AN ABSTRACT OF THE THESIS

Patrick Vaughan Sellars for the degree of Master of Science in Mechanical Engineering presented on January 5, 2021.

Title: Improved Lubrication Performance of Chainsaw Cutting Systems.

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John Parmigiani

Chainsaws serve as one of the primary tools used by logging corporations, ranches, and farms for forestry management. Lubricating oil remains one of the heaviest operational expenditures for chainsaws. This largely in part due to chainsaw lubrication being a total loss system in which nearly all lubricating oil applied is expelled during operation. The majority of lubrication research is focused on mitigating component breakdown due to wear or the inclusion of more environmentally friendly lubricating oils. Little research is available to the public on the improvement of chainsaw lubrication so that less lubricant can be used during operation. Patents and products exist that aid in lubricating chainsaw cutting systems but few are capable of reducing the lubricant required. An investigation into the current lubrication method of a chainsaw cutting system was conducted using a standard sprocket nose guide bar and accompanying saw chain. Testing utilized a lab-based test apparatus for controlling and operating the chainsaw cutting system along with an infrared camera for collecting steady-state guide bar temperature measurements. Observation of the guide bar's thermal profile during operation in a controlled environment aided in the design of a concept prototype. Preliminary free-running tests with varied oil-input flow rates indicated a 75% reduction in oil

flow rate while achieving the same steady-state maximum guide bar temperature was possible using the concept prototype. Developing this concept further into a prototype guide bar, a free-running test was conducted to compare the prototype to the standard guide bar. This tested both standard and prototype guide bars at 16lb and 22lb chain tension along with oil flow rates of 0.8mL/min and 3.3mL/min. The prototype guide bar operated at lower maximum guide bar temperatures at the 0.8mL/min flow rate at both 16lb and 22lb chain tension settings. Lastly, three replicates of the prototype and standard guide bar conducted 1,400 bucking cuts from which the wear on the guide bar rails and the stretch of the chain were measured. The prototype guide bar rails measured less average wear than the standard bar at 0.8mL/min flow rate. The saw chains used on the prototype guide bar also measured less stretch than those used on the standard guide bars at the same flow rate. The testing conducted indicated the prototype guide bars potential for reducing the amount of lubricant required while maintaining a similar amount of component wear.

Improved Lubrication Performance of Chainsaw Cutting Systems

by

Patrick Vaughan Sellars

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APPROVED:

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Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Patrick Vaughan Sellars, Author

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CONTRIBUTION OF AUTHORS

Dr. John Parmigiani provided support and technical feedback throughout chapters 1-5. Thomas Hope assisted with completing the free running and cutting tests in chapter 4.

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1 Introduction

The process of wear is one that takes time and energy with each material in contact handling this action differently. Methods of reducing wear such as changing material properties via hardening or using lubricants to separate surfaces have been practiced for hundreds of years. By far the biggest mitigation to wear has been the application of proper lubricants. Wear is defined as the removal of material through erosion or usage, the usage portion of this definition being rather difficult to get rid of. Lubrication serves as a means of separating two materials in contact with one another so that the asperities in contact do not break and exacerbate erosion. In almost all metal to metal contacts, there is a form of lubricant that is required to maintain a long life for the components. The technology and formulation of lubricants is a field that is still pursued to this day and individual companies continue to seek out specialized lubricants based on their application. One such application is cutting, of which there are many forms of cutting that can take places, such as shearing, punching, chip forming, and abrasive cutting. Most of these forms of cutting require lubrication to some degree whether it be for friction reduction, heat dissipation, or the fluid boundary layer.

The separation of material via cutting is an aggressive process that is used heavily in many manufacturing processes. Lubrication while cutting is often necessary to relieve the thermal stress on the cutting tool and cutting media caused by the separation of material. The majority of cutting experiences heat buildup and heat production in either the workpiece, tool, or cutter. The source of this heat buildup and production is often from cutting material plasticity, friction between the piece being cut, and operation friction of the tool. The one caveat to this is high feed forces during fast-paced cutting, this will increase all these conditions thus elevating the temperature. This elevation of temperature will reduce the life of the components and degrade material properties as the operation continues. Thus, lubrication is very important during operations such as these in that they reduce heat production and reduce friction through the separation of the materials in use.

The logging industry performs cutting operations daily, for extended periods, and under harsh and various cutting conditions. In the United States, the logging industry cut an estimated 42.2 billion board feet wood in 2017 alone [1]. The chainsaw is a common tool for professionals in the industry and has been used in operations over the last century. Chainsaws typically fall into two categories handheld or harvester. Handheld chainsaws are portable chainsaws, typically gas or electric, and are used by average homeowners, ranchers, or even professionals, this is what the vast majority of users have experience with. Harvesters are very similar except the components are much larger and stronger and are only mounted to industrial logging equipment as they are typically hydraulically powered. Some logging operations utilize only chainsaws, some utilize only harvesters, and some use a combination of the two.

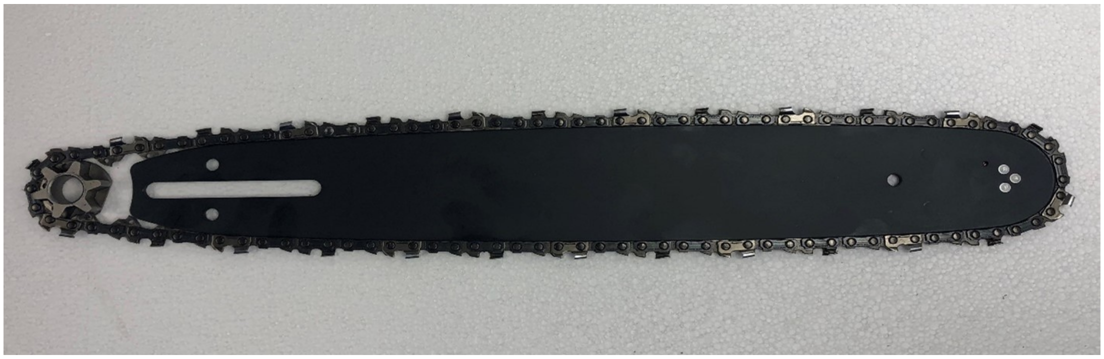

Figure 1: Handheld chainsaw cutting system

Harvester and handheld chainsaws are comprised of two systems, the powerhead, and the cutting system. The powerhead's sole purpose is to generate and transfer power to the cutting system using either electric, combustion for handheld and hydraulic motors for harvesters. The cutting system of a handheld chainsaw in figure 1 consists of a drive sprocket, guide bar, and a saw chain. The drive sprocket is connected to the powerhead output shaft which is then used to move the chain at high speeds. The guide bar is connected to the powerhead via mounting bolts and is designed to guide the chain around the contour for cutting. The guide bar contour is designed in such a manner so when the saw chain is tensioned onto the guide bar the saw chain may slide freely along the guide bar rails.

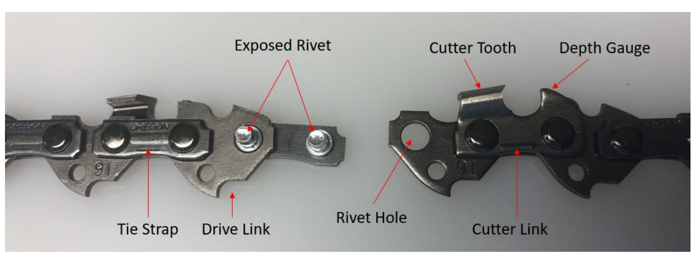

Figure 2: Saw chain component break down

The saw chain is an assembly broken down in figure 2 and is comprised of cutters and drive links that are riveted together with tie straps. The cutter link in figure 2 is comprised of the cutter tooth that cuts the wood and the depth gauge which controls the depth of cut. These two features are set and held at a specified difference in height so that when sharpening the saw chain, the depth of cut remains the same. This depth of cut is important to maintain to achieve optimal performance of the chainsaw while cutting. The drive links in figure 2 engage with the drive sprocket that transfers power from the motor. The drive links ride inside the guide bar groove and are shaped as such for clearing out the groove as it fills with debris. The drive links also pick up the lubricant as it is pumped into the guide bar groove at the upper tail section in figure 1. Finally, the tie straps serve to hold the assembly together with the footprints on both the tie straps and the cutter links sliding across the guide bar rails. The wood is comparably soft and tends to vary in moisture content, grain density, and grain orientation which can make cutting forces highly erratic. This variation has been observed within a single 30-inch section of the same 10-foot cant of wood. A cant of wood is defined as a piece of wood with generally three sides that have been sawn and are thicker than two inches.

