High Performance Blade Evaluation

Final Report

research for winter highway maintenance

University of Akron

Project 1031542/CR18-02
January 2023

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16. Abstract (Limit: 250 words)

The project began in the summer of 2019 and was completed in the winter of 2023. In this project, the research team investigated the wear of snowplow blades using three different sampling techniques. The first technique was large scale sampling that was completed in Idaho. The second sampling technique was small scale sampling that was completed in Norway. The third sampling technique was laboratory testing of individual snowplow blades. The results of this study provide the end user with a standard test protocol for testing snowplow blades. While the sampling size was limited, the results suggest that each of this sampling techniques are effective in measuring the wear of a snowplow blade.

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FINAL REPORT

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EXECUTIVE SUMMARY

Winter maintenance costs are nearly 27% of a state's Department of Transportation (DOT) maintenance budget (Highway Statistics 2018*)*. Winter maintenance costs encompass operators, mechanics, winter maintenance trucks, chemicals, plow blades, etc. The costs within winter maintenance should be monitored in order to maximize a DOTs limited budget. As a result of financial constraints, DOTs are constantly trying to make winter maintenance operations more efficient and effective. One of these costs is plow blades. Plow blades are the component of the plow that removes the ice and snow from the road; therefore, blades are usually the greatest wear part of a winter maintenance truck. To improve winter maintenance, DOTs should select plow blades that resist the most wear. This will ensure the blade is a cost- effective purchase for a DOT. The goal of this research is to help DOTs test plow blades to reduce costs.

A standardized protocol will help provide a quantitative metric which will ensure that a DOT has a plow blade that works for their winter maintenance goals. Creating a standardized protocol will save a DOT monetarily and will provide a quantitative model to assess a blade's function. To save money while not hindering operational performance is paramount in establishing how to capture the price in a standardized model.

The most common methods used for a standardized protocol include both field and laboratory tests. Field testing is the ability to test a product in its natural environment. Testing a blade in its natural environment allows the evaluator to see the product perform where it is intended; however, this testing environment has the greatest amount of variability which makes the testing more realistic (Aziz, Hassan 2017). Field testing may be expensive, time consuming, and allow for a large amount of variability due to different weather conditions, individuals taking measurements, and equipment being used. Small-scale field testing may limit variability that occurs with field testing. Decreasing the number of blades utilized and the individuals participating in a large-scale study should limit variability due to DOT. Limited variability of a small-scale study is due to controlling environmental factors which may be done by only using one operator (eliminating operator variation), plowing over one road (elimination road variation), or plowing on a dry road (eliminating weather conditions). Reducing factors should allow for a more controlled environment; however, this method is only useful for a finite number of blades due to the added labor cost.

Another testing method is laboratory testing. Laboratory testing has aspects that are controlled in the lab that have less variability than that of field testing; however, the controlled aspects may be argued are what make field results more realistic than lab results (Sun, Xu, and Andrew May 2013). Therefore, there are benefits and faults with laboratory testing and field testing. Combining the two may fully encompass the benefits of both testing methods.

The results from this study suggest formal testing is the recommended method of testing. Formally testing the blades is conducted utilizing either large-scale or small-scale field testing with laboratory testing. Performing large-scale or small-scale field tests will provide chronological information on the wear of the blade and the conditions which the blade encountered (weather or road material).

Laboratory testing may be conducted pre or post field testing to establish blade qualifications. Having the wear information on multiple blades will help establish the ranges of specifications. Over a period, a DOT will be able to utilize the wear and lab testing information to establish the ranges of high/poor performing blades and the specifications that indicate high/poor performing blades. This may be promoted by a DOT as the new specifications and ranges to seek out for a plow blade or avoid for a plow blade.

This study provides DOTs with tools for assessing the wear of plow blades and establish quantitatively if the blade is cost-effective or at least cost neutral. This study provides DOTs with the tools to conduct their own testing. In addition to providing testing methods, it also allows for a DOT to select testing based off its financial abilities. Additionally, the study allows DOTs to assess their blades for normal and abnormal performance as well as assess if the blade is a financially viable purchase or not. The last benefit of this study is the suggestion for implementing data warehousing which will allow for DOTs access a large amount of data which will decrease the cost to a specific DOT to have statistically significant results, make definitive standard graphs for blades, and allow for future blades to be easily tested and compared to past blades.

CHAPTER 1: INTRODUCTION

According to the Federal Highway Administration (FHWA), there are approximately 5,891,000 vehicle crashes each year. Of these crashes, roughly 21% are weather-related, which resulted in approximately 5,000 fatalities (FHWA 2020). Within the 21% of weather-related crashes, 18% are due to snow or sleet, 13% occur on icy pavement, and 16% of weather-related crashes take place because of snowy or slushy pavement (FHWA 2020).

Traditionally, winter maintenance agencies utilize equipment that is capable of chemically and/or mechanically removing snow and ice from the roadways. Chemical snow removal is used to discard or prevent ice from bonding with a roadway. Chemical snow treatment may be done prior to a storm, during, or post storm. Preventative chemical treatment is called anti-icing and occurs prior to a storm to prevent bonding of a roadway with ice; however, reactive chemical treatment is called de-icing and occurs during a storm in conjunction with mechanical snow removal (Schneider, W. 2017). Therefore, chemicals are used to prevent snow and ice from bonding to the road, while mechanical removal physically displaces the snow and ice from the road.

Winter maintenance costs are nearly 27% of a state's Department of Transportation (DOT) maintenance budget (Highway Statistics 2018*)*. Winter maintenance costs encompass operators, mechanics, winter maintenance trucks, chemicals, plow blades, etc. The costs within winter maintenance should be monitored in order to maximize a DOTs limited budget. As a result of financial constraints, DOTs are constantly trying to make winter maintenance operations more efficient and effective. One of these costs is plow blades. Plow blades are the component of the plow that removes the ice and snow from the road; therefore, blades are usually the greatest wear part of a winter maintenance truck. To improve winter maintenance, DOTs should select plow blades that resist the most wear. This will ensure the blade is a cost- effective purchase for a DOT. The goal of this research is to help DOTs test plow blades to reduce costs.

1.1 PURPOSE AND OBJECTIVES

The University of Akron, Norwegian University of Science and Technology, and Clear Roads Technical Panel, noted as the research team, will collaborate on the Clear Roads project 18-02: High Performance Blade Evaluation.

The four primary objectives of this project are as follows:

- <u>Objective One</u> – develop a standard field test protocol for evaluating blades to determine if the blades being tested are cost effective.
- <u>Objective Two</u>- identify existing laboratory testing that may be used with field testing.
- <u>Objective Three</u>- develop a protocol to assess if a blade is wearing normally and if a blade cost neutral.
- <u>Objective Four</u>- present a way to incorporate current and future blade testing into an efficient and comprehensive blade research warehouse for DOTs.

Objective one will help a DOT by providing an efficient and effective way to test new plow blades on wear, longevity, and cost.

Objective two will help ensure the quality of the plow blades that DOTs are receiving are what is expected. This in conjunction with field testing should help DOTs evaluate the wear of the plow blade.

Object three will provide a DOT with the tools to establish if a new blade is an effective purchase and is being worn as expected.

Objective four will help DOTs and researchers to evaluate the merit of comprehensive research potential in one central location. The suggested development of a data warehouse should house old research, supply more research, and help include significant data of plow blades for DOTs to utilize.

To meet objectives one and two, the research team will provide standard tests for not only a field setting but also a lab setting to promote multiple methods of assessment that a DOT may replicate for a reduced cost and a shorter duration. To meet objective three, the research team will present current wear and mileages associated with plow blades to assist a DOT in establishing if a blade is wearing normally. Additionally, the research team will use costs associated with plow blades and current blade wear and mileage rates to help a DOT determine if a blade is a cost neutral purchase. To meet objective four, the research team will establish the importance of data warehousing and detail specifically how it may be easily implemented into a DOTs standard practice.

1.2 BENEFITS FROM THIS RESEARCH

This research project should provide Clear Roads with a straightforward blade testing protocol that may be used to help winter maintenance operations. This testing protocol will be of great benefit. Standard testing protocol recommended by this study will allow DOTs to test blades in in-field, and post field settings in order to find a testing setting that best suite a DOT. In addition to field testing, a lab testing protocol is created to determine the blade's properties. The testing protocols will provide DOTs with a quantitative way to compare plow blades and will allow them to conduct their own evaluations so that they are receiving a higher quality product for their needs. In addition to testing protocols, the research team provides DOTs with methodologies to assess a blade for cost neutrality, which will save DOTs money and provide a quantitative metric that may be used in the future.

1.3 ORGANIZATION OF THIS REPORT

The organization of this report is divided into seven chapters. Chapter One introduces the topic of winter maintenance operations and the purpose of this report. Chapter Two involves the background of mechanical snow removal equipment. Chapter Three provides insight on the current state of the practice with a literature review, national survey, and a vendor survey. Chapter Four details the testing protocol, how the testing will be done, the importance of each factor, and case studies that are conducted utilizing the testing protocol, which includes field testing and laboratory testing. Chapter Five summarizes the standardization of the results. Chapter Six summarizes the purpose, importance, and benefits that data warehousing will provide to DOTs, and Chapter Seven summarizes the research conducted in this study.

CHAPTER 2: BACKGROUND

Mechanical removal of snow involves relocating the snow/sleet from a roadway lane to the median or rumble strip to make a safe passage for drivers. Mechanical snow removal uses a plow that may be oriented in four ways: tow, front, wing, and underbelly as seen in Figures 2-1 through 2-3.

Figure 2-1: Tow Plow

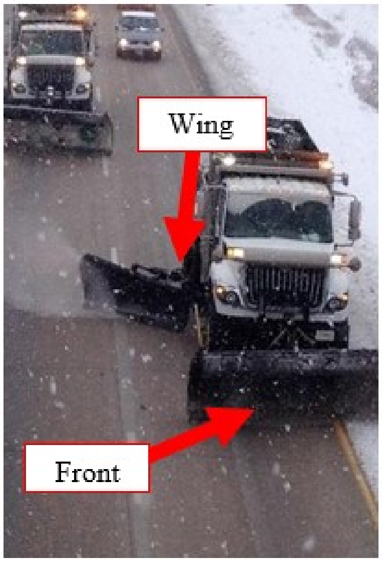


Figure 2-2: Wing and Front Plow ("Mechanically Removing Snow." (Crow 2017))

Figure 2-3: Underbelly Plow ("(A) Underplow." (Crow 2017))

The plow orientations displayed in Figures 2-1, 2-2, and 2-3 are dependent on the DOT. Figure 2-1 is a tow plow which is towed behind the snowplow truck. Figure 2-2 shows a front plow and a wing plow (Snow & Ice Control Guidebook 2016). Figure 2-3 is an underbelly plow which is located under the snowplow truck.

A combination of down pressure and angle of plow affects the wear of a plow blade. The angle of the plow is either determined by DOT/municipality, plow manufacturer, or blade manufacturer specifications. A plow blade manufacturer may recommend how the plow is angled to achieve an effective clearing of the roadway. A DOT has the final say on what angle recommendation they use or if they, from their own experience, have an angle they prefer.

2.1 FRONT PLOW AND COMPONENTS

The first component that a front plow may have been a tripping mechanism. Tripping mechanisms are used to protect a snowplow from damage which may occur from obstacles in the roadway (Pell 1994). These tripping mechanisms either use a moldboard or a trip-edge blade to allow the blade to roll or float once it hits an obstacle to reduce the risk of breaking (Day 2003). Figure 2-4 shows how a tripping mechanism helps a blade avoid damage from an obstacle.

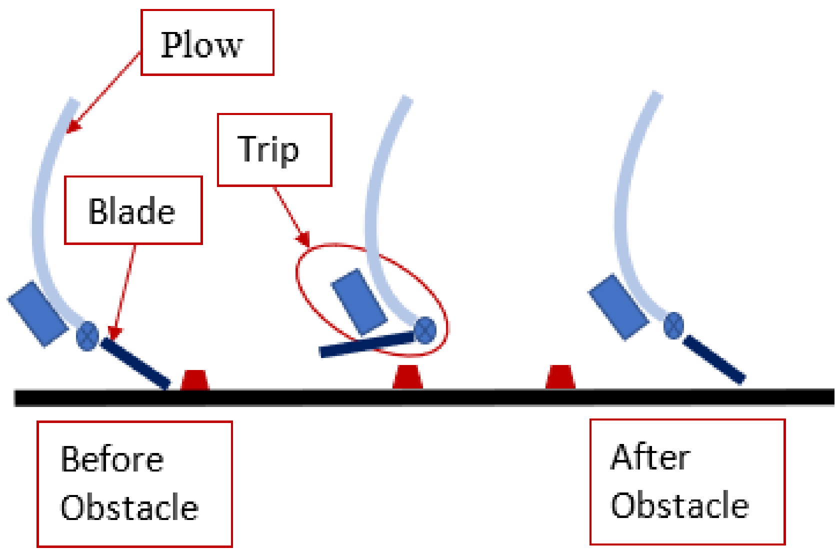


Figure 2-4: Tripping Mechanism

Aside from a tripping mechanism, shown in Figure 2-4, snowplows have multiple components that assist in the mechanical clearing of snow and ice from the road. The other potential components on a snowplow may be seen in Figure 2-5.

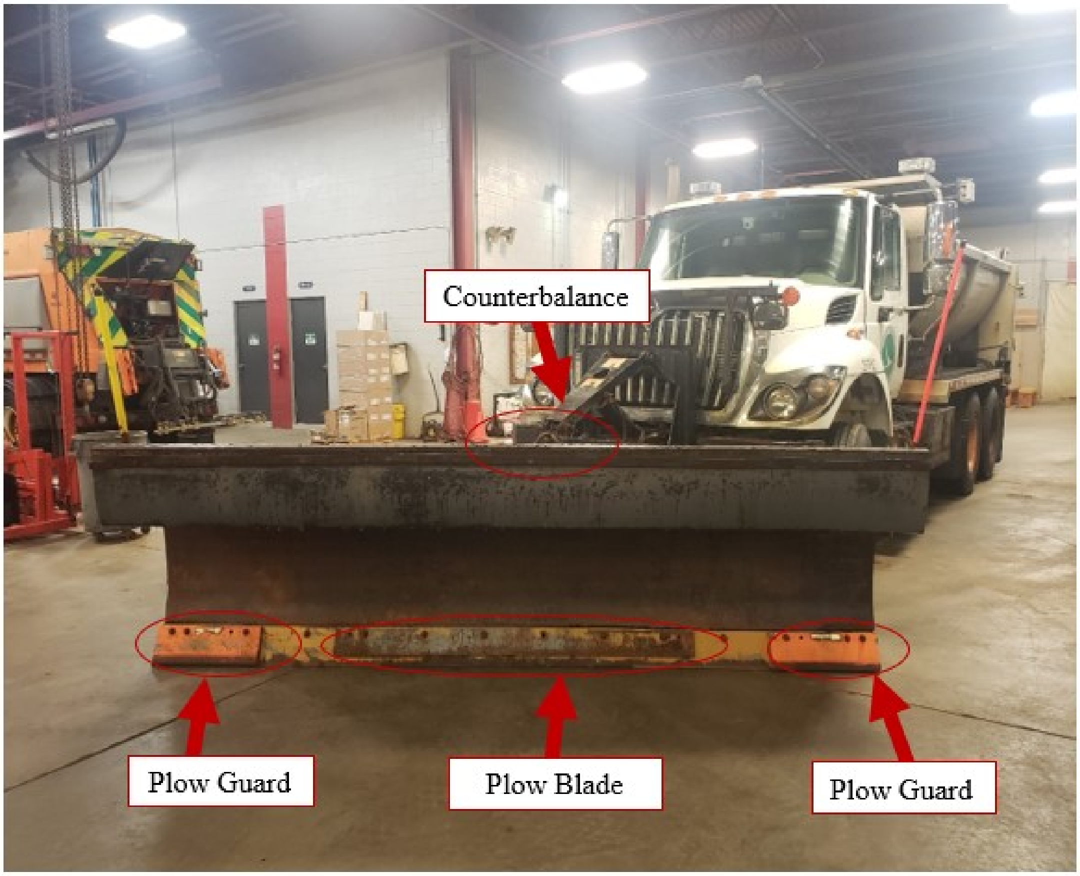


Figure 2-5: Front plow

The first component is the counterbalance which is used to offset the weight of the blade on a snowplow to ensure there is no tipping forward or backward dependent on its angle. The counterbalance engages a force that reacts to an opposite force to balance or limit influence of the opposite force. The second component is the plow guards. Plow guards are used to protect the plow blade from hitting obstructions and help reduce wear at the locations which they are placed. The third component is the plow blades. The plow blade is the component which experiences the greatest amount of wear due to the blade being in direct contact with the ground (Schneider et al 2015). A typical plow blade for DOT uses two generic orientations: a straight blade or an articulated blade. Figures 2-6 and 2-7 show the two orientations of a plow blade.

Figure 2-6: Straight Blade

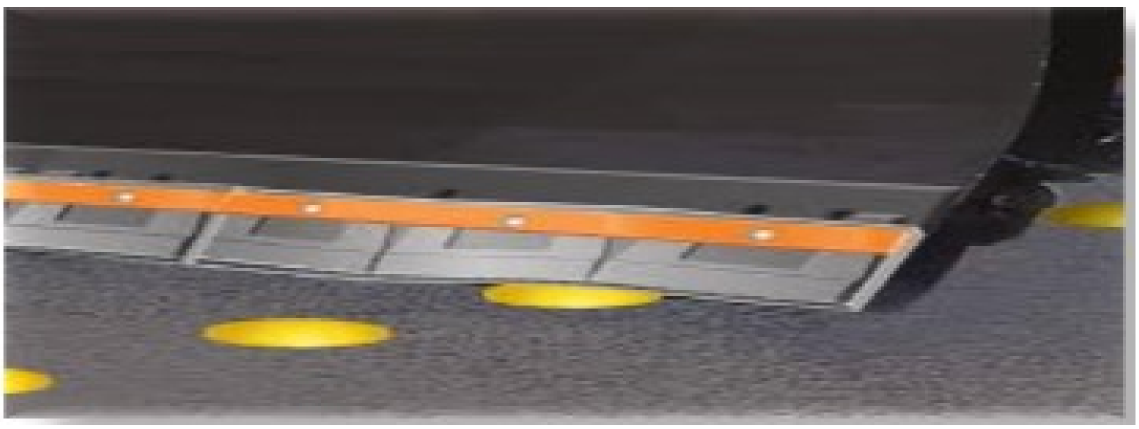


Figure 2-7: “Pictures of What Articulating Means”

Source: (Bartuseck 2016)

As seen in Figure 2-6, a straight blade is one cohesive piece blade with no breaks. A straight blade is typically more difficult to install as compared to articulating blades. Additionally, straight blades are less expensive than articulating blades. Articulating blades, as seen in Figure 2-7, are segmented lengths of plow blades of carbide, steel, and hybrids usually encased in rubber. Segmented blades tend to adhere to the road more closely than straight blades and prevent damage from roadway obstructions (Bartuseck 2016). Aside from having multiple options of plow blade orientations, there are also a variety of plow blade material compositions.

Plow blades are made of steel, carbide, rubber, rubber ceramic, and polymer. The material used for a plow blade helps determine its capital cost and how rapidly the blade will wear. The blade selected by a DOT is based off its hardness, toughness, strength (Seowerkz 2018), and ability to resist damage to property. Hardness is the ability of a material to resist abrasions or wear. Toughness is a material’s ability to resist fracture. The third property of interest is strength which is the materials ability to resist deformation. The ideal plow blade would be able to resist abrasions, resist breakage, and be able to withstand a heavy load; however, there is a tradeoff for mechanical properties which is dependent on the material. The last material property that DOTs are interested in is a materials ability to resist damaging property. This ability to resist damaging property occurs when the plow blade material may flex or morph around a permanent obstacle to ensure that the permanent obstacle is not damaged during plowing.

The first plow blade material typically selected by DOTs is steel. Steel is inexpensive, but it has the potential to snap when hitting obstacles (Nixon 2012), is difficult to install and remove, and wears faster than other materials (Snow & Ice Control Guidebook 2016). There are two varieties of steel blades: steel blades and steel blades with carbide inserts. Carbide inserts are used to increase steel blades' durability. Figure 2-8 shows how a carbide insert is configured into a plow blade.

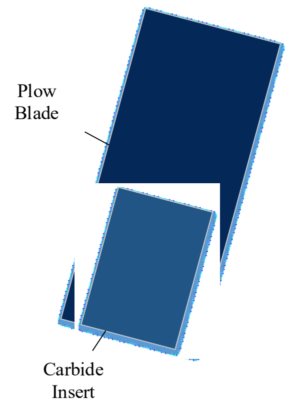


Figure 2-8: Carbide Insert

As shown in Figure 2-8, a carbide insert is a part of a plow blade. These inserts may be added to any type of plow blade to help reduce wear given carbide's hardness and toughness (Garcia et al. 2018). Carbide inserts are cemented carbide. Cemented carbide is powdered carbide, typically tungsten carbide, mixed with a metallic binder, typically cobalt. Tungsten carbide is the hardest material available in the market, which has a hardness close to that of a diamond (Shemi et al. 2018). Due to this hardness, tungsten carbide should have a long wear life; however, it has a reduced ability to resist fracturing.

The third material available for plow blades is rubber. Rubber is a less expensive blade material. It is preferred if the road has many obstacles because it morphs around the obstacle compared to other harder material types; however, a rubber blade wears faster than other materials (Nixon 2012). Rubber ceramic has the same characteristics as rubber, but rubber ceramic has a longer wear life and is better at clearing; however, rubber ceramic blades have the capacity to break easily should they be placed onto the ground too hard by the plow (Bartuseck 2016). This easy break capacity is due to the ceramic aspect of the blade.

The last plow blade material available is a polymer. Polymer blades are significantly quieter than traditional blades and are known to reduce vibration while plowing which is a favorable aspect; however, polymer blades are a newer product and not as frequently used. The material that a plow blade is composed of effects not only its cost but also its wear.

Wearing a plow blade may be categorized as normal or abnormal. Normal wear is due to an abrasive process through daily plowing. When a blade is no longer able to clear, it is considered a failure. (Jafari et al. 2018). Normal wear is expected meaning, it does not wear faster than anticipated; therefore, abnormal wear is when the blade wears faster than expected. Figure 2-9 shows the categorization of wear and its components.

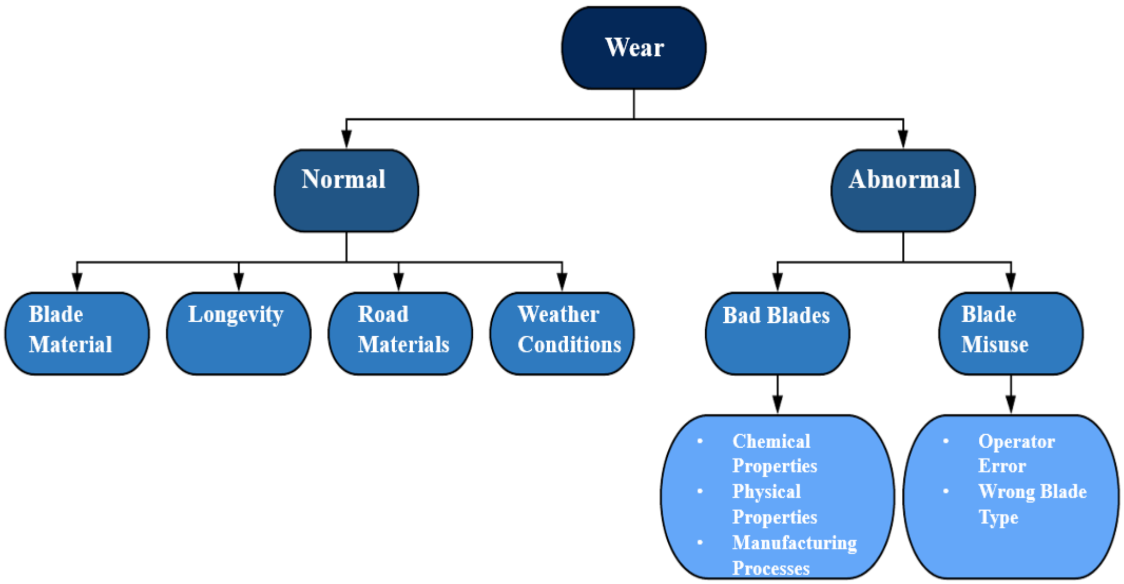


Figure 2-9: Wear of Blades

Normal wear of a plow blade occurs due to blade material, longevity, road materials (friction), and weather conditions. The first factor that affects normal blade wear is blade material type. A plow blade's composition may allow a lesser or greater mileage achieved before failure (Oberg 2016). The next factor is longevity, which may be noted as the duration spent plowing or the miles spent plowing. It is the duration or life the blade has spent in service. The wear longevity is determined by the blade material's chemical composition, hardness, toughness, and physical composition. Additionally, road materials are an important factor in blade wear. There are three main road types that a DOT plows over: asphalt, chip-seal, and concrete. The wear on a blade when traveling over asphalt is different than that of chip-seal and concrete. This variation in wear is due to how coarse the different road types are. The coarse the material the greater expectation for wear (Nixon 2012). Lastly, weather conditions affect how a blade will wear. Wet weather conditions (snow and slush) help cool the blade from overheating while plowing; therefore, dry weather conditions allow a blade to heat up and wear faster than in wet conditions.

Abnormal wear, as seen in Figure 2-9, occurs for two reasons: bad blades or blade misuse. Bad blades are blades that have improper chemical properties, physical properties, or manufacturing processes. The first bad blade factor is chemical properties. When the chemical properties of a blade are not as expected, the blade will not resist wear or resist breakage as a properly chemically composed blade. Inability to optimally resist wear or breakage will cause unexpected failure earlier than anticipated (Braun Intertec Corp. 2010). Additionally, having poor physical condition of a blade may cause abnormal wear. Abnormal physical properties of a blade may include the porosity of the blade. Increased porosity may increase wear or increase susceptibility to corrosion causing early failure (Braun Intertec Corp. 2010). Lastly, poor manufacturing processes may cause a bad blade. Poor manufacturing processes may cause microcracking of a blade which has the same problems as poor physical wear: increased wear or increased susceptibility to corrosion. In addition to bad blades, blade misuse also causes abnormal wearing of a blade.

Blade misuse is abnormal wear caused by operator errors or the selection of an inappropriate blade for the environment. Operator error may be in the form of improper down pressure, plowing into obstacles on the road, improper plowing techniques, plowing at a high speed, and truck maintenance. Improper down pressure and plowing into obstacles both cause breaking of a blade which will cause unexpected failure of a blade. Plow down and obstacle blade breaks may be due to improper plowing techniques. If a blade is used during optimum conditions that a plow driver may provide (down pressure, speed, and ability to avoid obstructions), a plow blade should perform properly with no increased wear (Braun Intertec Corp. 2010). Proper technique will ensure no increased friction or strain on a blade that may surge a blade's wear. To negate failure due to DOT error, the research team recommends training operators and supervisors.

Clear Roads Project 14-03 studied interchange plowing techniques and the most efficient and effect ways to remove the snow from these areas (Quin et al. 2018). The goal of Clear Roads Project 14-03 is to help agencies better train operators, manage resources, and improve service levels to the public. Ensuring that DOTs follow the most effective and efficient options may negate bad DOT practices and help the DOT with consistent training of their fleet. In addition to the report published by Clear Roads, they have a 66-minute video showcasing these practices which may be viewed by anyone (Clear Roads 14-03 2018). Clear Roads offers snowplow operator and supervisor training as flexible training modulus for supervisors and operators (Johnson, Grothaus 2017). For the purposes of negating blade breakage, the research team recommends module 1: plowing procedures, modular 2: truck operations, modular 16: weather basics, modular 20: record keeping, and modular 21: getting ready for winter; however, the other modulars are helpful training techniques that may be utilized prior to the winter season. After training materials are provided and reviewed, a DOT should commence field testing. Additionally, increased speed on a blade will cause failure faster than normally anticipated. Therefore, tracking the speed of the plow when plowing should assist in determining if the speed of the plow reached a faster than normal speed.

The last factor for abnormal wear is due to the wrong blade type for the environment. As discussed previously, there are benefits and negatives to numerous blade types. If blade misuse is occurring, it is typically because the blade material selection is not meeting the needs of the DOT to either resist wear, resist fracture, or resist force. When the blade type is improper a DOTs common problem may include:

1. Breaking blades,
2. Quickly wearing blades,
3. Removing raised markers, or
4. Increased driver fatigue.

These problems may be indicators of blade misuse. A blade breaking may be due to the blade being used not having the proper toughness. Switching to a blade that is more capable of resisting fracture or a blade that may morph when impacted should fix breakage (Nixon 2012). The second factor is fast wear. This factor may be blade misuse or bad blade. The third factor is if raised markers are being removed. If this is happening, then the DOT may want to switch to a more flexible blade material like rubber or an articulating blade (Bartuseck 2016). The last factor occurs when driver fatigue is an issue. Switching to a blade known for vibration suppression may help. This would include switching to a blade of rubber, polymer, or articulating may help with this problem. Understanding the problems that a DOT has with blades and their road conditions will avoid poor blade type related wear.

When monitoring of a blade is not done, it would not be possible to note whether failure is due to abnormal or normal wear; however, monitoring a blade's wear may help indicate if wear is abnormal or normal. For abnormal wear, field testing will capture blade misuse, and lab testing will capture a bad blade. Field testing may monitor abnormal and normal wear. Normal wear monitored in field testing is within the common treatment of plow blades by DOTs; therefore, abnormal wear is when a blade is treated uncommonly to induce greater wear. In addition to field testing capturing abnormal wear, certain aspects of lab testing may capture abnormal wear. Lab testing will test the quality of the blades to ensure that the chemical and physical attributes of the blade are of the correct specifications to withstand abrasive wear. To encapsulate both abnormal and normal wear, lab testing and field testing should be captured. This report will detail standard testing methods to assist DOTs in finding both normal and abnormal wear of a blade, and if this wear has made the blade purchased is cost neutral or not.

CHAPTER 3: STATE OF THE PRACTICE

The state of the practice is established by reviewing the literature and conducting a national DOT/ municipality survey as well as a separate vendor survey. Determining the state of the practice is important in confirming not only how studies are testing plow blades but also how the consumers of plow blades, which are DOTs, are using plow blades. The vendor survey helps establish the state of the practice by showing the research team what is currently available and what is considered high performance.

The literature review is categorized into three parts: plow blades, plows, and data collection methods from previous research projects. Plow blade details section represents the aspects of the study associated with plow blades including their quantity, the type of blade, and use of carbide inserts. The Plow details section describes the portion of the study in relation to the plow including its orientation, plow angle, and plow adjustment frequency. Data collection method section represents the aspects of the studies associated with data collection including how the data are collected, when data are collected, and what methods of analysis are used. The survey section of this report includes the national DOT/ municipality survey and the vendor survey. The national DOT/ municipality survey establishes the most common road conditions, truck abilities, plow blade types, truck settings and attachments. The vendor survey determines current blade vendors and the blades available during this study. The results of this chapter will establish the state of the practice in four ways:

1. What features of a plow are most used,
2. What quantity of blades are needed to assess wear on blades,
3. What aspects of road and weather conditions are typical, and
4. What vendors are available and the difference between blades. Literature Review

The literature review determines the standard practice for research on plow blades. Table 3-1 establishes how the plow is orientated in the study, the angle that the blade is tested, and if the plow is adjusted to ensure calibration. The plow blade section is presented in Table 3-2. This section examines previous studies' number of blades utilized, samples, blade type and carbide inserts. Data collection methods is the final section of the literature review which is visually displayed in Table 3-3. This section discusses how the blade was tested and under what conditions.

3.1.1 Plow

Establishing what plow orientation is being used, the angle of the plow, and the adjustment frequency are all important because plow type, angle, and adjustment relate to blade wear. Information in Table 3-1 is as follows: common plow orientation, angle of plow, and plow adjustment frequency.

Table 3-1: Literature Review: Plow

Plow Orientation[1]	Angle of Plow[2]	Plow Adjustment Frequency[3]	Reference
Comparison of tow plow to underbody/wing	Not Stated	Not Stated	Bandara et al. 2016
Front Plow	Not Stated	Periodically throughout winter season	Schneider et al. 2015
Front and Underbody Plow	Not Stated	Not Stated	Elhouaret al. 2015
Reverse snowplows	Polarflex was at angle 75-85 degrees. NDDOT operates at 50-70 degrees	Once	Mastel 2011
Front Plow	18 Degrees from vertical	Not Stated	Braun Intertec Corp., 2010
Front Plow	Not Stated	Not Stated	CTC and Associates LLC, 2010
Front and Underbody Plow	Recommended 60 degrees for all blades involved	Not Stated	Colson, 2010
Front and Underbody Plow	Not Stated	Not Stated	Colson, 2009

Note: [1] Orientation of the plow on the truck.
[2] This shows the angle of attack for scraping the road.
[3] This shows how frequently the plow was adjusted to ensure consistent plow positioning throughout the duration of the study.

The two key findings, shown in Table 3-1, are the plow blade orientation during the study and the adjustment frequency of the plow. As discussed in Chapter 2, plow orientation and plow adjustment frequency cause varying wear during a season. The plow orientation and adjustment frequency are both important in determining wear of a blade. With that knowledge and the information in Table 3-1, the most used plow orientation for research, 75%, is the front plow.

3.1.2 Plow Blades

Section 3.1.2 investigates the portion of the studies pertaining to number of plow blades, samples per type, plow blade types, and if carbide inserts are used. Table 3-2 provides specifications on the blade being studied. The number of blades represents the total amount of blades used in the study. Blades represent the number of blade types that are studied, and the samples represent how many of each type of blade is studied. An example would be testing a total of 12 blades which means four types of blades and three samples from each blade.

Table 3-2: Literature Review: Plow Blade

Number of Blades[1]	Blades	Samples	Blade Type	Carbide Inserts	Reference
Twelve			Steel plow blades	Not Stated	Bandara et al. 2016
Thirteen & Twenty-One[2]	Four & Four	Three & Three	Carbide tripped, JOMA, Polarflex, and BlockBuster XL Classic with standard flame hardened steel	All blades tested use Carbide Inserts	Schneider et al. 2015
Twelve	Two	Six	Polarflex blade with carbide inserts and a standard steel blade with dowel carbide inserts	Trapezoidal carbide inserts and Dowel-type carbide inserts	Elhouar et al. 2015
Fifteen	Four	Four & Three	Carbide Steel, JOMA, Polarflex, and stacked traditional carbide steel	3 four-foot sections ¾", 3 four-foot sections 1", 12 one-foot segments 1" and 6 four-foot sections with ¾"	Mastel, 2011
Thirty-Three [3]	Three	Three	Steel Plow Blades with 3 types of Carbide inserts	3 four- foot long insert	Braun Intertec Corp., 2010
Thirteen	Three	Four & Five	flexible blade plow blades, squeegee and scarified	Not stated	CTC and Associates LLC, 2010
Three	One	Three	Kueper – Tuca SX36 plow blades.	Standard, 2 four-foot and 1 three-foot section Tuca, triangular shaped cut outs	Colson, 2010
Eleven	One	Eleven	Kueper – Tuca SX36 with two sets of carbide inserts	Not Stated	Colson, 2009

Note: [1] Total number of blades used in research.

[2] These are separated because this is a two-year study; therefore, thirteen blades were tested one year and twenty-one were tested a second year.

[3] Nine of the blades were field tested and the other twenty-four were lab tested.

The largest one season field study has 21 blades with four samples of each, and the largest lab study used 24 blades with four samples of each. On average, 12 blades are tested in a season with three blade types and five samples of each. So, when conducting a large-scale study, the research team would recommend testing at least three blade types with five samples of each to be compliant with previous plow blade testing methodology.

3.1.3 Data Collection Methods

Operating speed, labor for installation, mileage tracking, and road conditions are aspects of Table 3-3 that are associated with the cost per mile of the blade. The specifics within Table 3-3 are used to assess the common practice in research and how wear of the blade is calculated.

Table 3-3: Literature Review: Data Collection

Data Collection[1]	Collection Type[2]	Statistical Model	Results	Road Conditions[3]	Testing	Duration	Reference
Visible conditions of roadway, operating speed of plows, and friction level of pavement behind different plow systems.	Dynatest "SURVEY" field collection with cameras for road visibility, and Dynatest highway friction tester a fixed slip tester for friction between wheel and roadway	Cost-benefit analysis and standard deviation for comparison	There is no conclusive connection between operating speed and road friction	Variety	Field Tested	2014-2015 winter season	Bandara et al. 2016
Video captured start and end time of plowing and start and end speed when plowing, road conditions, and distance plowing in ArcGIS. Measurements were collected along 5 sections of the blade to detect wear.	Digital video recording was used to track plow up and plow down and GPS was utilized to detect location and track mileage. Measurement sheets were given to operators of the truck to collect as frequently as possible.	Cost-benefit analysis	When reviewing two years of data an average savings of $778 per Polarflex blade and $426 per XL Classic blade implemented in place of a standard blade	Variety	Field Tested	2013-2015 winter season	Schneider et al. 2015
Stress and strain on the carbide inserts and speed of vehicle in addition to GPS location.	Piezo strain sensors to collect strain data, and GoPro for video collection and a Spy	Finite element model	The stress of the front and underbelly plows do not exceed 10,000psi. Using both a front and	Dry	Field Tested	2012-2014 winter season	Elhouar et al. 2015

	Chest to track speed and GPS location.		underbelly plow is ideal.				
Tracked record of hours of plowing roads, records on replacement of blades, records on time and labor required to replace, and difficulty of replacement.	Operators were used to record all variables in testing.	Cost-benefit analysis	JOMA and Polar Flex lasting on average 3 to 4 times longer than carbide steel blades.	Variety	Field Tested	2010-2011 fall through spring snow and ice season	Mastel, 2011
Hardness, Porosity, Grain Size, and Density. In field, 300 miles 45mph at 18-degree angle.	Used common testing practices: ASTM B294-92, ASTM 311-08, ASTM B276-05e1, ASTMD390-92(2006)	t-distribution for lab data, and t-test for field data	Excessive voids and internal cracks appeared in poor performing carbide inserts.	Dry	Lab Tested & Field Tested by Utah DOT		Braun Intertec Corp., 2010
Survey results for interest in multi-blade concept. States field tested independently on prototypes from vendors	Cameras were used to show road clearing abilities and operators reported on pros and cons of prototype	N/A	All states involved expressed continued interest in the concept of the multiple-blade plow. Vendors received feedback to help produce other prototype multiple-blade plows.	Variety	Field Tested	2008-2010 winter seasons	CTC and Associates LLC, 2010

Tracked mileage of wear life on blades	Driver storm reports for mileage tracking	Mileage of wear life comparison	Only two blades gave good data, which showed the Kueper blades lasted 2.25 times longer than the carbide. However, because of small sample size, more research is needed to verify.	Not Stated	Field Tested	2009-2010 winter season	Colson, 2010
Tracked mileage of wear life on blades, tracked user comments on prototypes, and tracked noise on blades.	Dosimeter testing for noise and driver storm reports for mileage tracking	Cost-benefit Analysis	More data need because of small sample size. Data was supposed to show a cost per mile.	Not Stated	Field Tested	2008-2009 winter season	Colson, 2009

Note: [1] Data Collection describes what data was collected.
[2] Collection Type describes how the data was collected.
[3] The conditions of the road describe what weather conditions the blades were tested under.

