 | 10.0 | 93.3 | 324.6 | 34.8 | 247.2 |
| E | | 26-Oct-16 | 2 | 10.0 | 9:17 | 8:13 | 2,276 | 1:04 | 82.1 | 11.5 | 92.8 | 356.8 | 38.4 | 227.6 |
| E | | 27-Oct-16 | 2 | 10.0 | 8:06 | 7:41 | 2,784 | 0:25 | 76.8 | 5.2 | 81.0 | 321.7 | 39.7 | 278.4 |
| F | | 29-Jul-16 | 2 | 10.0 | 8:40 | 6:54 | 2,270 | 1:46 | 69.1 | 20.3 | 86.7 | 274.2 | 31.6 | 227.0 |
| F | | 12-Aug-16 | 1 | 10.0 | 9:18 | 8:22 | 3,437 | 0:56 | 83.6 | 10.1 | 93.0 | 350.7 | 37.7 | 343.7 |
| F | | 19-Aug-16 | 2 | 10.0 | 9:13 | 8:07 | 2,811 | 1:06 | 81.2 | 11.9 | 92.2 | 317.2 | 34.4 | 281.1 |
| G | | 25-Jul-16 | 2 | 10.0 | 8:34 | 6:04 | 2,038 | 2:30 | 60.7 | 29.1 | 85.6 | 247.3 | 28.9 | 203.8 |
| G | | 26-Jul-16 | 2 | 10.0 | 8:19 | 6:17 | 1,159 | 2:03 | 62.8 | 24.6 | 83.2 | 258.2 | 31.0 | 115.9 |
| G | | 5-Aug-16 | 2 | 4.0 | 4:03 | 2:41 | 655 | 1:21 | 67.2 | 33.5 | 101.1 | 99.9 | 24.7 | 163.8 |

# APPENDIX II: ANOVA DATA

| Operator | Shift | Trees/SMH | Operator | Shift | Trees/SMH | Operator | Shift | Trees/SMH | Operator | Shift | Trees/SMH |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 1 | 147 | 1 | 2 | 147.5 | 1 | 2 | 86.1 | 2 | 1 | 146.7 |
| 1 | 1 | 165.9 | 1 | 2 | 186 | 2 | 1 | 76.2 | 2 | 1 | 130.4 |
| 1 | 1 | 156.8 | 1 | 2 | 123.2 | 2 | 2 | 125.2 | 2 | 1 | 138.2 |
| 1 | 1 | 176.3 | 1 | 2 | 96.1 | 2 | 2 | 136.9 | 2 | 1 | 145.9 |
| 1 | 2 | 140.5 | 1 | 2 | 92.1 | 2 | 2 | 194.1 | 2 | 1 | 132.9 |
| 1 | 2 | 138.63 | 1 | 2 | 83.7 | 2 | 2 | 149.3 | 2 | 1 | 168.6 |
| 1 | 2 | 191.2 | 1 | 2 | 112.4 | 2 | 1 | 156 | 2 | 1 | 118.4 |
| 1 | 2 | 174.4 | 1 | 1 | 98.8 | 2 | 1 | 173.6 | 2 | 1 | 66.3 |
| 1 | 1 | 147.5 | 1 | 1 | 126.3 | 2 | 1 | 137.6 | 2 | 1 | 92.7 |
| 1 | 1 | 180.2 | 1 | 2 | 155.1 | 2 | 1 | 150.7 | 2 | 2 | 136 |
| 1 | 1 | 169.4 | 1 | 2 | 162.8 | 2 | 2 | 145.2 | 2 | 2 | 87.8 |
| 1 | 1 | 187.3 | 1 | 2 | 202.8 | 2 | 2 | 110.9 | 2 | 2 | 81.7 |
| 1 | 2 | 172.1 | 1 | 2 | 188.9 | 2 | 2 | 100.17 | 2 | 2 | 149.6 |
| 1 | 2 | 154.3 | 1 | 2 | 164.5 | 2 | 2 | 172.45 | 2 | 1 | 91.3 |
| 1 | 2 | 215.7 | 1 | 1 | 223.5 | 2 | 2 | 147.5 | 2 | 1 | 124.6 |
| 1 | 2 | 218.4 | 1 | 1 | 154.1 | 2 | 1 | 144.1 | 2 | 1 | 154.9 |
| 1 | 1 | 189.9 | 1 | 1 | 168.7 | 2 | 1 | 80.1 | 2 | 1 | 157.2 |
| 1 | 1 | 156.1 | 1 | 1 | 152.3 | 2 | 1 | 173.4 | 2 | 1 | 136.1 |
| 1 | 1 | 190.2 | 1 | 1 | 174.3 | 2 | 1 | 159.4 | 2 | 2 | 112.1 |
| 1 | 1 | 170.2 | 1 | 2 | 158.1 | 2 | 2 | 131.9 | 2 | 2 | 99.7 |
| 1 | 2 | 133.3 | 1 | 2 | 138.7 | 2 | 2 | 174.8 | 2 | 2 | 110.5 |
| 1 | 2 | 184.2 | 1 | 2 | 131.2 | 2 | 2 | 184.1 | 2 | 1 | 159.6 |
| 1 | 2 | 179.4 | 1 | 2 | 115.7 | 2 | 2 | 150.2 | 2 | 1 | 139.6 |
| 1 | 2 | 156.1 | 1 | 2 | 98.3 | 2 | 1 | 188.5 | 2 | 1 | 72.2 |
| 1 | 1 | 138.2 | 1 | 1 | 120.8 | 2 | 1 | 141.8 | 2 | 1 | 139.4 |
| 1 | 1 | 138.9 | 1 | 1 | 52.4 | 2 | 1 | 187.1 | 2 | 1 | 142.3 |
| 1 | 1 | 159.5 | 1 | 1 | 75.2 | 2 | 1 | 135.6 | 2 | 2 | 70 |
| 1 | 1 | 180.1 | 1 | 1 | 97.8 | 2 | 2 | 113 | 2 | 2 | 109.4 |
| 1 | 1 | 184.8 | 1 | 2 | 81.9 | 2 | 2 | 129.1 | 2 | 2 | 86.8 |
| 1 | 1 | 157.9 | 1 | 2 | 103.4 | 2 | 2 | 101.2 | 2 | 2 | 105.2 |
| 1 | 1 | 216 | 1 | 2 | 80.7 | 2 | 2 | 147.4 | 2 | 1 | 80.6 |
| 1 | 2 | 131.8 | 1 | 2 | 87.46 | 2 | 2 | 185.4 | 2 | 1 | 128.9 |
| 1 | 2 | 149.1 | 1 | 1 | 105.1 | 2 | 2 | 127.9 | 2 | 1 | 65.8 |
| 1 | 2 | 120.4 | 1 | 1 | 99.93 | 2 | 2 | 139.2 | 2 | 1 | 84.4 |
| 1 | 2 | 127 | 1 | 1 | 67.7 | 2 | 1 | 164.6 | 2 | 1 | 138.6 |
| 1 | 2 | 198.1 | 1 | 1 | 98.3 | 2 | 1 | 194 | 2 | 1 | 89.1 |
| 1 | 1 | 182.6 | 1 | 2 | 94.5 | 2 | 1 | 68 | 2 | 1 | 94.4 |
| 1 | 1 | 121.5 | 1 | 2 | 77.7 | 2 | 1 | 193.5 | 2 | 1 | 112.1 |
| 1 | 2 | 146 | 1 | 2 | 68.3 | 2 | 1 | 178.1 | | | |