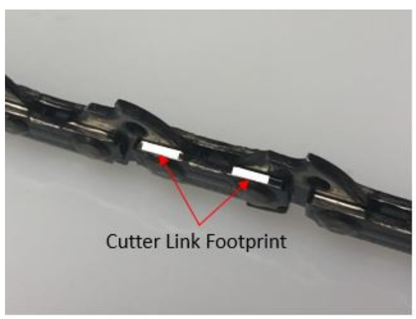

Figure 3: Underside view of saw chain showing the footprint wear on a cutter link

As these cutting forces change so does the feed rate of the cutting system which in turn affects the normal forces applied by the saw chain to the guide bar. The footprints on the cutter link of the saw chain bear the brunt of this normal force, as such, they require proper lubrication to mitigate wear visible in figure 3. Significant wear locations on the saw chain include the footprints of the tie straps and cutter links and the drive link rivet holes.

Lubricant is used to mitigate the heat generation and production in the cutting system caused by the saw chain and guide bar interaction. Lubricants act as a means of reducing friction between interacting surfaces and act as coolants reducing component temperatures. Reducing friction between the two sliding surfaces of the tie strap and cutter link footprints and the surface of the guide bar rails, along with the rivets on the drive links is the primary goal of chainsaw lubrication. A variety of bar and chain lubricants exist specifically for this application, commonly tailored for extending the life of the cutting system. The accuracy of these claims varies and is difficult to quantify in the field. Extensive testing on the lubricants themselves and their performance on the cutting system has been done recently and serves as a stepping stone to further increase the life of the components. All too common do professionals in the field purchase bar and chain lubricants to use alongside whatever is available to them on the job site. Many loggers avoid the price of the bar and chain oils and use vegetable oils or waste oils to save money. An investigation into the performance characteristics of bar and chain oils used on cutting systems was conducted by Suryan [2] and looked at the multiple factors affecting lubrication performance while cutting. A separate study was conducted by Orawiec [3] finding that some economy bar and chain oils along with the organic oils, performed better than their premium counterparts. In these studies, a method of comparing lubricants based on their thermal profile during free-running and cutting was used as the temperature was found to be a surrogate to wear at locations on the guide bar. A measurement of a lubricants performance on an active cutting system was thus developed for the analysis of lubricants or features claiming to aid in lubrication.

Attributes of the lubricant have been designed to reduce the coefficient of friction and to better entrap the lubricant onto the cutting system as all lubricant applied is virtually lost to the environment during operation. This is what is called a total loss system, and many designs have been tested in an attempt to improve lubricant application within the cutting system itself. The soft nature of the wood and the exposure to a variety of often harsh environments makes it difficult to properly lubricate the cutting system. Fine debris particles are developed during operation and can adhere to the cutters and chain and even build up along the inner rails of the guide bar. Components of the chain are designed to aid in expelling material from the system during operation, yet some debris will remain. Improvements to the bar and chain design have been made in the past to aid in ensuring proper lubrication and mitigation of lubricant starvation. Nevertheless, lubricant starvation still occurs due to cutting media and chainsaw usage varying at each job site and each end user. Some of the features developed are now obsolete while some remain in products today. A feature capable of reducing the lubrication required while maintaining the same performance and wear characteristics should be the goal in any lubrication feature on chainsaw products.

2 Literature Review

Improved lubrication in chainsaws has primarily been focused on the lubricant being applied, a few publications exist on the comparison of different types of bar and chain oil. These focus on reducing the wear on the cutting system through better lubricant attributes or focusing on the effectiveness of alternative lubricants such as organic oils. Organic or biodegradable lubricants offer a reduction in toxicity to the environment during use. Toxicity is a large concern with a chainsaw because they are total loss systems. Skoupy [4] found that roughly 55-85% of the oil applied was captured by the sawdust with 3-15% remaining on the timber surface, and 10-35% ending up on the ground. In a study conducted by Popovici [5], a professional logging firm recorded five months of consumables such as lubricating oil and found that for the 660m^2 of cut timber, 116.5 L of lubricating oil was consumed during this time. The wastefulness of the total loss system might be unavoidable but dampening the effect on the environment and the end-user is surely an effort many have attempted to address.

2.1 Standard Chainsaw Lubrication Method

Most forestry guide bars apply lubrication through the tail section of the guide bar, lubricant is pumped from the reservoir in the powerhead to the bar pad at the tail of the guide bar. Then a simple hole in the bar aligns with the oiling outlet on the bar pad so that lubricant may flow into a hole in the guide bar. It then fills the groove in the tail section for the saw chain drive links to pick up as it passes by, this is known as the standard method of lubrication. This method is quite simple and effective so long as the lubricant flow rate is high enough. The standard method of measurement for adequate lubrication is to run a chainsaw near the ground or tree trunk and inspect for small amounts of expelled lubricant. This visual cue is the method that is described in the owner manuals for the vast majority of chainsaws on the market. This archaic benchmark for proper lubrication serves the industry as guide bar manufacturers are largely interchangeable with different powerheads. Individual preferences for lubrication vary widely from user to user and as such most professional chainsaw powerheads come with adjustable flow rate settings. Flow rate adjustments are done with the engine off and are repeated until only small amounts of lubricant are observed being expelled. Industry experts at Blount International have determined flow rates can vary on average between 3.3-30mL/min for a variety of handheld chainsaw cutting systems. The former being on smaller 14-inch guide bars and the latter being on 35-inch guide bars. This flow rate range serves as a guide for this work as the optimal flow rate is highly subjective to individual users. The standard method applies lubrication to the saw chain before entering the effective cutting region on the guide bar. The effective cutting region begins a few inches from the bar mount pad just past the dog teeth on the chainsaw powerhead. The saw chain serves as both the object in need of lubrication and as the transport mechanism for lubricant around the guide bar. This method while effective, uses more lubricant than what is potentially required as a large amount of it is lost in the operation of the chainsaw.

2.2 Methods of Improving Lubrication

A means of improved lubrication was focused on including features into the cutting system to aid in lubrication. Many forestry companies have designed such features claiming to aid in lubrication, although few have accomplished this in a manner of enabling less lubricant to be used. One method of lubrication enhancement is through the means of alleviating lubricant starvation events or the probability of such events. Lubrication starvation can occur during the operation of the chainsaw as the sawdust and debris accumulate in the groove of the guide bar. Fine particle debris and oil can impede the straight oiling hole in the guide bar thus clogging and depriving the system of proper lubrication. Two particular methods exist for mitigating lubricant starvation and both are patented concepts from the 1970s.

The first method is an angled oiling hole patented by Outboard Marine Corporation [6] and exists on guide bars from various chainsaw manufacturers. The angled oil hole aims to defeat lubricant starvation by making the outlet angle of the oiling hole on the guide bar more in the line of travel of the saw chain rather than perpendicular to the direction of travel. The purpose here was to make it difficult for dust and debris to obscure the oiling hole while the chain passes through the tail section of the guide bar. The angled oiling hole would be harder to clog than a straight oiling hole that is perpendicular to the direction the saw chain travels. The simple design of angling a hole becomes a challenge to manufacture when such an angle has costly tolerances needed for implementation. While not impossible this remains a costly feature that guide bar manufacturers typically offer on only a few professional models and does nothing to reduce the lubricant required.

The second method is an angling of the oiling hole cross sectional area and was patented by Textron Inc [7]. The nozzle like feature mitigates lubrication starvation by accelerating the lubricant, making it harder to become clogged by sawdust and debris. The nozzle like oiling hole offers a simple method to mitigating lubricant starvation and certainly has the capability to work. Yet it faces a similar problem in manufacturing as side laminates on some guide bars can be between 0.040-0.078 inch thick. The tolerance required for this method faces severe challenges and as such is not found in modern guide bars. This feature is a good addition to guide bars but does not claim or show evidence of reducing the lubricant required.

A modern feature on many Oregon products is called Lubri-Dam and is a feature on the guide bar that prevents oil from traveling down towards the tail section. This is done with a small dam located on the center laminate of the guide bar just behind the oiling hole. The oil will pool up here rather than traveling down the groove to the tail section, thus Oregon states a significant increase in lubrication film thickness on the guide bar rails [8]. While oil is gathering by the dam it is brought closer to the drive links. Similarly, STIHL's Ematic Lubrication System also attempts to aid in bring lubricant closer to the drive links. The Ematic system utilizes ramps placed near the oiling hole to contain and bring the lubricant to the drive links on the saw chain [9]. From here STIHL's OILOMATIC grooves on each drive link guide the lubricant to the critical wear areas on the saw chain rivets [10]. STIHL states that the utilization of this system is capable of reducing the lubricant required by up to 50%. Both companies make claims to the effectiveness of their prospective systems and both features have been available for around the last 20 years or more. The fact remains that loggers still desire a chainsaw that uses less lubricant and are still looking for a means to reduce lubricant cost while maintaining the same wear.