As seen in Table 3-3, most studies use mileage tracking as their reference for longevity. Weighing the initial cost of the blade and the operational costs against mileage is currently the most common analysis for whether a blade is at least cost neutral for a DOT. Cost neutrality is the cost of a blade relative to its wear resistance compared to the standard blade. Being cost neutral ensures that the blade being tested is at least on par with blades currently being used. If a blade is greater than neutral, it is a more cost-effective purchase for a DOT, and if a blade is less than neutral, it is a less cost-effective purchase for a DOT.

From Table 3-3, the variables that are a part of the function for longevity are road conditions, weather conditions, mileage plowing, and speed while plowing, which all these factors are a part of normal wear conditions as noted in Figure 2-9. Road conditions and material are not kept consistent in studies (i.e. blades were being tested over asphalt, concrete, and chip-seal and in a variety of weather conditions). 50% of the studies tested on a variety of road conditions establish a variety of road types as the most common method for researchers. In practice, snowplows clear any road type under a variety of winter conditions. Having a variety of road and weather conditions provides a practical assessment of blades. The standard testing protocol recommended by this study will also follow the common practice of testing plow blades on a variety of roads.

Though field testing is extremely important for having a true representation of the field, financial and time constraints of the DOT may limit results. Potentially the most important finding of Table 3-3 is that only one study has conducted lab testing before. Lab testing of plow blades may assist in finding bad blades that may produce uncommon wear as described in Figure 2-9. The research team from Braun Intertec Corp. 2010 tested blades in the field and in the lab. The study created a standard lab testing protocol for carbide inserts. They discovered excessive voids in carbide inserts pre-field testing and discovered micro-cracking in poor performing carbide inserts post-field testing. Braun Intertec Corp. 2010 discovered that if a blade does not meet internal cracks (visual inspections), chemical composition (hardness and density), and/or mechanical reliability (porosity and voids) at the approved limits that the blade will perform poorly. They validated these claims of poor performance by testing the blades in the field. The blades that were expected to perform poorly based off laboratory findings did perform poorly in the field, and the blades that expected to perform well based off laboratory findings did perform well in the field. The field-tested blades were measured at two locations along the blades at the beginning and end of the test which plowed 300 miles at 45 MPH. The following ASTM Standards were discussed in Braun Intertec Corp and will be used in this research project: ASTM B294-92, ASTM 311-08, ASTM B276-05e1, ASTMD390-92(2006).

3.2 SURVEY

Surveys are conducted for national DOTs/municipalities and the vendors of plow blades. These surveys are produced to evaluate the end-user of plow blades (DOT) and the seller of the blades (Vendors). The national survey provides information on the current state of the practice. The vendor survey gives insight on plow blades, their material, their functions, how they are internally tested, and the best practices for field testing.

3.2.1 National Survey

With the help of Clear Roads, the research team may speak with personnel from state and local DOTs. The research team additionally contacted municipalities to see how their assessments vary from DOTs. The municipalities surveyed are selected for this study by using two criteria: weather and population. Contacting municipalities with large snowfalls of approximately 50 inches or more and winter temperatures of less than 40 °F provide the research team with information on how local DOTs deal with large snow and low temperatures and if these weather factors effect blade selection (Stockdale, 2019). With population consideration, the research team found the municipalities that have the greatest population in each state and/or are the state capitals. Below in Figure 3-1 are the states that were surveyed for the national DOT/municipality surveys.

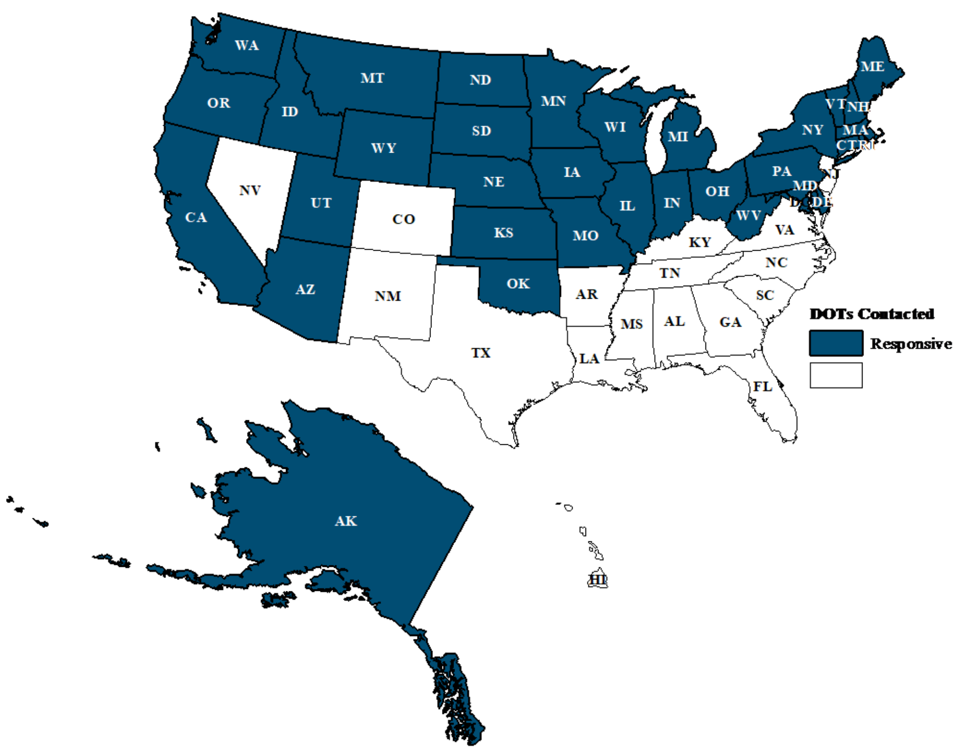


Figure 3-1: National Study Map

As seen in Figure 3-1, the research team through the national survey may contact 28 states and 10 municipalities. Given the geographic variation between east and west coast, the survey encompasses not only a variety of road and weather conditions but also a variety of snowplow trucks and their capabilities. The research team categorized the survey questions into four defined categories: truck settings and attachments, common truck abilities, plow blade types, and road conditions. The first category to help determine base standards for this project is truck settings and attachments.

Table 3-4 summaries truck settings and attachments associated with plow trucks from those surveyed. The settings and attachments used in a snowplow truck generally reduce the wear of the blade.

Table 3-4: Truck Settings and Attachments Survey Results

National Department of Transportation Survey: Truck Settings and Attachments	
Responses[1]	
Tripping Mechanism	
Yes	82%
No	11%
No Response	7%
Carbide Inserts	
Yes	68%
No	21%
No Response	11%
Plow Shoes	
Yes	57%
No	32%
Unsure	4%
No Response	7%
Plow Guards	
Yes	50%
No	14%
Unsure	4%
No Response	14%
Depends	18%
Counterbalances Used	
Yes[2]	29%
No	50%
Unsure	18%
No Response	4%

Note: 28 out of 100 responded via phone call or email survey.

[1] Numbers have been rounded to the nearest whole percentage

[2] Two counterbalances used were noted as hydraulic counterbalances, two were floating balances and the others were not specified as what counterbalance is used.

From Table 3-4, most entities use a tripping mechanism, carbide inserts, plow shoes, and plow guards. These attachments should be considered when conducting the field test given their popularity amongst entities. Additionally, Table 3-4 shows that most entities do not use counterbalances.

Table 3-5 summarizes DOTs common truck technology and blade types. GPS/AVL capabilities expedite mileage tracking in a less labor-intensive manner which minimizes the workload for DOTs who choose to replicate the testing protocol for this study. Plow orientation is associated with the wear on the blade which affects the mileage and the overall cost of a blade. The material of the plow blades affects the cost of blade.

Table 3-5: Plow Truck Technology and Blade Types

National Department of Transportation Survey: Plow Truck Technology and Blade Types	
Responses[1]	
GPS/AVL Capabilities	
Yes	79%
No	21%
Types of Plows Used[2]	
Front	68%
Underbelly	25%
Tow	32%
Wing	54%
Other	7%
Unsure	4%
Material of Plow Blades[2]	
Carbide	25%
Steel	57%
Rubber	18%
Polymer	7%
Other	4%
Manufacturers of Plow Blades[2]	
Chemung[3]	14%
Ironhawk	11%
Kennametal[4]	7%
Kueper	25%
JOMA (Sold by Winter Equipment)	36%
Winter Equipment	18%
Valley	18%
Valk	14%
Unsure	39%

Note: In some of the categories, multiple selections per stat was used
28 out of 100 responded via phone call or email survey.
[1] Numbers have been rounded to the nearest whole percentage.
[2] More detailed tables are available in Appendix A in Table A-2 to Table A-7.
[3] Chemung is a division of Evolution Edges.
[4] Kennametal works with Kueper on plow blades.

In Table 3-5, 79% of DOTs have GPS/AVL capabilities which will allow the DOT to track the truck's location, speed, the road material, and any obstacles the blade will encounter. Additionally, the most common type of plow used by a DOT is the front plow which is 68%. The most common plow type for research is also the front plow, 75%, which is seen in Table 3-1. The knowledge that most researchers and DOTs use front plows, provide the research team with the assurance that mandating front plows as the orientation of choice for the standard testing protocol is not only appropriate but also within common practice of DOTs and previous research. As presented in Table 3-5, the material of plow blades is seen which 57% of entities use steel as their plow blades; however, 67% of those surveyed used the JOMA blade which is a carbide articulating blade.

Table 3-6 summarizes the road conditions of those surveyed. Road conditions are associated with wear and influence how a DOT and a vendor select blades.

Table 3-6: Road Conditions Survey Results

National Department of Transportation Survey: Road Conditions	
Responses[1]	
Road Surface Types	
Majority Asphalt with Minor Concrete	54%
Majority Asphalt with Minor Chip Seal	4%
Majority Asphalt with Minor Concrete and Chip Seal	18%
Majority Concrete with Minor Concrete	4%
50-50 Asphalt and Concrete	14%
Unsure	7%
Average Winter Temperature[2]	
0-15	7%
15-30	61%
30-45	21%
No Response	11%
Average Snow Fall Accumulation[2]	
0-4”	11%
4-8”	7%
8-12”	7%
20-24”	4%
24”-28”	4%
28”-32”	11%
40”-44”	4%
44”-48”	4%
48”-52”	7%
72”+	36%
No Responses	11%
Salt Restrictions	
Yes	21%
No	71%
No Response	7%
Truck Speed (MPH)	
25 or less	14%
35 or less	32%
45 or less	4%
Area Dependent	11%
Not Set	32%
No Response	7%
Lane Miles Maintained	

> 3,000	25%
3,000 – 10,000	18%
10,000 – 25,000	18%
25,000 <	21%
Unsure	7%
No Response	11%

Note: 28 out of 100 responded via phone call or email.

[1] Numbers have been rounded to the nearest whole percentage.

[2] Average temperature and snow fall accumulation were used to get an assessment of general winter conditions; however, other sources were used to obtain a more accurate assessment of the winter conditions of each state.

Table 3-6 establishes that 54% of those surveyed have mostly asphalt with minor concrete. Wear due to road type stems from certain aggregates causing variable friction to the blade. A coarse pavement is assumed to increase friction against a blade causing more wear (Nixon 2012). Table 3-6 also shows that a majority of those surveyed have an average temperature of 15-30 degrees Fahrenheit and an average snowfall of 72 inches or more. Given that these are averages for the entire state, it is understood that some locations within the state have a warmer or colder temperature and an increased or decreased snowfall dependent on its location within the state; however, temperature and snowfall information are used to get a better understanding of the conditions in the state and potential challenges they face.

Salt restrictions would have an impact on what blades are recommended. If a state has salt restrictions, the blade may be required to scrape ice more than a blade in a state without salt restrictions due to the adhesion of ice to the road as discussed in Chapter 2. A blade that scrapes is usually thinner to detach the ice from the road easily. Establishing road type and weather conditions provides the research team with information that may affect the mileage of a blade, which will affect the overall cost of a blade.

Plow speed is commonly either 35 mph or slower or is not set at all according to Table 3-6. This variation may be due to the mixing of municipalities and DOTs. One interesting finding is some states do not have a set speed or a speed limitation when plowing, so drivers decide how fast or how slow is required for plowing. For lane miles maintained, the majority denoted less than 3,000 miles; however, the second largest category is greater than 25,000 miles. This variation of the lowest mileage option and the highest mileage option may be accounted for due to municipalities participating in the study as well as states.

Table 3-7 summarizes the portion of the national survey pertaining to blade evaluation. The research team wanted to discover how DOTs evaluate new blades, what they consider when selecting blades, and what they expect to get out of their plow blades.

Table 3-7: Blade Evaluation Survey Results

National Department of Transportation Survey: Blade Evaluation	
Response[1]	
Different Lifespan with Different Blades	
Yes	68%
No	11%
No Response	18%
Unsure	4%
State Evaluation of Blade Performance[2]	
Do not evaluate	25%
Cost vs. Lifespan	11%
No Response	25%
GPS to track Blade Life	
Yes	71%
No	18%
No Response	11%
Miles before needing a new blade	
>500	7%
500 < X > 1000	7%
Varies	14%
No Response	21%
Unsure	57%
Blade Selection Criteria[2]	
Cost	27%
Longevity	15%
Unsure	12%

Note 28 out of 100 responded via phone call or email.

[1] Numbers have been rounded to the nearest whole percentage.

[2] State Evaluation of blade performance and blade selection criteria reflect the three most popular categories and their respective percentages.

From Table 3-7, the research team discovered that DOTs:

1. Notice a difference in lifespan with different blades, 68%,
2. Use GPS/AVL to track blade life, 71%, and
3. When selecting blades seek out cost, 27%, and longevity, 15%.

However, the most interesting findings from Table 3-7 is that 25% of DOTs seek certain attributes and track mileage but do not evaluate blade performance. 57% of DOTs are unsure how many miles they obtain on a blade; therefore, DOTs are desiring blade attributes that they are not formally tracking and are unsure how many miles they get on a blade despite 71% of them tracking blade life with GPS/AVL. It may be concluded that DOTs are tracking in a more qualitative way rather than a quantitative way of establishing if a blade is effective.

Goal number one of this study is to make a standard testing protocol for DOTs. Knowing what their current testing methods are is important in understanding how DOTs test plow blades. From Table 3-7, it is discovered that DOTs do not formally evaluate blades. Given this information, the research team should create its standard testing protocol using the technology available to DOTs and attributes of a plow blade that are the most sought after.

Table 3-8 is used to survey the representative of the municipality and the state as a comparison. Below in Table 3-8 is the results of the desired features obtained from the Table 3-4 and 3-5.

Table 3-8: Comparison of Municipalities and States

National Department of Transportation Survey: Municipality and State Comparison		
	Municipality[3]	State[4]
Response[1]		
GPS/AVL		
Yes	90%	74%
No	10%	22%
No Response	0%	4%
Plow Up/Down Feature		
Yes	50%	33%
No	20%	26%
No Application	0%	19%
No Response	0%	22%
Unsure	30%	0%
Plow Type[2]		
Front	100%	81%
Tow	0%	63%
Underbelly	40%	37%
Wing	40%	78%
No Response	0%	15%
Blade Vendor[2]		
Built Blades	0%	4%
Chemung Supply	10%	11%
Ironhawk	0%	11%
JOMA	10%	37%
Kueper	0%	30%
Multiple Vendors	10%	4%
Mudder	0%	4%
Nordic	0%	4%
Northern Supply	10%	0%
Steel Sales Inc.	10%	0%
Valk	0%	11%
Valley	0%	22%
Winter Equipment	20%	15%
No Response	10%	37%
Unsure	50%	7%
Blade Material		

Articulating Rubber Carbide	0%	30%
Carbide	10%	15%
Rubber	50%	4%
Rubber Ceramic	0%	7%
Steel	60%	52%
Plastic Hybrids	10%	0%
Poly-Coated Steel	0%	4%
Polymer	10%	4%
Unsure	20%	0%
No Response	0%	33%

Note:[1] Numbers have been rounded to the nearest whole percentage.
[2] These blade categories have multiple responses possible.
[3] There were 10 Municipalities that responded to the survey.
[4] There were 27 states that responded to the survey.

As seen in Table 3-8, most municipalities and states have GPS/AVL, front plows, and steel blades. Most municipalities have plow up/down feature and are unsure of the brand they utilize for snowplows. Municipalities surveyed are more likely to use rubber blade material than states. Rubber blades are usually used when there are many obstructions in the road like in a city with grates, manholes, raised pavement markers, railroads, etc. Rubber may morph around the obstacle without breaking unlike a carbide or steel blade. Most states have plow up/down feature, however the difference between the other variables is within 12%, and besides "No Response" use JOMA brand blades. Table 3-4, 3-5, and 3-6 provide the team with information necessary to establish common road conditions, plow blades, and plow orientations and technology for DOT replication. The next section discusses the vendor survey to establish common blade types and blade manufacturers.

3.2.2 Vendor Survey

From the literature review and the national survey, the research team obtained a short list of plow blade vendors as seen in Phase One of Table 3-9. The list of vendors has been decreased to vendors who supply blades for DOT applications shown in Phase Two A. Phase Two B blades are vendors who manufacture their own blades. It was discovered through phone interviews that vendors may purchase blades from other companies. To negate the possibility of using the same blade from different vendors, the research team decided to not utilize blades from vendors who do not manufacture their own blades. This is not to comment on the quality of the blades but rather to disregard the possibility of duplicate blades. Phase Three shown in Table 3-9 summarizes vendors who passed through all phases and are responsive through the whole interview process. The list of vendors was obtained at the time of this survey and are held accurate during the duration of this study; therefore, this list in the future may change.

Table 3-9: Vendor Matrix

Vendor Matrix			
Web Search and Literature Review	**Best Equip for DOT Application**	**Manufacture Plow Blades**	**Responsive**
Phase One[1]	**Phase Two A[2]**	**Phase Two B[2]**	**Phase Three[3]**
Black Cat Blades	Black Cat Blades	Black Cat Blades	Boss Plows
Boss Plows	Boss Plows	Boss Plows	Evolution Edges
Buyers (SnowDogg)	Esco	Esco	Ironhawk
Esco	Evolution Edges	Evolution Edges	Kueper[4]
Everest	Flink	Flink	Valley (Polarflex)[4]
Evolution Edges	Gledhill	Gledhill	Winter Equipment[4]
Fisher Plow	Henderson, Mfg.	Henke	
Flink	Henke	Hiniker	
Gledhill	Hiniker	Ironhawk	
Henderson, Mfg.	Ironhawk	Kueper[4]	
Hiniker	Kueper[4]	Meyer	
Ironhawk	Meyer	Valk	
Kueper[4]	Monroe	Valley (Polarflex)[4]	
Meyer	Valk	Winter Equipment[4]	
Monroe	Valley (Polarflex)[4]		
SnoEx	Winter Equipment[4]		
Valk			
Valley (Polarflex)[4]			
Western Plow			
Winter Equipment[4]			

Note: [1] Manufacturers/vendors were obtained through web searches and literature review of plow blades. This list may be found in Appendix B in Table B-1, B-2, and B-3
[2] Manufacturers/vendors were filtered through survey.
[3] Manufacturers/vendors who were responsive to survey questions and manufactured their own plows blades. This list may be found in Appendix B in Table B-4.
[4] Manufactures/vendors who have participated in previous plow blade studies.

3.3 SUMMARY OF THE STATE OF THE PRACTICE

Table 3-10 summaries how many blades should be considered, roadway material, the orientation commonly used, and the attachments that may be considered in testing; therefore, Table 3-10 represents what the research team based its initial design plan after.

Table 3-10: State of the Practice

State of the Practice[1]	
Literature Review	
Blade Quantity	
Quantity of Blades that Yield Results	8-24
Samples of Blades	
Common Sample Size per Blade	5
Conditions of Roads and Weather	
Roads Type (Asphalt, Concrete, Chip-Seal)	Variety of Road Types
Weather Conditions (Dry, Wet, etc.)	Variety of Conditions
Plow Adjustments	
Angle of Plow Measured	38%
Frequency of Plow Adjustment	25%
Common Tools for Assessing Blade Wear	
Miles per Blade	63%
User Assessment	63%
National Survey	
Chemical Snow Removal Restrictions	
Salt Restrictions	21%
Speed of Plow Restrictions	
35 or less	46%
Not Set	32%
Plow Orientation	
Front Plow	68%
Blade	
JOMA	36%
Additional Plow Attachments Used	
Carbide Inserts	68%
Plow Guards	50%
Plow Shoes	57%
Tripping Mechanism	82%

Note: [1] Conclusions are drawn from Literature Review Summaries section 3.1.1-3.1.3 and the National Survey in Tables 3-4 and 3-8.

Table 3-10 is a summary of the current state of the practice. Based on all this information, the research team will recommend testing a total of at least eight blades and a common sample size of five. When practicing the testing protocol, a variety of road types and weather conditions should be experienced. Additionally, the testing protocol will track miles per blade and include a user review due to 63% of studies utilizing these practices. Based off of the national survey, as seen in Table 3-10, the research team will recommend the blade to be plowed at 35 or slower MPH, on a front plow, and have JOMA blades as the baseline blade due to the commonality amongst DOTs.

CHAPTER 4: BLADE TESTING PROTOCOL

A standardized protocol will help provide a quantitative metric which will ensure that a DOT has a plow blade that works for their winter maintenance goals. Creating a standardized protocol will save a DOT monetarily and will provide a quantitative model to assess a blade's function. To save money while not hindering operational performance is paramount in establishing how to capture the price in a standardized model.

4.1 COST OF A PLOW BLADE

The cost of a plow blade, as seen in Equation 4-1, is a function of operational cost, capital cost, and the wear of the blade. Equation 4-1 assumes that the plow blade wears normally meaning that the blade is wearing as advertised and is not failing earlier than anticipated. In other words, the assumption is that this blade works as expected. Equation 4-1 is the cost of a plow blade, as seen below.

$$Cost = \frac{OC + CC}{W}$$

Equation 4-1

where,

OC is the operational cost,

CC is the capital cost, and

W is the wear in 100 miles.

The cost per 100 miles should be the lowest cost rate compared to other blade types or at least cost neutral. It is important for a new blade to at least be cost neutral so that it costs and wears as much as the existing blade used by the DOT. Anything less than neutral means that the blade either costs less than existing or wears slower (meaning more total plowed miles). Either way, the new blade is more cost effective for a DOT due to decreased cost for more miles plowed. Being cost neutral ensures a DOT is not spending more money than they currently are on blades.

The first component of Equation 4-1 is operational cost which is the function of personnel's wages, duration of installation, and number of personnel installing a blade in Equation 4-2, as seen by

$$Operational\ Cost = f(LR, D, N)$$

Equation 4-2

where,

LR is the labor rate,

D is the duration of installation, and

N is the number of personnel installing blades.

The first aspect in Equation 4-2 is the operational cost based on the personnel's hourly wage. This factor will vary by DOT. The higher the wage of the personnel, the greater the operational cost. The second factor associated with operational cost is the duration of installation. Duration of installation may be dependent on blade type and blade orientation. For example, if the duration of installation increases, while the other factors remain the same, the operational cost will increase. Additionally, when a blade wears faster, the blade will need replaced more frequently which increases the duration of installation increasing the overall operational cost. The third factor for operational cost is number of personnel installing the blade. If two individuals are necessary to install a blade as opposed to one individual, the cost of operating will increase.

The next component, in Equation 4-1, is capital cost. Capital cost is a function of cost related to purchasing a plow blade, the quantity that is purchased, and contractual language which is displayed in Equation 4-3, as seem by

$$Capital\ Cost = f(N, BT, CL)$$

Equation 4-3

where,

N is number of blades purchased,

BT is blade type, and

CL is a contractual language.

As seen in Equation 4-3 the first influence on capital cost is the number of blades purchased. Typically, the more blades purchased, the lower the individual costs. The second factor of capital cost is blade type. As discussed in Chapter 2, the cost of a blade varies by the material type of the blade. Flexible carbide blades are the most expensive, and rubber blades are the least expensive. Therefore, depending on the material of blade, the cost may increase or decrease. The third factor of capital cost is contractual language. Contractual language to the vendor may include a guarantee of performance that increases the cost of the blade. When contractual language is strict, the greater the cost initially due to guarantees and laboratory testing. The strict language over time will be cost effective for a DOT due to the blade's quality being assured.

The last component of Equation 4-1 is wear, which is a function of weather, road material, speed while plowing, roadway obstacles, blade type, plow trucks settings and orientation, and operator training. Equation 4-4, the wear of a plow blade, is a function of many variables as seen by

$$Wear = f(W, RM, S, RO, BT, PSO, OT)$$

Equation 4-4

where,

W is the weather,

RM is the road material,

S is the speed while plowing,

RO is the roadway obstacles,

BT is the blade type,

PSO is the plow truck settings and orientation, and

OT is the operator training.

The first two aspects of wear are weather and roadway material. For example, if a plow blade encounters a dry winter (light snow) then the blade will heat and wear more rapidly than normal. This is also exaggerated by the blade's material. Roadway material also has the ability to cause increased wear. The more abrasive the material of the road, the greater the wear. The third factor for wear is the plowing speed. The faster the speed a plow blade is subjected to, the greater the wear due to increased friction and chance of fracture with obstructions (MacIver 2003). The fourth factor that affects wear of a plow blade is roadway obstructions. If there are more roadway obstructions, then the blade has a higher probability of fracture, and the lowered surface areas may induce greater wear (MacIver 2003). In addition to roadway obstructions, the plow truck settings, and the orientation effect wear. Depending on the type of plow blade (front, wing, underbelly, and tow), there is an associated down pressure and weight of the plow that increase or decrease the pressure on the blade against the roadway surface which causes greater friction and, therefore, increased wear. The last factor, within Equation 4-4, is operator training. Operator training may increase or decrease wear of a plow blade. The better trained an operator is, the minimal wear due to operator that may occur; however, the less training and lower experience an operator has the greater the wear that may occur.

Table 4-1 presents how a blade may be cost neutral given a variety of situations.

Table 4-1: Cost

Goal	IF	THEN	
Cost Neutral	↑ Operational Cost[1]	↓ Capital Cost or	↑ Wear
	↑ Capital Cost[2]	↓ Operational Cost or	↑ Wear
	↓ Wear[3]	↓ Operational Cost or	↓ Capital Cost

Note: [1] If a blade has a high operational cost, the capital or the wear should be low for a blade to be cost neutral.
[2] If a blade has a high capital cost, the operational cost should be low or the wear should be high to be cost neutral.
[3] If a blade plows a small wear, the operational cost should be low or the capital cost should be low to be cost neutral.

Table 4-1 summarizes how a blade may achieve cost neutrality. To achieve cost neutrality, it would mean the blade that is purchased performs similarly to the existing blade. Using Equation 4-1, a DOT will have the ability to establish a formal quantitative performance metric which may be important in blade selection. For example, if a blade has a capital cost of $1,000 greater than another blade, the blade would either need to have a lower operational cost or plow for a greater mileage to be cost neutral. Also, if a plow blade plows a low mileage, then in order to be cost neutral, the blade either needs to have a low operational cost and/or a low capital cost.

4.2 TESTING METHODS

There are multiple ways to measure the variables associated with cost/100 miles as seen in Equation 4-1. In this study, the research team evaluated three testing protocols: large-scale field testing, small-scale field testing, and laboratory testing. Large-scale and small-scale field testing are defined by the research team based upon the literature review conducted in Chapter 3.

Field testing is the ability to test a product in its natural environment. Testing a blade in its natural environment allows the evaluator to see the product perform where it is intended; however, this testing environment has the greatest amount of variability which makes the testing more realistic (Aziz, Hassan 2017). Field testing may be expensive, time consuming, and allow for a large amount of variability due to different weather conditions, individuals taking measurements, and equipment being used. Small-scale field testing may limit variability that occurs with field testing. Decreasing the number of blades utilized and the individuals participating in a large-scale study should limit variability due to DOT. Limited variability of a small-scale study is due to controlling environmental factors which may be done by only using one operator (eliminating operator variation), plowing over one road (elimination road variation), or plowing on a dry road (eliminating weather conditions). Reducing factors should allow for a more controlled environment; however, this method is only useful for a finite number of blades due to the added labor cost.

Another testing method is laboratory testing. Laboratory testing has aspects that are controlled in the lab that have less variability than that of field testing; however, the controlled aspects may be argued are what make field results more realistic than lab results (Sun, Xu, and Andrew May 2013). Therefore, there are benefits and faults with laboratory testing and field testing. Combining the two may fully encompass the benefits of both testing methods.

4.3 FIELD TESTING

Field testing is the most representative of a plow blade's normal condition. It encompasses all the challenges a DOT normally faces in the winter: weather conditions, road conditions, and obstructions as seen in Equation 4-4. This method is also the most popular among researchers. This section is categorized into large-scale and small-scale field testing.

4.3.1 Large Scale

Large-scale field tests may be conducted either nationally or statewide. Large-scale studies should be conducted using three blade types with five samples of each, according to the standard blade testing quantities as seen in the summary of Table 3-2. Additionally, large-scale studies should be performed using multiple locations to obtain variations in weather and road conditions.

4.3.1.1 State Selection or County Selection

It is important to establish who should be conducting the study in order to collect data properly and efficiently. DOTs should seek these ideal components for the study:

1. GPS/AVL,
2. Plow up/down feature,
3. Interest in participating, and
4. Manpower and financial capability to work on project.

As discussed in Table 3-8, GPS/AVL with plow up/down feature is not necessary for conducting this testing; however, it does ease the time of data collection since the plowed mileage, truck location, and speed is collected by the technology. Garages are assumed to be willing to collect data in a timely and dedicated manner; therefore, this will ensure data collection and field testing are a priority. Aside from having the technical capabilities and an interest in participating, a DOT should seek a local garage that has the manpower and the financial ability to participate. This will ensure that the DOT participating has enough people to conduct the study properly but also has the financial assurance to be able to obtain blades and conduct the extra work necessary to complete the study.

The research team recommends selecting blades based on three factors:

1. Current blade inventory,
2. Financial capabilities, and
3. Current vendor contracts of the DOT.

Selecting blades using these three factors is assumed to be done if the DOT has a limited budget or has contractual stipulations that limit vendor selections. With that being said, the current blade inventory should be considered when recommending blades. Using inventory blades should give a state the ability to assess whether the current blades are of high quality before searching for other blades to bring into their fleet. Since it is the most feasible option which will affect the capital cost as seen in Equation 4-3. A DOTs budget should always be considered when recommending blades. In addition to blade inventory and financial capabilities, current vendor contracts and obligations is a considerable factor. A DOT may have a contract that stipulates using a vendor's blade for a certain duration, so it may be in the DOTs best interest to test blades from that vendor rather than seeking a different one.

4.3.1.2 Large-Scale Field-Testing Protocol

Large-scale field collection will encompass two major roles for DOTs: statewide data collection and local garage participation. The state DOT will obtain the data for GPS/AVL for the trucks in the evaluations study and the GIS Roads layer for the state.

Garages will provide the state coordination with blade, mechanic, and operator collected data. The sections below describe the deliverables, the frequency of delivery, and how the data should be transferred. The information expected to be collected may be seen in Figure 4-1.

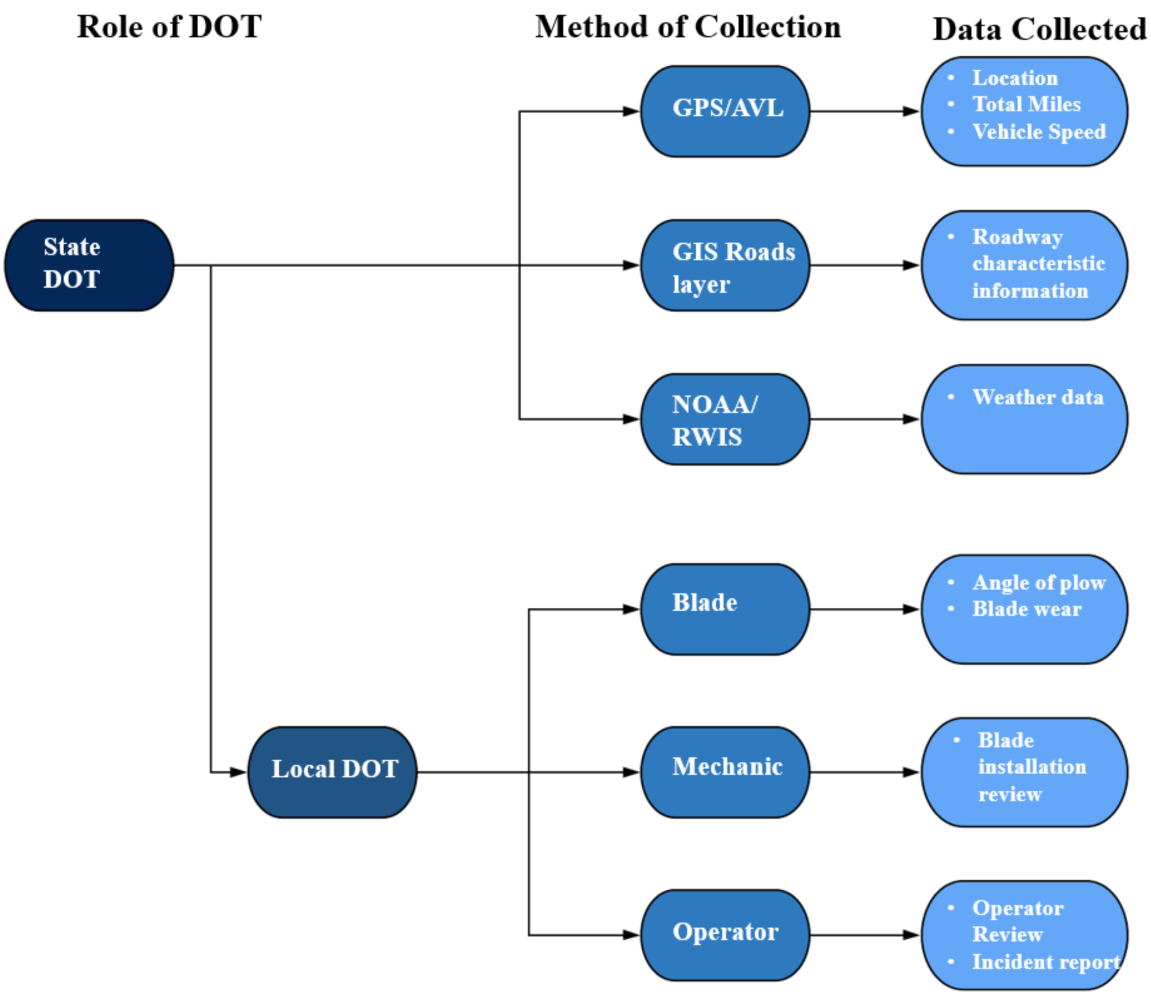


Figure 4-1: Blade Testing Protocol

Two main representatives are the state DOT and the site selected garages. Throughout this project, there should be constant communication between the two representatives. The state representative is responsible for less frequently needed data and cleaning of that data. The garage (Site Selected) DOT is responsible for more frequent blade wear specific data (i.e. measurement data).

4.3.1.3 State Level

The state coordinator will be responsible for obtaining the GPS/AVL information and the GIS roads layer for trucks and counties participating. The GPS/AVL information should be collected during field testing and will provide information on the plowing location of a truck, total mileage, and vehicle speed, which are all aspects of wear as seen in Equation 4-4. Truck location in conjunction with ArcGIS roads layer will allow the state to determine what type of road the blade is used on and for how long. GPS/AVL with plow up/down feature will allow the DOT to determine total lane miles. Vehicle speed will help with wear of blade by determining friction. The state coordinator will need the ArcGIS roads layer information for counties participating in this study to follow the trucks route to establish road type and mileage. The ArcGIS roads layer should contain information on road material, road location, and bridge locations. All these variables are associated with the wear of the blade as seen in Equation 4-4. The GPS/AVL information once collected should be placed in ArcGIS as a shapefile and a polyline. After the GPS/AVL information has been added, a polyline and datapoints should be included on the map to show the route that the truck took. Then python coding should be used in order to pull data on miles plowed, road material, and bridge decks encountered. The third responsibility of the state DOT is obtaining the National Oceanic and Atmospheric Administration (NOAA) data which will determine the weather conditions while plowing. Lastly, the state coordinator will also need to select the counties who are to participate.

The garage(s) selected will need to have the capacity to do the study in terms of time and fleet size. This will be based off three factors: lane miles, average miles plowed per season, and if the garages have done previous blade tests. These recommendations are to help ensure that a variety of pavement types and optimal plowing routes provide adequate snow plowing during the winter season. Additionally, it is important to have highway maintenance personnel who are familiar with testing and methodology that is required with blade testing.

The garage will provide data to the state coordinator. The expectations of the garage are described in the following section.

4.3.1.4 Garage (Site Selection)

All data are expected to be provided by local DOT should be scanned or a photo taken of and emailed to the state representative. Garage personnel will provide measurements of blades. These measurements should be taken based on usage; therefore, more frequent blade use should result in more frequent measurements. The form that blade measurements should be written on may be found in Appendix C. Blade measurements are important in understanding the physical wear on the blade. In addition to measuring blade wear, installation information should be written down. Garage mechanics will provide a survey after every blade installation. The appropriate forms may be found in Appendix C. Providing the state with installation information will help assist in the cost benefit analysis and assess the blade on a personal level (easy to install etc.). Blade installation descriptions and comments from the vendors may be included in the operational cost as seen in Equation 4-1. Mechanics forms will provide information on the duration and equipment used to install the blade which are a part of the function of operational cost as seen in Equation 4-2.

The local DOT mechanic will provide a form after an incident has occurred in case of any damage to a blade. The appropriate forms may be found in Appendix C. This form is important in understanding if a blade were to hit an obstacle and break, how it occurred to assess the blades durability and potential blade misuse, as discussed in Figure 2-9.

Lastly, establishing how the blade installation processes changes for different blades, learning how the blade performs on the road by those who plow is equally as important. Local DOT operators will provide a survey after the season of using a new blade. The appropriate forms may be found in Appendix C. From the literature review, a survey from the operators is important because it reflects the views of those who frequently use the plow blades.

Table 4-2 describes the expected deliverable from the state and local DOT as well as the frequency it should be sent.