# APPENDIX III: SPSS ANOVA OUTPUT

**Between-Subjects Factors**

| | | Value Label | N |
|---|---|---|---|
| Operator | 1.00 | A | 79 |
| | 2.00 | B | 76 |
| Shift | 1.00 | Day | 81 |
| | 2.00 | Night | 74 |

**Descriptive Statistics**

Dependent Variable: TreesPerSMH

| Operator | Shift | Mean | Std. Deviation | N |
|---|---|---|---|---|
| A | Day | 148.0981 | 40.77355 | 36 |
| | Night | 138.7857 | 41.05661 | 43 |
| | Total | 143.0293 | 40.93198 | 79 |
| B | Day | 132.3000 | 37.11881 | 45 |
| | Night | 129.5071 | 32.00153 | 31 |
| | Total | 131.1608 | 34.92651 | 76 |
| Total | Day | 139.3214 | 39.33859 | 81 |
| | Night | 134.8987 | 37.57565 | 74 |
| | Total | 137.2099 | 38.44622 | 155 |

**Levene's Test of Equality of Error Variances**[a]

Dependent Variable: TreesPerSMH

| F | df1 | df2 | Sig. |
|---|---|---|---|
| .934 | 3 | 151 | .426 |

Tests the null hypothesis that the error variance of the dependent variable is equal across groups.

a. Design: Intercept + Operator + Shift + Operator * Shift

**Tests of Between-Subjects Effects**

Dependent Variable: TreesPerSMH

| Source | Type III Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|
| Corrected Model | 7298.809[a] | 3 | 2432.936 | 1.667 | .176 |
| Intercept | 2853290.178 | 1 | 2853290.178 | 1955.458 | .000 |
| Operator | 5959.763 | 1 | 5959.763 | 4.084 | .045 |
| Shift | 1388.806 | 1 | 1388.806 | .952 | .331 |
| Operator * Shift | 402.836 | 1 | 402.836 | .276 | .600 |
| Error | 220330.402 | 151 | 1459.142 | | |
| Total | 3145746.099 | 155 | | | |
| Corrected Total | 227629.211 | 154 | | | |

a. R Squared = .032 (Adjusted R Squared = .013)

**Lack of Fit Tests**

Dependent Variable: TreesPerSMH

| Source | Sum of Squares | df | Mean Square | F | Sig. |
|---|---|---|---|---|---|
| Lack of Fit | .000 | 0 | . | . | . |
| Pure Error | 220330.402 | 151 | 1459.142 | | |

## Estimated Marginal Means

**1. Operator**

Dependent Variable: TreesPerSMH

| Operator | Mean | Std. Error | 95% Confidence Interval | |
|---|---|---|---|---|
| | | | Lower Bound | Upper Bound |
| A | 143.442 | 4.315 | 134.917 | 151.967 |
| B | 130.904 | 4.458 | 122.095 | 139.712 |

**2. Shift**

Dependent Variable: TreesPerSMH

| Shift | Mean | Std. Error | 95% Confidence Interval | |
|---|---|---|---|---|
| | | | Lower Bound | Upper Bound |
| Day | 140.199 | 4.271 | 131.761 | 148.637 |
| Night | 134.146 | 4.500 | 125.255 | 143.038 |

**3. Operator * Shift**

Dependent Variable: TreesPerSMH

| Operator | Shift | Mean | Std. Error | 95% Confidence Interval | |
|---|---|---|---|---|---|
| | | | | Lower Bound | Upper Bound |
| A | Day | 148.098 | 6.366 | 135.519 | 160.677 |
| | Night | 138.786 | 5.825 | 127.276 | 150.295 |
| B | Day | 132.300 | 5.694 | 121.049 | 143.551 |
| | Night | 129.507 | 6.861 | 115.952 | 143.062 |