Another saw chain lubrication feature is found on Oregon saw chain and is called

Lubriwell and Lubrilink. The Lubriwell feature consists of a hole in the drive link of the saw chain for carrying more oil to the nose but also serves to lubricate the inner walls of the guide bar groove [11]. The Lubrilink feature is on the tie straps and attempts to retain lubricant in a raised recess portion of the tie strap inner side-wall. These two features are unique in that they focus on entrapping the lubricant, which for a total loss system is an ideal approach to increasing lubricant efficiency. The entrapment of lubricant on the Lubrilink and Lubriwell saw chain components only allow for a minimal amount of lubricant to be held within these features. Improvements to the Lubriwell design have been patented by Blount International [12] with the hopes to further improve lubrication of the drive link and aid in removing material and debris from the guide bar groove. The Lubriwell and Lubrilink features, while aiding in the current effort for lubrication do not appear to be able to reduce the amount of lubricant required as the primary focus is on entrapment, and only so much lubricant can fit inside these features during continuous use.

Another feature for enhancing chainsaw lubrication aims to utilize leftover lubricant near the nose sprocket. This feature is found on replaceable nose sprockets the of Titanium XV harvester bar and was recently patented by GB Forestry [13]. Like the standard method, the lubricant is applied to the upper tail section of the guide bar where it is common for some lubricant residing at the bottom of the groove to make its way towards the nose of the guide bar. This happens as a side effect of the saw chain drive links picking up the lubricant, resulting in lubricant being pushed in the direction of travel of the saw chain. Rather than being flung off by centrifugal force at the nose, this feature utilizes channels cut along the inner walls of the nose sprocket laminates to aid lubrication. These channels connect the bottom of the groove to the inner bearing assembly inside the nose sprocket. The nose sprocket picks up the saw chain off the bar rails as the saw chain rounds the nose of the guide bar. For guide bars with nose sprockets, when the saw chain makes contact and wears at the tip of the nose this is deemed to be the guide bar's end of life as exponential wear of the cutting system is imminent. This feature means to elongate the life of the guide bar by using what lubricant would be thrown off to extend the life of the bearing assembly and thus the guide bar. The channels at the nose rely on the lubricant to make it from the tail to the nose via the bottom of the groove. This groove is known to accumulate sawdust and debris not to mention its exposure to the varying elements. The debris accumulation and lubricant expulsion during operation mean that potentially the same if not more lubricant is speculated to be required to achieve the lubrication enhancements. Thus, it does not claim to provide a means of enhancement that any sort of reduction of lubricant required would be possible whereas it does aim to elongate the life of a critical component.

Lastly, a concept that has been patented but is no longer implemented on commercial products in forestry is a guide bar with oil channels [14]. The oil channel concept was patented in 1990 by Sandvik AB and aims at improving the lubricant being applied by applying it closer to where it is needed. This concept connects the oiling ports on the tail section to the ends of the upper and lower-middle section of the center laminate. This feature was implemented on laminated bars consisting of 3 sheets of material welded together typically. The two outer laminates are identical in every way and the center laminate is smaller and shorter to create the groove shape in the bar leaving room for the chain and nose sprocket assembly. The oil channels would deposit lubricant to the bottom of the drive link tangs at the edges of the center laminates next to the nose sprocket. This concept works to bring lubricant closer to locations of visible wear and to also lubricate the nose sprocket assembly. It is speculated that this was unable to improve lubrication as the lubricant applied at the bottom of the groove near the nose relies on the saw chain having enough of an interaction with the lubricant. Distances between the bottom of the groove and the tip of the drive link can vary but can be as large as 0.038 inches and tend to fill with debris, thus limiting the interaction between the two. This concept of spraying lubricant at the bottom of the drive links before they encounter the nose sprocket would vary in its effectiveness as different lubricants and working conditions would affect the fluid mechanic properties that this so relies on. As such no claims of reduced lubrication are made and would appear to prioritize the nose sprocket assembly for wear reduction and prolonged life.

2.3 Lubrication Performance Measurement

The evaluation methods for lubrication have changed over the last century as technology has progressed creating a way for improved measurement methods for lubrication. In tribological studies, there is a strong correlation between improper lubrication and temperature from frictional heating. Using this known relationship chainsaw cutting systems were analyzed with infrared cameras or thermocouples to observe the thermal profiles and temperatures of the cutting systems during operation. Doing so has many advantages while also requiring strict operating parameter control when conducting tribological studies on a chainsaw cutting system. Stanovsky [15] attempted to distinguish the difference between vegetable-based bar and chain oils and synthetic used motor oil in a field experiment with actual chainsaw equipment and an infrared camera and found no significant difference between the two. A large contributor to this outcome is that many parameters such as humidity, air temperature, chain speed, cutting forces, and wood characteristics were not sufficiently controlled. A lab-based apparatus was needed for studies such as this and to this end Nordfjell [16] created a test apparatus for simulating cutting loads in a controlled environment.

This experiment utilized an electric motor to operate the cutting system that had a saw chain with no cutters on it. This was done so that the cutting system could be lowered onto a rubber wheel which would simulate cutting while using a thermocouple to measure temperature on the guide bar. Lubricant testing was conducted under these conditions and was able to adequately control operating parameters that Stanovsky's [15] experiment could not. A disadvantage to this lab-controlled test apparatus was the test apparatus's inability to cut wood, which would lack representative cutting forces and conditions and include natural interactions of wood debris on the cutting system. An apparatus that most notably has the capability of representing conditions in the field while controlling operating parameters adequately was designed and made by Otto [17] for research on chainsaw cutting characteristics of actual wood samples. This test apparatus was later modified for work by Suryan and Orawiec [2, 3] for lubrication studies. The culmination of which being a test apparatus capable of conducting lubrication studies on the cutting system during active chainsaw operation in a controlled setting.

This literature review described the standard method of lubrication, a brief overview of a few patents and products aiming to improve lubrication, and finally a brief coverage of the constraints and requirements for using temperature as an evaluation method. The patent and product claims stated in this review were not tested and served only to inform the current state of reduced lubrication. This review highlights a gap in knowledge on the development of reducing chainsaw lubrication and will serve as the area of focus for this thesis. By utilizing the equipment and methods available at Oregon State Universities Prototype Development Lab and Blount International, improvements to chainsaw lubrication will be further investigated. This work aims to develop a method of lubrication based on the need of the chainsaw cutting system in hopes of reducing the amount of lubricant required.

Chapter 3

3 Materials and Methods

This work was provided with materials and expertise from Blount International to obtain the desired data. Equipment at both OSU's Prototype Development Lab and Blount International were utilized in tandem with research and testing methods from previous research conducted at OSU. The following is a description of the equipment, materials, and analytic methods used for collecting and analyzing the test data.

3.1 Test Equipment

3.1.1 Miniswath Test Apparatus

Testing was conducted in a lab on a custom-built saw chain testing apparatus called the miniswath. This test apparatus has been used for chainsaw cutting system studies and lubrication studies by Otto, Suryan, and Orawiec [17,2,3], and as such no further modifications to the miniswath were needed for conducting the testing and research within this body of work.

Figure 4: Miniswath test apparatus enclosure and control panel

The miniswath is housed in an aluminum and Plexiglas enclosure and armed with a 3/8 inch steel plate to protect the operator from possible chain breaks. A ventilation system in figure 4 is connected above the enclosure to the inner chamber of the miniswath to evacuate smoke and potentially harmful mist. The computer and the control panel to the left of the miniswath are used for controlling the apparatus during testing. Next to the miniswath but not shown in figure 4 is the oil pump for lubricants and the air compressor for the miniswath's pneumatic control components.