Table 4-2: Methods of Collection

Method of Collection[1]	Frequency	Data Transfer
GPS/AVL	Per storm	State coordinator will obtain
GIS roads layer	1 time	Electronically sent to state coordinator
Blade	Once a week	Written form[2] is to be filled out by operator, scanned, and emailed to the state coordinator
Mechanic	End of season	Written form[2] is to be filled out by mechanic, scanned, and emailed to state coordinator
Operator	End of season	Written form[2] is to be filled out by operator, scanned, and emailed to the state coordinator
NOAA	Per storm	State coordinator will obtain

Note: [1] These tasks are in the flow chart above in Figure 4-1.
[2] The forms should be seen in Appendix C labeled as Table C-1 and Table C-2, Figure C-2 and Table C-3 in their respective orders.

GPS/AVL information should be accessed as frequently as the state coordinator is able. GIS roads layer is a onetime sent item. Blade information should ideally be sent once a week; however, the state coordinator should recognize less frequent information collection may occur so that the daily operations of the facility are not affected. Data protocol varies dependent on whom is represented. Different entities have aspects that they are responsible for. All aspects being collected are for either the assessment wear or assessment of cost neutrality.

4.4 CASE STUDY: LARGE SCALE

This section discusses the case study conducted in Idaho during the 2019-2020 winter season. Idaho DOT followed the field-testing protocol detailed in section 4.3.1. The research team recommends having a state representative clean the data and upload it into a data warehousing system, ideally on the Clear Roads website.

4.4.1 DOT Garages and Site Locations

This section discusses the garages and site locations of the Idaho case study. ArcGIS is utilized in order to show the locations of garages. The following factors should be taken into consideration when deciding where to test blades:

1. Manpower,
2. Financial ability,
3. Previous participation in plow blade studies, and
4. Weather conditions.

These factors should be considered because they either ease the strain on the DOT or should ensure successful testing. Manpower and financial ability will help the DOT through increasing the amount of people able to participate in the project and increasing the amount of money will ensure the ability to purchase new blades to participate in the study. Previous participation in a plow blade study should ensure that the staff are familiar with the expectations and demands of the study. The weather conditions of the site to be selected should be taken into consideration. Selecting an area with the least amount of snow may not represent the state in the best manner or be appropriate for a plow blade study.

4.4.2 Idaho Site

The following counties were selected by the state representative for participation:

1. Latah County, and
2. Caribou County.

Figure 4-2 below shows the counties participating in blue on the Idaho state map. Idaho does not have abbreviations for its counties, so the state is labeled with its license plate codes which are county specific (Idaho DOT 2016). “1L” is Latah County. “3C” is Caribou County.

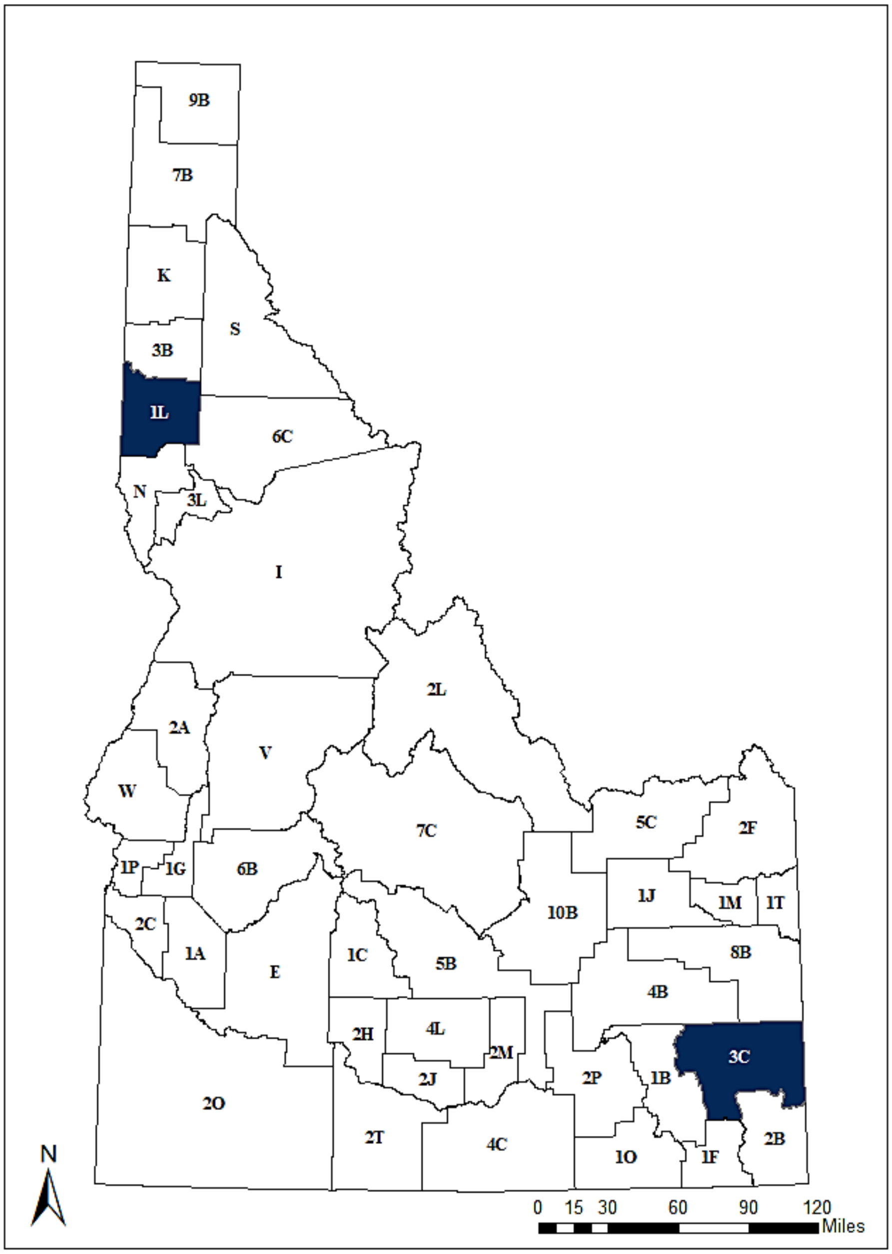


Figure 4-2: Idaho State Map

Caribou and Latah counties are participating due to their manpower, financial ability, and interesting in participating. Latah county is a part of District 2 in Idaho. District 2 maintains 1,500 lane miles and 180 bridges. Caribou County is a part of District 5. District 5 maintains 1,900 lane limes and 315 bridges.

Table 4-3 summarizes the weather conditions of these two counties and the lane miles they maintain.

Table 4-3: Idaho County Conditions

County	ID	Garage	Average Winter Weather (°F)[1]	Average Snowfall (Inches)[2]	Lane Miles
Caribou	3C	Soda Springs	25°F	9.0"	283
Latah	1L	Moscow/Potlatch	35°F	9.6"	240

Note: Average weather and snowfall came from NOAA. The average temperatures were averages of highs and lows per month from November to March which is an average winter season.
[1] The numbers have been rounded to the nearest whole number.
[2] The numbers have been rounded to the nearest tenth place.

Table 4-3 summarizes the average roadway and average weather conditions of the case study. Soda Springs and Moscow Potlatch average winter weather, as recorded by NOAA, is 25°F and 35°F, respectively. As seen in Table 3-6 of the national survey these sites are within the most common winter temperature range of 15-30 °F. The average snowfall in Soda Springs and Moscow/Potlatch is 9.0" and 9.6", respectively. In addition to weather conditions, the roadway conditions of Soda Springs are provided. The lane miles serviced by Soda Springs in Caribou County is 283 miles, and the lane miles maintained by Moscow/Potlatch in Latah County is 240 miles. The sites selected for this case study are within the range of most common weather conditions and road conditions that most DOTs.

The distribution of the blades between the three counties is summarized below in Table 4-4.

Table 4-4: Idaho Blade Distribution

County	Blade	Blade	Blade
Caribou	Blade one[1]	Blade two	Blade three
Latah	Blade one[1]	Blade four	

Note: [1] Blade one was the only blade utilized in multiple regions within the state.

As seen in Table 4-4, blade one is tested in multiple locations. The distribution of blades in Idaho provides variation in weather and road conditions as discussed in section 4.3.1. All the blades in the Idaho case study are carbide articulating blades.

The summary of the Idaho case study is presented in Table 4-5. This includes the blades tested, the trucks used, the total miles plowed, and the total inches of snow recorded during the active blade season. The miles plowed and the inches of snow influence the wear of the blade as seen in Equation 4-4.

Table 4-5: Summary of Idaho

Counties Participating	Blades Tested	Trucks Used	Miles Plowed[1]	Inches of Snow[2]
Caribou	3	2	1,021.7	59.6”
Latah	2	2	2,131.4	36.3”

Note: [1] Miles plowed was obtained through GPS/AVL in the trucks and ArcGIS.
[2] Inches of snow was obtained through NOAA.

As seen in Table 4-5, the total number of blades tested in Caribou County and the trucks used to plow are five and two respectively. The miles plowed and the inches of snow provide descriptive information about the wear of the blades and the weather conditions. Caribou and Latah counties plowed 1,021.7 and 2,131.4 during the winter season. The inches of snow obtained in both locations are similar. Caribou county received 59.6”, and Latah County received 36.3”. The next step to processing the results is to discuss the operator and installation reviews of the blades. Operator and Installation reviews of blades are common research review processes, as seen in Table 3-3.

4.4.3 Operator and Installation Review

The operator and installation reviews from Idaho provide a firsthand view from those who use the plow blades most frequently and pull an expert opinion on their ability to complete a task and how difficult it was to install.

Table 4-6 is the operator review of the blades tested in the case study conducted in Idaho during the winter season of 2019-2020.

Table 4-6: Operator Review

Blade Types	Noise Level	Clearing Ability	Ice Clearing Ability	Maneuverabilit y
Blade one[1]	Quiet	Average to Above Average	Moderate to Average	Average
Blade two	Average	Average	Average	Average
Blade three	Moderately Quiet	Above Average	Average	Above Average
Blade four	Quiet	Above Average	Above Average	Above Average

Note: Review was completed by operators utilizing the blades. The review by the operator is an opinion-based survey on the blade’s ability; however, ability is not related to wear.
[1] Blade one was tested in two different locations.

As seen in Table 4-6, blade one and blade three are viewed as quieter than the average; however, blade one had average clearing ability while blades two and three had an average to above average rating. Blade one also performed poorly in the eyes of the operators for ice clearing ability compared to blade three and two. Blade three is considered above average in maneuverability than blade two and one which was ranked as average. Table 4-6 may be useful to a DOT in seeking better expectations of a certain blade for noise, clearing ability, and maneuverability. If a DOT has issues with ice on roads, it may need to consider an operator review of its ice clearing ability to see if the blade should be fully implemented in the next season.

Table 4-7 is the installation review for the case study conducted in Idaho during the winter season of 2019-2020.

Table 4-7: Installation Review

Blade	Average No. of Persons for Installation	Average Duration of Installation	Comment
Blade one[1]	2	1 hour and 25 minutes	
Blade two	2	29.5 minutes	
Blade three	2	15 minutes	Easy to Install
Blade four	2	1 hour	

Note: [1] Blade one was tested in two locations. One of the locations needed training for installation of the blade which explains the increased blade installation duration.

Table 4-7 establishes that the blades used in the case studies all required two people to install a blade. The duration of the installation is where the blades varied. Blade three took 15 minutes while blade two took 29.5 minutes to install. Blade, one took the longest amount of time to install. This increased duration may be due to one of the garages needing training on how to install. The second longest installation duration is blade four which took one hour.

4.4.4 Data Processing

The trucks from Idaho all have GPS/AVL capabilities, so they are able to provide data on the trucks, which includes:

1. Time spent in the field,
2. Location in the field,
3. Road temperature and air temperature,
4. Vehicle speed, and
5. Plow location.

GPS/AVL allows Idaho to obtain the information listed above without having to exert any extra effort to track. The raw data sheets from the field data are available in Appendix D. First, time spent in the field is labeled as “Date_Time” and provides the date and duration for route. The location in the field is displayed as latitude and longitude. Additionally, the road and air temperature are used to establish weather conditions when plowing. The speed of the vehicle is also recorded using GPS/AVL. This may help determine if the wear is normal or abnormal. The last factor captured by GPS/AVL is the plow location. This feature denotes whether the plow is down and plowing or is up not plowing. Plow location appears as "UP" which represents plow up and "DOWN" which represents plow down. The sensor for plow up and down is located on the truck and is usually read by the pressure in the plow.

The raw data are used in conjunction with ArcGIS to establish what road material the blades plow on and how many bridge joints the blade encounters. Figure 4-3 is an example of the blade three that plowed on January 9th, 2020. The route is highlighted in red.

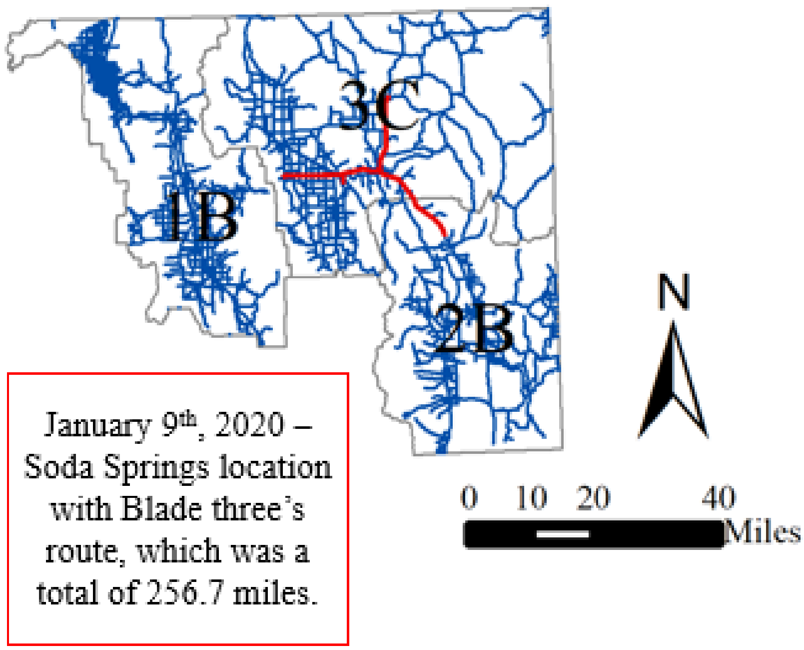


Figure 4-3: Route of Blade Three January 9th

Figure 4-3 shows the path that truck T31893 performed on January 9th, 2020. The routes of the trucks that plowed with the case study blades are created in ArcGIS. These maps are available in Appendix D. After the route is placed on the map, python coding is used to determine road material, number of bridge decks encountered. The results section below breaks down the blades from the raw data provided, the ArcGIS data created, and the NOAA data obtained.

4.4.5 Results

The results of the Idaho data show the wear, cost, mileage, and road conditions that the plow truck experienced in the case study which is associated with the cost of a plow blade as seen in Equation 4-1.

The roadway material and the number of bridge decks encountered affects the wear of the blade as discussed in Chapter 2. Table 4-8 summarizes the roadway material the blades encountered during its route.

Table 4-8: Roadway Material

Location	Blade Type	Number of joints plowed over[1]	Percent of Concrete[2]	Percent of Asphalt[2]
Soda Springs	Blade one	0	1%	99%
	Blade two	0	0%	100%
	Blade three	0	0%	100%
Moscow/ Potlatch	Blade one	1,996	1%	70%[3]
	Blade four	2,718	1%	70%[3]

Note: [1] The number of bridge joints was obtained by utilizing Idaho's bridge location layer in ArcGIS and the trucks routes from the truck's GPS/AVL system.

[2] The percent of concrete and asphalt encountered while plowing was discovered by utilizing Idaho's roads layer and the routes of the trucks from GPS/AVL.

3 The residual percent of material plowed over was asphalt concrete, which was 26% for blade one and 27% for blade four, respectively.

As seen in Table 4-8, none of the blades ran over bridges. The percent of asphalt that a blade plowed over is significantly greater than the percent concrete. Concrete was only encountered on one of the routes. Having a plow that runs over most of the asphalt and a minor amount of concrete is common for DOTs as seen in Table 3-6. Understanding the conditions that a blade is ran over is important, but it is also important to understand how the blade physically wore.

Table 4-9 summarizes the longevity of the blade, the cost of the blade, and the speed while plowing. As discussed in Chapter 2, speed and distance influence the wear of the blade.

Table 4-9: Blade Wear and Cost

Location	Blade Type	Average Wear (inches)[1]	Distance Plowed (miles)[2]	Wear Rate (Inch/100 Miles)[3]	Average Plowing Speed (MPH)[4]	Capital Cost
Soda Springs	Blade one	0.9	550.7	0.154	35	$3,371
	Blade two	1.2	214.2	0.560	30	$1,780
	Blade three	1.6	256.8	0.604	36	$2,798
Moscow/ Potlatch	Blade one	0.9	1,756.1	0.051	32	$3,371
	Blade four	0.6	375.3	0.157	29	$2,685

Note: The blades discussed in this table are just a sample. More blades are required to make a formal recommendation.

[1] The average wear was calculated from the sum of wear of all five measurement locations.

[2] The distance plowed was obtained from GPS/AVL tracking within the trucks and ArcGIS.

[3] The wear rate was calculated by average wear divided by the distance plowed.

[4] The average plowing speed was obtained through GPS/AVL and ArcGIS.

As shown in Table 4-9, the most wear, 1.6", occurred in blade three which plowed 256.8 miles. Blade three is the second most expensive blade utilized in this study. Blade one in either Soda Springs or Moscow/Potlatch wore the least and plowed the most miles. Additionally, blade one is also the most expensive blade tested. The interesting take away from the average wear, distance plowed, and capital cost is that the blades that are the least expensive and wore more quickly than the blades more expensive blades.

Blade speed is obtained through GPS/AVL on the trucks utilizing the blades for this study. Blade three is plowed at a faster speed than the other blades. 36 MPH is just above the most common plowing speed of 35 or less, from Table 3-6. In addition to the increased speed, blade three also had the second highest distance plowed and average wear. The interesting take away from Table 4-9 is that the blade's cost and their wear are disproportionate. To completely understand wear experienced by the blades, it is important to understand the road conditions where the blade was utilized.

Tables 4-10 through 4-14 and Figures 4-4 through 4-8 represent the wear of each plow blade. The tables are the measurement sheets which are in Table C-1. The wear is taken at the predetermined locations of A, B, C, D, and E, as seen in Figure C-2. The figures visually represent the wear of the blade. The lines are varying in color to indicate wear taken later in the study. The dark colors are the initial measurements and fade to lighter colors to indicate later measurements.

Table 4-10 summarizes the wear of blade one that is tested in Soda Springs, Idaho. Figure 4-4 visually displays the wear summarized in Table 4-10. The average snow fall during the lifespan of the blade is 2.6" with an average ground snow of 3.3" (NOAA 2020). The average temperature while plowing is 31.2 °F with an average road temperature of 30.65 °F. This blade is utilized for 23 days and plowed 550.7 miles.

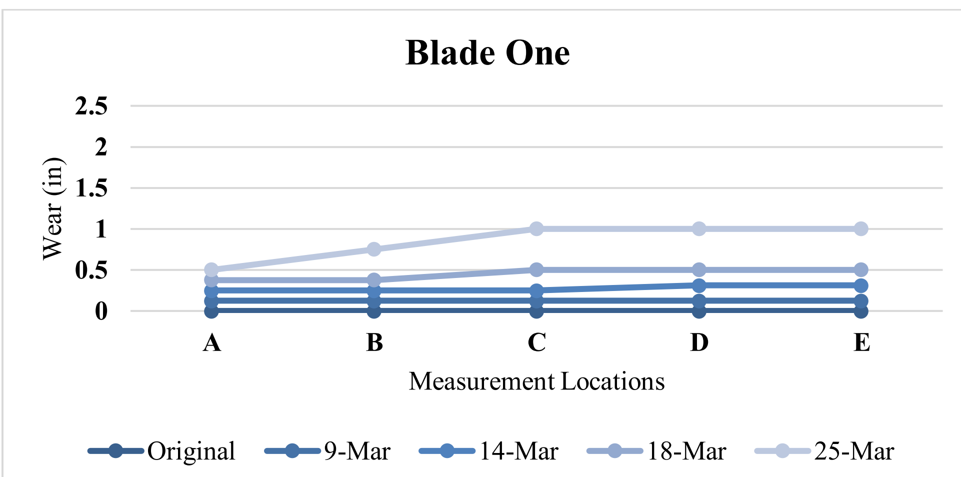


Figure 4-4: Blade One tested in Soda Springs

Table 4-10: Blade One tested in Soda Springs

Date	Measurement Locations				
	A(in)	B(in)	C(in)	D(in)	E(in)
9-Mar	5.375	5.375	5.375	5.375	5.375
14-Mar	5.25	5.25	5.25	5.188	5.188
18-Mar	5.125	5.125	5	5	5
25-Mar	5	4.75	4.5	4.5	4.5
Note: This blade ran for approximately 550.70 miles with the plow down.					

As seen in Table 4-10 and Figure 4-4, the wear of the blade one is uneven. Wear at locations C, D, and E are relatively similar and obtained the most wear, which was 1”. The uneven wear of the blade may be due to the crest of the road, obstructions, or potential rutting in the road; however, uneven wear may also be due to bad blade. Laboratory testing may be performed to determine if the uneven wear is due to bad blade.

Table 4-11 summarizes the wear of blade one that is tested in Moscow/Potlatch, Idaho. Figure 4-5 visually displays the wear summarized in Table 4-11. The average daily snow fall during the lifespan of the blade is 1.12” with an average daily ground snow of 3.7” (NOAA 2020). Snowfall and ground snow at the beginning of the season was higher than snowfall at the end of the season. The average temperature while plowing is 32.5 °F with an average road temperature of 34.8 °F. This blade is utilized for 82 days and plowed 1,753.1 miles. The x-axis represents the measurement locations. The y-axis represents the wear on the blade in inches.

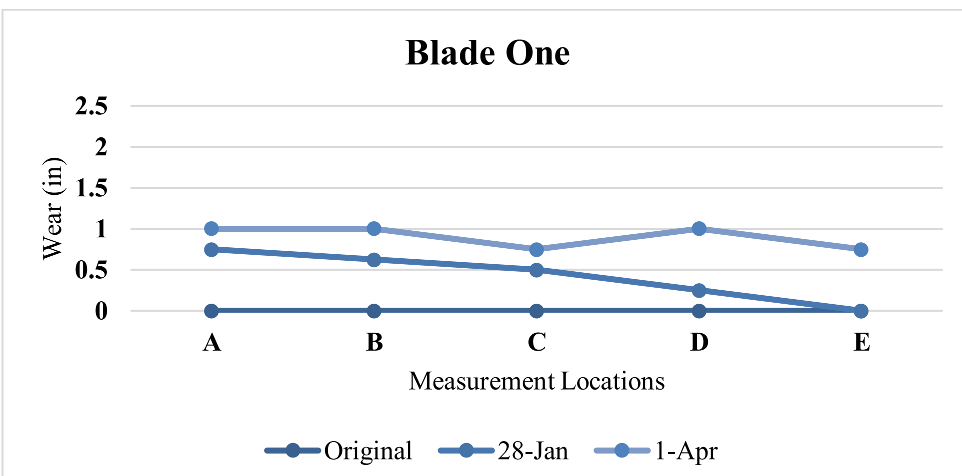


Figure 4-5: Blade One Tested in Moscow/Potlatch

Table 4-11: Blade One Tested in Moscow/Potlatch

Date	Measurement Locations				
	A(in)	B(in)	C(in)	D(in)	E(in)
9-Jan	8.75	8.875	9	9.25	9.5
1-Apr	8.5	8.5	8.75	8.5	8.75
Note: This blade ran for approximately 1,756.12 miles with plow down.					

As seen in Table 4-11 and Figure 4-5, the blade wore relatively linear. Again, this uneven wear may be due to the crest of the road, potential obstructions, or rutting. Uneven wear may also be due to bad blades. A blade may be laboratory tested to determine if wear is due to road conditions or bad blade. Location A, B, and C appear to wear at a seemingly consistent rate. The greatest wear occurred at location A, B, and D which was 1". The next blade that was tested is blade two.

Table 4-12 summarizes the wear of blade two which is ran in Soda Springs, Idaho. Figure 4-6 visually displays the wear of blade two at the predetermined locations along the blade. The average snow fall during the lifespan of the blade is 7.7" with an average ground snow of 8.0" (NOAA 2020). The average temperature while plowing is 22.7°F with an average road temperature of 24.2°F. This blade is utilized for 14 days and plowed 214.2 miles. The x-axis and the y-axis are the same as seen in Figure 4-5.

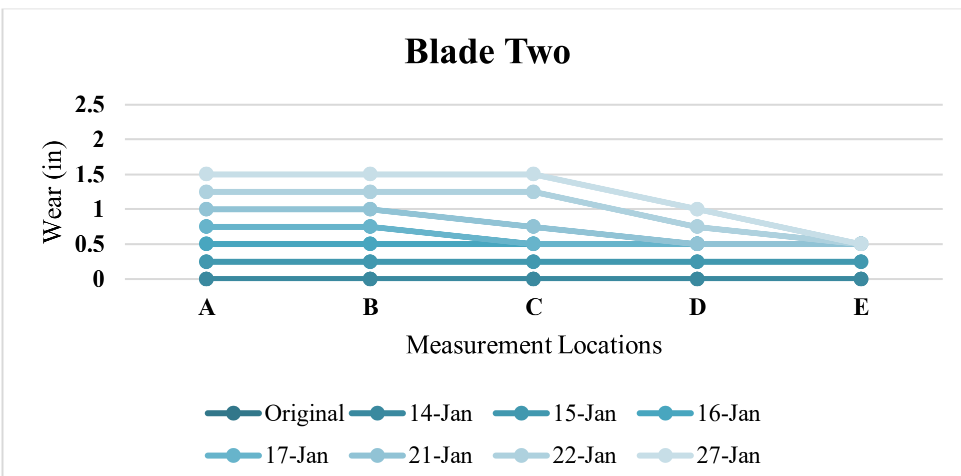


Figure 4-6: Blade Two tested in Soda Springs

Table 4-12: Blade Two tested in Soda Springs

Date	Measurement Locations				
	A(in)	B(in)	C(in)	D(in)	E(in)
14-Jan	6.5	6.5	6.5	6.5	6.5
15-Jan	6.25	6.25	6.25	6.25	6.25
16-Jan	6	6	6	6	6
17-Jan	5.75	5.75	6	6	6
21-Jan	5.5	5.5	5.75	6	6
22-Jan	5.25	5.25	5.25	5.75	6
27-Jan	5	5	5	5.5	6
Note: This blade ran for approximately 214.2 miles with plow down.					

As seen in Table 4-12 and Figure 4-6, blade wore unevenly; however, the wear is more even than that of blade one. Again, this uneven wear may be due to the crest of the road, potential obstructions, or rutting. Location A, B, and C appear to wear at a seemingly consistent rate. These locations had the greatest wear which was 1.5”. The next blade tested in the case study is blade three.

Table 4-13 summarizes the wear results of blade three. Figure 4-7 visually displays the wear of the blade. This blade is run in Soda Springs, Idaho. The average daily snow fall during the lifespan of the blade is 1.4” with an average ground snow of 7.5” (NOAA 2020). The average air temperature while plowing is 26.8 °F with an average road temperature of 26.0 °F. This blade is utilized for 10 days and plowed 251.1 miles. The x-axis and the y-axis are the same as seen in Figure 4-5.

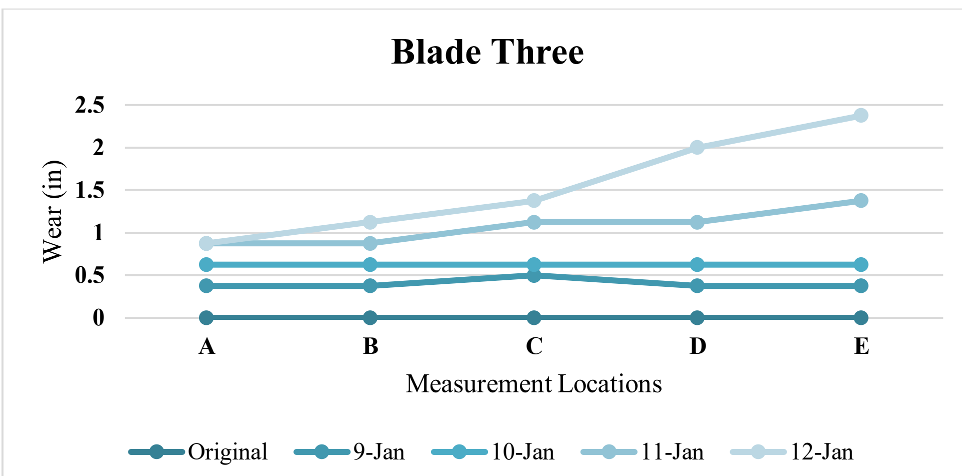


Figure 4-7: Blade Three tested in Soda Springs

Table 4-13: Blade Three tested in Soda Springs

Date	Measurement Locations				
	A(in)	B(in)	C(in)	D(in)	E(in)
9-Jan	7	7	6.875	7	7
10-Jan	6.75	6.75	6.75	6.75	6.75
11-Jan	6.5	6.5	6.25	6.25	6
12-Jan	6.5	6.25	6	5.375	5
Note: This blade ran for approximately 256.7 miles with plow down.					

As shown above, blade three wore unevenly. This may be due to the crest of the road, obstructions, or rutting. Uneven wear may also be due to bad blades. Location E had the greatest wear of the blade, 2.375”, which is the measurement location near the centerline of the road while plowing. As seen in Figure 4-7, the blade wear is linearly decreasing from location A to location E. After assessing the last blade, the blades need to be compared to a standard to ensure they are a cost neutral purchase for a DOT.

Table 4-14 summarizes the wear results of blade four. Figure 4-8 visually displays the wear of the blade. This blade is run in Moscow/Potlatch, Idaho. The average daily snow fall during the lifespan of the blade is 1.1” with an average daily ground snow of 3.7” (NOAA 2020). The snowfall at the beginning of the season was much larger than the snowfall at the end of the season. The average air temperature while plowing is 26.9 °F with an average road temperature of 29.1 °F. This blade is utilized for 91 days and plowed 375.3 miles. The x-axis and the y-axis are the same as seen in Figure 4-5.

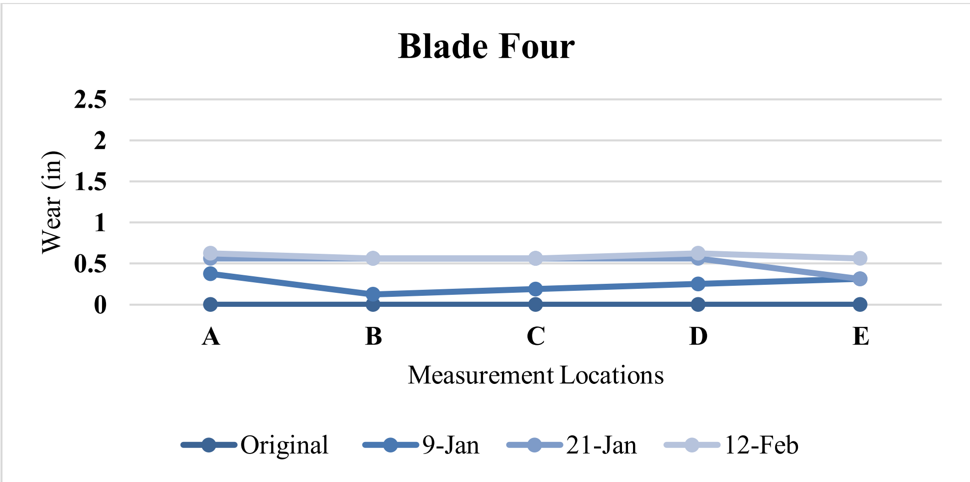


Figure 4-8: Blade Four tested in Moscow/Potlatch

Table 4-14: Blade Four tested in Moscow/Potlatch

Date	Measurement Locations				
	A(in)	B(in)	C(in)	D(in)	E(in)
9-Jan	6.125	6.375	6.313	6.25	6.188
21-Jan	5.938	5.938	5.938	5.938	6.188
12-Feb	5.875	5.938	5.938	5.875	5.938

Note: This blade ran for approximately 375.3 miles with plow down.

As shown above, blade four wore peculiarly compared to the other blade's tests in this study. Locations A and D had the greatest wear of the blade, 0.625", which is odd. Typically, the greatest wear is seen at location A, C, or E due to the crest of the road. After assessing the last blade, the blades need to be compared to a standard to ensure they are a cost neutral purchase for a DOT.

4.4.6 Conclusion

The next step after blade testing is to check cost neutrality. This is to see if the blades would be cost effective for Idaho.

Using Equation 4-1, Table 4-15 is created to summarize the cost of each blade. Using the installation review, see Table 4-7, the duration of installation and the number of people needed to install is available. These variables are used as a part of the installation portion of the cost equation, as seen in Equation 4-2. The research team is provided with the pay scale of the individuals who assisted in the installation process. The average hourly rate is utilized as the hourly rate in the operational portion of cost. The capital cost of the blades may be found in Table 4-9. Capital cost of each blade is utilized as the capital cost portion of the cost equation as seen in Equation 4-3. The last component of cost, wear, is provided in Table 4-9. The wear of each blade is the physical wear of the blade in inches divided by the plowed down mileage of the blade is seen in Equation 4-4. Only one blade failed during the duration of the study which is blade one in Moscow/Potlatch. The blades tested in Soda Springs were only on a plow for about 2 weeks and did not fail. The remaining blade tested in Moscow/Potlatch is blade four, which was on a plow for 3 months; however, it did not fail during the season. The summarized cost calculation for the failing blade is seen in Table 4-15.

Table 4-15: Cost

Blade Type	Cost ($/ 100 Miles)
Blade one- Moscow/ Potlatch	192.46

Note: The results of the Idaho Case Study are only a sample for DOTs to utilize as a example of how testing should be conducted. The results, due to the limited quantity being tested, are not enough to make a definitive statement about the cost.

As seen in Table 4-15, blade one costs $192.46/100 miles. This blade had failure due to chipping within the carbide insert and gravel located between the rubber and the steel blade. It may be seen in Figure 4-9.

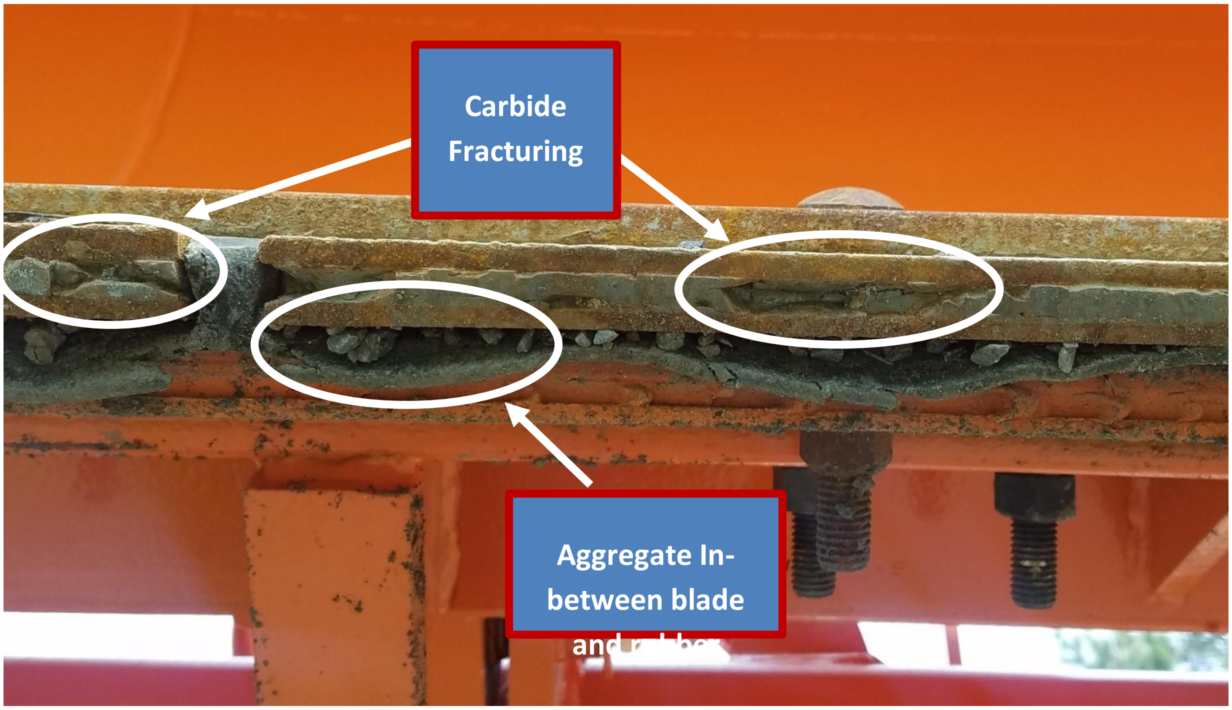


Figure 4-9: Blade Failure in Idaho Case Study

Table 4-15 is just an example of how to utilize Equations 4-1 through 4-4. The sample tested in the case study is not significant to make definitive claims. Further testing should be conducted to validate the results within this case study. To establish if these findings are meaningful or significant, more blades should be tested.

4.5 SMALL SCALE FIELD TESTING

A small-scale field test was conducted in Trondheim, Norway to compare the wear performance of two types of blades on one specific location during a whole winter season. In Norway, winter maintenance is performed by private contractors that are bidding for maintenance contracts on a specific geographical area, for a period of typically five years. Due to contractual conditions and commercial interests, the costs of the blades and estimate of hours and wages for blade replacements could not be shared with the research team. Nevertheless, this small-scale field study did provide valuable data on the wear of two blade sets, and applicability of the testing protocol.

4.5.1 Location

The test site for this study was a 13.6 miles road section of highway E6. This is mainly a four-lane road. A map of the route is shown in Figure 4-10. This route has the highest maintenance class (also known as Level of Service) used in Norway, meaning that it practices an anti-icing strategy throughout the winter season. The Road surface on the test site consists of bituminous pavements of the type stone mastic asphalts (Ska) and asphalt concrete (Ab). The maximum plowing speed under operation is limited to 40 km/h by regulations from the Norwegian Public Roads Administration.