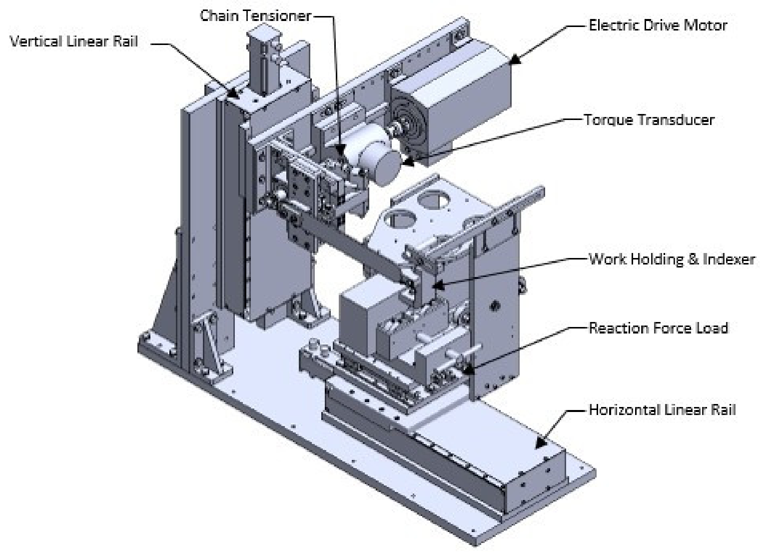

Figure 5: Mechanical subsystems of the miniswath

The inside of the miniswath contains an assembly of mechanical subsystems for data acquisition and control of the movements of the cutting system and the cutting media, these components and the assembly itself are shown in figure 5. The motion control system inside is set up to run either down bucking or boring cuts. Down bucking cuts are performed via movement of the cutting system along the vertical linear rail while the cutting media in the work holding and indexer is stationary. The guide bar is driven by a 3.0kW AC motor capable of reaching shaft speeds of 12,000 RPM. Shaft speed and torque are measured with sensors attached inline to the drive system. All load cell and torque data acquisition are done so at 2.0 kHz during both cutting and free-running tests. The load cell for the chain tension is mounted between two linear bearings that hold the bar pad and measures the reactionary forces between the guide bar and the drive sprocket. These two components are pulled together by the saw chain loop, as such only half of this value is reported as static chain tension. This load cell data is utilized by a PID controller to drive a linear actuator thus allowing the chain tension variable to be controlled in the existence of any thermal expansion of components or physical wear. This data is then sent through a low-pass filter to separate vibrations from thermal expansion and contraction. Lubricating oil is applied similar to that on an actual chainsaw in that it is applied into the oiling port through the bar pad. A peristaltic pump is connected to the bar pad through a hose so that a steady flow rate of lubricant may be applied. This set up allows for easy control and variation of lubricant type and flow rate during free-running and cutting tests. Rectangular pieces of timber are held in place in the work holding and indexer apparatus as seen in figure 5. Forces generated while cutting are measured with sensors located in the work holding and indexing apparatus. The forces generated while cutting are cutting forces and feed forces. Cutting forces are that which are exerted horizontally by the chain onto the workpiece and feed forces are that which are exerted vertically as the guide bar and saw chain is fed through the cutting media. These forces can vary depending on timber conditions, type, and even saw-chain type and sharpness. Instances of a dull or improperly sharpened chain will cause these forces to increase, as such saw chain conditions are monitored through the loads displayed while operating. Lastly the miniswath and all of its functions are controlled using LabVIEW 2018 with a National Instruments cRIO-9047 chassis.

3.1.2 Infrared Camera

Figure 6: FLIR A655sc infrared camera fixed to miniswath door

Fixed on the door of the miniswath is a FLIR A655sc infrared camera for measuring guide bar temperature. This camera provides images of the guide bar temperature field during free-running and cutting tests. The camera is fixed onto the door of the miniswath for ease of testing and image analysis as seen in figure 6. The camera comes with 640 by 480-pixel detection and an accuracy of 3.6 °F when emissivity is 0.95. During free-running testing images are taken manually through the LabVIEW interface on the miniswath computer. During the cutting tests, images are automatically taken by specifying the start and stop locations on the cutting media. For all cutting tests, a pre-cut image is taken immediately before plunging into the timber and then a post-cut image is taken immediately after finishing the cut but before returning to the home position. This automation for cutting allows for more reliable cut to cut temperature data to be taken.

3.1.3 Software

The miniswath runs and operates using the LabVIEW software, storing cutting and operating data on the cRIO-9047 chassis. This data is brought over to the miniswath computer using WinSCP for the file transfer protocol. The FLIR camera is operated using both LabVIEW and ResearchIR. The latter being used as the main operating window for setting up the camera and for observations during testing.

3.1.4 Chain Stretch Fixture

The saw chain wear was measured using a standard method provided by Blount International. A measurement apparatus measures total stretch in a broken loop of saw chain via a Matco Tools 1 inch dial indicator with 0.001-inch graduations as seen in figure 7.

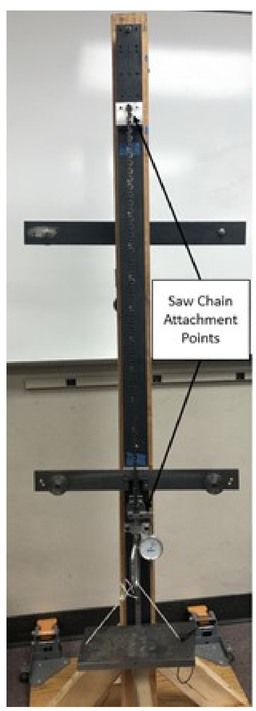

Figure 7: Chain stretch fixture with broken and stretched chain loop attached

A 12.5lb weight is hung at the bottom saw chain attachment point to pull the saw chain taut. Running a metal rod along drive links for the length of the saw chain works loose any stuck components or kinks in the saw chain assembly. Once complete, a measurement is recorded and then the saw chain is rotated and reattached to the attachment points and the process is repeated. Wear measurements on the saw chain are conducted only after cutting tests so that representative operating conditions can be tested. The amount of free running test time required to generate enough measurable wear on the saw chain is quite large compared to cutting tests. Operating parameters could be increased to accelerate wear and decrease testing times but would no longer represent standard chainsaw usage.

3.1.5 Guide Bar Rail Wear Fixture

Guide bar rail wear is measured using a custom-built wear fixture using fixed locating pins and a Mitutoyo ID-C Series 543 Digital Dial Indicator with an attachment to mate with the locating pins on the wear fixture. The wear fixture in figure 8 contains similar fit pins that align with the oiling port and tooling hole on the guide bar and come together with light use of a rubber mallet. This aligns and centers the laminated guide bars for fast and repeatable measurements.

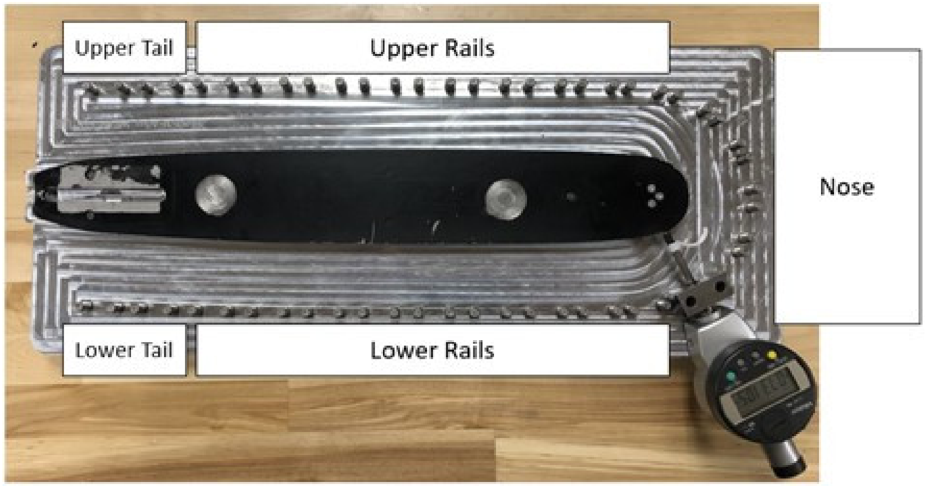

Figure 8: Guide bar rail wear fixture displaying the categorized wear sections and dial indicator

From here the displacement of material on the guide bar rails at several locations along the guide bar contour are measured using an initial measurement and a final measurement after cutting. The dial indicator and attachment are placed onto one of the 28 pairs of locating pins where it is zeroed with a custom zeroing block. Zeroing takes place at each location just before collecting a measurement with the dial indicator. After zeroing, the zero block is removed while the dial indicator remains in place and the measurement is recorded. This process is repeated all around the guide bar resulting in 28 measurements for an initial or final measurement.

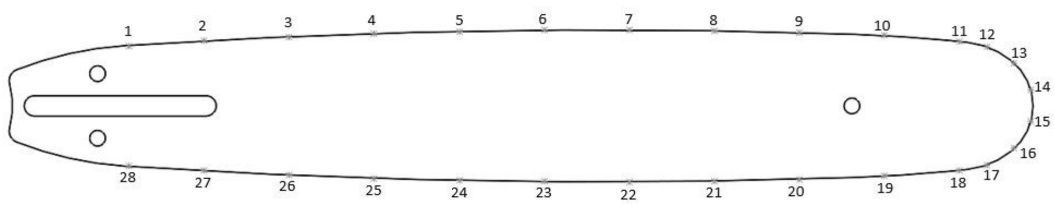

Figure 9: Locations of wear measurement on guide bar

The 28 individual wear measurements in figure 9 are categorized into sections of the guide bar. These sections are also divided by the upper and lower portions of the guide bar, which can then be attributed to sections that experienced cutting. A total of five wear sections are produced from this and they are the upper tail, upper rail, nose, lower rail, and lower tail. Rail wear measurements are only conducted on cutting tests as the measurable amount of wear during free-running is too small for this fixture.

3.2 Testing Materials

3.2.1 Cutting System

The saw chains used in this study were standard off the shelf Oregon 91PX saw chain made into 52 drive link loops driven by a standard six tooth spur style sprocket. The guide bars used were standard off the shelf Oregon 140SXEA041 guide bars and a modified prototype of the same Oregon 140SXEA041 bar.

Figure 10: Standard guide bar painted black and machined fiducials

The standard guide bar is an assembly of three sheet metal laminates spot-welded riveted together as seen in figure 10. The outer laminates are identical in every way and serve as a means for the chains tie straps to ride along. The center laminate is there for support of the assembly and is smaller than the outer laminates to form the groove that the drive links ride in. The thermal profile of the standard guide bar during free running was investigated for clues as to how to reduce lubrication in the cutting system.

3.2.2 Cutting Media

The timber used for this test was 6x6x30 inch sections of douglas fir timber sourced from a local lumber yard similar to that in figure 11. Knots are an inevitable variation and for equal treatment knots bigger than three quarters an inch in diameter were avoided to achieve a steady and equal wear rate across all groups. In cases such as these, the section with the knot would be skipped so as not to cut through the knot. Examples of this can be seen in cant 7 while cant 6 met the allowable knot criteria.

Figure 11: Variety of wood off cuts showing the variation in grain orientation, density, and composition

Using this style of dimensional lumber saved on cost of testing and replicated more closely the grain style and structure to be found by a professional logger. The variation in the grain size, direction relative to cut, and density in figure 10 displays the differences in the cutting media that cutting tests undergo. While this creates more noise in the operating temperature and other chainsaw parameters this is more representative of the actual use cases in the field.

3.2.3 Lubricant

A plethora of bar and chain lubricants exist and have been tested in the past. Handheld chainsaws predominantly use oil as the bar and chain lubricant and many popular brands exist. As such, all testing in this body of work was done so using STIHL Bar and Chain oil as it is a common bar and chain lubricant used in the field.

3.2.4 Preparation of Testing Samples

For temperature studies using the infrared camera, the guide bar must undergo preparation before any testing. First, the guide bar faces are painted flat black using high-temperature resistant paint so that emissivity can be independent of temperature. Temperatures on the cutting systems are well under 500°F and so a wide variety of paints exist for low-temperature applications such as this. Masking of the rails is done so that paint does not interfere with the saw chain during operation. Once the paint has dried the guide bar is machined with two fiduciary circles at predetermined locations on the guide bar. The fiduciary marks are made using a flat one-inch end mill to score the paint and expose the laminate metal in a one-inch diameter. Doing this allows for the fiduciary circles to be easily spotted on the infrared camera. These markings are used for the temperature to location correlation in the post-processing Mathematica program. With the guide bars fiduciaries in place, the guide bars are then placed in a 212°F oven for 4 hours to bake the paint onto the metal. After the bake time, the guide bars are then cooled over the process of several hours at room temperature. The guide bars are now ready for the last step which is the break-in process. The break-in process eliminates any asperities and microscopic defects in the chain and the guide bar. The break-in process consists of free-running the guide bar and saw chain at 9000 RPM with 22lb chain tension and 3.3mL/min oil flow rate for a total of four hours. These parameters are held during this four-hour period as well. Doing this allows for a highly repeatable cutting system to be tested at any point in the future without having to undergo another break-in process. The maximum temperature varies significantly if this break-in process is not followed as asperities in the saw chain and guide bar cause large temperature fluctuations at the locations of greatest wear.

3.3 Testing Method

3.3.1 Free Running Test Method

The metric used for lubrication performance is the measured amount of wear on the cutting system, locations of wear experience frictional heating which become locations of higher temperature that can be observed through the infrared camera. Thus as the wear rate increases so does the temperature, making temperature a surrogate to wear. Parameters such as chain tension, shaft speed, torque, and flow rate need to be strictly controlled so that a steady-state temperature can be achieved. While these two parameters have a large effect on the temperature, by far the most difficult variable to control is the cutting media. Wood of the same species can vary with every 30-inch section of a cant. Due to this high variability causing fluctuating temperatures between cuts a free-running analysis is first conducted when testing lubrication performance or prototypes. Free running tests consist of a 15-minute warm-up period immediately followed by data collection every minute for eight minutes. During the entire test, all chainsaw running parameters are held in place to attain repeatable and reliable data.

3.3.2 Cutting Test Method

Cutting tests involve using the miniswath to it's fullest capabilities by running an automated sequence cutting actual timber, this test method is a more controlled version of what takes place in the field but is still representative of what the cutting system experiences in the field. Cutting tests differ from free-running procedures in that there is a two-minute free-running warm-up period before the cutting system first begins the sequence of cutting. This allows the system to reach steady-state temperature faster, maximizing the number of usable cuts on the cutting media. Cuts on the miniswath are automated and run off of a run-list that reads in the specified running parameters. The chainsaw starts the cutting sequence by free-running to acquire the specified running parameters via a PID control loop. Once attained the machine locks in place the chain tension and begins to maneuver to a predetermined starting cut position relative to the cutting media. At which time the infrared camera takes an image of the currently free-running cutting system before the cut and then another is taken immediately after the cut but before the cutting system returns to the home position. The miniswath is capable of holding 30-inch sections of a cant which on average can go through 40 cuts on the cutting system before needing a new piece of timber. For equal treatments, guide bars are given the same number of cuts per 30-inch section of wood, this was done to be as fair as possible to the wood variation across all groups.

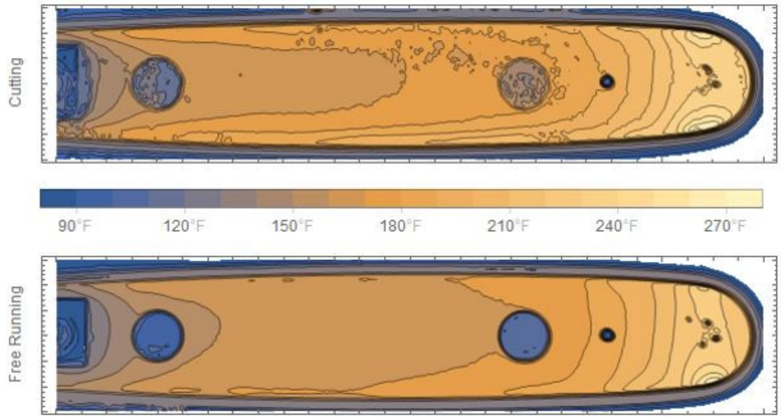

Figure 12: Temperature profiles of the same bar immediately after cutting (top) and while free running (bottom)

The infrared images are sent through a post-processor using a Mathematica program to generate a temperature field with bar location data as seen in figure 11. Performing at field rated operating parameters means that reaching the end of life on cutting system components is typically not met within a reasonable time frame. Therefore, cutting tests were limited to 1,400 cuts per each guide bar and saw chain to expedite testing and to be able to reliably measure wear on the guide bar rails and the saw chain. Given the miniswath enclosure space and the equal number of cuts for each bar per 30-inch cant of wood, this would roughly equate to 55 cant's of wood for each group and would provide enough variability amongst groups to not favor one over the other.

3.4 Data Analysis Methods

The temperature on a running guide bar has been found to have a high correlation to the wear on the guide bar rails in certain areas of the bar. Visible and excessive wear is observed on the upper and lower tangencies of the nose as seen in figure 12. These upper and lower nose tangencies have the largest change in radius occurring along the guide bar rails as the contour changes from an elliptical to circular and then back to an elliptical contour. These locations are also locations where the normal forces from chain tension are highest on sprocket nose guide bars. The sprocket nose serves to lift the chain off the guide bar rails when traveling around the nose, thus enabling tighter chain tension and greater chain speeds while not sacrificing the life of the cutting system.