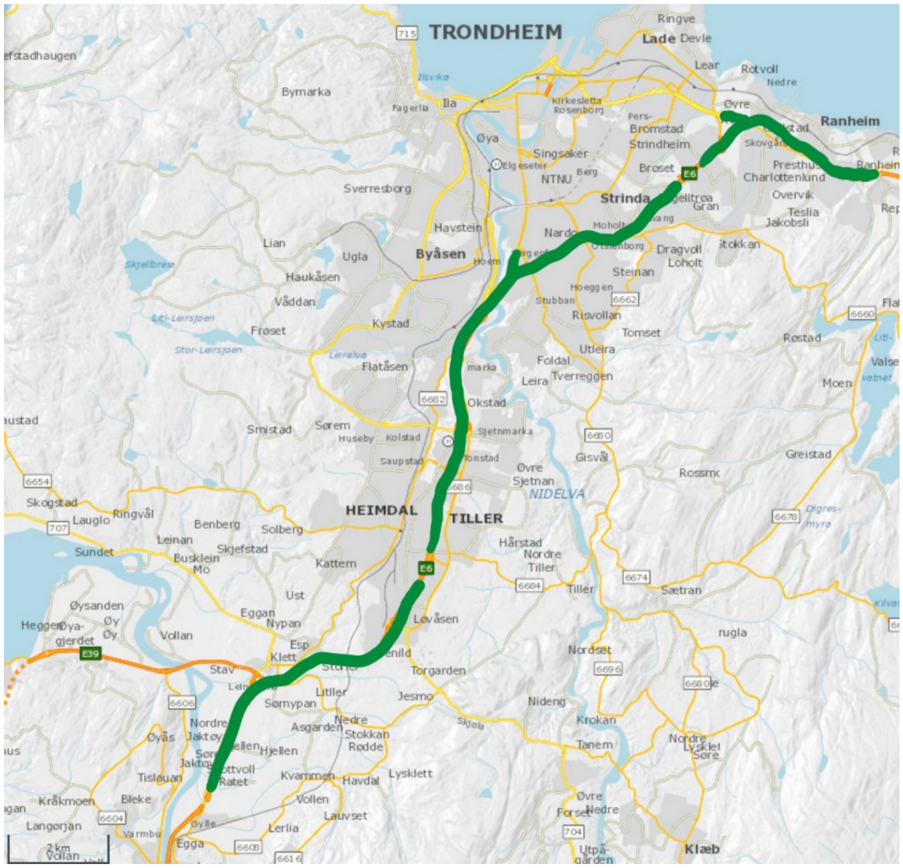


Figure 4-10: Small-scale Case Study Location in Trondheim, Norway.

Blades were tested on 13 miles of a four-lane highway including ramps in Trondheim Norway by a private contractor, called Mesta. The blades were fitted on one snowplow truck, equipped with a Meiren MSP front plow. This truck was solely used for snow plowing on the 13 miles route, throughout the season and therefore ideal for a comparative test between two types of blades. Figure 4-11 displays the used snowplow fitted on the truck.

Figure 4-11: Mesta Snowplow in Trondheim, Norway.

4.5.2 Blades

The first type of blades were steel blades with rubber and ceramic inserts, called Nordic combi double. The second type was of blades had a core of Polyurethane, sandwiched between two steel plates. Both blades were reversible, meaning that the blades can be worn down from one side first, and then rotated 180 degrees, to be worn off from the other side. The blades are illustrated in Figure 4-12 and one set of blades consist of six 2-feet blade elements. Since each blade set could be worn off from both sides they were marked as A1, A2, B1, B2, etc. The capital letter marks a given blade that was installed and number “1” refers to the first side that was worn down, and “2” refers to the second side.

Figure 4-12: Two Blade Types tested in Trondheim, Norway.

4.5.3 Data

For this small-scale field study, the research team and cooperating contractor wished for a more detailed dataset of the wear along the plow. The number of datapoints in the test protocol were therefore increased from 5 to 12. This provided two measurements per 2-feet blade. The lowest mounting holes were used as accurate reference point for the wear measurements, while the blades were fitted to the plow by bolts through the upper holes, illustrated in Figure 4-13.

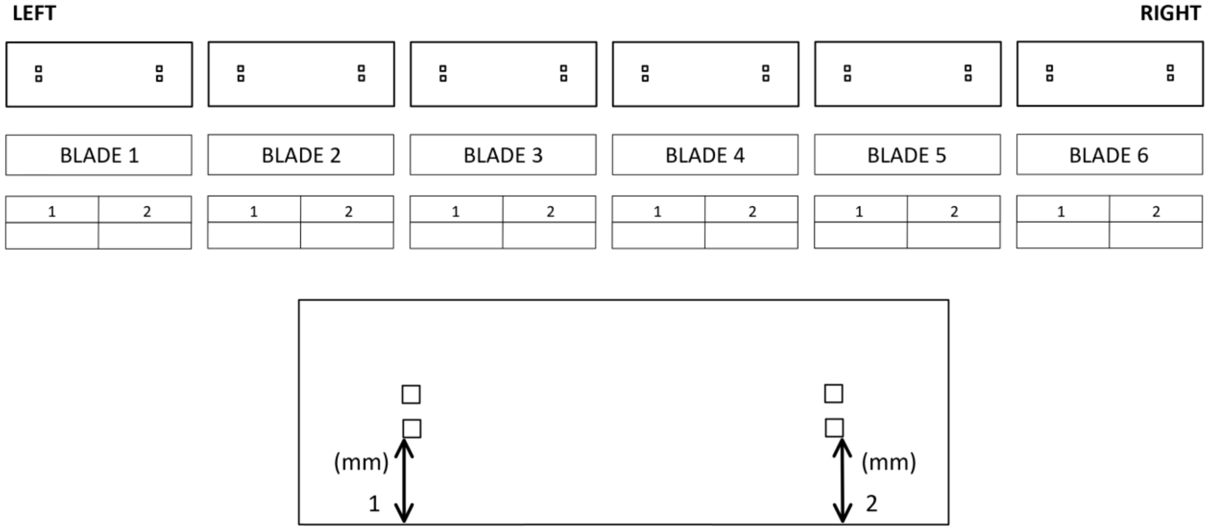


Figure 4-13: Measurement Locations along a Blade in Trondheim, Norway

AVL data are utilized to provide GPS location of the plow truck, miles with the plow down. Norwegian maintenance contracts specify that plowing should be performed at maximum 40 km/h (25 miles/h). Contractors risk penalties if they drive faster. Therefore, all data was collected at this driving speed.

An RWIS station along the route was used to collect the following weather / road surface parameters between every wear measurement:

- Total amount of snowfall (in mm),
- average air temperature (°C),
- Average road surface temperature (°C),
- Relative Humidity (%), and
- Snow and Ice coverage (%).

The percentage snow and ice coverage were determined visually from the camera at the RWIS station. A snow/ice coverage from 0 to 100% is visually assessed, and a percentage value (0, 25, 50, 75, 100) are given to each relevant picture. Table 4-16 presents the different coverage ranges, values, description, and example pictures. The visual assessment process was done five times and the most frequently assigned value was used to ensure a consistent assessment.

The time (t) at which the plow truck passed the RWIS station was taken from the AVL data. The coverage as the time of passage was linearly interpolated between the closest measurement before and after the passage.

Table 4-16: Snow/Ice Coverage Definitions

Coverage	Description	Illustration
0 % Assigned value: 0	Bare wet asphalt. No snow covering the road or road markings on the sides.	
0<25 % Assigned value: 25	Mostly bare wet asphalt. Some patches of snow/ice/slush, or snow covering road markings on the sides.	
25<50 % Assigned value: 50	Some snow/ice/slush on the road, with bare tire tracks. Clearly visible that the salt has started to melt the snow/ice, leaving wet asphalt. Especially in right lane, which may be almost cleared of snow.	
50<75 % Assigned value: 75	Snow/ice/slush covering everything except the tire tracks in the right lane.	
75≤100 % Assigned value: 100	Road totally covered with snow or ice.	

4.5.4 Results

From the start of December 2019 to early April 2020, Mesta AS plowed 6800 km (4225 miles) on the test route. This resulted in five sets of blades that were worn out, or for other reasons replaced and one blade that was partly worn at the end of the season. Each side of the reversible blades were treated as a separate blade set. Table 4-17 presents the key results for each set. The raw data of the wear measurements is presented in Appendix D, Figure D-11. The total wear is calculated from the average of the 12 measurements points along the plow. Table 4-17 shows that the average wear rate of the Nordic Combi Double (0.034 mm/km) was significantly lower than the Steel/Polyurethane blades (0.054 mm/km). So, the Nordic combi double was more wear resistant and a fully worn blade set gave a total mileage of 1803 km (1120 miles). That said, operational factors like a broken back plate and a whole blade set (A2) that could not be used because the other side (A1) was worn too far, reduced the total mileage the contractor got out of all blade sets.

Table 4-17: Key results of the small-scale field test

Set ID	Total Wear		Total Plowing Distance		Total Wear Rate		Reason for Replacement
	[mm]	[Inch]	[Km]	[Miles]	[mm/Km]	[Inch/ Mile]	
				Nordi Combi Double			
A1	54.72	2.1545	1804	1121	0.030	1.92 E-03	Blade 3 and 5 of this blade set were worn out too far. Therefore, the blade set could not be reversed. (no A2 data).
C1	20.52	0.808	598	372	0.034	2.18 E-03	Blade 3 worn in an improper way due to broken blade holders (back plate)
C2	55.76	2.195	1801	1119	0.031	1.96 E-03	Blade 3, 4 and 6 worn out.
D1	39.94	1.572	981	610	0.041	2.58 E-03	Not fully worn blade set when the winter season was over.
Avg	55.24	2.175	1803*	1120*	0.034	2.09 E-03	
				Steel / Polyurethane			
B1	47.72	1.879	931	578	0.051	3.25 E-03	Blade 5 and 6 worn out
B2	36.68	1.444	645	401	0.057	3.60 E-03	Blade 5 worn out
Avg	40.20	1.58	788	490	0.054	3.39 E-03	

* *The average of the total plowing distance is only calculated using the fully worn blade sets A1 and C2*

The accumulated wear as function of plowing distance is presented in Figure 4-14 for all blade sets. It illustrates that even for the same type of blades, the accumulated wear changes significantly. After about

1000 km plowing, Blade set A1 had only 12 mm wear, whereas D1 had worn 40 mm. The wear rate (= the steepness of the line between two successive measurement points) vary greatly, both within the same blade set and between different sets of the same type.

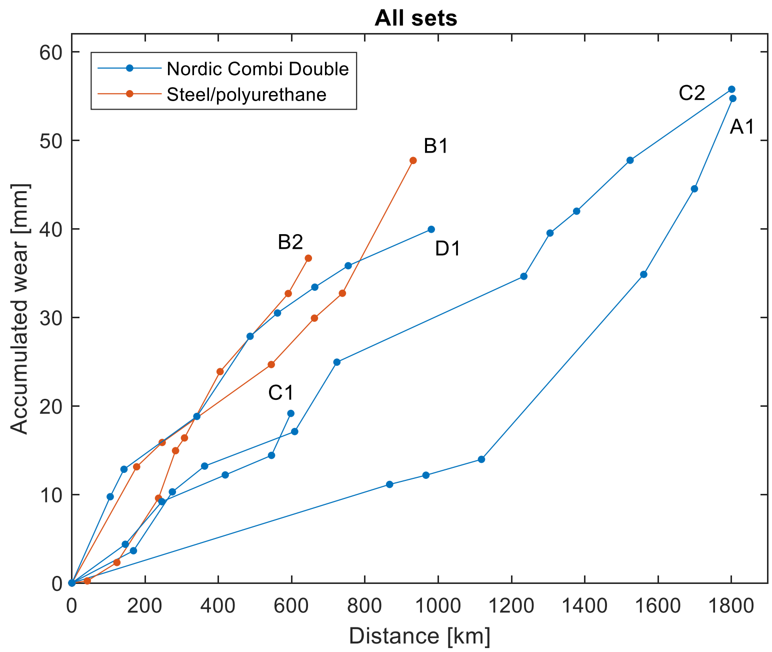
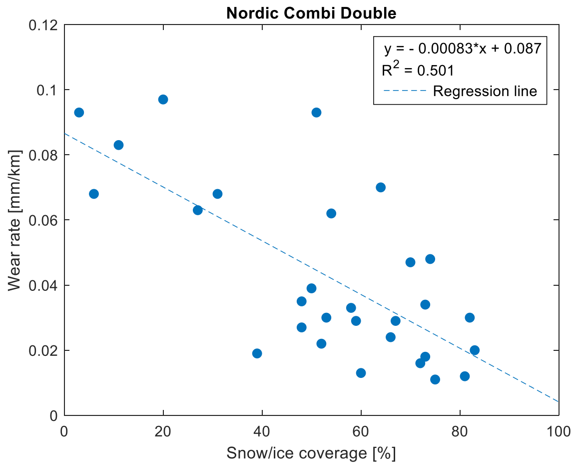


Figure 4-14: Accumulated Wear as a Function of Plowing Distance

The wear rate was calculated between each two successive wear measurements and the effect of the different weather factors was investigated by making scatter plots, presented in Appendix D, Figures D12-D16. The goodness of fit (R2-value) of a linear relationship between the wear rate and each weather/road surface factor is summarized in Table 4-18. Only the snow and ice coverage correlated reasonably well with the wear rate, with R2-value above 0.4. The other factors had basically no explanatory value for the wear rate. The correlation between the snow/ice coverage and the wear rate is shown in Figure 4-15 and Figure 4-16. Higher wear rates were correlated with a lower snow/ice coverage.

Table 4-18: Goodness of fits (R^2-values) for Wear Rate and Investigative Factors

Weather / road surface factor	Goodness of fit (R^2)	
	Nordic Combi Double	Steel / Polyurethane
Amount of snowfall (mm)	0.125	0.055
Road surface temperature (°C)	0.137	0.018
Air Temperature (°C)	0.104	0.096
Relative Humidity (%)	0.013	0.030
Snow/ice Coverage (%)	0.501	0.423



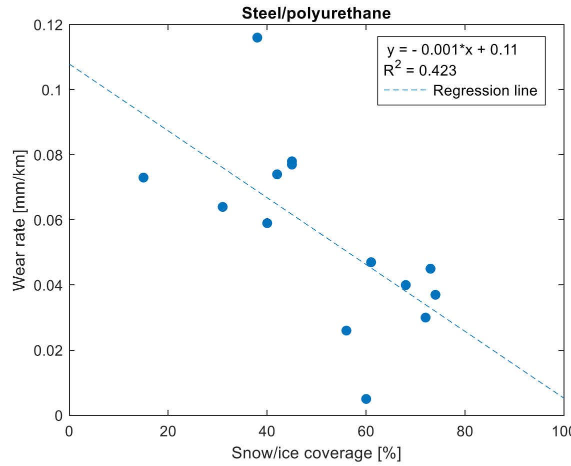


Figure 4-15: Correlation of Wear Rate and Snow/Ice Coverage for Nordic Combi Double Blades

Figure 4-16: Correlation of Wear Rate and Snow/Ice Coverage for Steel/Polyurethane Blades

The observation that the wear rate largely depends on the snow/ice coverage was expected. Particularly when anti-icing chemicals are applied, the snowplow runs for significant periods of time on almost bare pavements. Snowplow truck drivers explained to the research team that “the last round” after a snowfall has often little snow on the road. Nevertheless, it is important to remove even these small amounts of snow/ice before the final application of chemicals to ensure a high concentration. For comparative testing purposes, it can be useful to conduct testing on wet pavements, to illuminate the variability caused by the snow coverage, which is inherently difficult to control in a test setting.

4.6 LAB TESTING

The third testing method recommended by the research team is laboratory testing. This section details how to conduct lab testing, who should conduct lab testing, what testing should be performed and what quantity of blades should be tested.

4.6.1 Survey

The research team conducted a survey of labs to confirm the testing that is to be recommended is appropriate, easily replicated, and available in most labs. The initial laboratory search utilized labs that the technical panel recommended which are smaller scale laboratories. After discussions with smaller labs, the research team began searching for larger labs. Laboratories are found by searching for metallurgy testing laboratories. The laboratories are verified to meet ISO 17025 certification, test metals, nonmetals, and polymers, and utilize ASTM testing. The laboratory information is seen in Table 4-19.

Table 4-19: Laboratory Information

Laboratory Qualifications	
Certified in ISO 17025	
Yes	All
Years of Experience	
Minimum	23
Average	63
Maximum	190
Number of Employees	
Minimum	30[1]
Average	4,395.21
Maximum	94,000
Number of Facilities	
Minimum	5[1]
Average	336
Maximum	2,600
National or International	
International	53%
Testing Methods	
Conduct Metallurgical, Polymer/Rubber Testing	All
Utilize ASTM Standards	All

Notes: 17 out of the 20 responded via multiple phone calls and emails with information regarding testing.
[1] The low minimum numbers are due to initially utilizing technical panel references for laboratories. These labs were smaller than most of the labs contacted.

Table 4-19 summarizes the average criteria that distinguish the labs contacted as credible and competent to discuss testing of plow blades. All of the laboratories are certified with ISO 17025, conduct metallurgical, and polymer/rubber testing, and utilize ASTM test standards. This ensures the laboratories contacted are certified laboratories and are able to test all materials within a plow blade. Additionally, the labs interacted with have been in business for an average of 63 years with an average number of 4,395 employees indicating that these laboratories are well established businesses. Table 4-19 shows that the average number of facilities is 238 with over 53% of the labs contacted having international locations. Contacting labs with multiple facilities ensures that DOTs from around the country may find laboratories that are credible.

Once the laboratories discovered are determined to be appropriate and able to test plow blades, the laboratories are contacted multiple times to establish an understanding of the product being tested but also that the tests being sought after are appropriate for the material. Additionally, the laboratories are asked the following questions:

1. If the testing sought after for each material, is to be done pre or post field testing?
2. What standard testing methods are most applicable for the specifications?
3. What are the prices for the recommended tests?
4. How long will pre and post testing take?

5. Are any tests being missed?

The results and recommendations of those conversations are detailed below. Section 4.6.2 summarizes what to test, what standard to hold a blade accountable to, and suggest ranges to adhere to. The tests within the tables are validated through conversations with the laboratories that the tests recommended are reasonable.

The testing methods suggested below are from the American Society for Testing and Materials (ASTM), the American Welding Society (AWS), and NASPO 2012 contracts. ASTM and AWS are suggested based off their precise testing requirements as well as their familiarity amongst metallurgy testing labs. This ensures the testing methods are easy to follow, standardized, trusted, and easily replicable; however, other testing methods may be applicable.

4.6.2 Testing

The materials of the blades should be tested to ensure the specifications provided by the vendor are true and representative. Carbide, steel, and rubber have distinct tests due to the different chemical, physical and mechanical properties of each materials. Section 4.6.3 through 4.6.6, the individual specifications, test methods, and costs are suggested for braze, carbide, rubber, and steel, respectively. Figure 4-17, for example, is a flexible carbide blade that encompasses all the blade materials.

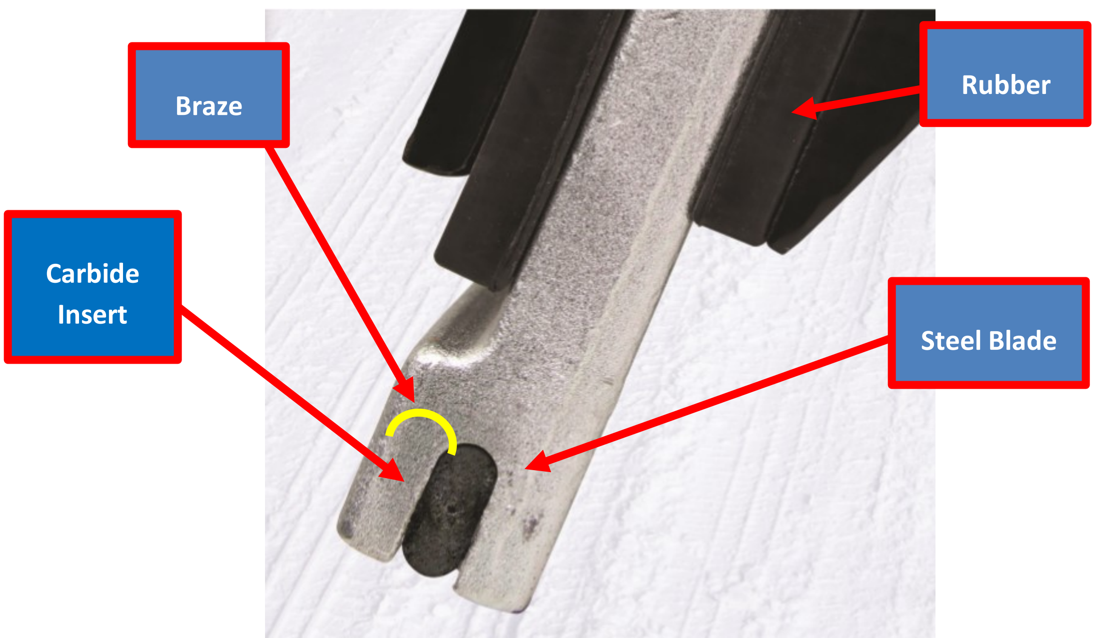


Figure 4-17: Polarflex Blade (Polarflex 2020)

This blade encompasses all four major components that specifications may be checked:

1. Braze,
2. Carbide,
3. Rubber, and
4. Steel.

The first material type is brazing which is the welding component that keeps the carbide insert in place in the steel blade. Typically, if a carbide insert is used, a brazing material is used to secure its placement. In addition to brazing, the second component is the carbide insert which is also utilized in plow blades. The third component in this example is rubber which is used in flexible blades. The rubber encompasses the carbide insert blade to allow for flexibility. The last material a plow blade is commonly made from is steel.

As discussed in Chapter 2, plow blades require a certain hardness, toughness, and strength for the blade to resist wear, fracture, and deformation. The specific properties tested of a material indicate a blade's resistance to wear, fracture, and deformation. These important factors are provided in Tables 4-19, 4-20, 4-22, and 4-24.

Testing every specification of all the components within a plow blade may be costly; therefore, the research team created a tier system of the tests for the components of plow blades. The tier system is determined by two technicalities:

1. Predictors and
2. Cost.

The first technicality is predictors which is the chemical or physical attributes being tested may indicate poor qualities of other characteristics. This ensures the aspects, whether chemical or physical, of a plow blade are tested in order of importance. For example, hardness of a material will indicate poor porosity, poor density, or poor grain size of a material (Braun Intertec Corp. 2010). So, if hardness is low then it may be assumed that porosity, density, and grain size are also not correct. In addition to utilizing predictive specifications, the research team recommends low-cost tests and if possible nondestructive tests over destructive tests. To alleviate some of the financial strain lab testing may add, the research team recommends tests that are less expensive in a lower tier and more expensive in a higher tier. A DOT may also conduct all the testing if they have no restrictions financially. Due to the size of plow blades, one plow blade should be sufficient for a lab to perform all tests suggested.

The suggested tests in sections 4.6.3 through 4.6.6 are recommended due to their association with hardness, toughness, and strength. As discussed in Chapter 2, these qualities are most important for plow blades and their resistance to wear, fracture, and deformation. The "importance" section defines what the test recommends helps define in terms of: hardness, toughness, strength, and bonding. The first component of plow blades to discuss is brazing.

When a DOT is conducting a lab test, the ranges for the specifications should come from either the vendors of the blades they are interested in or from the state's plow blade quality requirements if applicable. If the DOT does not have contract specifications for blades, they should check the blades against the vendor sheets and potentially other state conditions. All plow blade vendors have specification sheets of each blade they sell. Additionally, each component within the blade will be detailed in the specification sheet. An example of this may be seen in Table 4-21 as the JOMA, TXS, Polarflex, Tuca SX Wave, and the Econoflex blade specifications are all available. These blades are from different vendors and are easily obtained by just inquiring. The detailed specification sheet should be used as a basis for testing. Over time the ranges provided will be replaced with ranges that DOTs find most applicable or most successful. The ranges that DOTs establish may vary from state to state due to different needs for hardness, toughness, and strength.

The ranges provided for testing are initially established through NASPO 2012 contracts and vendor specification sheets as seen in Table 4-20. The specifications from the NASPO contract are validated through not only laboratory testing as specified above but also through the vendor specification sheets. A few of the specification sheets are seen in Table 4-20.

Table 4-20: Blade Specifications and Ranges

Specifications	Ranges NASPO 2012	Flexible Blades JOMA	TXS	Polarflex	TUCA SX	Econoflex
Braze						
Braze Composition				Not Provided		
Copper/Silver	46-50%	46.0-50.0%	46.0-50.0%			46.0-50.0%
Silicone	0.04-0.25%	0.04-0.25%	0.04-0.25%			0.04-0.25%
Nickel	9.0-11.0 %	9.0%	9.0-11.0%			9.0-11.0%
Phosphorus	0.25 %	0.25%	0.25%			0.25%
Aluminum	0.01 %	0.01%	0.01%			10.01%
Lead	0.05 %	0.05%	0.05%			0.05%
Zinc	Remainder	Remainder	Remainder			Remainder
Shear Strength	70,000 PSI	70,000 PSI	70,000 PSI	Not Provided	Not Provided	70,000 PSI
Carbide						
Carbide percent by weight	89%	89%	89%	89%		89%
Cobalt percent by weight		11%	11%	11%		
Specific gravity		14.35-14.60	NA	14.5		14.35-14.6
Density			14.35-14.60		14.40 g/cm^3	

Rockwell Hardness	87.5-88.8 Rockwell A	87.5-88.8 Rockwell A	87.5-88.8 Rockwell A	88 Rockwell A	1100-1300 HV10 ISO 3878	87.5-88 Rockwell A
Transverse Rupture Strength	351,000-428,000 PSI	351,000-428,000 PSI	351,000-428,000 PSI	2800N/mm^2	2700N/mm^2	351,000-428,000 PSI
Porosity						
Grain Size					5-7 micron	
Rubber						
Ultimate Elongation	582%	582%	582%	530%		582%
100% Modulus	276 PSI	279 PSI	276 PSI	NA		276 PSI
Tensile Strength	3113	3113	3113 PSI	10.6Mpa		3113 PSI
Shore A Durometer	60 pts	60 pts	70 pts	60 pts		70 pts
Tear Strength	641 PPI	341 PPI	341 PSI	27kN/M		341 PSI
Compression Set	26.5%	26.5%	26.5%	27%		36.5%
Low Temperature Brittleness	No cracks at -40C	No cracks at -40C	No cracks at -40C	No cracks at -40C		No cracks at -40C
Steel						
Composition	Cast Steel			ASTM 5140	Dillibur	
Rockwell Hardness					43 Rockwell C, 114 Rockwell B	
Brinell Hardness						

Notes: [1] This is one example of specifications sheets from vendors and an example of the NASPO 2012 contract for flexible plow blades. Flexible blades are used for this example due to flexible blades encompassing all materials recommended for laboratory testing.

As seen in Table 4-20, the ranges associated with the specifications are vendor dependent. DOTs should utilize the vendor specification sheets prior to testing in order to ensure the quality of the blade tested meets the ranges provided.

4.6.3 Brazing

Brazing is the joining of two metals that are dissimilar. A filler material is heated to a point of fluidity and flows into the joint to merge dissimilar metals together (Way et al. 2020). Braze is used in plow blades to join the carbide insert and the steel blade together.

Brazing has had great advances; however, the reliability of brazed joints is one of the least developed fields of structural analysis (Sekulić, 2013). For this reason, knowing if a blade failure is caused by brazing will require further research to establish if testing brazing is necessary or not.

Table 4-21 summarizes specifications, ranges, and standard tests one may want to use when inspecting the brazing of a plow blade.

Table 4-21: Braze Composition

Specifications	Importance[1]	Ranges[2] Carbide Tipped Blades	Carbide Inserts	Flexible Blades	Standard Tests[3]	Average Cost
Braze Composition, %	1. Bonding[4] 2. Strength	High Strength Alloy	High strength silver alloy	46-50 Copper/Silver 0.04-0.25 Silicone 9.0-11.0 Nickel 0.25 Phosphorus 0.01 Aluminum 0.05 Lead Remainder Zinc	AWS B2.1/B2.1M:2014, ASTM E32, ASTM B215-15	$336.67
Shear Strength, psi	1. Strength	Min. 30,000	Min. 30,000	Approximately 70,000	AWS C3.2M/C3.2:2008	$225.00

Note: All specifications, ranges, and testing methods should be verified and adjusted by the DOT, vendor, or lab. Some of the tests may not be applicable due to the design of the plow blade.

[1] The importance factor dictates if the specification indicates a material's hardness, toughness, and strength in order for the blade to resist wear, fracture, and deformation.

[2] The ranges are based off NASPO 2012 contracts and vendor specification sheets.

[3] The standard test description is available in Appendix E.

[4] Bonding is an aspect that is important in plow blades for bonding between steel blade and carbide insert.

Table 4-21 contains two specifications composition and shear strength to be tested for brazing. Braze composition is the first specification and is important in understanding the strength of the joint, the brittleness of the joint, and different mechanical characterizations. The composition of the brazing material promotes bonding with the metals it is linking (Way et al. 2020). Since the composition influences bonding and strength, establishing a set braze composition will help promote strength and bonding necessary to hold an insert in place in a plow blade. The brazing material composition is related to the function of the product and materials that the material is joining (Sekulić, 2013). For carbide tools, silver/copper-based fillers are used to bond the two metals that are being joined. Proper bonding ensures the materials are brazed together and that the braze is not a point of brittleness. The second specification to inspect is shear strength. Shear strength is essential due to the force caused by the two metals being shear, understanding its capacity ensures that the brazing is not critically weak. The shear strength depends on composition and brazing practices (Buhl et al. 2010). Having a shear strength baseline ensures that the braze is not failing at a low shear loading.

If a DOT may test one of the discussed specifications, the research team recommends testing the braze composition. The filler composition, the space between the joined metals, and how clean and rough the joined materials are influencing strength; therefore, if a filler material is improper, it will determine the strength of the braze (Way et. al 2020).

4.6.4 Carbide

Carbide is a common material in plow blades due to relative hardness and toughness. Carbide is used in a variety of ways for plow blades:

1. Carbide tipped blades
2. Carbide inserts blades, and
3. Flexible blade carbide inserts.

The specifications of interest for carbide are carbide and cobalt specific weight, specific gravity, Rockwell hardness rating, transverse rupture strength, density, porosity, and grain size.

In the NASPO 2012 contract, they note specific gravity to be tested; however, through lab surveys, it is established that the density of the blade provides the same information as specific gravity, but density testing is easier and less expensive to perform. For this reason, the research team recommends testing for density rather than specific gravity. However, if DOTs want to test the specific gravity for the carbide inserts, the laboratories may calculate the specific gravity from density though Archimedes principle.

Table 4-22 summaries the carbide specifications, importance, ranges, standard tests, and average cost.

Table 4-22: Carbide Specifications

Specifications	Importance [1]	Ranges[2]			Standard Tests [3]	Average Cost
		Carbide Tipped Blades	Carbide inserts Blades	Flexible Plow Blades		
Tungsten Carbide Specific Weight, %	1. Hardness	87.0-88.0	87-88	89	ASTM B657-18, ASTM B665-19	$211.50
Cobalt Binder Specific Weight, %	1. Toughness	11.0-12	10-12			$31.00
Hardness Range (Rockwell Rating)	1. Hardness	87.5-89.0 (“A”)	87.5-88.5 (“A”)	87.5-88.8 (“A”)	ASTM B294-17, ASTM E18	$166.67
Transverse Rupture Strength, psi	1. Strength	Min. 350,000	Min. 350,000	351,000-428,000	ASTM B406-96(2015)	$962.00
Density	1. Hardness 2. Toughness	14.1-14.6 GMSLCC	14.0-14.5 g/cc		ASTM B311-08	$120.00
Porosity	1. Hardness 2. Toughness	A06, B00, C00			ASTM B276-05E1	$325.00
Grain Size	1. Hardness 2. Toughness	10M/10C, 15% or less samples have large voids when viewed under a microscope			ASTM B390-92(2006), ASTM B657	$300.00

Note: All specifications, ranges, and testing methods should be verified and adjusted by the DOT, vendor, or lab. Some of the tests may not be applicable due to the design of the plow blade.

[1] The importance factor dictates if the specification indicates a material’s hardness, toughness, and strength in order for the blade to resist wear, fracture, and deformation.

[2] The ranges are based off NASPO 2012 contracts and vendor specification sheets.

[3] The standard test description is available in Appendix E.

The first specification seen in Table 4-22 is tungsten carbide and cobalt percentages which are important because these components influence hardness, abrasion resistance, and toughness (Ke, Zheng, et al 2019). Cobalt increases a blade’s toughness but decreases its hardness and abrasion resistance to breaking; however, too much cobalt may make a blade wear quickly (Santhanam, A.T. 2003). It is necessary to have an idea of carbide to tungsten percentage to have a baseline toughness and hardness.

In addition to carbide and cobalt percent weights, hardness is another specification to be lab tested as seen in Table 4-22. Hardness measures the relative ability of a material to resistance wear, abrasion, or indentation by another material (Santhanam, A.T. 2003). Hardness is affected by the composition, porosity, and microstructure (Santhanam, A.T. 2003). A carbide's rockwell hardness rating will ensure that the carbide is hard enough to withstand the abrasive process that is snowplowing.

The fourth specification in Table 4-22 is transverse rupture strength which is the modulus of rupture or the flexural strength. It is the measure of stress in a material before it yields. Transverse rupture strength increases as the content of cobalt increases (Nahak et al. 2015). The process of snowplowing causes the blade to flex, so the flexural strength of a blade is essential to not fail earlier than anticipated. In addition to transverse rupture strength, density of carbide blades is to be tested. The density of carbide blades varies dependent on composition (general carbide).

The last specification in Table 4-22 is porosity and grain size which influence the carbide's hardness, toughness, and resistance to abrasions (Santhanam, A.T. 2003). Porosity is the presence of microscopic pores in the tungsten carbide/ cobalt. Grain size is also related to wear, hardness, and impact. The coarser the grains the less resistance it has to abrasions (Nahak et al. 2015). A plow blade needs a combination of hardness, toughness, and resistance to abrasions to perform properly in the field which is affected by porosity and grain size.

The research team determined which testing methods are the most important for testing in a tier system. As noted in Braun Intertec 2010, their research team created a "Carbide Blade Insert Selection Framework for Lab Tests and Results" which details tests in a step system from least expensive and easy for laboratories to perform to more expense and difficult for laboratories to perform. The research team utilized the Braun Intertec 2010 selection framework and recommendations from contacted laboratories to create Table 4-23.

Table 4-23: Carbide Tier Testing

Tier	Specification	Standard Test	Cost
One	Density	ASTM B311-17	$120.00
	Hardness	ASTM B294-17, ASTM E18	$166.67
Two	Grain Size	ASTM B390-92(2006), ASTM B657, ASTM B930-03 (2017)	$300.00
	Porosity	ASTM B276-05E1	$325.00
	Tungsten Carbide Specific Weight	ASTM B657-18, ASTM B665-19	$211.50
Three	Cobalt Binder Specific Weight		$31.00
	Transverse Rupture Strength	ASTM B406-96(2015)	$962.00

Note: All testing may be done pre or post-field testing as long as the sample is a minimum of 0.2" x 0.25" x 0.75".

As seen in Table 4-23, the first tier is density and hardness. Hardness, as discussed in the previous paragraph is influenced by material composition, porosity, and microstructure; therefore, if the hardness of a tested carbide is not correct, it is within the realm of possibility that the composition, porosity, or microstructure of the blade is also incorrect.

The second tier of tests that the DOT should test are grain size, porosity, and tungsten carbide specific weight. Grain size and porosity will affect the wear to abrasions and hardness of a carbide. These tests are in the second tier because hardness is an indicator of poor porosity and grain size; therefore, these tests are indirectly measured in the first tier, but they are recommended in the second tier due to their low cost and how easily these properties are tested. The third specification of tier two is tungsten carbide specific weight. As discussed in the previous paragraph, tungsten percentage is an indicator of hardness which hardness is tested in tier one. However, tungsten carbide specific weight is more costly, which is why it is recommended in the second tier.

Tier three has the specifications of cobalt binder specific weight and transverse rupture strength. This is due to cobalt binder specific weight being able to be estimated based off tungsten carbide specific weight which is in tier two. The second specification of tier three is transverse rupture strength. This is due to the transverse rupture strength test being the most expensive test.

4.6.5 Rubber

Rubber blades, as shown in Table 3-5, are not typically used by state DOTs unless specifically desired; however, rubber, for state DOT use, is used as a component in a flexible plow blade. The rubber portion of the blade is what makes the blade flexible. There are components of the rubber that should meet a certain standard for the rubber to not tear, to withstand tensile and compressive forces, to remain elastic, and to meet a certain hardness.

Table 4-24 represents the suggested specifications, importance, ranges, standard tests, and costs that a rubber utilized in flexible blades may be held to. The specifications for rubber that are of interest are ultimate elongation, 100% modulus, tensile strength, shore a durometer, tear resistance, compression set, and low temperature brittleness.

Table 4-24: Rubber Specifications

Specifications	Importance[1]	Ranges[2] Flexible Blades	Standard Tests[3]	Average Cost
Ultimate Elongation, %	1. Retention[4]	582		
100% Modulus, psi	1. Retention[4]	276	ASTM D1456-86(2020)	
Tensile strength, psi	1. Strength	3113	ASTM D412-16	$175.00
Shore a durometer, pts	1. Hardness	60	ASTM D2240 – 15e1	$87.50
Tear strength, ppi	1. Strength	641	ASTM D624 – 00(2020)	$150.00
Compression set, %	1. Retention[4]	26.5	ASTM D395 - 18	$275.00
Low temperature brittleness, temperature	1. Hardness 2. Toughness 3. Retention[4]	No cracks at -40C	ASTM D2137-11(2018) Test Method A	$316.67

Note: All specifications, ranges, and testing methods should be verified and adjusted by the DOT, vendor, or lab. Some of the tests may not be applicable due to the design of the plow blade.

[1] The importance factor dictates if the specification indicates a material's hardness, toughness, and strength in order for the blade to resist wear, fracture, and deformation.

[2] The ranges are based off NASPO 2012 contracts and vendor specification sheets.

[3] The standard test description is available in Appendix E.

[4] Retention is an important characteristic specific to rubber. Flexible rubber for plow blades needs to be able to retain its shape to help with flexing.

As seen in Table 4-24, the first specification is ultimate elongation. Elongation is the percentage of increase or strain due to the application of tensile force or stress (McGrosky 2018). As elongation increases, hardness, tensile strength, and modulus decrease. Rubber for plow blades needs to be able to elongate without rupture. Due to the conditions a plow blade is under, it will need to maneuver without rupture. If a rupture occurs the plow blade will fail.

The next specification in Table 4-24 is 100% modulus. 100% modulus is the force required to produce elongation (McGrosky 2018). The 100% modulus of rubber notes that the higher the psi the more resilient the rubber is to extrusion. The third specification is tensile strength of rubber. Tensile strength is the force needed to tear the specimen. It signifies the point of failure from the stretched rubber (Schaefer 2002). The rubber in a plow blade will be stretched during the plowing process, so the rubber needs to have a baseline tensile strength to be appropriate for plow blades. In addition to tensile strength, shore a durometer is an important specification.