Figure 13: Typical heavy wear at the nose tangency

These two points are the primary locations for driving the temperature for the entire bar during both free-running and cutting. The temperature difference between free-running and cutting tends to vary but commonly results in a phase shift in temperature due to the varying contact loads and debris of the cutting media. With this in mind, the maximum temperature is used for the analysis of lubrication performance rather than the average temperature across the entire bar. During the development of this metric, the maximum single point temperature was compared to the average temperature in a region around the maximum single point temperature. The difference between the maximum single point temperature and the average temperature in the region was found to be less than 3%. The single point maximum temperature was therefore used as collecting a region around this point would sometimes include temperatures, not on the guide bar. The locations of these points are checked against the thermal profile for inconsistencies or locations, not on the guide bar. The infrared images collected during testing are exported to a comma-separated value format using the ResearchIR software from the FLIR camera. These files are then analyzed in a Mathematica program that finds the fiduciary locations and trims and aligns the image so that pixel data is then transformed into two-axis location data with temperature. This initial processing simplifies investigation methods for outlying temperatures such as the ones found on the locations of greatest wear. From here the thermal profiles like the one in figure 11 are assembled and analyzed for locations of maximum temperature. The maximum temperatures for each image are then categorized into a list for each sample being tested, from which statistical analysis can take place.

4 Results for Improved Cutting System Lubrication

This chapter of the work will be discussing the path taken for improving chainsaw lubrication and the results of the tests conducted. The testing procedures outlined in chapter three were followed to obtain and pass the data and its findings to Blount International. In some cases, the comparisons between the temperature and wear data from this testing and that from pre-existing testing will be discussed.

4.1 Concept Results

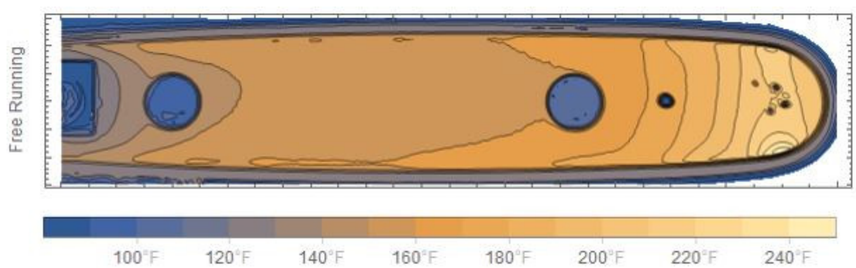

Figure 14: Steady-state thermal profile of standard guide bar and saw chain while free running at 22lb chain tension, 9000 RPM, and 3.3mL/min oil flow rate

The free-running thermal profile in figure 14 shows that while the oil is applied at the upper tail section, the upper and lower tangencies at the nose are the locations of greatest wear and as such the maximum temperature. The lower nose tangency as seen in figure 14 is the location of the maximum temperature. That being said the upper tangency is within 5-10 °F on average of the lower tangency. An idea of inputting lubricant closer to the nose and closer to the rails was developed with the hopes of reducing temperature and wear at these hot spot locations. The prototype concept sample in figure 15 was made to compare inputting oil at the tail (location 1) versus near the nose on the upper half of the guide bar and closer to the rail via a drilled hole in one of the side laminates which then connects to a tube to supply lubricating oil (location 2). In testing, oil was applied to only one location at a time, with location 2 being applied on the side not facing the camera so as not to skew the thermal profile and location 1 being applied as normal. While testing a location, not in use was sealed and covered to prevent leaking oil out of the treatment.

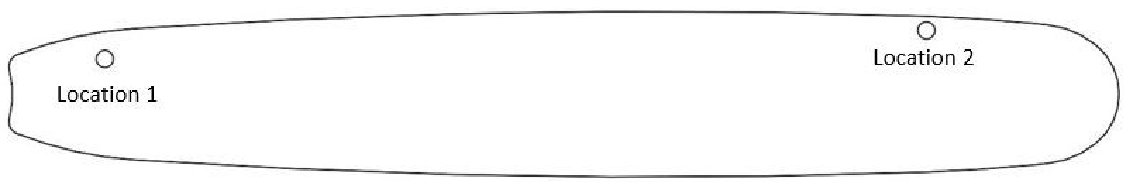

Figure 15: Concept test guide bar consisting of location 1 the standard method and location 2 the new method, external equipment like hoses and fixtures are not shown

The concept test guide bar underwent preliminary free-running testing in which the oil flow rate was varied during the test from 4.1 mL/min to zero mL/min. The test was conducted using the concept test guide bar and began with a 15 minute warm-up at 4.1 mL/min oil flow rate followed by 5 minutes of data collection at 4.1 mL/min. After which the flow rate was then reduced to 3.1 mL/min for an additional five minutes of data collection. This data collection period and flow rate reduction sequence was repeated for flow rates of 2.1, 1.1, 0.5, 0.3, and 0.0 mL/min. Each oil input location was tested three times for a total of six times for the entire test. Additionally, a control test was conducted with oil input at location 1 and a constant oil flow rate of 4.1 mL/min for the entire test duration. Results showed that under the control test conditions, no significant temperature change occurred. However, the testing with decreasing oil-input flow rate resulted in a maximum guide bar temperature consistently increasing several degrees. An important conclusion being that the temperatures corresponding to location 1 were consistently greater than those for location 2 and the difference increased as the flow rate decreased. As such location 2 appeared to be better and become so even more as the oil-input flow rate decreased.

The results of the preliminary free-running test showed promise in reducing the amount of oil required while maintaining the same steady-state free-running maximum temperature. The test indicated location 2 was capable of using 75% less oil during operation than location 1. The results of this indicated two key design concepts, the first being to lubricate closer to the locations of greatest wear. The second being that the oil engagement via oiling through the side laminates closer to the rail is a key feature for ensuring lubrication in the cutting system. Most likely because the distance between the side laminates and the drive link is a fraction of the distance between the bottom of the groove and the drive link tang.

4.2 Prototype Design

Using the design concepts of the method of lubrication in location 2 a prototype guide bar was designed. Channels on the inside of the guide bar would bring the lubricant from the upper tail section forward near the nose. To replicate the oil hose applying lubricant directly to the side of the drive link, an insert was designed to be inserted during the assembly of the laminated guide bar.

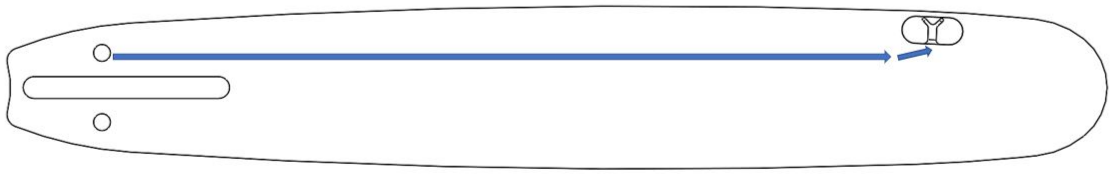

Figure 16: Redirection of oil from the tail to the nose inserts through channels inside the laminated guide bar

The sole purpose of the insert is to take the oil from the center channels and redirect it closer to the rails. Oil is then deposited from the insert onto the sides of the drive link.

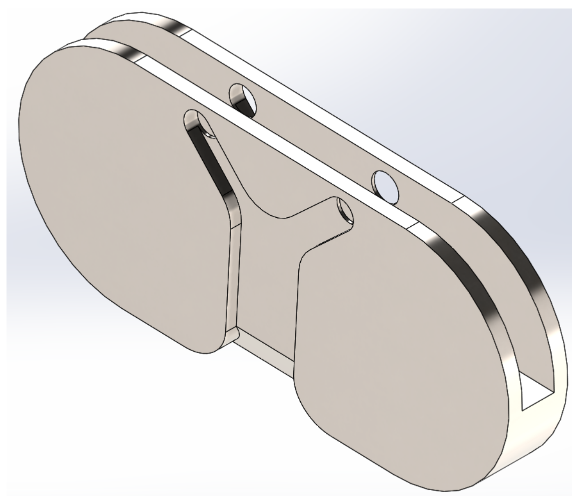

Figure 17: Isometric view of metal insert for redirecting oil from the center channels to the sides of the drive links closer to the rail

The inserts have a wedge at the bottom that splits the oil in half and is directed up the spine of the Y-shaped channel where it is then split in half again to then be deposited out the two holes on each side of the insert as seen in figure 17. As the drive link passes it is washed with oil from a total of four outlet holes, two on each side of the drive link. Four holes were chosen to help mitigate lubricant starvation when a hole gets clogged. These redundant holes will increase the oil outlet velocity for every hole that becomes clogged. Thus making it difficult for other holes to become clogged when one becomes clogged.

Figure 18: Prototype guide bar painted black and machined fiducials showing the exterior plates used for holding the inserts in place while running

The prototype bar in figure 18 was assembled using the same materials as the standard off the shelf guide bar with a few exceptions. The first being that the center laminates had oil channels cut out for maneuvering oil from the tail section towards the nose of the bar. The second modification is the cut-out sections toward the nose, these cut-outs serve to hold in place individual metal inserts. The cutouts and exterior plates allow for testing of the concept while maintaining all tested bars have the same standard heat treat process and as such the same material wear characteristics. All bars tested underwent the prescribed sample preparations described in chapter 3.