Shore durometer is a measure of inherent hardness. It is the rubbers resistance to indentation (Schaefer 2002). Understanding a rubbers indentation resistance is essential in plow applications since it is in contact with dissimilar pavement conditions and roadway obstructions that may indent the rubber which may compromise the structural integrity of the rubber rendering it to failure.

The fifth specification, in Table 4-24, is tear resistance which is the resistance of an elastomer to the development of a cut or nick at a concentrated location when tensions is applied. Tears may also occur due to vibrations which may fracture the rubber component causing tearing (Schaefer 2002). Tension and vibrations occur when plowing, so it is necessary to have a measure of tear strength to establish the rubber is applicable for plowing.

The sixth specification, in Table 4-24, is compression set which is the percent to which an elastomer fails to return to its original thickness upon releasing a compressive load. The rubber is compressed and exposed to an elevated temperature. Then the rubber is measured to see the thickness post testing (Schaefer 2002). Compression set is an applicable specification to blade testing because plowing causes compression of the rubber and heat when scraping against a roadway. The rubber needs to be able to compress as well as expand back to maintain replicable plowing. The last specification is low temperature brittleness which is essential for plow blade application. Rubber, as temperatures decrease, is hardening, stiffening, and less resilient (Schaefer 2002). Since plow blades will be running during the colder temperatures in the state, it is important to know that the rubber blade will not break when applied to a road due to temperature induced brittleness.

The recommended tier system for rubber, that is a portion of a flexible plow blade, is seen in Table 4-25.

Table 4-25: Rubber Tier Testing

Tier	Specification	Standard Test	Cost
One	Low Temperature Brittleness	ASTM D2137-11(2018) Test Method A	$316.67
	Shore A Durometer	ASTM D2240 – 15e1	$87.50
	Tensile Strength	ASTM D412-16 Type A	$175.00
Two	Compression Set	ASTM D395 - 18	$275.00
	Tear Strength	ASTM D624 – 00(2020) Type B	$150.00
Three	100% Modulus	ASTM D1456-86(2020)	
	Ultimate Elongation		
Note: All testing may be done pre or post-field testing as long as the sample is of 0.49” x 1.14”			

The first tier for rubber, as seen in Table 4-25, has low temperature brittleness, shore a durometer, and tensile strength. Low temperature brittleness is an important characteristic to test for initially. Due to the climate that the material will be in and the specification not being indicated by any other test, it is recommended to be tested in tier one. As described in Chapter 2, there is a tradeoff for hardness and toughness. Ensuring that the rubber for plow blades meets its shore a durometer and tensile strength will validate that the rubber used will be able to resist wear appropriately.

4.6.6 Steel

Steel specifications vary dependent on the type of steel blade. Tungsten carbide tipped blades, hardened steel blades, and carbon steel blades have different grades of steel and specifications for hardness and material composition.

Jafari et al. 2018, summarized the results of two studies that tested wear vs hardness of steel blades with varying compositions and microstructures. The results of these studies defined that hardness, by itself, is not accurate for a steel's wear performance; however, hardness, chemical composition, and microstructure are vital factors in a steel's wear performance (Jafari et al., 2018). Microstructure is not discussed in the NASPO 2012 contract; however, based off Jafari et al. 2018, the microstructure of steel is an important factor for wear and, therefore, is included in the testing of steel for this study. Hardness for a metal is measured by Brinell hardness or Rockwell hardness; however, Rockwell hardness is a more accurate test, provides faster results, and is relatively inexpensive (Hermann, 2011). Additionally, Rockwell hardness may be done and converted to obtain the required Brinell hardness specification.

Table 4-26 summarizes the specifications, ranges, standard tests, and the average costs associated with steel laboratory testing.

Table 4-26: Steel Specifications

Specification	Importance[1]	Ranges[2] Carbide Inserts	Ranges[2] Hardened Steel	Ranges[2] Carbon Steel	Standard Tests[3]	Average Cost
Brinell Hardness	1. Hardness			275-325	ASTM E10	$53.00
Material Composition	1. Hardness 2. Strength 3. Toughness	Carbon 0.18-0.23 Manganese 0.60-0.90 Phosphorous- Max. 0.4 Silicon- Max. 0.5		Carbon 0.85-1.00 Manganese 0.60-0.90 Phosphorous- Max.0. 4 Sulphur- Max. 0.5 Silicon- Max. 0.30	ASTM A1018	$321.33
Microstructure	1. Hardness				ASTM E3	
Rockwell Hardness	1. Hardness		Primary: 61.5-62.5 (Rockwell C) Secondary: 49.5-50.5 (Rockwell C)		ASTM E18	$91.50

Note: All specifications, ranges, and testing methods should be verified and adjusted by the DOT, vendor, or lab. Some of the tests may not be applicable due to the design of the plow blade.

[1] The importance factor dictates if the specification indicates a material's hardness, toughness, and strength in order for the blade to resist wear, fracture, and deformation.

[2] The ranges are based off NASPO 2012 contracts and vendor specification sheets.

[3] The standard test description is available in Appendix E.

In Table 4-26, the first specification is hardness. Hardness may be measured by Rockwell hardness or Brinell hardness. Hardness range measures the relative ability of a material to resist wear, abrasion, or indentation by another material. The difference between Rockwell and Brinell is that Rockwell utilizes a diamond indentor and Brinell utilizes a metal indentor. The second specification of interest is material composition. Different alloys make a steel vary in toughness, hardness, and durability dependent on its alloy composition. When an increased percentage of carbon is present, it makes the steel more susceptible to brittle fracture. Iron with the addition of other alloys strengthens the steel (Nutting et al., 2019). So, understanding the alloys in the metal may be used to predict how the blade will wear, resist breaking, and reduce shock. The last specification is microstructure. This may be determined by etching a steel sample to reveal its grain sizes and shapes. Microstructure is important to discover of a steel because it influences the wear resistance of a blade (Jafari et al., 2018).

The tier system for steel is seen in Table 4-27.

Table 4-27: Steel Tier Testing

Tier	Specifications	Standard Test	Cost
One	Material Composition	ASTM A1018	$321.33
	Rockwell Hardness	ASTM E18	$91.50
Two	Microstructure	ASTM E3	

Note: All testing may be done pre or post-field testing as long as the sample is a minimum thickness of 0.06”.

As seen in Table 4-27, tier one shows Rockwell hardness and material composition. Rockwell hardness is an easier test method to perform than Brinell hardness, and Rockwell hardness number may be converted to Brinell hardness number (Swartzentruber, 2020). ASTM E140-12B is the standard hardness conversion table for metal relationships that a laboratory may use to discover the Brinell hardness utilizing the Rockwell hardness if desired. For this reason, Rockwell hardness is in tier one. Material composition is recommended in tier one to ensure the grade of metal is as expected.

4.6.7 Breakage Testing

In addition to the mechanical, physical, and chemical testing recommended above. There is the possibility to conduct failure testing. Failure testing may be done by microstructural analysis and fractography, corrosion analysis, and material verification.

Microstructural analysis and fractography is analyzing a material to see any appearances of fracture. The second failure testing is corrosion analysis which establishes if the failure is due to corrosion. Corrosion has a distinct pattern that is left behind on a product that may be seen utilizing a microscope and SEM/EDS. The third failure testing is material verification which is what is recommended in Tables 4-22, 4-23, 4-25, and 4-27.

If failure in a flexible blade occurred due to breakage, this could be attributed to plowing down to hard or low toughness. The low toughness may be tested for utilizing the “importance” column in Tables 4-

22, 4-23, 4-25, and 4-27. After establishing what testing may be done, it is important to establish when to test the blades.

4.6.8 Potential Wear Tests

Through research and conversations with laboratories, it is discovered that there are standard tests for abrasive wear. It was not a unanimous recommendation to utilize these tests due to the abrasive testing not being completely reflective of the abrasive process plow blades are typically utilized in. These wear tests are to be utilized on hard metals, so these tests are applicable to carbide and steel blades. The three abrasive wear tests are ASTM G75-15 (2015), ASTM B611-13(2018), and ASTM G105(2016). These methods all use a rotating wheel system with an abrasive material fed in between the test material and the rotating wheel. The difference between the tests is how the abrasive material is fed between the wheel and the test material and if fluid is utilized. These tests do not show wear characteristics; however, they do show the difference in resistance to abrasive use (ISO 28080:2011), which may be useful for DOTs trying to compare abrasion resistance of multiple blades. The Iowa Department of Transportation, in 1996, conducted abrasive wear testing on three different vendors carbide inserts utilizing test B611. The difference between the three blades was not significant to indicate if one blade would perform better than another (Youkin, 1996). This is only one study and does not provide conclusive evidence that the ASTM abrasive wear tests are not applicable for plow blades; however, further research may be able to make conclusive statements on the relationship between the abrasive wear tests and blade wear in the field.

4.6.9 Time Frame for Testing

It is essential to evaluate if the testing is destructive or not when assessing what testing to conduct on the different materials utilized for plow blades. The tests recommended in this study are considered nondestructive tests; however, there are two challenges for plow blades:

1. The multiple materials being used, and
2. The size of the material.

The first challenge for lab testing plow blades is the multiple materials utilized within a plow blade. Many of the test methods being suggested are not inherently destructive; however, with multiple materials, the lab testing process will be destructive. Tests like the density of cemented carbide inserts is not destructive in its nature; however, to test the cemented carbide, it needs to be removed from the steel blade which renders it useless for plowing application. Additionally, the second challenge when lab testing a plow blade is the size of the plow blade. The tests suggest requiring a certain size specimen to be placed in an apparatus for testing. To fit the apparatus, the plow blade needs to be cut. Cutting instructions are found within the standards tests. Therefore, if a plow blade is four feet long and the apparatus requires a five-inch length, the plow blade will need to be cut to be able to conduct the test. Cutting the blade will be destructive since it will no longer be useful for plow blade application once cut. For these reasons, the research team would consider most of the testing methods are destructive to a plow blade. Once determined if the tests will destroy the blades or not, the research team wanted to establish when to test the blades: pre-field or post-field testing. According to the surveyed laboratories, the tests suggested may be done pre or post field testing if a sufficient sample is provided. A sufficient sample is achieved if there is enough material to test. The appropriate measurements for testing are available at the bottom of the materials tier tables, which are tables 4-24, 4-26, and 4-27.

4.6.10 Formal Lab Testing

Sections 4.6.10 through 4.6.16 was done by Element Materials Technology. The authors were Dustin J. Wenninger and Elena M. Moore.

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Pallets of snowplow blades were submitted with several blades of multiple types, of which, Joma 6000 blades, identified as Iowa, North Dakota – New, and North Dakota – Used, were selected for a material analysis of the metallic and polymeric components of the blades. It was reported that some of the Joma 6000 blades, possibly of a different vintage, were observed to have differences in wearing performance. It was further reported that the blades may have been produced by different suppliers. It was specifically requested to determine any differences between blades supplied by different municipalities that could attribute to differences in performance. No further details concerning the history or processing of the submitted Joma 6000 blades were reported.

4.6.10.1 Lab Testing Objectives

The objective of this investigation was to characterize the materials for the individual components of the submitted Joma 6000 blades. The scope of this evaluation was to include visual examination, spectroscopic and thermal analysis, hardness, and microhardness testing, scanning electron microscopy, energy dispersive spectroscopy, metallographic examination, and polymer mechanical testing. Due to the integrity of the North Dakota – Used sample, microhardness testing, metallographic examination, scanning electron microscopy and energy dispersive spectroscopy of the Blade and Carbide components could not be performed. Table 4-28 shows the preliminary justification for these tests.

Table 4-28: General Overview of Testing

Test/Description	Results	Price	Priority
Chemical analysis of metallic components and alloy determination	What material is it made from	Low/Medium	Medium/High
ASTM B311: Carbide density evaluation	How dense/compact the carbides are	Low	Low/Medium
Metallographic cross-section preparation and evaluation of microstructure	Gives information about how the material was processed	Low/Medium	Medium/High
SEM/EDS of metallic components to determine relative chemical composition	What elements are present, in relative amounts	Medium/High	Low
Microhardness testing	Average hardness	Low	Medium/High
Fourier transform infrared spectroscopy (FTIR) of rubber components to identify base polymer, any additives, contaminants, etc.	What material/polymer is it made from	Low/Medium	Medium/High
Differential scanning calorimetry (DSC) of rubber components to determine thermal properties	Glass transitions, melting temperatures, etc. to confirm polymer used, identify any contamination, etc.	Medium/High	Medium/High
Thermogravimetric analysis (TGA) of rubber components to determine composition and thermal stability	Volatile, polymer, and filler contents; thermal stability temperatures	Medium/High	Medium/High
ASTM D2240-15e1: Durometer hardness of rubber components	Average hardness	Low	Medium/High
ASTM D412-A: Tensile testing of rubber components	Tensile strength and elongation	Medium/High	Low
ASTM D624-00 (2020), Die C: Tear resistance testing of rubber components	Tear strength	Medium/High	Low

ASTM D575-A: Compression testing of rubber components	Compressive strength	Medium/High	Low

4.6.11 Metals Evaluation Testing and Results

4.6.11.1 Visual Examination

The North Dakota – New, North Dakota – Used, and Iowa Blades are presented as received in Figure 4.18. Each of the blade's exposed metallic components exhibited rust. Orange and white colored debris on the rubber surfaces of all three blades were observed.

Figure 4-18: Submitted Plow Blades

Note: The submitted North Dakota – New (top), and North Dakota – Used (center), and Iowa (bottom) Joma 6000 blades and presented as received. A segment from each of the submitted blades was excised along the dashed lines, to permit characterization of the individual components within their respective blades. The scale is in inches.

The North Dakota – Used Blade exhibited indications consistent with mechanical damage and abrasion of the blade components, which was consistent with the reported used condition. The components for the North Dakota – New and Iowa Blades appeared to be undamaged and showed no indications of use, which was consistent with the reported new condition. A section of each of the analyzed blades was excised along the dashed lines indicated in the view, to permit characterization of the individual metallic components within their respective blades. A closer view of a representative section is presented in Figure 4-19.

Figure 4-19 Representative Blade Segment

Note: A representative blade segment is presented. The Ring component and Blade/Carbide assemblies were excised from the remainder of the blade segment along the yellow and orange dashed lines, respectively. Metallographic cross-sections were prepared at the approximate planes of intersection designated by the green and blue arrows for the Ring component and the Blade/Carbide assemblies, respectively. The scale is millimeters.

The metallic components of interest were designated as Ring, Blade, and Carbide for the purposes of this investigation, and are indicated in the view. The construction of the Joma 6000 blade is such that the Carbide components are inserted into the Blade component and subsequently brazed. The Ring component was excised from the remainder of the section along the yellow dashed line in the view. The Blade/Carbide portion of the section was excised along the orange dashed line in the view.

4.6.11.2 Chemical Analysis Results

Chemical analyses of the Blade, Ring, and Carbide components of the blades were performed for the North Dakota – New, North Dakota – Used, and Iowa blades via OES. The test results are summarized in Tables 4-29 through 4-33. Each of the samples were compared to the most closely matching grade/alloy.

Evaluation of the North Dakota – New and North Dakota – Used Blades, revealed relatively similar chemical compositions to one another, which did not conform to the chemical requirements of the most closely resembled alloy Grade 5120 steel per ASTM A29, due to lower than specified manganese content, as evident in Table 4-29.

Table 4-29: Chemical Analysis Results – North Dakota Blades (Weight Percent)

Element	New	Used	ASTM A29-20 Grade 5120 Requirements
Carbon	0.21	0.19	0.17 – 0.22
Manganese*	0.53	0.66	0.67 – 0.93
Phosphorus	0.006	0.013	0.035 max
Sulfur	<0.001	0.006	0.040 max
Silicon	0.25	0.22	0.15 – 0.35
Chromium	0.75	0.82	0.70 – 0.90
Nickel	0.04	0.01	Not specified
Molybdenum	0.01	<0.01	Not specified
Aluminum	0.01	0.01	Not specified
Cobalt	<0.01	<0.01	Not specified
Copper	0.05	0.04	Not specified
Niobium	<0.01	<0.01	Not specified
Titanium	<0.01	<0.01	Not specified
Vanadium	0.01	0.01	Not specified
Iron	Balance	Balance	Balance

*Analysis completed using Optical Emission Spectroscopy (CS-05). *Specified range expanded via permissible variations for product analysis of alloy steel per ASTM A29, Table 4-33.*

Evaluation of the Iowa Blade revealed a composition, which met the chemical requirements of Grade 1518 steel per ASTM A29, as evident in Table 4-30.

Table 4-30: Chemical Analysis Results – Iowa Blade

Element	Blade	ASTM A29-20 Grade 1518 Requirements
Carbon	0.17	0.15 – 0.21
Manganese	1.25	1.10 – 1.40
Phosphorus	0.006	0.040 max
Sulfur	0.027	0.050 max
Silicon	0.26	Not specified
Chromium	0.33	Not specified
Nickel	0.03	Not specified
Molybdenum	0.01	Not specified
Aluminum	<0.01	Not specified
Cobalt	<0.01	Not specified
Copper	0.06	Not specified
Niobium	0.01	Not specified
Titanium	0.05	Not specified
Vanadium	0.01	Not specified
Iron	Balance	Balance

(Weight Percent) Analysis completed using Optical Emission Spectroscopy (CS 05).

Evaluation of the North Dakota – New and North Dakota – Used Rings, revealed relatively similar chemical compositions, which met the chemical requirements of Grade 1020 steel per ASTM A29, as evident in Table 4-31.

Table 4-31: Chemical Analysis Results – North Dakota Rings (Weight Percent)

Element	New	Used	ASTM A29-20 Grade 1020 Requirements
Carbon	0.19	0.22	0.18 – 0.23
Manganese	0.43	0.51	0.30 – 0.60
Phosphorus	0.006	0.015	0.040 max
Sulfur	<0.001	<0.001	0.050 max
Silicon	0.23	0.23	Not specified
Chromium	0.09	0.05	Not specified
Nickel	0.04	0.01	Not specified
Molybdenum	0.01	<0.01	Not specified
Aluminum	<0.01	0.01	Not specified
Cobalt	<0.01	<0.01	Not specified
Copper	0.05	0.02	Not specified
Niobium	<0.01	<0.01	Not specified
Titanium	<0.01	<0.01	Not specified
Vanadium	<0.01	<0.01	Not specified
Iron	Balance	Balance	Balance

Note: Analysis completed using Optical Emission Spectroscopy (CS-05).

Evaluation of the Iowa Ring revealed a chemical composition, which met the chemical requirements of Grade 5140 per ASTM A29. In comparison to the North Dakota Rings, the Iowa Ring had higher levels of carbon, manganese, and chromium, as evident in Table 4-32.

Table 4-32: Chemical Analysis Results - Iowa Ring (Weight Percent)

Element	Ring	ASTM A29-20 Grade 5140
Carbon	0.38	0.38 – 0.43
Manganese	0.66	0.70 – 0.90
Phosphorus	0.009	0.035 max
Sulfur	0.001	0.040 max
Silicon	0.22	0.15 – 0.35
Chromium*	0.95	0.65 – 0.95
Nickel	0.01	Not specified
Molybdenum	<0.01	Not specified
Aluminum	0.03	Not specified
Cobalt	<0.01	Not specified
Copper	0.01	Not specified
Niobium	<0.01	Not specified
Titanium	<0.01	Not specified
Vanadium	<0.01	Not specified
Iron	Balance	Balance

*Note: Analysis completed using Optical Emission Spectroscopy (CS-05). *Specified range expanded via permissible variations for product analysis of alloy steel per ASTM A29, Table 4-33.*

Evaluation of the chemical compositions for the North Dakota Carbides and Iowa Carbide are reported in Table 4-33, revealing variations in cobalt, nickel, iron, chromium, copper, and titanium contents amongst the evaluated carbide samples.

Table 4-33: Chemical Analysis Results - Carbides (Weight Percent)

	North Dakota		Iowa
	New	Used	
Cobalt	14.0	13.8	12.9
Carbon	5.4	5.5	5.4
Nickel	0.16	0.12	0.25
Iron	0.09	0.06	0.16
Chromium	0.52	0.45	0.59
Manganese	0.01	0.02	0.01
Copper	0.13	0.39	0.06
Silicon	0.04	0.04	0.04
Titanium	0.08	0.01	0.15
Vanadium	<0.01	<0.01	0.01
Niobium	0.01	<0.01	0.04
Aluminum	0.01	0.01	0.01
Zirconium	<0.01	<0.01	<0.01
Tungsten	Balance	Balance	Balance

Note: Analysis completed using ICP-OES (CS-03). Carbon and sulfur content are determined using a Combustion/IR technique (CA-06).

No ASTM specification regarding chemical composition for tungsten carbide was found, and therefore the chemistries were reported for comparison purposes amongst the three analyzed samples.

4.6.11.3 Carbide Density Evaluation

The density of the carbide fragments from the North Dakota – New, North Dakota – Used, and Iowa Carbide samples were determined in accordance ASTM B311. Prior to conducting the density evaluation, one of the Carbide samples was Soxhlet extracted overnight with measurements of the weight of the sample before and after Soxhlet extraction taken. No changes in weight were observed following Soxhlet extraction, suggesting the Carbide samples were not oil impregnated. The densities for the evaluated samples are reported in Table 4-34, revealing similar densities between the North Dakota and Iowa Carbide samples.

Table 4-34: Density Analysis Results - Carbides

		Density (g/cm^3)
North Dakota	New	14.36
	Used	14.30
Iowa		14.27

Note: (Weight Percent) Analysis completed per ASTM B311 (CM-02)

4.6.11.4 Metallographic Cross-Section Preparation

Metallographic cross-sections were prepared from the Blade/Carbide assemblies, for the North Dakota – New and Iowa samples, at the approximate plane of intersection represented by the blue dashed line shown previously in Figure 4-19. The sample integrity of the North Dakota – Used Blade/Carbide assembly precluded metallographic preparation and subsequent examination; however, due to similar chemistries observed for the Blade components for the North Dakota samples, the construction was likely similar. Metallographic cross-sections were also prepared from the Ring components for the North Dakota samples and Iowa sample at the approximate plane of intersection represented by the green dashed line in Figure 4-19.

4.6.11.5 Scanning Electron Microscopy and Energy Dispersive X-ray Spectroscopy

The North Dakota – New and Iowa Blade/Carbide assembly metallographic cross-sections were examined using a scanning electron microscope (SEM) equipped with an energy dispersive X-ray spectrometer (EDS). SEM allows examination of surfaces at high magnification with great depth of field. EDS permits determination of the relative chemical composition of surfaces and features examined using the SEM. The locations for each sample were examined using back scattered electrons (BSE), which provides information regarding the relative atomic weight of the regions being examined. In BSE views, regions appearing darker are atomically lighter, relative to atomically heavier regions, which appear brighter.

A BSE scanning electron micrograph of the North Dakota – New cross-section is presented in Figure 4-20.

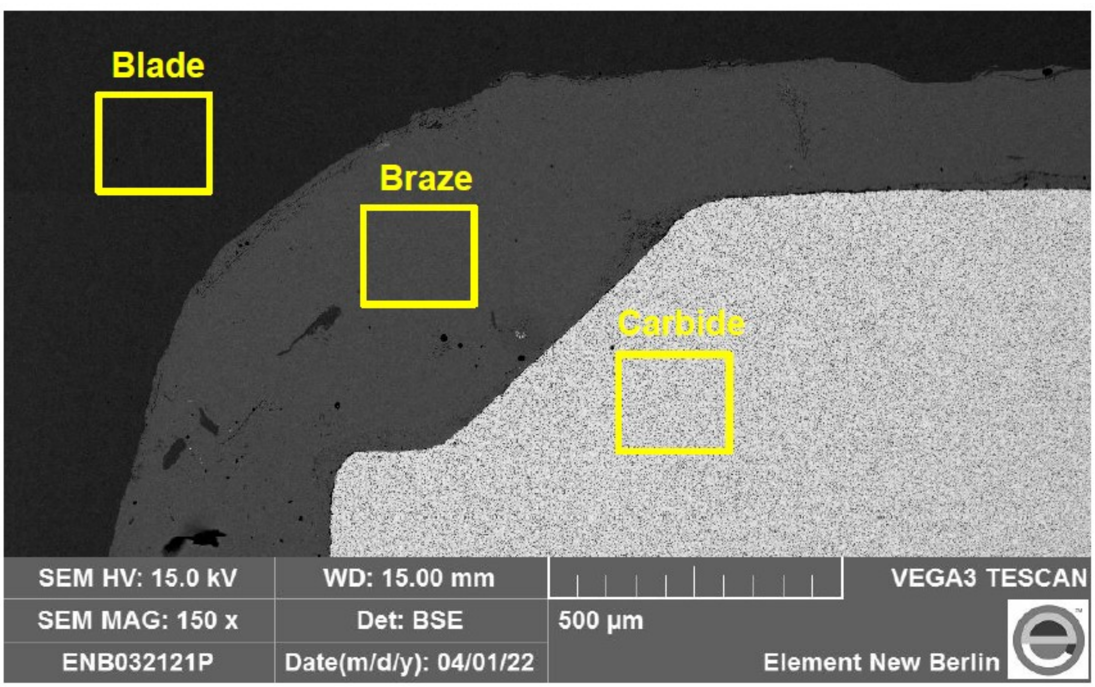

Figure 4-20: A BSE Scanning Electron Micrograph

Note: A BSE scanning electron micrograph of the metallographic cross-section prepared from the North Dakota – New Blade, at the approximate plane of intersection indicated by the blue dashed line in Figure 4-19, is presented. Regions from the blade, braze, and carbide were evaluated with EDS, with results reported in Table 4-35 as polished.

EDS analyses were conducted for regions of the cross-section that corresponded with the Blade, braze material, and Carbide components, as indicated in the view, with the results reported in Table 4-35.

Table 4-35: Summary of EDS Results – North Dakota – New Cross-Section (Relative Weight Percent)

Element	Location			AWS A5.8M/A5.8:2019 Specification	
Area	Braze	Blade	Carbide	AWS RBCuZn-D (UNS C77300)	AWS BCuP-6**** (UNS C55280)
Figure No.	3	3	3		
Carbon	3.0	2.7	5.6	---	---
Oxygen	1.3	---	---	---	---
Aluminum	---	---	---	0.01* max	---
Silicon	---	0.4	---	0.04 – 0.25	---
Phosphorus	---	---	---	0.25 max	6.8 – 7.2
Titanium	---	---	0.5	---	---
Chromium	---	0.9	0.4	---	---
Manganese	2.8	---	---	---	---
Iron	---	96.0	0.4	---	---
Cobalt	1.2	---	14.8	---	---
Nickel	---	---	---	9.0 – 11.0***	---
Copper	54.6	---	---	46.0 – 50.0**	Remainder
Zinc	34.8	---	---	Remainder	---
Silver	2.3	---	---	---	1.8 – 2.2
Tungsten	---	---	78.4	---	---
Lead	---	---	---	0.05* max	---

Note: --- = Not Detected

EDS analysis can detect and quantify elements from atomic no. 5 (boron) and greater on the Periodic Table. Relative percentages of the detected elements can be determined and are normalized to a total of 100%. Therefore, the results of these analyses are relative rather than absolute values.

** The brazing filler metal shall be analyzed for those specific elements for which values and/or asterisks are shown in this table. If the presence of other elements is indicated in the course of this work, the amount of those elements shall be determined to ensure that their total, plus the values for those elements marked with an asterisk, does not exceed Other Elements, Total (0.50 max).*

*** Includes residual silver.*

**** Includes residual cobalt.*

***** The brazing filler metal shall be analyzed for those specific elements for which values and/or asterisks are shown in this table. If the presence of other elements is indicated in the course of this work, the amount of those elements shall be determined to ensure that their total, plus the values for those elements marked with an asterisk, does not exceed Other Elements, Total (0.15 max).*

The relative composition of the braze material consisted predominantly of silver, copper, and zinc, which did not specifically match any of the braze filler metals listed in AWS A5.8; however, brazing alloy RBCuZn-D (UNS C77300) and AWS BCuP-6 (UNS C55280), were the closest matches.

A BSE scanning electron micrograph of the Iowa cross-section is presented in Figure 4-21.

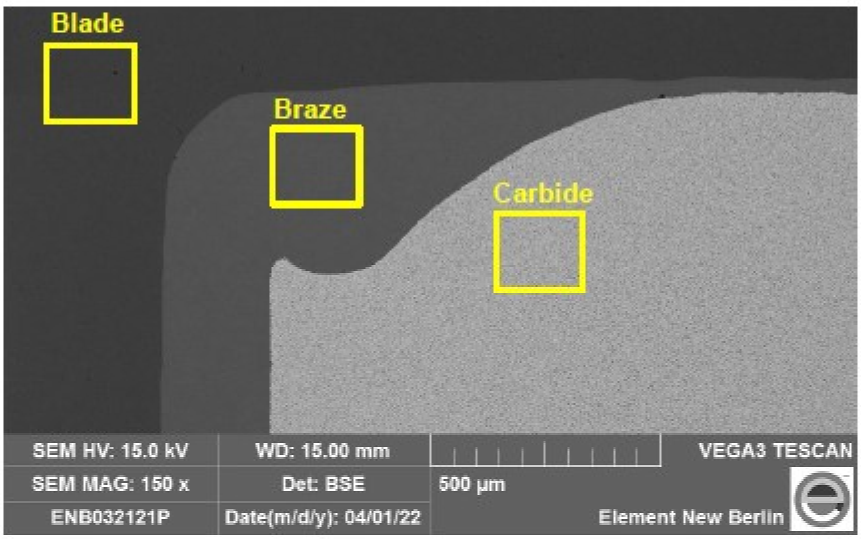

Figure 4-21: A BSE Scanning Electron Micrograph

Note: A BSE scanning electron micrograph of the metallographic cross-section prepared from the Iowa Blade, at the approximate plane of intersection indicated by the blue dashed line in Figure 4-19, is presented. Regions from the blade, blaze, and carbide were evaluated with EDS, with the results reported in Table 4-36. As polished.

EDS analyses were conducted for regions of the cross-section that corresponded with the Blade, braze material, and Carbide components, as indicated in the view, with the results reported in Table 4-36.

Table 4-36: Summary of EDS Results – Iowa Cross-Section (Relative Weight Percent)

Element	Location			AWS A5.8M/A5.8:2019 Specification
Area	Braze	Blade	Carbide	AWS RBCuZn-D (UNS C77300)
Figure No.	4	4	4	
Carbon	2.9	2.6	5.5	---
Oxygen	1.6	---	0.5	---
Aluminum	---	---	---	0.01* max
Silicon	---	0.2	---	0.04 – 0.25
Phosphorus	---	---	---	0.25 max
Titanium	---	---	0.5	---
Chromium	---	0.3	0.3	---
Manganese	---	1.2	---	---
Iron	1.7	95.8	0.5	---
Cobalt	---	---	12.1	---
Nickel	9.1	---	---	9.0 – 11.0***
Copper	46.9	---	---	46.0 – 50.0**
Zinc	37.8	---	---	Remainder
Tungsten	---	---	80.6	---
Lead	---	---	---	0.05* max

Note:

--- = Not Detected

EDS analysis can detect and quantify elements from atomic no. 5 (boron) and greater on the Periodic Table. Relative percentages of the detected elements can be determined and are normalized to a total of 100%. Therefore, the results of these analyses are relative rather than absolute values.

** The brazing filler metal shall be analyzed for those specific elements for which values and/or asterisks are shown in this table. If the presence of other elements is indicated in the course of this work, the amount of those elements shall be determined to ensure that their total, plus the values for those elements marked with an asterisk, does not exceed Other Elements, Total (0.50 max).*

*** Includes residual silver.*

**** Includes residual cobalt.*

The relative composition of the braze material consisted of predominantly nickel, copper, and zinc, which did not specifically match any of the braze filler metals listed in AWS A5.8; however, brazing alloy RBCuZn-D (UNS C77300) was the closest match.

4.6.11.6 Microhardness Testing Results

The average hardness for the North Dakota – New and Iowa Blade components was determined via microhardness testing with a Vickers indenter and 500-gram force load, with the results reported in Table 4-37.

Table 4-37: Microhardness Testing Results – Blade (HV 0.5)

Reading	North Dakota New	Iowa
1	186.6	457.8
2	205.8	472.0
3	213.0	454.7
4	186.7	455.7
5	222.1	461.7
Average	203	460
Conversion	93 HRB	46 HRC

Note: Tested in accordance with ASTM E384.

Conversion per ASTM E140, Tables 4-27 (HRC) and 4-28 (HRB)

The results of the testing revealed the North Dakota - New Blade to be significantly softer than the Iowa Blade, with average equivalent hardness values of 93 HRB (203 HV) and 46 HRC (460 HV), respectively.

The average hardness for the North Dakota – New and Iowa Carbide components were determined via microhardness testing with a Vickers indenter and a 30-kilogram force load, with the result Micros reported in Table 4-38.

Table 4-38: Microhardness Testing Results – Carbide (HV 30)

Reading	North Dakota New	Iowa
1	1,124.7	1,273.6
2	1,144.7	1,291.2
3	1,140.1	1,291.5
4	1,151.0	1,296.4
5	1,162.6	1,285.3
Average	1,145	1,288

Note: Tested in accordance with ASTM C1327.

The results of the testing revealed relatively similar hardness values for the North Dakota – New and Iowa Carbides, with average hardness values of 1,145 HV and 1,288 HV, respectively.

4.6.11.7 Metallographic Evaluation

Metallographic cross-sections prepared from the Blade/Carbide assemblies, for the North Dakota – New and Iowa Blade components, at the approximate planes of intersection represented by the blue dashed lines in Figure 4-19, are presented in Figures 4-22 and 4-23, respectively, revealing significantly different microstructures for the North Dakota – New and Iowa Blades.

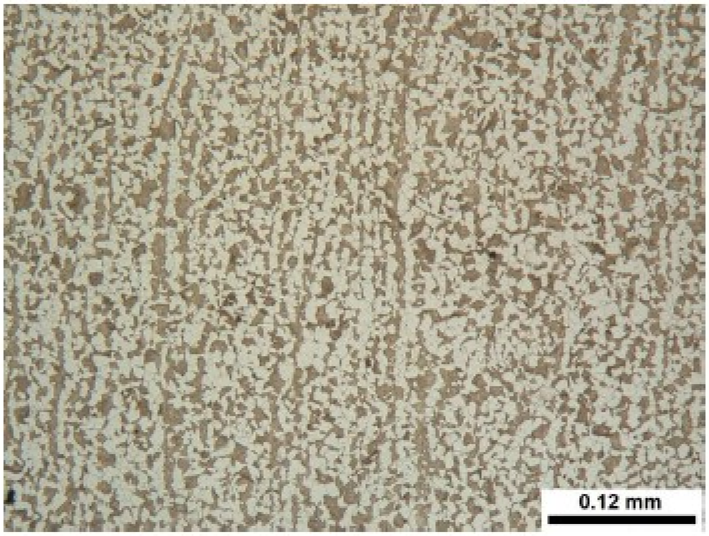

Figure 4-22: A Digital Photomicrograph North Dakota

Note: A digital photomicrograph of the representative etched microstructure for the North Dakota – New Bridge component is presented. The microstructure consisted of pearlite and ferrite, with a ratio consistent with the analyzed chemistry. 2% Nital.

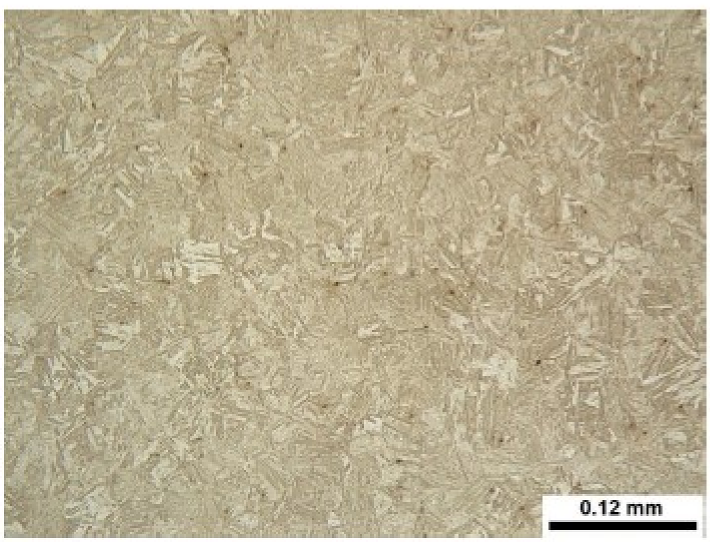

Figure 4-23: A Digital Photomicrograph of the Iowa Blade

Note: A digital photomicrograph of the representative etched microstructure for the Iowa Blade component is presented. The microstructure consisted of predominately tempered martensite with some mixed transformation products, which is consistent with the analyzed chemistry and evaluated hardness. 2% Nital.

The North Dakota – New Blade microstructure consisted of pearlite and ferrite, with a ratio consistent with the analyzed chemistry. The Iowa Blade microstructure consisted of predominantly tempered martensite with some mixed transformation products, which was consistent with the analyzed chemistry and evaluated hardness.

Evaluation of the Carbide microstructures for the North Dakota – New and Iowa samples, revealed relatively similar microstructures, consisting predominantly of tungsten carbides with a cobalt binder, which was consistent with the analyzed chemistries, as evident in Figures 4-24 and 4-25, respectively.

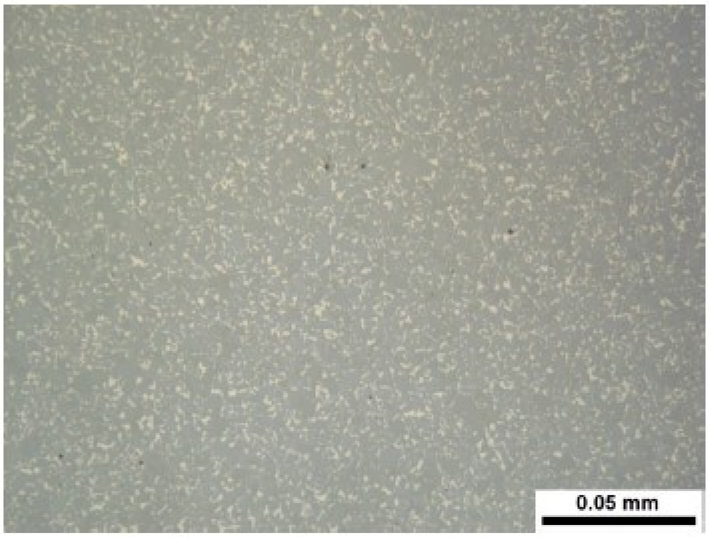

Figure 4-24: A digital photomicrograph from North Dakota

Note: A digital photomicrograph of the representative unetched microstructure for the North Dakota – New Carbide component is presented. The microstructure consisted of predominately tungsten carbide with a cobalt binder, which is consistent with the analyzed chemistry. Slight staining of the sample was observed from etching of the North Dakota – New Blade component. As polished.