4.3 Free Running Comparison Results Discussion

All samples first conducted the prescribed break in procedure followed by a free-running test to verify that steady-state temperatures were able to be achieved. All samples successfully achieved steady-state temperatures and so a random bar from the three prototype bars was chosen to conduct a comparison free running test. Using one broken in prototype and standard guide bar a randomized second level three-factor full factorial free-running experiment was conducted with blocking on three replicates. The three factors for this experiment were chain tension, oil flow rate, and guide bar type. The two levels for each factor were 16lb and 22lb for chain tension, 0.8mL/min and 3.3mL/min for oil flow rate, and standard and prototype bar for guide bar type. In figure 19 the guide bars at 22lb chain tension can be seen to have performed differently based on the average maximum temperatures. At the 3.3mL/min flow rate, the prototype bar runs hotter than the standard bar by 3°F. When the flow rate was reduced to 0.8mL/min the performance switched and the guide bars increased temperature but the prototype increased by 8°F and the standard increased by 23°F. Similarly in figure 20, the guide bars were at 16lb chain tension and the prototype bar ran only 2°F hotter than the standard bar at the 3.3mL/min flow rate. When reduced to 0.8mL/min it switched with the prototype bar increasing by 4°F and the standard bar increasing by 15°F.

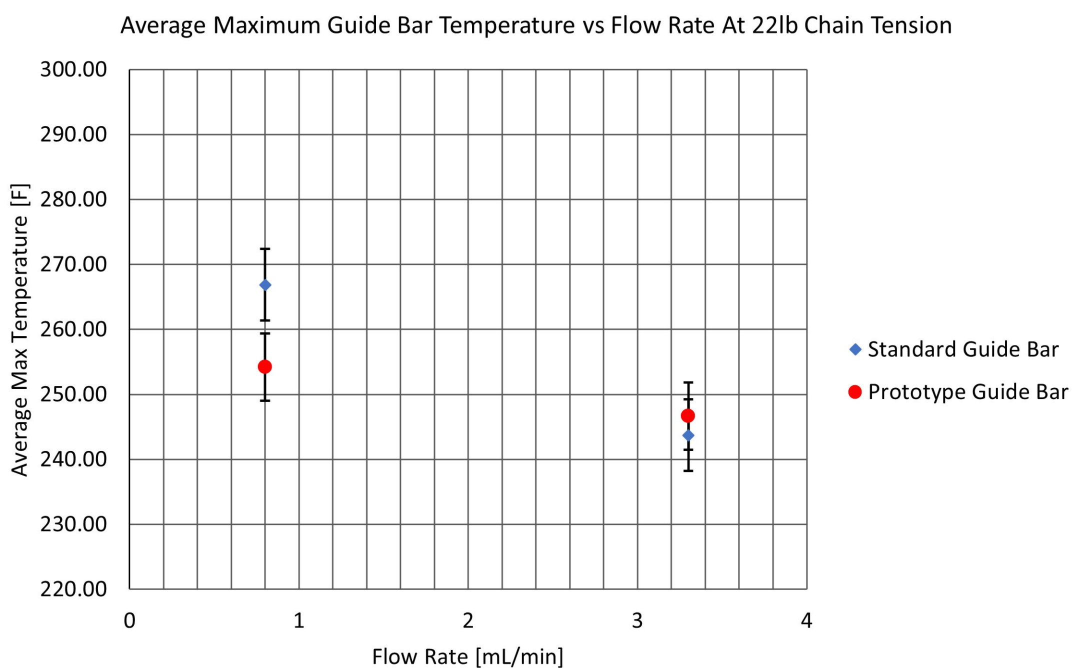

Figure 19: Free running temperature comparison test of standard and prototype guide bars at 22lb chain tension

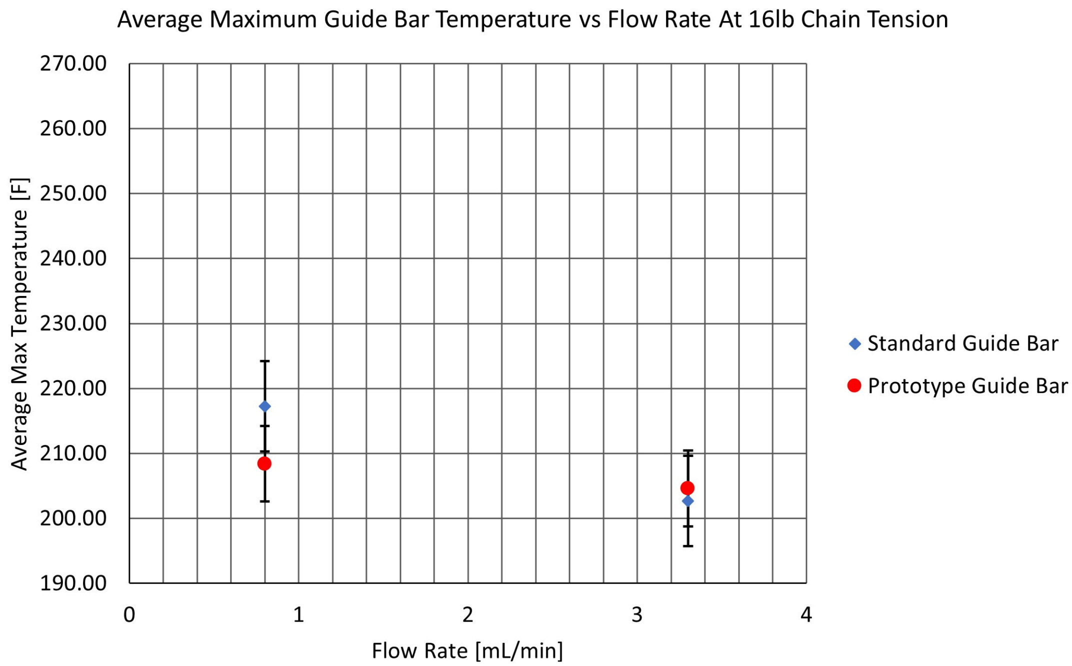

Figure 20: Free running temperature comparison test of standard and prototype guide bars at 16lb chain tension

The results of the free-running test confirmed previous understandings about lubrication on the cutting system. The first being that a reduction in oil flow rate will inevitably lead to an increase in temperature on the cutting system regardless of chain tension. The differences in the method of application of the oil follow this trend but with different rates at which the temperature increases. The prototype guide bar and method of lubrication resulting in a smaller increase in temperature giving confidence that the trend should continue during cutting by less wear being measured. Comparing the rates of temperature increase from both figures 19 and 20 would conclude that a chain tension value exists where these two temperature rates become more or less the same. This fact is likely true but as the chain tension decreases the probability of throwing the saw chain off the guide bar while cutting increases. This is a well-known phenomenon in forestry and is typically avoided by properly tensioning the cutting system.

4.4 Cutting Comparison Result Discussion

The free-running results showed that the prototype guide bar performed better than the standard guide bar at a reduced oil flow rate but a cutting experiment was needed to validate. With the miniswath only allowing for a maximum of 30-inch sections of wood, the 22lb chain tension parameter was chosen to move forward as this better represents chain tensions used in the field. An equal number of cuts for each guide bar type was performed so that equal treatments to the wood variation would be seen on each group. Each group consisted of one prototype guide bar and one standard guide bar to compare the average wear on all three groups after each guide bar performs 1,400 cuts at an oil flow rate of 0.8mL/min. The individual measurement locations on the guide bar rails around the guide bar were broken into groups denoting sections of the guide bar rail as described in chapter 3. These five groups and the correlating bar rail wear measurements with them can be seen in figure 21.