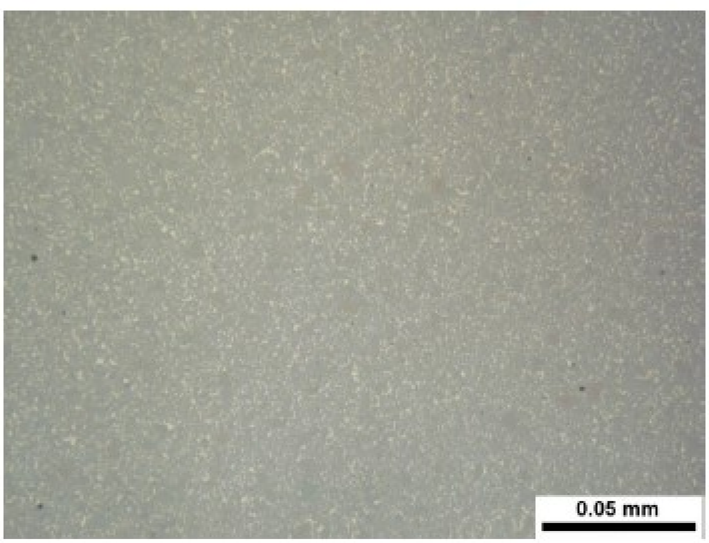

Figure 4-25: A digital photomicrograph from Iowa Carbide

Note: A digital photomicrograph of the representative unetched microstructure for the Iowa Carbide component is presented. The microstructure consisted of predominately tungsten carbide with a cobalt binder, which is consistent with the analyzed chemistry. Slight staining of the sample was observed from etching of the Iowa Blade component. As polished.

Digital photomicrographs of the Ring microstructures for the North Dakota – New, Iowa, and North Dakota – Used samples are presented in Figures 4-26 through 4-28, respectively.

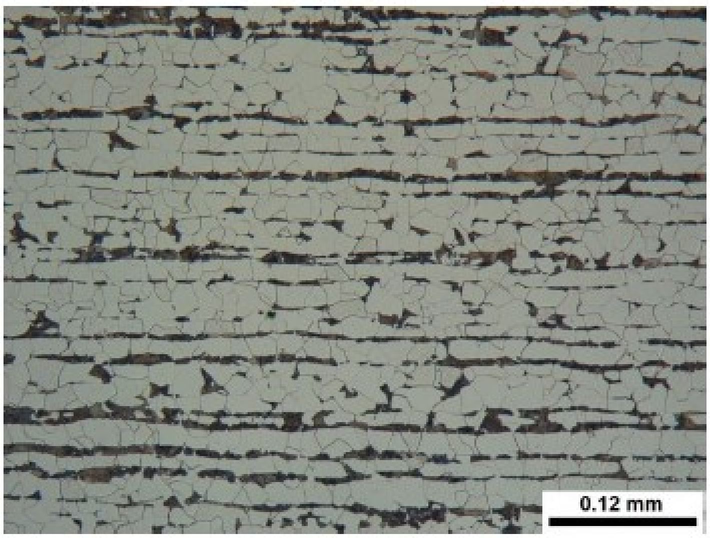

Figure 4-26: A Digital Photomicrograph from North Dakota

Note: A digital photomicrograph of the representative etched microstructure for the North Dakota – New Ring component is presented. The microstructure consisted of pearlite and ferrite, with a ratio consistent with the analyzed chemistry. 2% Nital.

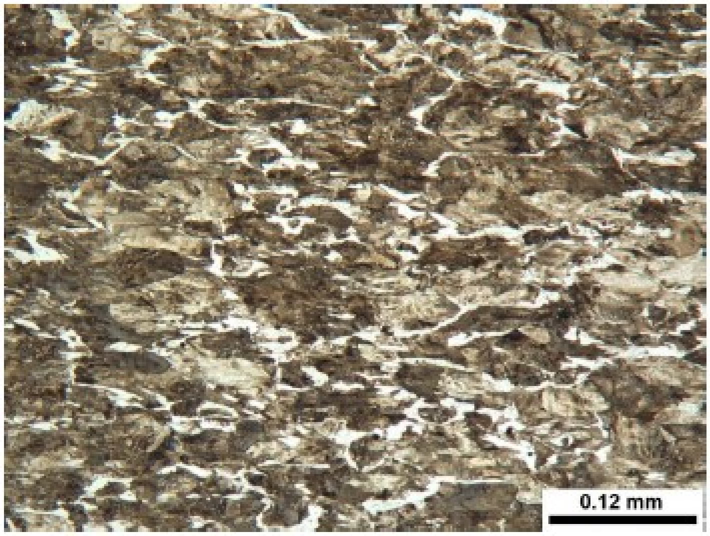

Figure 4-27: A Digital Photomicrograph from Iowa

Note: A digital photomicrograph of the representative etched microstructure for the Iowa Ring component is presented. The microstructure consisted predominantly of pearlite with some ferrite, which is consistent with the analyzed chemistry. 2% Nital.

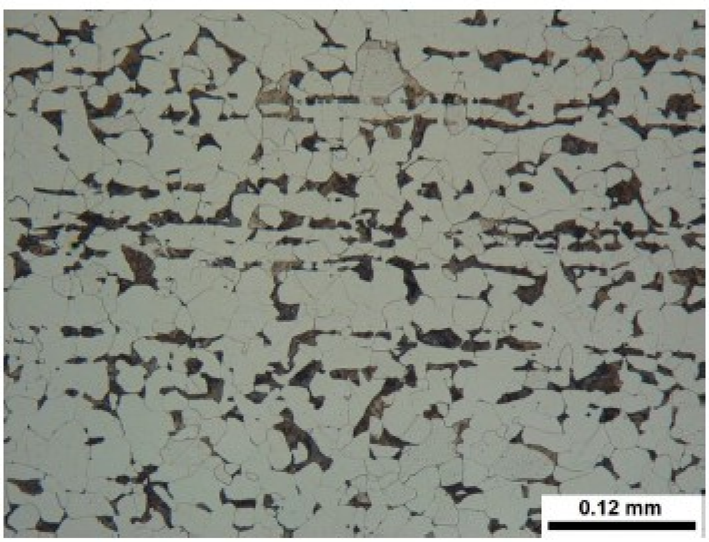

Figure 4-28: A Digital Photomicrograph from North Dakota

Note: A digital photomicrograph of the representative etched microstructure for the North Dakota – Used Ring component is presented. The microstructure consisted of pearlite and ferrite, with a ratio consistent with the analyzed chemistry. 2% Nital.

The microstructures of the North Dakota samples were like one another and consisted of pearlite and ferrite, with a ratio consistent with analyzed chemistries. The microstructure for the Iowa Ring sample consisted predominantly of pearlite with some ferrite. Additionally, the differences in the microstructure suggested the North Dakota Ring samples were machined, whereas the Iowa Ring sample was formed.

4.6.12 Tests and Results – Polymers Evaluation

4.6.12.1 Fourier Transform Infrared Spectroscopy

The rubber component of each blade was analyzed via FTIR in the attenuated total reflectance (ATR) mode with a Smart iTR™ attachment and a diamond crystal. FTIR involves the study of molecular vibrations. A continuous beam of electromagnetic radiation is passed through or reflected off the surface of a sample, causing individual molecular bonds and groups of bonds to vibrate at characteristic frequencies and absorb infrared radiation at corresponding frequencies. Because of this, different molecules will generate distinct patterns of absorption called spectra, allowing characterization and identification. This analysis was performed in accordance with Element New Berlin Procedure PA-01.

For this method, representative rubber material from each blade was contacted by the ATR crystal, and a spectrum was collected. The resulting spectra are provided in Figure 4-29.

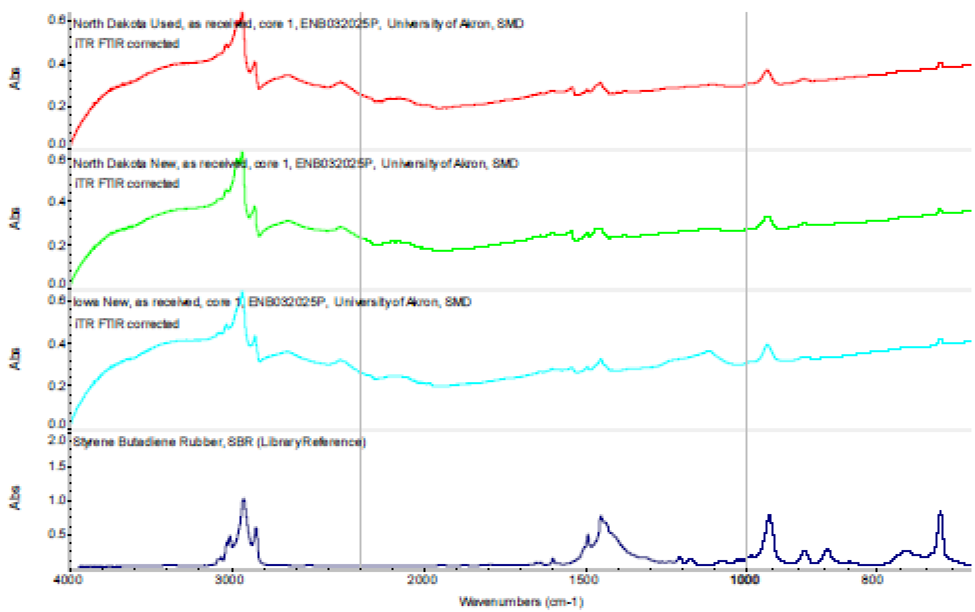

Figure 4-29: FITR Spectra Obtained on the Polymer Component of the Blades as Received.

Subsequent library searching and interpretation indicated that the absorption bands associated with each sample were characteristic of a butadiene-based rubber material, more specifically a styrene-butadiene rubber.

To further analyze the polymer components, a hexane extraction was performed on samples of the parts, in which several pieces were soaked in hexane overnight. The solvent was then poured into a watch glass and allowed to evaporate. The remaining residue was then analyzed and produced the spectra in Figure 4-30.

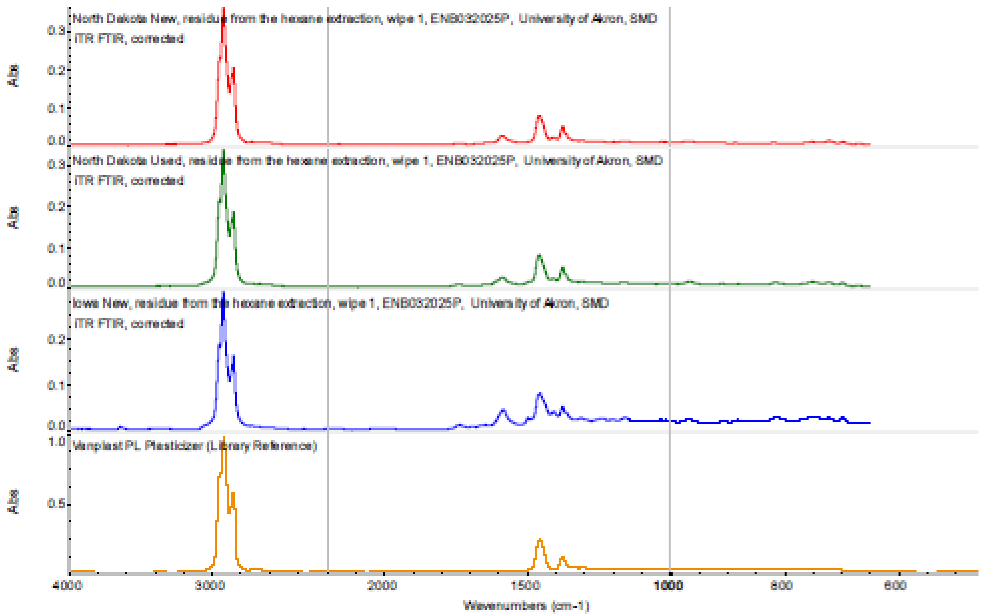

Figure 4-30: FTIR Spectra Obtained on the Hexane Residues of the Blade Polymer Components

Analysis of the spectra indicated that the residues are consistent with a hydrocarbon-based plasticizer.

4.6.13 Differential Scanning Calorimetry

The rubber material from each blade was further analyzed using differential scanning calorimetry. Differential scanning calorimetry (DSC) measures the temperature and heat flow associated with transitions in materials as a function of time and temperature. Such measurements provide quantitative and qualitative information about physical and chemical changes involving endothermic or exothermic processes, or changes in heat capacity. This testing was performed in accordance with Element New Berlin procedure PA-06.

Representative material samples from each rubber component were subjected to a three-step test methodology in which the samples were equilibrated at -80°C, heated to 150 °C, control cooled to -80 °C, and reheated to 150 °C, all at a heating/cooling rate of 10 °C/min in nitrogen. The first heating run was used to determine the status of the material in the as-received state, while the second heating run was used to determine the status of the material after the processing history had been removed. In other words, data obtained during the second heating run allows for a direct comparison of the material properties under normalized conditions.

The DSC thermograms obtained on the samples during the second heating cycle are shown in Figures 4-31 through 4-34 with overlays shown in Figure 4-31.

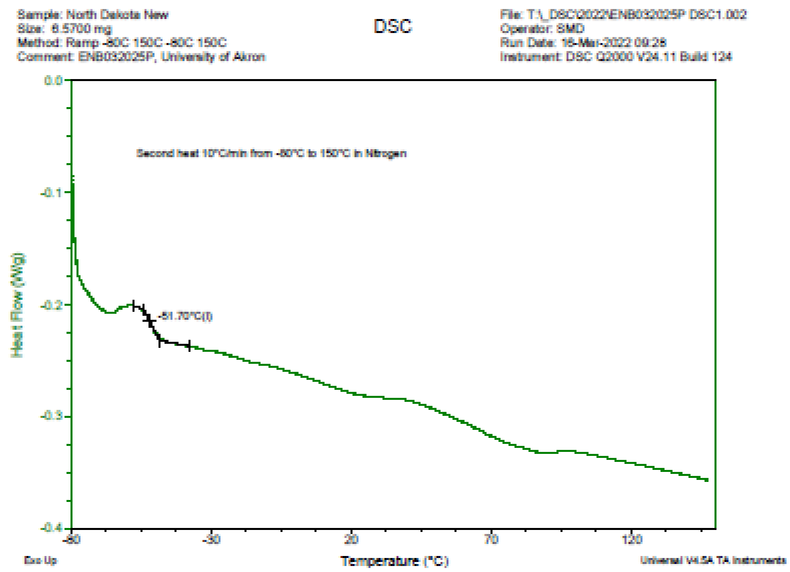

Figure 4-31: DSC thermogram Obtained on the North Dakota – New Polymer Component During the Second Heating Cycle

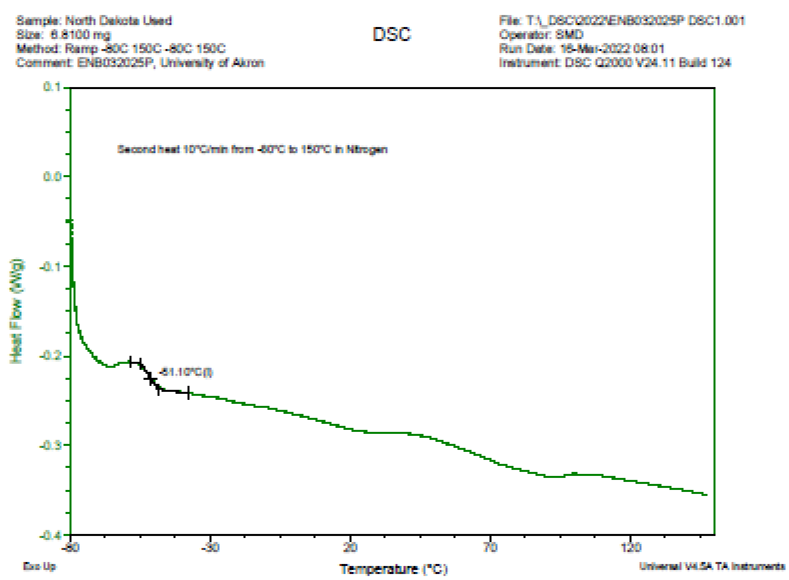

Figure 4-32: DSC thermogram Obtained on the North Dakota – Used Polymer Component During the Second Heating Cycle

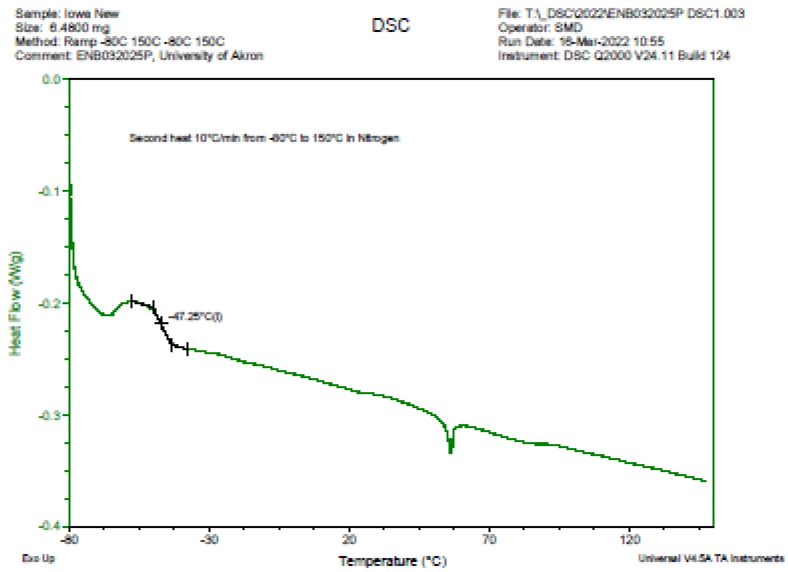

Figure 4-33: DSC Thermogram Obtained on the Iowa Polymer Component During the Second Heating Cycle

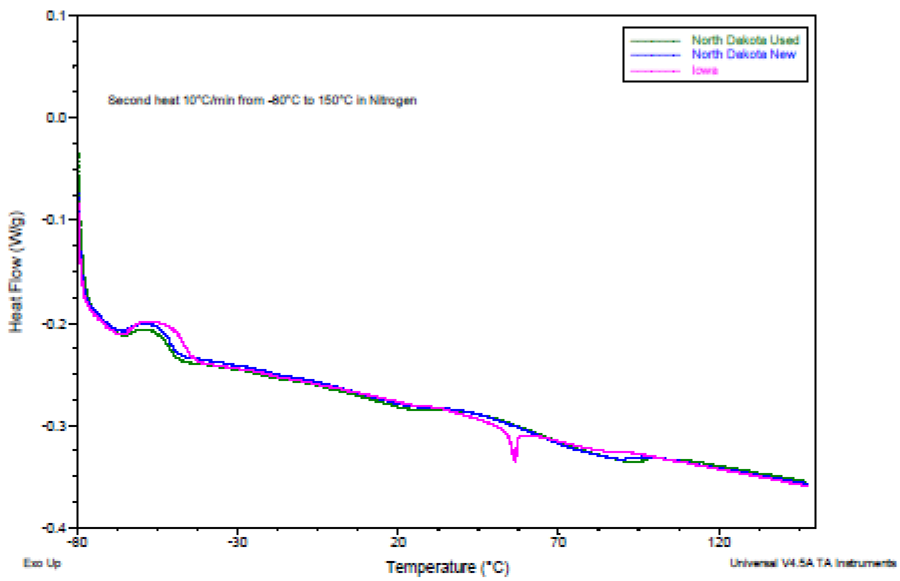

Figure 4-34: Overlay of the DSC Thermograms Obtained on the Three Polymer Components During the Second Heating Cycle

Each of the blades produced a baseline shift centered between -47 °C and -52 °C, consistent with a styrene-butadiene rubber material.

4.6.14 Thermogravimetric Analysis

Representative material samples of each component rubber component were then analyzed using thermogravimetric analysis (TGA). TGA is a thermal analysis technique that measures the amount and rate of change in the weight of a material as a function of temperature or time in a controlled atmosphere. Measurements are used primarily to determine the composition of material and to predict thermal stability at temperatures up to 1000 °C. The technique can characterize material that exhibits weight loss or weight gain due to decomposition, oxidation, or dehydration. This analysis was performed in accordance with Element New Berlin Procedure PA-04. The TGA thermograms are shown in Figures 4-35 through 4-37 with overlays in Figure 4-38.

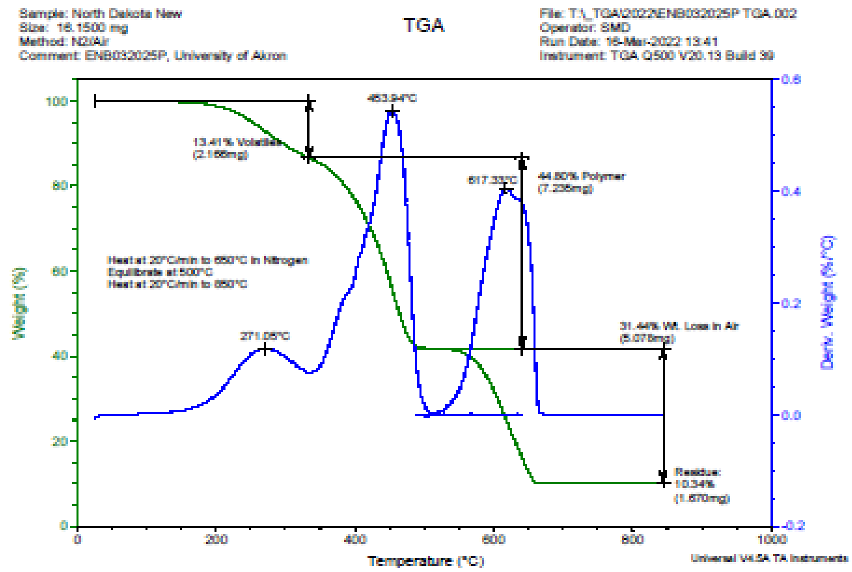

Figure 4-35: TGA Thermogram Obtained on the North Dakota – New Polymer Component

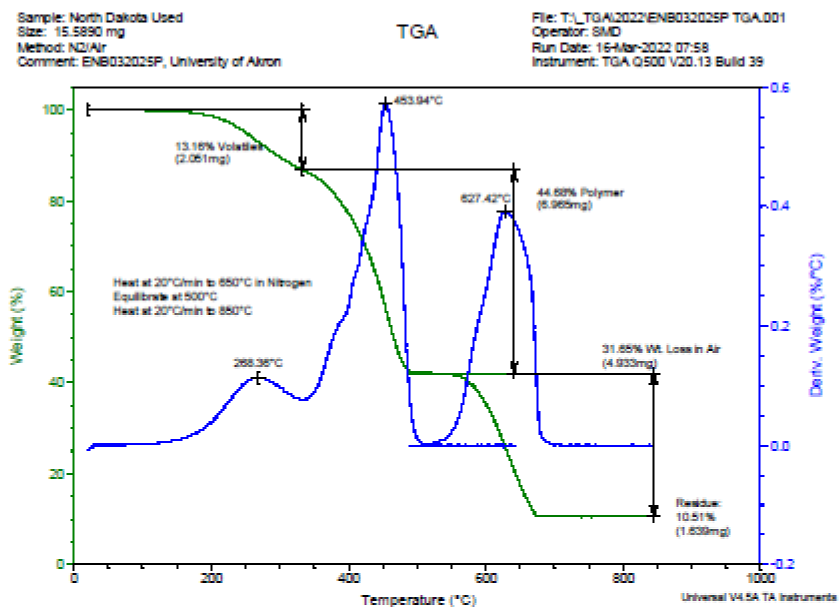

Figure 4-36: TGA Thermogram Obtained on the North Dakota -- Used Polymer Component

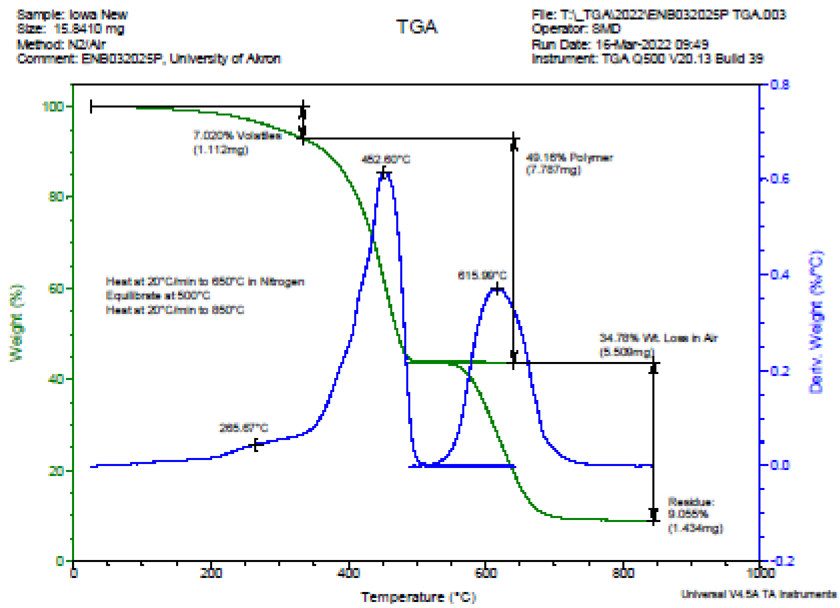

Figure 4-37: TGA Thermogram Obtained on the Iowa Polymer Component

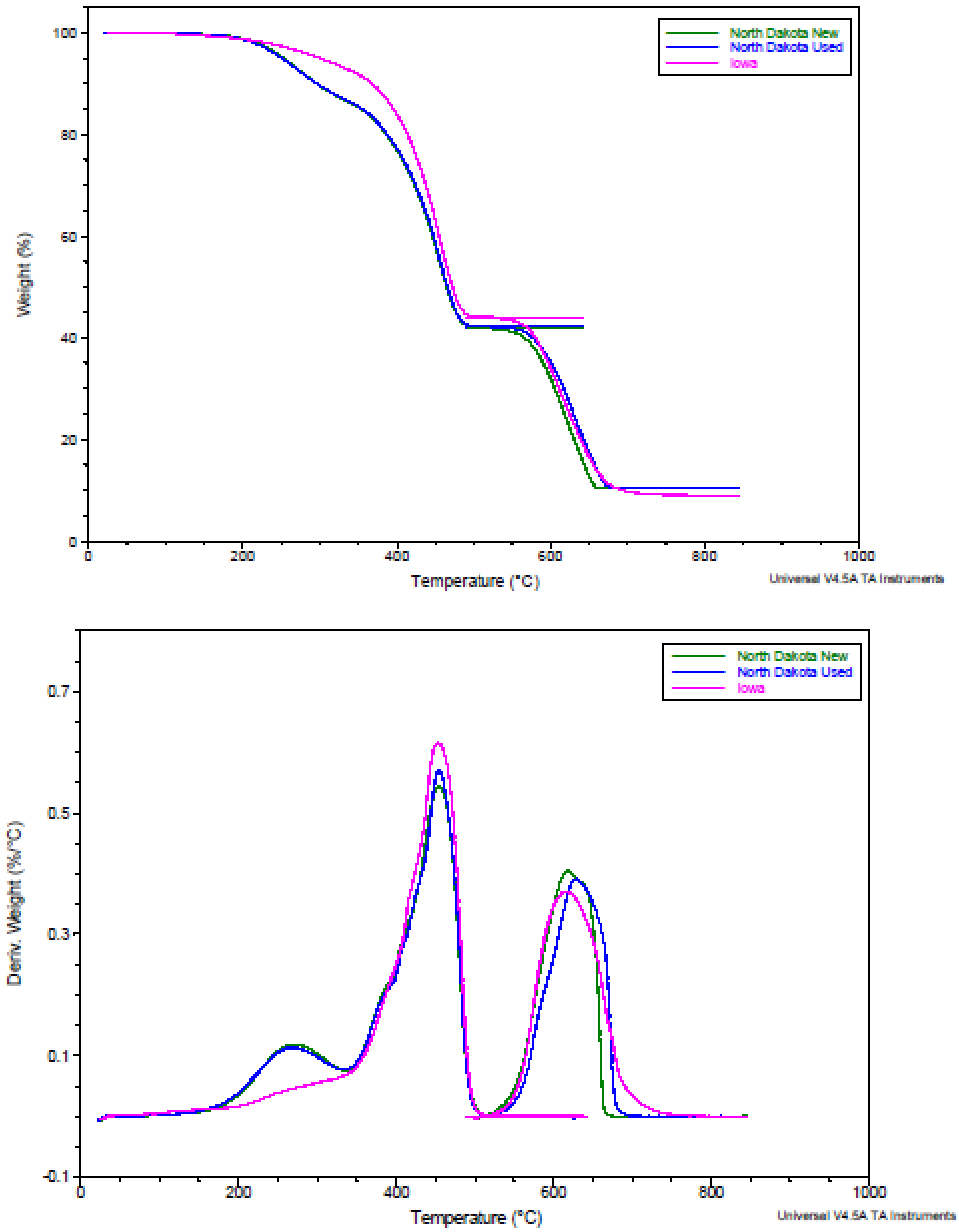

Figure 4-38: Overlay of the TGA Thermograms

Note: Overlay of the TGA thermograms obtained on the three polymer components, including the wight loss profiles (top) and the weight loss derivative profiles (bottom).

A summary of the results is shown in Table 4-39.

Table 4-39: TGA Results.

Characteristic	North Dakota New	North Dakota Used	Iowa
Volatiles (N2), %	**13.4**	**13.2**	**7.0**
Weight Loss Rate Maximum, °C	*271*	*268*	*266*
Polymer (N2), %	**44.8**	**44.7**	**49.2**
Weight Loss Rate Maximum, °C	*454*	*454*	*453*
Weight Loss in Air, %	**31.4**	**31.7**	**34.8**
Weight Loss Rate Maximum, °C	*617*	*627*	*616*
Residue/Filler Content, %	**10.3**	**10.5**	**9.1**

The polymer components of the three blades produced similar weight loss profiles. The blades produced an initial weight loss of 7.0-13.4% attributed to the decomposition of low molecular weight compounds and volatiles, such as plasticizers and absorbed water. During continued heating to 650°C in nitrogen, the blades produced a weight loss of 44.7%-49.2% attributed to the decomposition of the polymer. Upon conversion to an air environment, the blades exhibited a weight loss event associated with the combustion of carbon-based char produced during the initial decomposition and carbon black. At the conclusion of the analyses, the polymer components produced a residue content of approximately 10%.

4.6.15 Durometer Hardness

The durometer hardness of the polymer component of each blade was evaluated in accordance with ASTM D2240-15e1. Conditioning was performed per ASTM D618-13 at ambient laboratory conditions of 23 ± 2 °C and 50 ± 10% relative humidity for 40 hours. The results are shown in Table 4-40 on the Shore A scale.

Table 4-39: Durometer Hardness Test Results (Shore A).

Reading	North Dakota New	North Dakota Used	Iowa
1	73	69	75
2	71	69	74
3	72	68	75
4	71	69	72
5	70	70	74
Average (Std. Dev)	**72** (0.8)	**69** (0.7)	**74** (1.2)

4.6.15.1 Tensile Testing

Tensile testing was performed on an MTS universal tester in a manner like ASTM D412, test method A. Die C dog-bone specimens were die-cut from the rubber component of each blade. The specimens were then conditioned for a minimum of 24 hours at 23 ± 2 °C and 50 ± 10% relative humidity and then were allowed a minimum of 30 minutes at test temperature prior to testing. Testing was performed using a constant speed of 20.0 in/min and a 500 lbf load cell at 0 °C (32 °F). Extension was measured using a 1-inch extensometer. The results are summarized in Tables 4-41 through 4-43.

Table 4-40: Tensile Test Results -- North Dakota New.

Specimen	100% Modulus (M100), psi	Tensile Strength at Break, psi	Elongation at Break, %
1	1,085	3,280	284
2	1,161	3,122	254
3	1,139	3,007	258
4	1,093	2,818	243
5	1,093	3,035	264
Average	**1,114**	**3,052**	**261**
Standard Deviation	33	169	15

Table 4-41: Tensile Test Results -- North Dakota Used.

Specimen	100% Modulus (M100), psi	Tensile Strength at Break, psi	Elongation at Break, %
1	926	2,558	256
2	1,001	2,175	209
3	964	2,623	251
4	919	2,548	264
5	982	2,643	262
Average	**958**	**2,509**	**248**
Standard Deviation	35	191	23

Table 4-42: Tensile Test Results – Iowa.

Specimen	100% Modulus (M100), psi	Tensile Strength at Break, psi	Elongation at Break, %
1	1,209	2,771	248
2	1,184	2,727	248
3	1,197	2,802	257
4	1,260	2,885	264
Average	**1,213**	**2,796**	**254**
Standard Deviation	33	66	8

*Note: *One specimen slipped in grips; only four data points presented.*

4.6.15.2 Tear Testing

Tear resistance testing was performed in accordance with ASTM D624-00 (2020). Five Die C specimens were excised from the rubber component of each blade. Prior to evaluation, the specimens were allowed to condition at 23 ± 2 °C and 50% ± 10% relative humidity for a maximum of 24 hours. The specimens were tested at 0 °C (32 °F) using a 500 lbf load cell and a test speed of 20.0 in. /min. The results are summarized in Tables 4-44 through 4-46.

Table 4-44: Tear resistance Results -- North Dakota New.

Specimen	Thickness, in	Peak Load, lbf	Tear Strength, (lbf/in)
1	121.0	28.3	233.8
2	120.5	29.0	240.6
3	125.0	30.1	240.5
4	125.5	30.2	240.8
5	126.0	29.3	232.5
Average	**123.6**	**29.4**	**237.7**
Standard Deviation	2.6	0.8	4.1

Table 4-43: Tear Resistance Results -- North Dakota Used.

Specimen	Thickness, in	Peak Load, lbf	Tear Strength, (lbf/in)
1	125.5	29.3	233.7
2	125.5	28.8	229.8
3	121.5	28.7	236.2
4	122.5	30.0	245.3
5	123.5	28.5	230.9
Average	**123.7**	**29.1**	**235.2**
Standard Deviation	1.8	0.6	6.2

Table 4-46: Tear Resistance Results Iowa.

Specimen	Thickness, in	Peak Load, lbf	Tear Strength, (lbf/in)
1	123.0	30.6	249.2
2	129.0	32.7	253.7
3	126.0	31.0	246.1
4	126.0	35.1	278.3
5	124.5	28.7	230.4
Average	**125.7**	**31.6**	**251.5**
Standard Deviation	2.2	2.4	17.3

4.6.15.3 Compression Testing

The compressive properties of the rubber materials were determined in accordance with ASTM D575-A. Specimens were die-cut from the blades. Prior to evaluation, the specimens were allowed to condition for a minimum of 24 hours at 23 °C at 50% relative humidity. Testing was performed at 0 °C (32 °F). The force was applied and removed in three successive cycles with the readings taken during the third application of force. The results are provided in Tables 4-47 through 4-49

Table 4-47: Compression Testing Results - North Dakota.

Sample	Load at 65% Strain, lbf	Stress at 65% Strain, psi
1	7,990	8,750
2	7,500	7,950
3	7,210	7,730
4	8,440	9,000
5	6,200	9,710
Average	**7,470**	**8,630**
Standard Deviation	850	805

Table 4-48: Compression Testing Results -- North Dakota Used.

Sample	Load at 65% Strain, lbf	Stress at 65% Strain, psi
1	5,920	6,830
2	7,150	8,070
3	5,530	6,130
4	6,360	6,960
5	6,160	7,140
Average	**6,220**	**7,030**
Standard Deviation	603	698

Table 4-49: Compression Testing Results -- Iowa

Sample	Load at 65% Strain, lbf	Stress at 65% Strain, psi
1	6,520	8,200
2	8,060	8,990
3	7,610	8,380
4	8,210	8,450
Average	**7,600**	**8,510**
Standard Deviation	764	340

*Note: *One specimen used for establishing test parameters.*

The findings presented herein are given with a reasonable degree of engineering certainty using currently available data. Element New Berlin reserves the right to supplement or amend this report should additional information become available.

If you have any questions concerning the contents of this report, please contact the author. It should be noted that it is our policy to retain components and sample remnants for 30 days from the date of this report, after which time they will be discarded. Please contact the author of this report should you wish to make alternate arrangements for the disposition of the material.

4.6.16 Lab Results Conclusions

- Comparisons between the North Dakota – New and North Dakota – Used Blade, Ring, and Carbide components were like one another with respect to their chemical composition and microstructures for their respective components.

- Comparison of the North Dakota and Iowa Blade and Ring components differed with respect to their chemical compositions and their resultant microstructures and Blade hardness.

- Evaluation of the density for the Carbide components for the North Dakota – New, North Dakota – Used, and Iowa samples were found to be very similar to one another.

- Evaluation of the braze material utilized in the Blade/Carbide assemblies for the North Dakota – New and Iowa were different from one another, with the main elemental constituents of the braze material for the North Dakota – New consisting predominantly copper, zinc, and silver, whereas the main elemental constituents of the braze material for the Iowa consisted predominantly copper, zinc, and nickel.

- Hardness testing of the Carbide components for the North Dakota – New and Iowa samples, revealed average hardness values, that were like one another, with hardness values of 1,145 HV and 1,288 HV, respectively.

- Spectroscopic analysis of the blade polymer components indicated that the rubber materials were comprised of a styrene-butadiene based material. Residues extracted with hexane were consistent with a hydrocarbon-based plasticizer.

- Thermal analysis of the polymer components also produced consistent results. A glass transition was observed via DSC at approximately -50 °C, consistent with a styrene butadiene rubber. Additional analysis via TGA produced similar weight loss profiles with a filler content of approximately 10%.

- The three polymer components produced a durometer hardness range of 60 to 74 on the Shore A scale with the North Dakota Used blade exhibiting the lowest hardness and the Iowa blade exhibiting the highest hardness.

- The tensile evaluation produced relatively similar property values with the highest tensile strength exhibited by the North Dakota New blade and the lowest tensile strength exhibited by the North Dakota Used.

- The tear strength properties of the polymer components were rather similar, in which the North Dakota New and Used blades were consistent with one another, while the Iowa blade produced a slightly higher tear strength.

- Compression testing of the rubber materials revealed that the North Dakota New and Iowa blades were relatively stiffer than the North Dakota Used rubber material.

Tables 4-50 and 4-51 are summary tables with respect to cost and general expectation of results from the tests.

Table 4-50: Polymer Evaluation Synopsis.