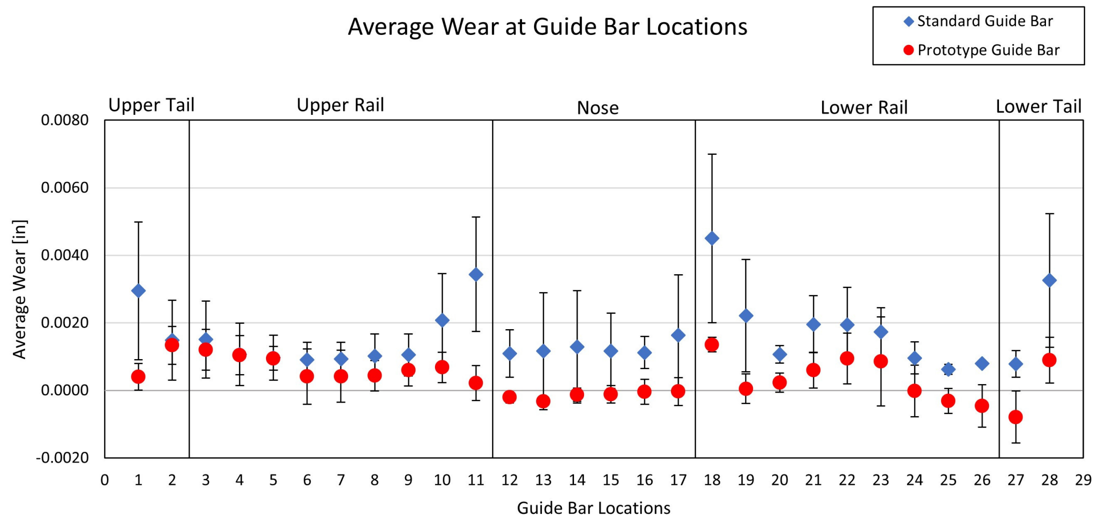

Figure 21: Average guide bar wear at locations on prototype and standard guide bar after 1,400 bucking cuts

Wear measured on the upper tail and upper rail sections of the prototype and standard guide bar show that the prototype guide bar performed the same if not marginally better than the standard bar. The exception to this is locations 10 and 11 which are near the upper nose tangency of the guide bar that is a known location of excessive wear. Interestingly enough is that the upper tail and upper rail sections are the first to receive lubricant on the standard guide bar yet the lubricant is not applied to the prototype guide bar until location 10. It is speculated that lubricant retention is greater on the prototype guide bar as oil is applied directly to the upper portion of the drive links and is not expelled as easily. The nose section data in figure 21 would suggest that the prototype guide bar performed better in this section. Unfortunately, locations 13-15 on the standard guide bar in the first group experienced slightly more wear while cutting. This trend did not continue on the other two groups or at all on any of the prototype guide bars and if the first group's data is thrown out completely then locations 13-15 on both guide bars performed similarly. As such the standard deviations on the nose section of the standard guide bar are larger than what would be anticipated. Just before the lower nose tangency at location 17 and then near it with locations 18 and 19, the prototype guide bar performed better. These locations are also areas of known excessive wear during the operation of the cutting system and are locations preceding the active cutting regions on the guide bar. The lower rail section was directly involved with the bucking cuts and in figure 21 it can be seen that the prototype guide bar performed better on average than the standard bar. Locations 25, 26, and 27 on the prototype guide bar in figure 21 experienced a small amount of raised deformation on the outer edges of the guide bar rails likely caused by the chain striking the guide bar during cutting. These small but visible dents are located on a portion of the guide bar that is after the cutting zone where the chain is no longer in direct contact with the wood. A theory as to why denting takes place at these locations is that the chain transitioning from out of cutting the wood is erratic enough to cause the chain to whip and impact the guide bar. Further testing with a high-speed camera recording these locations would be able to determine if the chain is impacting the guide bar at these locations. Overall there is an indication that the average guide bar rail wear on the prototype guide bar was less than the standard bar at lower flow rates.

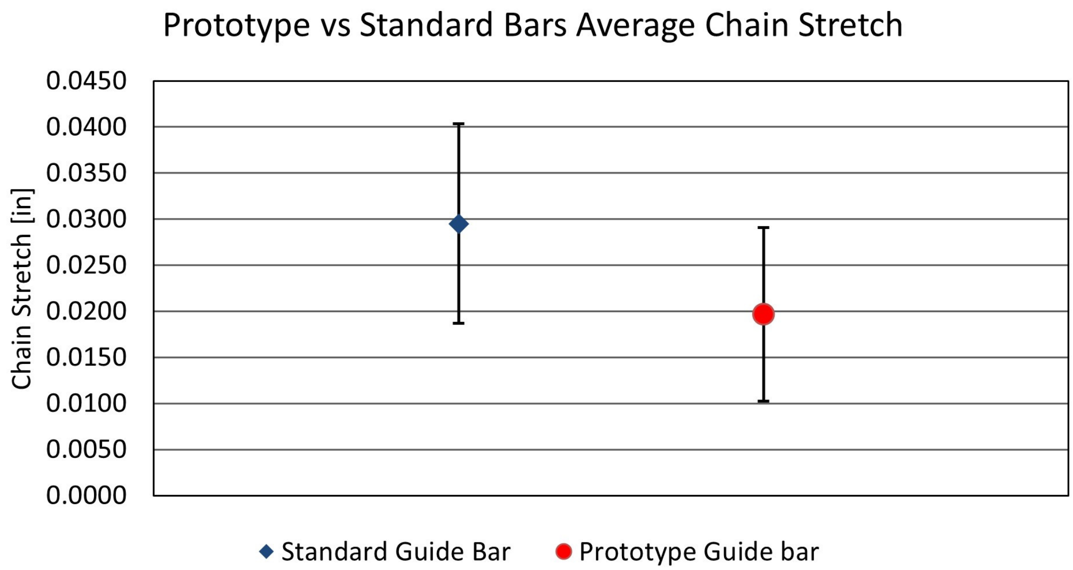

Figure 22: Average chain stretch comparison of saw chain ran on prototype and standard guide bars after 1,400 cuts each

The average stretch on the saw chains for each guide bar type in figure 22 utilized the saw chain wear fixture described in chapter 3 for obtaining measurements. These were off the shelf components with the only difference being to what guide bar the saw chain was assigned to. From figure 22 it can be seen that saw chains on the standard bar experienced more wear than saw chains on the prototype bar. Again concurring with the methodology behind the prototype bars lubrication, applying oil closer to the nose and closer to the rails should aid in getting the lubricant to the places that it needs to go. That being said the saw chain wear's standard deviation shows more overlap between the two groups than the majority of the sections of the guide bar rail wear. Overall the wear data collected from the cutting tests indicate a statistically significant reduction in wear along the nose, lower rail, and lower tail on the prototype bar compared to the standard bar when operating at low flow rates. These results concur with the previous free running test results with the prototype bar operating at lower temperatures at a lower flow rate than the standard bar at the same flow rate. The 1,400 cuts performed on each guide bar is a fraction of the guide bar's expected life but indicates the potential of this lubrication prototype. The next step for this pursuit should be the redesigning of the prototype to be all-inclusive in the current guide bar assembly so that all modes of cutting may be tested. Boring cuts and biased cutting load the saw chain and guide bar differently and are certainly worthy of study as these cutting techniques are used in the field. The down bucking cuts performed in this body of work was chosen as it remains the primary cutting technique used in the industry. Along with this, field testing would provide considerable feedback as it remains the ultimate test as to whether users will notice the difference in lubrication enough to consider a guide bar that uses considerably less lubricant.

5 Conclusion

The primary goal of this body of work was the improvement of the lubrication performance on the chainsaw cutting system through the means of a prototype feature capable of reducing the lubricant required by the cutting system. A vast amount of research exists on lubricants with some of them being specifically on the cutting system. Tribological studies have been conducted on oils in the hope to better improve the lubrication performance. Included in these studies are environmentally friendly lubricant options since the lubrication of a chainsaw is a total loss system, throwing off a lot of the lubricant applied. These studies aid in decreasing the impact that forestry operations have on the environment while also keeping the chainsaw users in mind. This work sought to aid in lessening the environmental impact while also enabling the chainsaw user to purchase less lubricant. The investigation of a standard hand-held guide bar and saw chain using methods developed for a lab-based test apparatus gave clues as to how lubrication performance could be improved. A concept was then built around the findings of the investigation and tested using preliminary free-running testing with varying flow rates. This testing showed promising results in improved lubrication performance at location 2 but required additional testing. A small batch of prototype bars was constructed with new lubricating features and tested against a small batch of standard bars using both free-running testing and cutting test methods. The results from the free-running test showed that the lubricating features in the prototype bar improved lubrication to the point that 76% less lubricant could be used with only a marginal increase in maximum guide bar operating temperature. While the cutting test results showed that a 76% reduction in lubricant saw less wear on the prototype guide bar than the standard guide bar at the same reduced flow rate. The material provided by Blount International was done to expand the knowledge and attempts at lubrication reduction. The testing methods and the methods of wear measurement were established with the help of the industry experts at Blount International. Throughout this investigation into lubrication reduction, some results supported previous findings and knowledge about lubrication while some results confirmed theories and hypotheses about lubrication of the cutting system. Further testing of a finalized design with various cutting modes and field testing will truly reveal the potential of the concepts behind this lubricating feature. This author hopes that the continuation of this work by Blount International will result in a cutting system capable of using less lubricant while maintaining the same if not less wear than the current standard today within the near future.

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