Polymer Evaluation			
$1,000[(1), (2)]	FTIR and Durometer hardness	Determine base resin, additives, contaminants; determine relative hardness	Wrong compositional make up = different properties and performance; change in hardness = more or less susceptible to penetration or permanent indentations
$2,000[(1), (2)]	$1,000 category plus DSC and TGA	Determine base resin, additives/filler contents, contaminants; cure/thermal stability; determine relative hardness	Wrong compositional make up, incorrect processing = different properties and performance; change in hardness = more or less susceptible to penetration or permanent indentations
$3,500[(1), (2)]	Tensile, Tear, Compression, Durometer	Determine tensile, tear, and compressive strengths; determine relative hardness	Mechanical properties provide insight into yield and tensile strengths as well as elongation to compare strength, ductility, toughness of materials and changes to these properties can help determine how susceptible the materials are to failure in the field - environmental conditions can have an effect on these properties as well, e.g. temperature; change in hardness = more or less susceptible to penetration or permanent indentations
$6,500[(1), (2)]	(All tests) FTIR, DSC, TGA, Durometer hardness, Tensile, Tear, and Compression	Determine base resin, additives/filler contents, contaminants; cure/thermal stability; determine relative hardness; determine tensile, tear, compressive strengths	Wrong compositional make up, incorrect processing = different properties and performance; change in hardness = more or less susceptible to penetration or permanent indentations; yield and tensile strengths, elongation provide comparisons of strength, ductility, toughness (same comments as above)

Notes:

1) Estimated cost (Approx. Total @ 2 samples, machining not included),
2) Can be presented as a cert style report (data only with minimal interpretation); additional cost for report style with full descriptions and interpretations. Machining time not included with prices, as this may change depending on how difficult cutting may be or the amount required for the specific test.

Table 4-51: Metallurgical Evaluation Synopsis.

Metallurgical Evaluation			
\$1,500 (1), (2)	OES of Blade Rockwell Hardness Testing	Alloy determination Average material hardness determination	Different materials = different properties and performance, may have overlaps with properties and performance, the alloy and elemental additives allow for the differences by changing the properties; Rockwell Hardness = resistance to deformation, HRC range higher is harder, HRB range softer than HRC and similarly higher is harder
\$3,250 (1), (3)	\$1,500 category plus icp-oes of carbide, density of carbide	Verification/characterization of carbide composition, determination of carbide density	Different materials = different properties and performance; density = mass/volume, a higher density has a higher mass to volume ratio, likely indicates that there is less porosity assuming same chemistry. Theoretically a fully dense part with zero porosity (not possible), will result in the best properties.
\$5,000 (1), (4)	\$3,250 category plus metallographic cross-section preparation and evaluation of microstructure	determine the microstructural constituents present within the metal and carbide	metallography of metal = gives you information about how it was manufactured and processed, depending on the manufacturing and processing you can tailor the properties and performance, could be overlap between materials that would be able to be differentiated, cheaper material with more expensive processing and heat treatment might be similar to more expensive material with less post processing and heat treatment metallography of the carbide - rate microstructure for apparent porosity, uncombined carbon, grain size, carbide grain size, eta phase, gamma phase, and alpha phase = effectiveness of the processing of the carbide and identification/rating of deleterious phases that may adversely affect properties and performance

7500+ [(1), (5)]	\$5,000 category plus tensile testing of blade component, Charpy impact testing of blade component	Determine mechanical properties of blade component	Tensile testing = gives mechanical properties such as yield strength, tensile strength, elongation, and reduction of area, which will allow for comparisons in strength, toughness (combination of strength and ductility), and ductility (how much something stretches), example being ceramics have high strength but low ductility in general very strong but brittle, metals are not as strong as ceramics but significantly more ductile, polymers are not as strong as metals but usually more ductile; depends on additives) impact testing = gives the amount of energy absorbed during impact (a measure of toughness), some metals will have better or worse impact properties at cold, room temperature, and elevated temperatures

Notes:

1) Estimated cost (per sample basis/machining included (unless otherwise noted), additional samples will likely be less that full tier price as there is savings when prepping in multiples/batches).
2) Can be presented as a cert style report (data only), additional cost for report style with full descriptions and interpretations
3) Can be presented as a cert style report (data only), additional cost for report style with full descriptions and interpretations. Isolation of the carbide from the remainder of the blade requires extensive saw cutting and consumables due to the extreme hardness of the carbide.
4) Can be presented as a cert style report (data only), Can be presented as a cert/letter report (data and minimal interpretation); can be presented as report style with full descriptions and interpretations. Priced middle of the road.
5) Will only be presented as report with full descriptions and interpretations. As the rubber would need to be removed and excised sections machined into tensile specimens and Charpy impact specimens some time has been added for machining however it has been left open ended as it is unclear how much machining it would take, but is an approximate estimation

4.6.17 Quality Control Testing

It is essential to find an appropriate sample size to best reflect the population without having to test the overall population. Testing the entire population would be costly and time consuming, so if there is a way to test less blades than the population and still achieve a high percent of accuracy, that should be done. The research team provides two sample size selection processes: one based off statistics and the other based off economic constraints. Statistics based selection is utilizing known sample size selection processes; however, this may not be financially possible or realistic for DOTs to achieve. Therefore, the research team is also recommending a financial approach to laboratory testing.

4.6.17.1 Statistics based Selection of sample size

Statistical sampling is sampling to achieve initial statistical significance. For the research team to begin statistical selection, sample size needs to be established. Since the research team is creating this methodology for varying size DOTs, Cochran's formula should be utilized, due to the population size being known or varying. The following equation, Equation 4-5, is used to calculate sample size for an unknown population:

$$n = \frac{z^2 * p * (1 - p)}{\varepsilon^2}$$

Equation 4-5

where,

n is the sample size,

z is the z-score,

p is the population proportion, and

ε is the margin of error.

The first factor in Equation 4-5 is n is the sample size which is the number of blades to be tested. Second factor is the population proportion, p which is the fraction of the population that has a characteristic of interest (Stephanie, 2017). When the population proportion is unknown, the population proportion is assumed to be 50% which is conservative. The third factor is $\mathcal{E}$ which is the margin of error. It is standard to have a confidence interval of 95% with a margin of error of either 5% or 2.5% (Bartlett et al., 2001). Confidence interval implies that if the estimation is repeated with random samples, then 95% of the samples should contain the true value (*Hazra, 2017).*

The last component of the equation is the z score which is an associated standard deviation derived from the confidence interval. Since the DOTs performing this study will know the number of blades they are purchasing, which is the population, noted as N. The following equation, Equation 4-6 should be used following Equation 4-5. Equation 4-6 is used to calculate the true sample size for a known population with the modified Cochran's formula for small populations:

$$n' = \frac{n}{1 + \frac{n-1}{N}}$$

Equation 4-6

where,

n' is the modified sample size,

n is the sample size, and

N is the population.

After establishing the sample size for a population, the research team recommends systematic sampling. Systematic sampling allows for testing of one out of every k subjects within a population in order to achieve the desired sample size (Siegle, 2015). Systematic sampling will limit data sampling errors, and will negate any accusation of data manipulation, which due to randomness is less likely than simple random sampling (Blokhin, 2020). Equation 4-7 should be used to establish how many blades should be selected out of every k.

$$k = \frac{N}{n'}$$

Equation 4-7

where,

k is the random sample number,

n is the population, and

n' is the modified sample size.

Utilizing Equations 4-5, 4-6, and 4-7, the research team may calculate the sample size. The results are financially unrealistic for DOTs. For example, if a DOT has a blade population size of 1000, the sample size is 200. This would mean that if DOTs test 200 blades, they will have to purchase another 200 to replace them for their fleets. This is just not feasible for DOTs.

4.6.17.2 Financial based Selection

As discussed in section 4.6.10.1, the appropriate statically correct sample size may not be the most financially feasible option for a DOT. The research team recommends three types of financially based sample size selections.

1. Failure based testing,
2. Random seasonal testing, and
3. Success based testing.

The first financial based selection process would be failure-based laboratory testing. This would allow a DOT to test blades that are failing prematurely. Using a failure-based selection process would provide DOTs with information on if the failure is caused by bad blade abnormal wear. Shown previously in Figure 4-9, shows a plow blade with a few faults that may be appropriate to conduct laboratory testing.

In Figure 4-9, the first problem seen with the carbide articulating blade tested in Idaho is carbide fracturing. Carbide fracturing is associated with abnormal wear. In the case above, laboratory testing may be conducted to see if the fracturing is due to bad blade or blade misuse. With carbide fracturing, the failure may be associated with carbide to cobalt percentages, density, porosity, and grain size due to its relationship with resistance to fracture and wear. If the lab testing concludes that the blade meets all the specifications, then the failure is more likely to be due to blade misuse and should be corrected appropriately; however, if the blade does not pass the appropriate lab tests, then a portion of the failure is due to the bad blade. The second blade failure, shown previously in Figure 4-9, is aggregate between the blade and the rubber portion of the flexible blade. This is a failure due to how the rubber and the blade are connected. Failure blade testing will help DOTs establish what specifications are the most important in resisting wear and fracture.

The second financial based selection process is random seasonal testing. This is similar conceptually to the random systematic testing discussed above with Equation 4-7; however, this method is to be utilized on a non-replicable process. Meaning random systematic sampling may dictate sampling 1 in every 5, and this methodology will be selecting the 30th blade then the 12th blade and then the 8th. This methodology will allow the randomness necessary to not skew results while negating the financial strain of random systematic sampling.

The third financial based selection process is success-based testing. Success-based testing suggests that a DOT conducts lab testing on their most successful blades. This method will provide information on successful blades' specifications. As stated in Table 4-18, the ranges provided are recommendations based off current vendor specifications or individual state contracts. With success-based testing, DOTs will obtain specifications that are preferred due to their success in the field rather than relying on specifications that are provided. For example, in the NASPO 2012 specifications, the range for tungsten carbide specific weight is 87-88%; however, hypothetically, a DOT may find a blade that is most successful in the field has a tungsten carbide specific weight of 80-81%. This is knowledge that would only be acquired through testing of successful blades to establish more preferential specifications.

4.6.18 Lab Qualification

To establish that the third-party laboratory is qualified, utilizing a certified lab is necessary. Certification is the provision by an independent body of written assurance that the product, service, or system in question meets specific requirements. Certification provides the assurance that the lab is trustworthy.

For a laboratory to be credible, the laboratory should be ISO/IEC 17025 certified. ISO is the International Organization for Standardization. ISO provides the standards for industries to adhere to. ISO/IEC 17025 is the "general requirements for the competence of testing and calibration of laboratories" (ISO 2018). For a DOT to select a laboratory to conduct the testing recommended in this study, the laboratory must be certified for ISO/IEC 17025. Since ISO does not provide certification that a standard is met, a third party must be used to certify.

Whom accredits a laboratory will vary; however, the most important factor is to ensure that the laboratory is ISO/IEC 17025 certified. Though testing may be done in house at the DOTs, the research team recommends using a third part vendor. This provides assurance to vendors and DOTs that the tests are conducted with complete neutrality.

4.7 AUTHENTICATE LAB SPECIFICATIONS AND RANGES

Table 4-21, shown previously, summarizes the NASPO 2012 contract and four different vendor's specification sheets. Table 4-21 was utilized for DOTs to have a starting point for laboratory testing; however, it is possible for DOTs to provide their own preferential ranges. Initially, DOTs will have to rely on the vendor specification sheets to determine the quality of the blade as expected; however, a DOT may be able to establish ranges that they would like to hold plow blades to. This is accomplished through the integration of laboratory and field testing. Integration of lab and field testing is discussed below in terms of formally testing and informally testing. Formal testing is recommended by the research team and follows the field and lab testing suggested in section 4.3. Informal testing is for DOTs who would like to participate but do not have the means to perform a full-scale study. The breakdown of lab and field testing is seen in Figure 4-51 below.

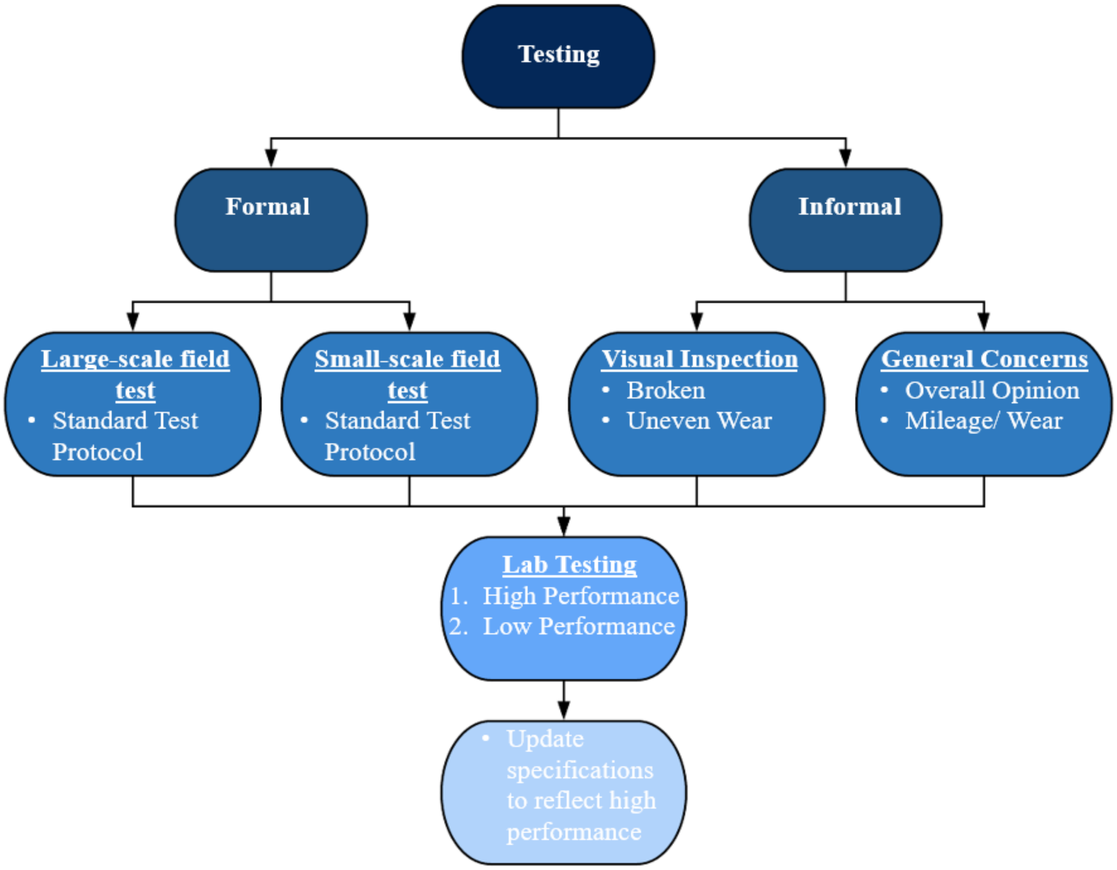

Figure 4-39: Integration of Field and Lab

Starting from the left of Figure 4-39, formal testing is the recommended method of testing. Formally testing the blades is conducted utilizing either large-scale or small-scale field testing with laboratory testing. Performing large-scale or small-scale field tests will provide chronological information on the wear of the blade and the conditions which the blade encountered (weather or road material). Laboratory testing may be conducted pre or post field testing to establish blade qualifications. Having the wear information on multiple blades will help establish the ranges of specifications. Over a period, a DOT will be able to utilize the wear and lab testing information to establish the ranges of high/poor performing blades and the specifications that indicate high/poor performing blades. This may be promoted by a DOT as the new specifications and ranges to seek out for a plow blade or avoid for a plow blade.

On the right side of Figure 4-39 is the informal testing of plow blades. Using this method may allow a DOT to conduct testing without costing time or finances. If a DOT would like to participate but does not have the ability to commit to a large scale or small-scale field test with lab testing, the research team recommends testing blades through visual inspections as seen in Figure 4-39. Visual inspection should be done on the front and underside of the blade. Figure 4-40 displays the underside of a blade that was tested in the Idaho case study.

Figure 4-40: Blade Four from the Idaho Case Study

Visual inspections should be done to see if blades are broken and wears unevenly. If the visual inspection indicates poor quality due to a bad blade, it is suggested to send the blade in for laboratory testing. The second informal testing method is general concerns which encompasses overall opinion and mileage/wear. Overall opinion may be monitored based off operator comments or mechanics comments. Once established that the blade is performing abnormally, the DOT should take measurements to monitor its performance as frequently as possible. If the measurements and frequency of changing a blade appear to be abnormal, it is recommended to send the blade in for laboratory testing.

For a DOT to find specifications they prefer, formal or informal testing should be conducted. Formal and informal testing includes the integration of both laboratory and field tests. If a DOT is unable to perform formal testing, the research team recommends selecting blades during the winter season that are performing extremely high and/or low or selecting blades at random which has been recommended for lab testing in section 4.6.10.2. Lab testing high and low performing blades will allow DOTs to establish which specifications note high performance and low performance as seen in Figure 4-12. Aside from testing high and low performing blades, randomly selecting blades is also recommended. Randomly selecting blades for testing will provide general information on blades being tested rather than information on high and low performing blades. A DOT will also be able to determine what specific ranges they prefer for enhanced performance, which will either prove the NASPO 2012 contract valid or invalid.

The specifications in the NASPO 2012 contracts are recommendations to start with. Regardless of if a DOT utilizes formal or informal integration of lab and field data, the research team recommends employing data warehousing. Data warehousing will provide a central location for DOTs to submit their formal or informal data that other DOTs may utilize. Over time the data within the warehouse will become large and substantial. With a large amount of data, DOTs should be able to establish their preferred specifications and ranges for plow blades.

CHAPTER 5: STANDARDIZATION OF RESULTS

5.1 OBJECTIVES AND GOALS

The objective of this chapter is to help a DOT assess a plow blade in terms of wear and cost. The objective will be achieved by:

1. Phase One: establish a standard for wear rates for carbide, carbide articulating, and steel blades.
2. Phase Two: determine the probability of achieving specific mileages and wear (inches).
3. Phase Three: develop a standard protocol to help assess if a blade is a cost neutral purchase.

5.2 EMPIRICAL DATA

In this chapter the research team will use three sets of data for their evaluation. The first data set is from Schneider et al 2015. The second data set are field data from the Idaho case study conducted during the 2019-2020 winter season. The third and final data set are from Clear Roads 13-03. Table 5-1 is the descriptive wear statistics from Schneider et al. 2015 and the Idaho case study which summarizes the mean, median, standard deviation, skewness, minimum value, maximum value, and count.

Table 5-1:Descriptive Wear Statistics

Descriptive Statistic	Measurement Location[1]	Schneider et al 2015[2] Carbide	Carbide Articulating	Steel	Idaho Carbide Articulating
Mean (Inches)	outside	0.51	0.34	0.84	0.19
	inside	0.69	0.35	0.89	0.21
Median (Inches)	outside	0.06	0.34	0.30	0.16
	inside	0.67	0.27	0.51	0.25
Standard Deviation (Inches)	outside	0.83	0.27	0.96	0.22
	inside	0.79	0.31	1.00	0.20
Skewness (Inches)	outside	2.02	0.34	1.04	1.50
	inside	1.53	0.72	0.90	0.74
Minimum (Inches)	outside	0	0	0	0
	inside	0	0	0	0
Maximum (Inches)	outside	2.5	0.94	3.63	0.88
	inside	2.63	1.17	3.25	0.67
Count	outside	11	45	78	25
	inside	11	45	77	25

Note: The numbers have been rounded to the nearest hundredth place.

[1] Measurement location outside are the measurement locations farthest to the right and farthest to the left of the blade. The inside measurements are the inner three measurement locations.

[2] Schneider et al. 2015 was utilized as historic data.

As seen in Table 5-1, the greatest mean wear is from the steel blades, and the lowest mean wear is from the carbide articulating blade. An interesting fact from this data set is the mean wear for the outside wear of carbide articulating, carbide, and steel is smaller than the wear that occurs on the inside of the blade. The minimum wear for all blade types is zero due to the first measurement occurring on a blade without wear.

Table 5-2 summarizes the descriptive mileage statistics from Schneider et al. 2015 and the Idaho case study. All the mileages start at zero which is logical because the first measurements of the blades occur before the blade is worn.

Table 5-2: Descriptive Mileage Statistics

Descriptive Statistic	Schneider et al 2015			Idaho
	Carbide	Carbide Articulating	Steel	Carbide Articulating
Mean (Miles)	332	916	500	631
Median (Miles)	142	513	346	375
Standard Deviation (Miles)	460	960	550	643
Skewness (Miles)	2.15	1.14	1.24	2.02
Minimum (Miles)	0	0	0	0
Maximum (Miles)	1564	3789	2375	1756
Count	11	45	76	5

Note: The numbers have been rounded to the nearest hundredth place.

As seen in table 5-2 the largest mean mileage is obtained from the carbide articulating blades when compared to the carbide and steel blades. Additionally, the standard deviations of all the blade types are greater than the average wear. This may be due to variation in the end user, operator error, or due to a bad blade.

The research team also used Clear Roads 13-03 which is the cost-benefit of various winter maintenance strategies. The objective of Clear Roads 13-03 is to assess and communicate cost and benefits of maintenance strategies to maintain a level of service, economic impacts, corrosive impacts, safety impacts, and, most importantly for this study, abrasive wear and tear impact (Fay et al. 2015). Clear Roads Project 13-03 was also used to validate the standard graphs created utilizing Schneider et al. 2015. This may be seen in Table 5-3.

Table 5-3: Descriptive Statistics for Clear Roads 13-03

Blade Type	Mileage
Carbide	809-3600+
Carbide Articulating[1]	1200-1500
Steel	300-4430+

Note: The data used in this table are from Clear Roads 13-03 (Fay et al. 2015)

[1] Carbide articulating blades in Clear Roads 13-03 are called "Combination Blades"; however, the blades described in Clear Roads 13-03 are the blades that the research team call carbide articulating blades. Hence, these blades will be called carbide articulating blades.

Table 5-3 summarizes the mileage a blade is able to obtain as discussed in Clear Roads project 13-03. The largest variation in mileage is seen in steel, carbide, and carbide articulating blades, respectively. The mileage ranges for steel, carbide and carbide articulating in Table 5-3 encompasses the mileages captured in the Schneider et al. 2015 and the Idaho case study as seen in Table 5-2. After summarizing the descriptive statistics, the data needs to be further analyzed before creating the models.

5.3 STANDARD WEAR AND MILEAGE

Using the three data sets described above, the research team is going to develop a series of models that will be useful to the end user by establishing a normal range for wear. If the blade is performing poorly, it should be laboratory tested as discussed in Chapter 4. Additionally, if the blade is performing better than average, the blade should be laboratory tested. This will help a DOT establish early if a blade is performing in a standard manner or in a bad manner. The Idaho case study blades only had one blade reach failure. The data for all the blades in the Idaho case study may be used because the wear rates are still useful even if the blades did not achieve failure.

The first step when building the models is to evaluate the general data. In this case, the historic data is Schneider et al 2015 and Idaho case study. One interesting point is the initial measurement of the blade. In this study, the first 250 miles of a blade are considered the setting period in which the first 0.25" of wear occurs. This uneven wear is due to the high burn period in the first 250 miles. Utilizing the historic data, there are 55 measurements that were taken in the initial 250 miles. The first 250 of the miles from the data used are plotted in Figure 5-1.

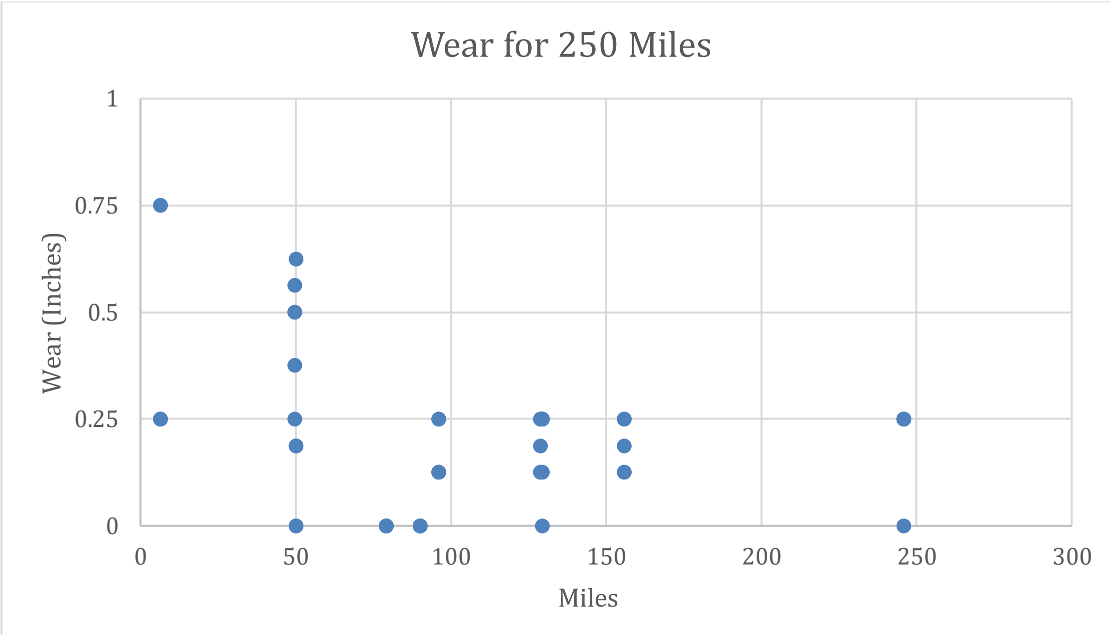

Figure 5-1: First 250 miles of plowing

As seen in Figure 5-1, of those 55 measurements, 44 measurements had at least 0.25” of wear, which means 80% of the first 250 miles had 0.25” of wear. Due to this high percentage, the research team excluded the first 250 miles from the standard wear graphs due to its misrepresentation of wear.

5.3.1 Statistical Methodology

The research team separated the data by material type and compared the individual material types. The variety of materials used for blades is carbide, carbide articulating, and steel.

To create the carbide and steel blade models, the research team used 75% of Schneider et al. 2015 data to build the models and the residual 25% to validate the model. To create the carbide articulating blade model, the research team used 100% of the Schneider et al 2015 data and used the Idaho case study to validate the model. The residual 25% of the data and the Idaho case study data, are used by the research team to calculate the standard error for blades. The standard error equation is as follows:

$$Standard\ Error(\%) = \left(\frac{Y - Y'}{Y}\right) * 100$$

Equation 5-1

where,

Y is predicted simulated value, and

Y’ is residual 25% including the Idaho case study.

Equation 5-1 is used to show the error from the simulated values and the values obtained in the field. For example, if a blade is simulated to achieve 1.5”, and the blade achieves 2.0”. The standard error is -33%, which means the actual value is 33% greater than that simulated. The error is negative because the simulated value is less than that of the actual. If the simulated value is greater, the standard error would be positive.

From what the research team has collected, there are over 84 blades available to DOTs with six blade types which may be seen in Appendix B. In addition to blade selection indicating large variation, the field offers a large amount of variation including weather, road material, and operator use, which all provide conditions that will vary year to year and location to location. The assumption with plow blades is that they work relatively similar within their blade type categories; however, there are blades that will perform well and poorly. Performance may be measured in mileage or wear in inches. Due to that level of uncertainty and given there is not a lot of historic data to utilize, a large variation in the data is appropriate. The level of uncertainty comes not only from the variety of field data but also variability from the amount of options available.

As a result of the variations within the blades and the environment, it is not feasible nor appropriate to suggest that blades have one estimated value; therefore, the use of a simulation that allows for a range of acceptable values is the most applicable. Monte Carlo is the best method for estimating the performance of plow blades. The equation used for Monte Carlo simulation is seen in Equation 5-2.

$$Y = \mu + \sigma * RV(d, 1)$$

Equation 5-2

where,

μ is the mean,

σ is the standard deviation,

RV is the random assigned value, and

d is the simulated value.

The data used to create the standard wear graphs are the wear per mile per blade type blade type, otherwise known as the wear rate. The wear rate of the data are calculated using Table 5-1 and Table 5-2. The data are simulated over 250,000 times in Matlab allowing for a general distribution of the results. Matlab is a programing site utilized by engineers and scientists to analyze data, develop algorithms, and create models and applications (developed by MathWorks, Natick, Mass.). 250,000 iterations of the simulation are selected due to a range of 100,000 and 500,000 iterations producing a large confidence interval and more precise estimates for the average (Liu 2020). The general distribution has a variation of wear or mileage that may be achieved. Figure 5-2 displays an example of the simulated wear rate for a carbide blade.

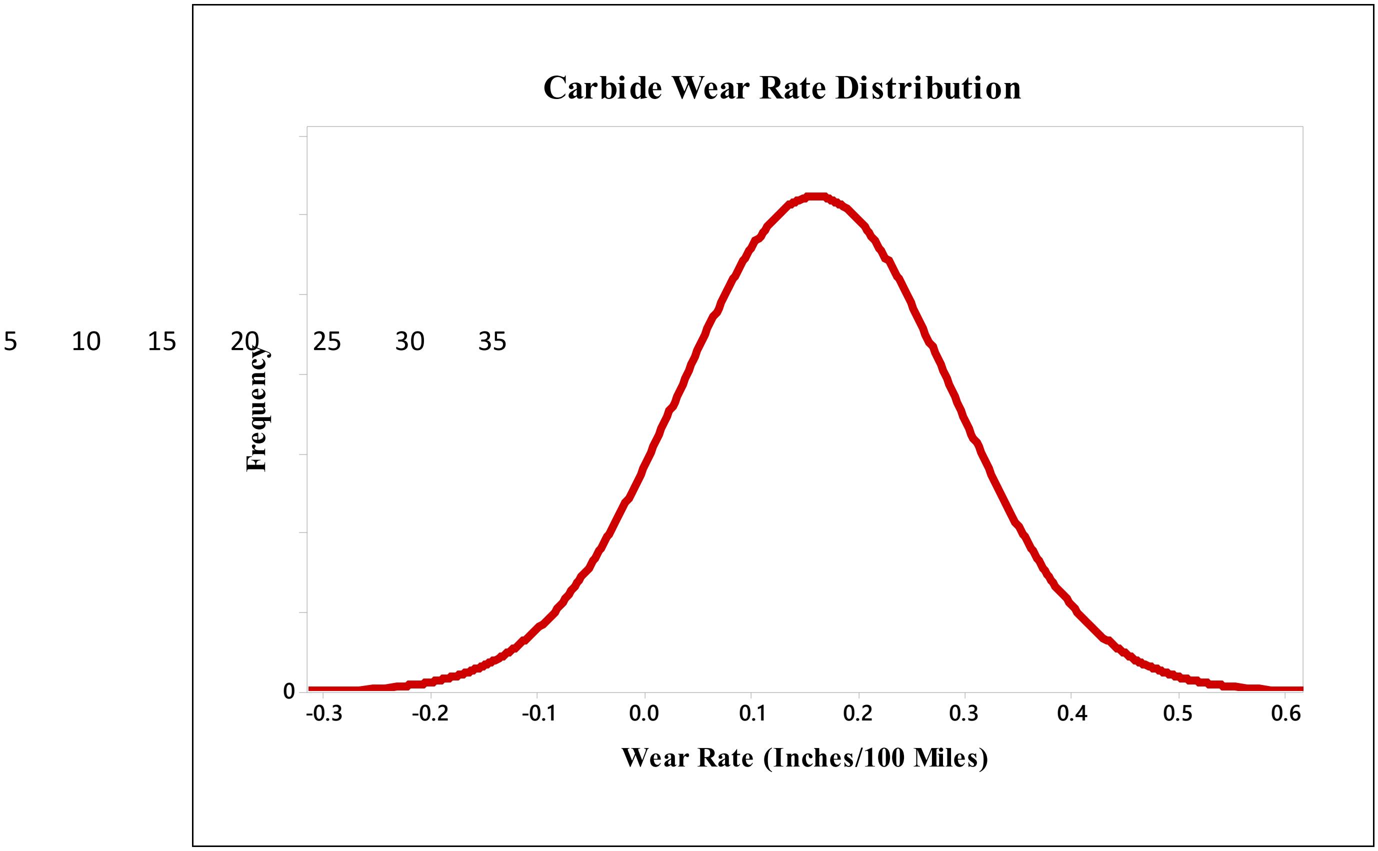

Figure 5-2: Carbide Wear Histogram

Utilizing the average total wear and the total mileage captured on a blade, a rate of wear for the blade was established. The average rate of all the blades was taken and the standard deviation was determined to place in Monte Carlo. Figure 5-2 reflects the general wear of a blade meaning that most blades wear similarly but there are some blades that wear well and wear poorly. This is captured utilizing a normal distribution.

5.3.2 Simulation

Figure 5-3 shows the carbide insert blade standard wear. The x-axis is the mileage on the blade. The y-axis is the wear in inches on the blade. The dotted line is the upper bound average wear per mile. The dashed line is the average wear per mile. The bottom line is a dashed and dotted line which represents the lower bound average wear per mile. If a blade is within the lower and upper bound, the blade is wearing as anticipated and no action should occur.

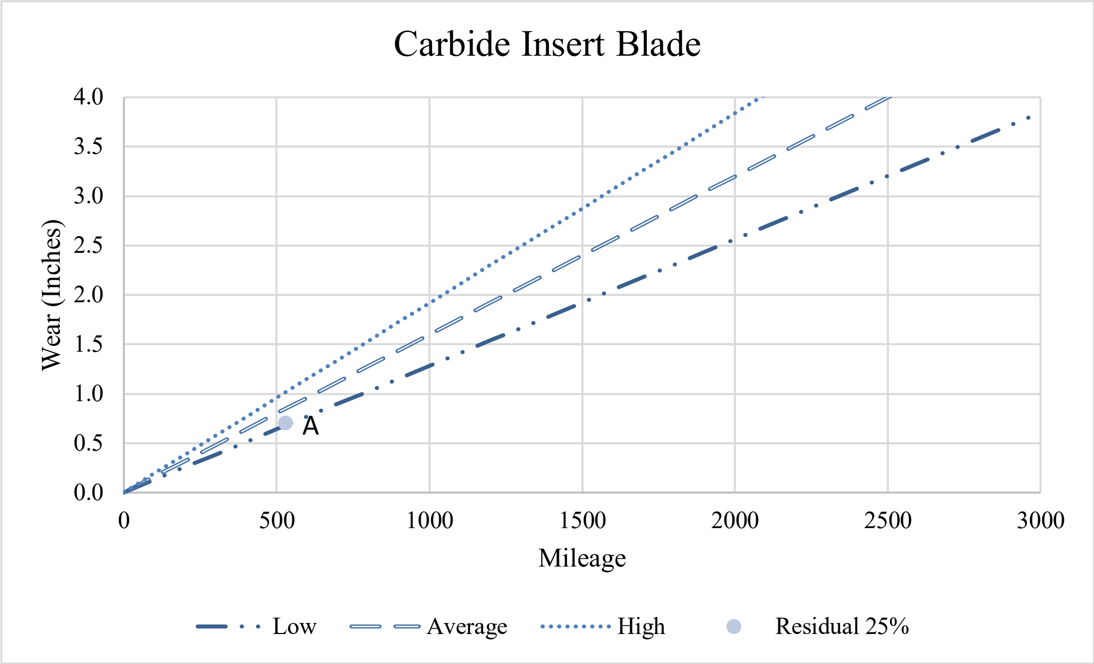

Figure 5-3: Carbide Insert Blade

The equations of the lines created for carbide insert standard wear are shown in Equations 5-3 through 5-5. Equation 5-3 is the simulated average wear rate, Equation 5-4 is the simulated low average wear rate, and Equation 5-5 is the simulated high average wear rate.

$$Y = 0.0016 * X$$

Equation 5-3

$$Y = 0.00128 * X$$

Equation 5-4

$$Y = 0.00192 * X$$

Equation 5-5

where,

Y is the wear (inches), and

X is the miles with plow down.

These lines are the anticipated wear of the blade. Anything outside of the three lines is considered wearing poorly or better than expected. The residual 25% of blade data are within the low and high bounds, and therefore, these blades wore as expected. The residual 25% data point is located at A. The standard error of this data point for the low average is -2.9% which means the data point is greater than the predicted low average. Therefore, the data point for carbide is within the range of average and low average for standard wear. The limitations with Figure 5-3 are due to the small amount of data available to create the graphs. Once more data are collected, the standard deviation or the upper and lower bounds should become closer to the average.

Figure 5-4 displays the anticipated wear of a carbide articulating blade. The carbide articulating data from Schneider et al. 2015 was utilized 100% for the model, and the Idaho case study data are used to plot and validate the simulation. The x-axis and y-axis are the same as Figure 5-3. There are three distinct lines on the Figure 5-4, which are the same as in Figure 5-3.

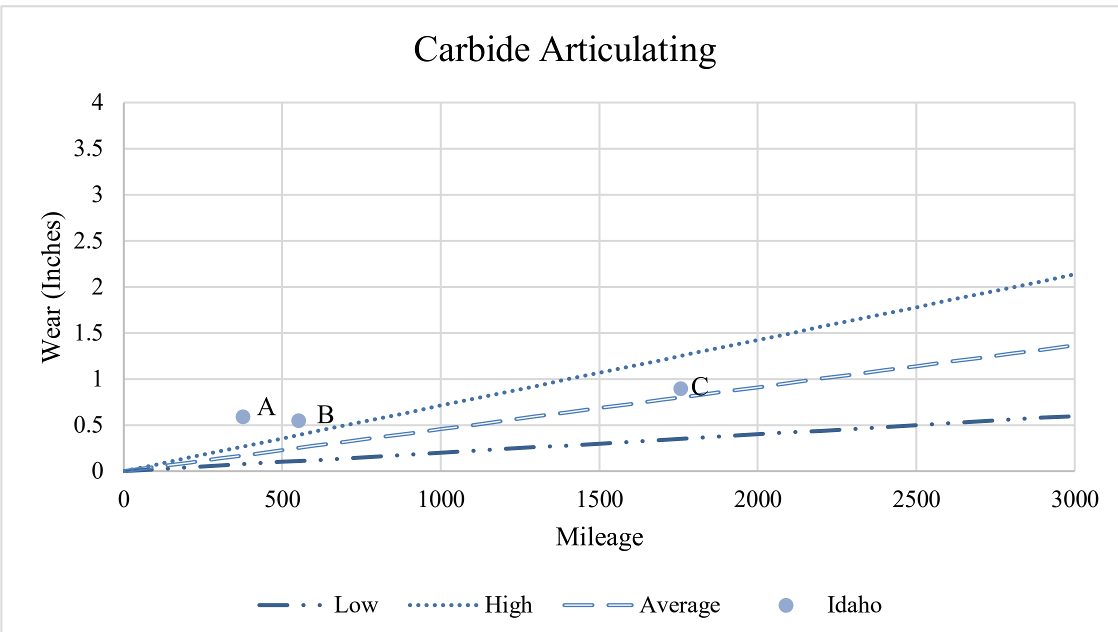

Figure 5-4: Carbide Articulating Blade

Figure 5-4 shows the simulated standard wear graph for the carbide articulating blade. The data points are from the Idaho case study. The equations to create the standard graph for wear are seen in Equations 5-6 through 5-8. Equation 5-6 is for the simulated average wear rate, Equation 5-7 is the simulated low average wear rate, and Equation 5-8 is the simulated high average wear rate. These lines highlight the anticipated wear of the blade. Wear outside of the three lines is considered wearing poorly or better than expected.

$$Y = 0.00046 * X$$

Equation 5-6

$$Y = 0.0002 * X$$

Equation 5-7

$$Y = 0.00072 * X$$

Equation 5-8

where,

Y is the wear (inches), and

X is the miles with plow down.

As seen in Figure 5-4, the range for the average wear of a carbide articulating blade is large. The vast deviation is due to the historic wear of carbide articulating blades. The data points on the graph from Idaho are located at A, B, and C. The data point B is within the standard graph for wear. The other two blades, A and C, are outside of the standard graph would be considered poor performing and would be recommended for laboratory testing. The limitations with Figure 5-4 are the same as Figure 5-3. The amount of data available is small and allows for a large amount of variability. Once more data are collected, the standard deviation or the upper and lower bounds will become closer to the average. This will narrow the acceptable ranges and give DOTs a better idea of blade performance.

Figure 5-5 shows the wear of the blade per mile including Equations 5-9 through 5-11. The x-axis and y-axis are the same as Figure 5-3 and Figure 5-4. There are three distinct lines on the Figure 5-5. The lines within the graph represent the acceptable averages as discussed in Figure 5-3 and Figure 5-4.

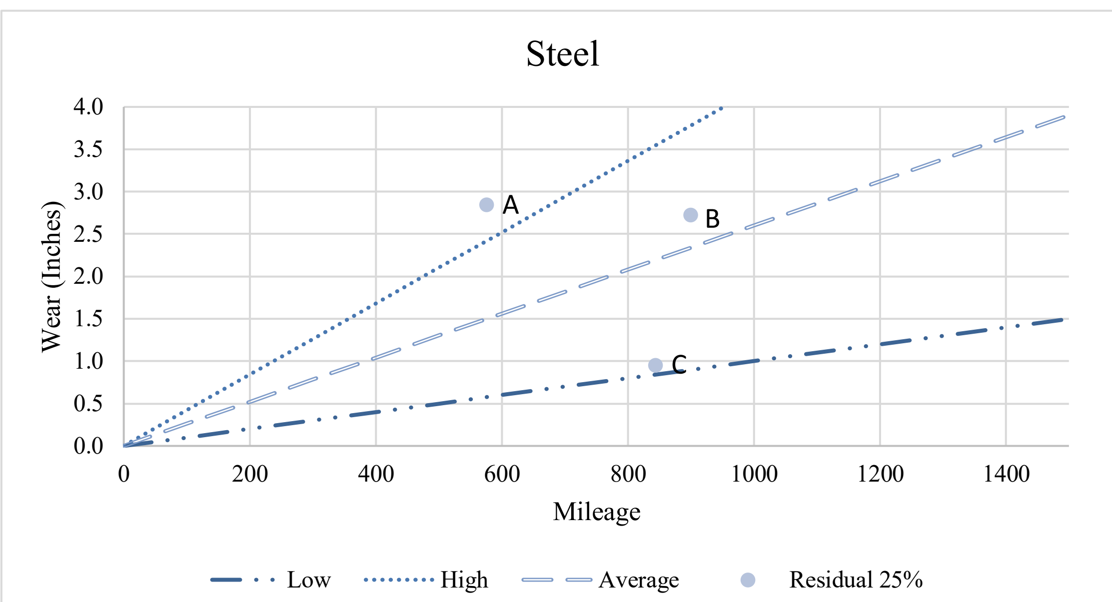

Figure 5-5: Steel Blade

Figure 5-5 is the simulated standard wear of steel blades. The equation for the standard wear of steel blades is seen in Equations 5-9 through 5-11. Equation 5-9 is the simulated average wear rate, Equation 5-10 is the simulated low average wear rate, and Equation 5-11 is the simulated high average wear rate.

$$Y = 0.0026 * X$$

Equation 5-9

$$Y = 0.001 * X$$

Equation 5-10

$$Y = 0.0042 * X$$

Equation 5-11

where,

Y is the wear (inches), and

X is the miles with plow down.

As seen in Figure 5-5, the standard steel wear graph has three residual data points. Of those data points, two are within the standard graph, which are points B and C. The point outside of the acceptable range is blade A. Utilizing the standard graph, the standard error of this data point is -17%. The standard error is negative because the actual value is higher than predicted. Therefore, the blade is wearing more rapidly than the anticipated wear, which indicates that the blade should be laboratory tested as suggested in Chapter 4.

5.3.3 Results

The results of the simulated data in Figures 5-3 through 5-5 are as expected. The carbide articulating blade wears the least over increased mileages, and the steel blade wears the most over increased mileages. The results further highlight the general expectations of the industry. Even as more data are collected, the acceptable ranges will decrease; however, Figures 5-3 through 5-5 regardless of the quantity of data collected, the acceptable blades wear, and mileages will always be a range. The acceptable data will never be a singular data point. This is due to the variability within the product, the conditions it is used in, and the personnel handing the product. Figures 5-3 through 5-5 may be taken advantage of by DOTs to compare a blade that is being tested to a standard graph.

5.4 PROBABILITY OF MILEAGE AND WEAR

The goal of this section is to establish how probable it is to obtain a certain mileage or wear for a plow blade based off past data. Material type and its cost heavily predict its anticipated wear and mileage. Meaning, the mileage of a blade is expected to increase as cost increases. So, the more expensive a blade is the more mileage it is expected to endure. For example, a DOT should not expect a steel blade to withstand the same mileage as a carbide articulating blade. Historically, carbide articulating blades last much longer than steel; therefore, creating probabilities for a DOT will help with reasonable expectations for the blades they are testing.

5.4.1 Statistical Methodology

Section 5.4.1 estimates how probable it is for a blade to obtain a certain mileage or a specific wear in inches for a season. The figures and probabilities in this section are formed through the utilization of section 5.2 and data from Schneider et al 2015 and the Idaho case study. The relevant descriptive data from Schneider et al. 2015 and the Idaho case study may be seen in Table 5-4.

Table 5-4: Probability Descriptive Statistics

		Mileage		Wear(Inches)	
Data Source	Blade Types	Mean	Standard Deviation	Mean	Standard Deviation
Schneider et al. 2015	Carbide	332	460	1.0	0.8
	Carbide Articulating	916	960	0.4	0.3
	Steel	500	550	1.2	1.0
Idaho case study	Carbide Articulating	631	643	0.2	0.2

Note: Schneider et al. 2015 and the Idaho case study data has been summarized.

As seen in Table 5-4, the research team used the averages and standard deviations for mileages and wear in inches. The wear and the mileage for carbide, carbide articulating, and steel is simulated using Monte Carlo simulation 250,000 times, which is within the range to have a high confidence level distribution or a good estimate (Liu 2020). This establishes the standard wear in mileage and the standard wear in inches.

After establishing the standard wear for the three blade types, the research team calculated the probability of obtaining certain mileage or specific wear for each blade during a study. Lognormal distribution is commonly used when data are unable to be less than zero and are positively skewed (Harvey et al. 2020). A plow blade’s wear and mileage will never be negative. It is not possible for a blade to gain material, which would be negative wear, or a blade to obtain negative miles; therefore, utilizing a lognormal distribution is appropriate.

To apply lognormal distribution, the values of wear and mileage need are converted into a natural logarithm value using Equation 5-12.

$$X' = \ln X$$

Equation 5-12

where,

X is the mileage or wear, and

X' is the natural logarithm mileage or wear.

After determining the logarithmic values for the simulated wears and mileages, the averages and standard deviations are calculated.

Equation 5-13 is the probability density function for a lognormal distribution.

$$f(x) = \frac{1}{x} * \frac{1}{\sigma\sqrt{2\pi}}^{-\frac{(\ln x - \mu)^2}{2\sigma^2}}$$

Equation 5-13

where,

x is the value of interest,

σ is the standard deviation, and

μ is the mean.

The probability density function shows the probability of a value being within the range of value, while the area under the probability density curve is the probability.

Equation 5-14 shows the cumulative distribution function.

$$f(x) = \phi(\frac{\ln x}{\sigma})$$

Equation 5-14

where,

ϕ is the error function, $f(x) = \int_{-\infty}^{x} \frac{e^{-x^2/2}}{\sqrt{2\pi}}$, x is the value of interest, and

σ is the standard deviation.

Equation 5-14 establishes the probability of obtaining a certain mileage or wear.

5.4.2 Results

Figures 5-6 through 5-17 display the distribution of the wear and mileages measured on the carbide, carbide articulating, and steel blades studied in Schneider et al 2015.

Figure 5-6 displays the seasonal wear of a carbide blade as a probability density distribution. The x-axis is mileage, and the y-axis is the probability density. Figure 5-7 displays the cumulative probability of achieving a certain mileage on a carbide blade in a study. The x-axis is the mileage, and the y-axis is the probability.

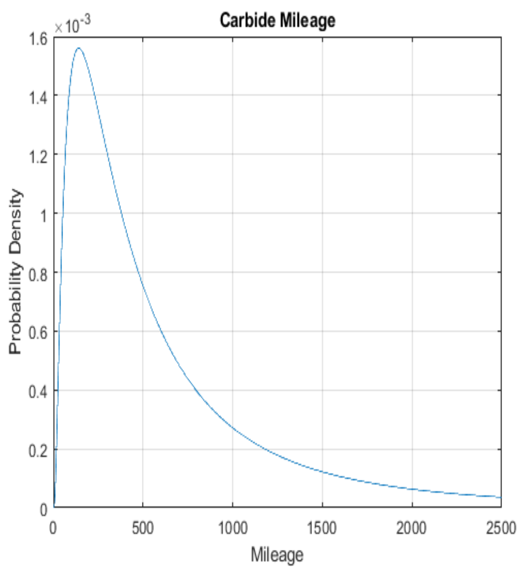

Figure 5-6: Carbide Mileage Probability Density

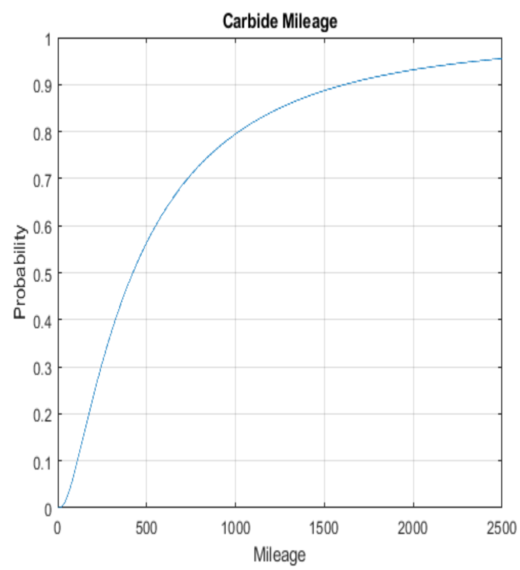

Figure 5-7: Carbide Mileage Cumulative Distribution

Figure 5-6 shows the probability density distribution for carbide mileage, which is calculated using Equation 5-13. The mileage of the carbide blade is skewed towards the 500 miles. This is where the largest density of the probability lies, meaning the majority of the data was measured at 500 miles. The width of the probability density function is relatively narrow which shows the majority of the data is within 500 miles. The spread of the distribution for carbide mileage is small compared to carbide articulating and steel.

Figure 5-7 shows the cumulative mileage distribution of a carbide blade which is calculated using Equation 5-14. This figure is useful to see where the data in the studies lie. The majority of the data are taken from zero (installation) to a maximum of 2,500 miles, which is the largest mileage measured during the study. Figure 5-7 also shows that it is probable for a carbide blade to obtain 2,000 miles, 93%, while achieving above 2,000 miles is only 7%, based off of the data available to the research team.

Figure 5-8 displays the probability density distribution wear of carbide blades. The y-axis is the same as Figure 5-6, but the x-axis is wear in inches. The figure on the right, Figure 5-9, is the cumulative probability distribution. The y-axis is the same as Figure 5-5; however, the x-axis is wear in inches.

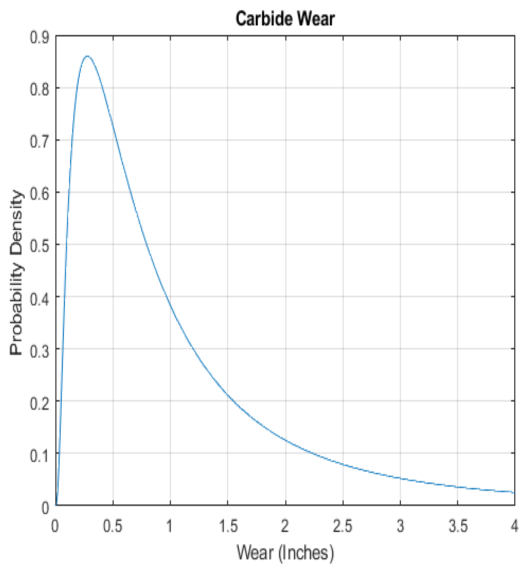

Figure 5-8: Carbide Wear Probability Density Distribution

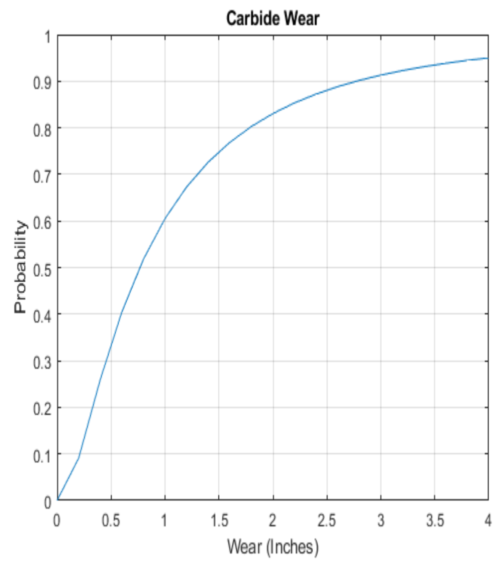

Figure 5-9: Carbide Wear Cumulative Distribution

Figure 5-8 is the probability density distribution for carbide insert wear which uses Equation 5-13. The data are skewed around wear of 0.5 inches which is where most measurements are taken. This shows where the data are skewed, where the most probability lies, i.e. the largest density. The carbide blade has a spread that is larger than carbide articulating but less than steel. Indicating that the variability within the anticipated wear of carbide is greater than carbide articulating but less than that of steel.

Figure 5-9 shows the cumulative probability distribution which is Equation 5-14. The average measurement of wear for carbide blades from the data is 0.97”, which is the location of the most measured wear. Carbide blades wear is less than that of steel but more than that of carbide articulating. The range for wear has a maximum of 4” due to the blades being studied having an average width of 4” or 5”.

Figure 5-10 summarizes the seasonal probability density distribution of mileage for carbide articulating blade. The x-axis and y-axis are the same as Figure 5-6. Figure 5-11 is the cumulative distribution of the mileage for a carbide articulating blade. The x-axis and y-axis are the same as Figure 5-7. The maximum measurement for the y-axis is at 2,500 miles given it is the largest mileage measurement obtained from the study.

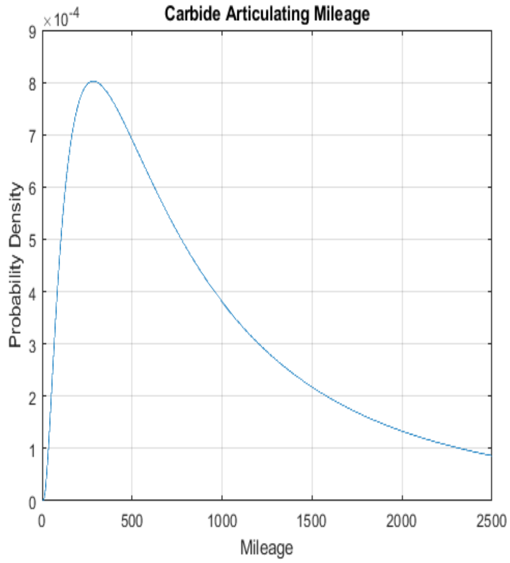

Figure 5-10: Carbide Articulating Mileage Probability Density Distribution

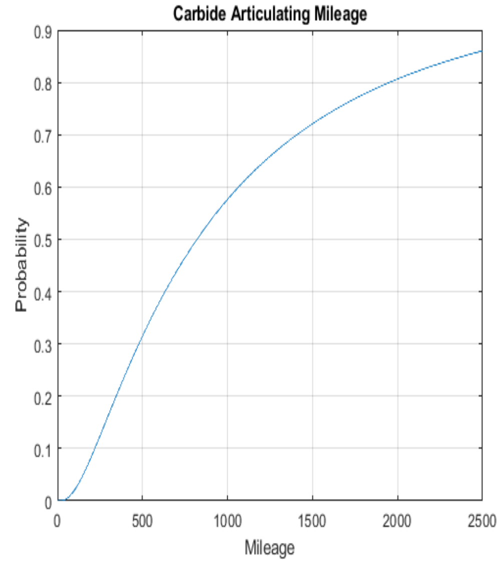

Figure 5-11: Carbide Articulating Mileage Cumulative Distribution

Figure 5-10 is the probability density distribution for carbide articulating wear which was calculated from Equation 5-13. The data are skewed between 500 and 1,000 miles which is where the majority of the mileage measurements were taken. Figure 5-10 shows that the data set has a large variability. The probability density from 2,000 to 2,500 indicates that it is more likely to achieve greater mileages than that of carbide blades, seen in Figure 5-6.

Figure 5-11 is the cumulative distribution of mileage for a carbide articulating blade which is calculated from Equation 5-14. As seen in Figure 5-11, the s-curve is stretched out indicating that data are not condensed in one area. This means that the carbide articulating mileage encompasses larger mileages, which indicates larger mileage measurements were captured on carbide articulating than that of steel or carbide. It is much more probable on a carbide articulating blade to achieve mileages of 2,500 miles, 86%, than that of carbide, 96%. From Figure 5-11, if there is no premature breaking of a blade or abnormal wear, the carbide articulating blade will last the longest mileage compared to carbide or steel.

Figure 5-12 displays the seasonal wear of carbide articulating blade as a probability density distribution. The x-axis and the y-axis are the same as Figure 5-8. Figure 5-13 displays the seasonal wear of carbide articulating blade as a cumulative probability distribution. The x-axis and the y-axis are the same as Figure 5-9.

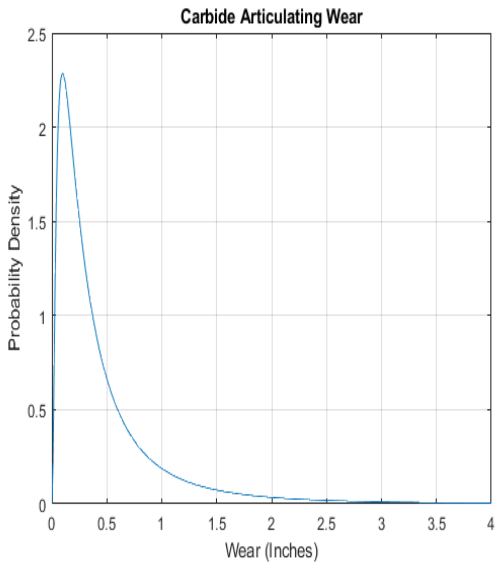

Figure 5-12: Carbide Articulating Wear Probability Density Distribution

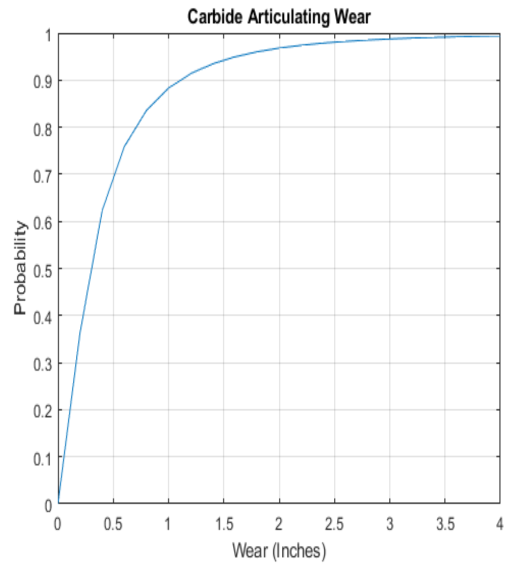

Figure 5-13: Carbide Articulating Wear Cumulative Distribution

Figure 5-12 is the probability density distribution for carbide insert wear which uses Equation 5-13. The width of the probability density curve is not very large indicating that the wear is relatively uniform. This is especially seen when comparing to the carbide blade, which has a spread two times as large as that of carbide articulating, as seen in Figure 5-8. The carbide articulating blade has a maximum wear of 4 inches given that the average width of the blades utilized are between 4" and 5".

Figure 5-13 is the cumulative distribution of mileage for a carbide articulating blade which is calculated from Equation 5-14. Carbide articulating blade has a lower wear than carbide. This is shown by how close the peak of the wear is to zero. This is seen in Figure 5-13 with the probability around 0.37" being 50%, which is where the curve is at the middle of the s-shape. 0.37" is where the majority of the wear measurement locations were taken. Carbide articulating blades wear less inches in a season than either carbide or steel.

Figure 5-14 displays the seasonal probability density distribution mileage of steel blades. The x-axis and y-axis are the same as Figure 5-10. Figure 5-15 displays the seasonal mileage of steel blade as a cumulative probability distribution. The x-axis and the y-axis are the same as Figure 5-11.

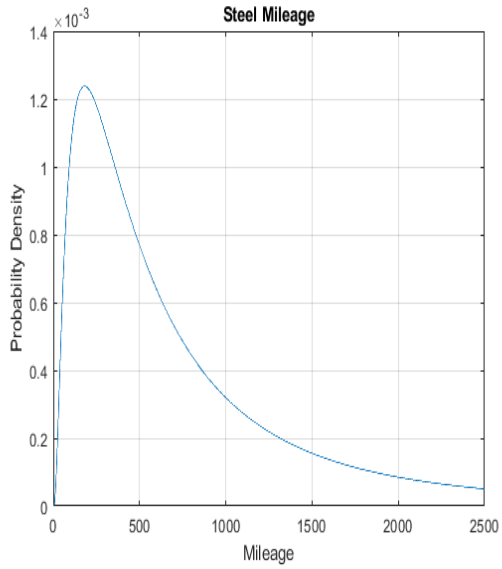

Figure 5-14: Steel Mileage Probability Density Distribution

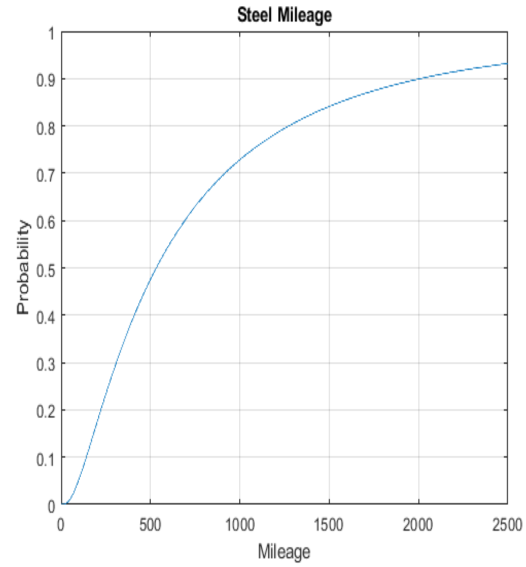

Figure 5-15: Steel Mileage Cumulative Distribution

Figure 5-14 is the probability density distribution for carbide insert wear which uses Equation 5-13. The spread of the distribution is not as large as carbide articulating and is larger than that of carbide. The spread indicates that the variability in steel mileage is larger than carbide but is smaller than that of carbide articulating, which is logical. The range for mileage is limited to 2,500 miles due to the data having a maximum mileage measurement of 2,500.

Figure 5-15 shows the steel mileage cumulative distribution which is calculated from Equation 5-14. The average mileage for steel is the second highest with carbide articulating as the highest and carbide as the lowest. The majority of the mileage measurements for steel is 685 miles and a standard deviation of 575 miles. This graph shows that the studies obtained less mileage on steel blades than a carbide articulating blade. The probability of a steel blade reaching above 2,000 miles is 10%, and the likelihood of a carbide articulating blade to plow above 2,000 miles is 20%. This is given the limited amount of data available.

Figure 5-16 displays the seasonal wear probability density of steel blades. The x-axis and y-axis are the same as Figure 5-12. Figure 5-17 displays the seasonal wear of steel blade as a cumulative probability distribution. The x-axis and the y-axis are the same as Figure 5-15.

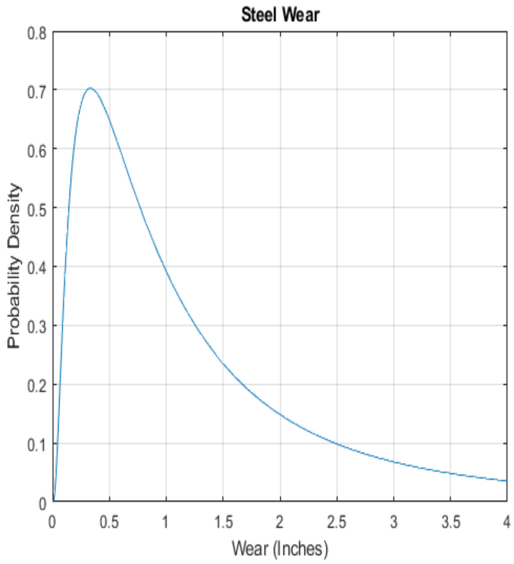

Figure 5-16: Steel Wear Probability Density Distribution

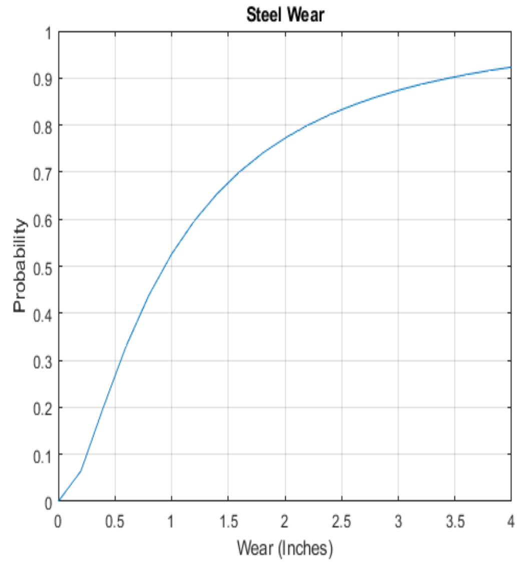

Figure 5-17: Steel Wear Cumulative Distribution

Figure 5-16 is the probability density distribution for steel wear, which is calculated from Equation 5-13. Steel blades wear is the greatest compared to carbide and carbide articulating. The spread of the distribution is also the largest of the three blade types indicating the steel blade has the greatest variability in wear. The range of wear is limited to 4" due to the average width of a blade being studied being 4" or 5".

Figure 5-17 shows the cumulative probability distribution of steel wear which is calculated from Equation 5-14. The average measurement of wear for a steel blade is 1.20", which is seen with the probability of 1.2" of wear being around 50%. The wear measurement of a steel blade is greater than that of a carbide and a carbide articulating blade, in that respective order. For steel blade wear, it is 17% probable to achieve 2.5" or greater of wear, while the probability to achieve 2.5" or greater for carbide is 12% and for carbide articulating is 2%. Therefore, the steel blade wears the most from the data available.

The probability density lognormal graphs and the cumulative distribution graphs show the distribution of wear and mileage for Schneider et al. 2015. Figure 5-6 through 5-17 show the most probable wear and mileage measurements performed in a winter season. The figures do not show the probability of failure; however, they do show that the wear and mileage measurements are skewed towards the beginning of the season, meaning more data obtained at lower mileages and wears compared to more data obtained towards the end of the season.

If a DOT is assessing the likelihood of a blade lasting an entire winter season, calculating the cumulative distribution for failure will assess the probability of achieving a specific mileage, as seen in Equation 5-14. To calculate the cumulative distribution for failure, the research team utilized the wear rates from

Figures 5-3 through 5-5. The rates may be seen in Equations 5-3 through 5-11. These wear rates were used due to the data from Schneider et al. 2015 being front skewed, meaning most of the measurements are located at the beginning of the season rather than the end, and the data set is small and limited; therefore, using the wear rates which were Monte Carlo simulated allow for variation and provide a better estimate for failure. The mileages were obtained from the wear rate by limiting the wear of the blade to 4". As previously discussed, the average width of blades in this study were 4" or 5"; therefore, complete failure would occur at 4". The wear was obtained from limiting the mileage of the blade to the mileage that causes 4" of wear.

Using the cumulative distribution to find the probability, the research team established mileages and wear for failure which is seen in Table 5-5 and 5-6, respectively. Table 5-5 show the probability of failure for mileage. The probability upper limit is at 3,000 miles due to most lane miles maintained by a DOT is less than 3,000, which may be seen in Table 3-6. A small probability indicates that the blade is less likely to fail at the number indicated or less. A higher probability means that the blade is more likely to fail at the number indicated or less.

Table 5-5: Mileage Probability

	Mileage[4, 5]					
Blade Type	**P ≤ 500**	**P ≤ 1,000**	**P ≤ 1,500**	**P ≤ 2,000**	**P ≤ 2,500**	**P ≤ 3,000**
Carbide[1]	27%	36%	42%	47%	50%	66%
Carbide Articulating[2]	18%	24%	29%	32%	34%	37%
Steel[3]	34%	44%	50%	54%	57%	60%

Note: [1] The carbide distribution may be seen in Figure 5-6.
[2] The carbide articulating distribution may be seen in Figure 5-10.
[3] The steel distribution may be seen in Figure 5-14.
[4] The probabilities for the mileages were obtained utilizing the simulated mean and standard deviation with the Equation 5-14.
[5] The data simulated was from Schneider et al. 2015.

As seen in Table 5-5, carbide and steel mileages have a similarly expected failure. Carbide has a probability of failing before 3,000 miles of 66% and steel has a probability of 60%. The carbide articulating blade is able to obtain the most mileage before failure compared to the carbide and steel blade, respectively. This is seen by the probability of failing before 3,000 miles as 37%. Given this percentage, it is less likely for a carbide articulating blade to fail before 3,000 miles compared to carbide and steel, respectively.

The mileages obtained in the Idaho case study for carbide articulating blades is 550.7, 214.2, 256.8, 1,756.1, and 375.3 miles; however, the only blade that failed in Idaho was the blade that obtained 1,756.1. The probability of a carbide articulating blade failing at 1,756.1 miles is 30%. This blade failed before the average mileage of failure, which may be due to bad blade or operator error. It would be recommended to laboratory test the blade.

Table 5-6 shows the probability of failure with a specific wear in inches. The range for wear is limited to 4" due to the width of the blades in the studies being around 4" or 5". A small probability indicates it is less likely to fail at an inch measurement or less; therefore, a large probability indicates it is more likely to fail at an inch measurement or less.

Table 5-6: Wear Probability

	Wear[4]							
Blade	**P ≤ 0.5"**	**P ≤ 1.0"**	**P ≤ 1.5"**	**P ≤ 2.0"**	**P ≤ 2.5"**	**P≤3.0"**	**P≤3.5"**	**P≤4.0"**
Carbide[1]	7%	23%	38%	50%	59%	67%	72%	77%
Carbide Articulating[2]	0%	2.4%	21%	50%	74%	88%	95%	
Steel[3]	0%	6%	27%	50%	69%	81%	89%	94%

Note: [1] The carbide normal distribution may be seen in Figure 5-8.
[2] The carbide articulating normal distribution may be seen in Figure 5-12.
[3] The steel normal distribution may be seen in Figure 5-16.
[4] The probabilities for the mileages were obtained utilizing the simulated mean and standard deviation with the Equation 5-14.

As seen in Table 5-6, carbide articulating blade is likely to obtain a smaller wear for failure, which may be seen as the probability of obtaining less than 3.5" is 95%. The next blade that is likely to obtain a smaller wear for failure is the steel blade, which may be seen as the probability of obtaining less than 3.5" is 89%. Lastly, the carbide blade is likely to obtain a larger wear for failure which has a probability of failure at 3.5" of 72%. The carbide data, however, may be skewed because of all the data sets utilized, carbide has the smallest. To compare data, the research team used the Idaho case study. The only blade to fail in the Idaho case study had an average wear of 0.9" which has a probability of failure of less than 2.4%. This blade should be laboratory tested.

5.4.3 Results

For mileage, the probability of failure for carbide articulating blade is expected to occur at a mileage of greater than 3,000 miles. The probability of failure for wear is likely to occur at a lower inch in carbide articulating than that of carbide and of steel. This is on par with industry expectations. The probability establishes ranges a DOT may expect blades to fall within and shows that the blade types heavily influence the ranges that a blade may wear. Tables 5-5 and 5-6 may be used by a DOT to establish if a blade will fail within a season. Additionally, carbide articulating blades had the smallest variability in wear compared to carbide or steel, as seen in Figure 5-8. This low variability may be due to the limited number of blades available for DOTs. In Table B-1 in Appendix B, the carbide articulating blade had the lowest number of available blades, 9, and vendors, 5. This is the smallest number of blades available compared to carbide and steel. The steel blade has the greatest spread in its wear distribution, as seen in Figure 5-16. This may be due to the amount of steel blades available being larger than that of carbide or carbide articulating. As seen in Table B-3 in Appendix B, the steel blade not only had the largest number of blades, 40, but also the largest number of vendors, 12. This may account for some of the variability in wear as well as the environmental conditions.

5.5 COST BENEFIT

The purpose of the cost benefit section is for DOTs to be able to assess a new blade to see if the blade is a cost-effective purchase or is at least cost neutral. The goal of this section is to create a standard that is both useful currently and in the future.

5.5.1 Descriptive Data

Section 5.4 above assists a DOT in evaluating if a blade is wearing normally or abnormally. This section assesses if a blade is a cost-effective purchase for a DOT. If a blade is worn poorly then the blade will not be cost effective; however, when a blade is performing as expected, then it should be evaluated for cost to see if it is effective for a DOT to implement financially. The descriptive cost statistics for the studies used to create the standard graphs are seen in Table 5-7 and Table 5-8.

Table 5-7: Capital Cost Descriptive Statistics

Capital Cost[1]	Schneider et al. 2015[2]			Idaho Case Study
	Carbide	Carbide Articulating	Steel	Carbide Articulating
Average	$879.08	$3,216.36	$550.02	$2,799.20
Standard Deviation	$100.23	$494.39	$107.95	$584.09

Note: The data utilized was from Schneider et al. 2015 and the Idaho case study.

[1] The capital cost, as seen in Equation 4-3, is influenced by quantity and contractual language.

2 The costs associated with Schneider et al. 2015 have been updated to reflect 2019 pricing utilizing Equation 6-3 and Table 6-2.

Table 5-7 displays the capital cost for Schneider et al. 2015 and the Idaho case study which will be a part of the cost of a plow blade. The research team used the capital costs for carbide and steel from Schneider et al 2015; however, the research team utilized the Idaho case study costs for carbide articulating. This is due to the Idaho case study having costs that reflect the current economic conditions.

The second cost aspect of plow blade is associated with operational costs. Table 5-8 displays the operational costs from Schneider et al. 2015 and the Idaho case study.

Table 5-8: Operation Cost Descriptive Statistics

	Descriptive Statistic	Schneider et al 2015[1]	Idaho case study
Labor Cost	Average	$19.96	$22.00
	Standard Deviation	$3.33	$2.00
Number of People to Change	Average	3	2
	Standard Deviation	0.5	0
Time to Change (hours)	Average	0.7	0.79
	Standard Deviation	0.25	0.45

Note: The data utilized was from Schneider et al 2015 and the Idaho case study.
[1] The costs associated with Schneider et al 2015 has been updated to reflect 2019 pricing utilizing Equation 6-6 and Table 6-3.

Table 5-8 summarizes the cost associated with operational costs. The research team utilized the Idaho case study numbers due to the values being from the current economic conditions.

5.5.2 Statistical Methodology

For a DOT to confirm if a blade is a good or bad purchase, standard graphs should be created in order to formally assess. Cost neutrality is calculated utilizing Equations 4-1 through 4-4. Equation 5-15 and Equation 5-16 are recaps of Equation 4-1 through 4-4 in Chapter 4.

Cost of a blade is the

$$Cost\ (\$) = CC + OC$$

Equation 5-15

where,

CC is the capital cost, and

OC is the operational cost.

The function of operational costs may be seen in Equation 5-16.

$$OC\ (\$) = LR\left(\frac{\$}{hr}\right) * D * N$$

Equation 5-16

where,

LR is the labor rate,

D is the duration of installation, and

N is the number of people needed for installation.

The components in Equation 5-15 and 5-16 are provided by the states participating in the study. To create the standard graphs for cost neutrality, the research team used Monte Carlo simulation. The average mileage, wear (inches), operational costs, and capital costs are simulated 250,000 times to ensure a precise estimate and a high confidence interval (Liu 2020). The simulation is created in Matlab. Monte Carlo simulation allows for the data to be replicated repeatedly to account for variations over time. This simulation accounts for 75% of the data selected at random. The 75% in the standard graphs of Figure 5-1 through 5-3 are different from the 75% in the standard graphs below, as seen in Figure 5-19 through 5-21. A new random number was assigned to the data set. 75% of the largest random numbers selected to create Figure 5-19 through 5-21. The residual 25% is then used to validate the figures.

5.5.3 Standard Graphs

The research team created standard graphs to show when blades are cost neutral to a DOT. These standard graphs follow Equation 4-1. The data are then used to create the standard graphs for cost neutrality.

Standard graphs are created to show if a DOT purchases a blade of a certain cost, how much more or less a blade is expected to wear. The expected wear is seen in Equation 5-17.

$$Y = \frac{CC * IR + OC * ECI}{X} * WR$$

Equation 5-17

where,

X is a cost range from low to high blade cost,

Y is the wear rate in $\frac{inch}{100\ mile}$,

CC is the capital cost of the old blade,

IR is the inflation rate (if the old blade's costs are associated with a different year),

OC is the operational cost of the old blade,

ECI is the employment cost index (if the personnel rates are associated with a different year), and

WR is the wear rate of the old blade.

X has a range of low and high costs which was established from Appendix B. X is the probable range of costs that a blade may cost a DOT. The cost of a steel blade is significantly less than that of a carbide articulating blade; therefore, the ranges for costs for carbide, carbide articulating, and steel are different and vary for each type.

For a DOT to be able to establish cost neutrality, Figure 5-18 is useful.

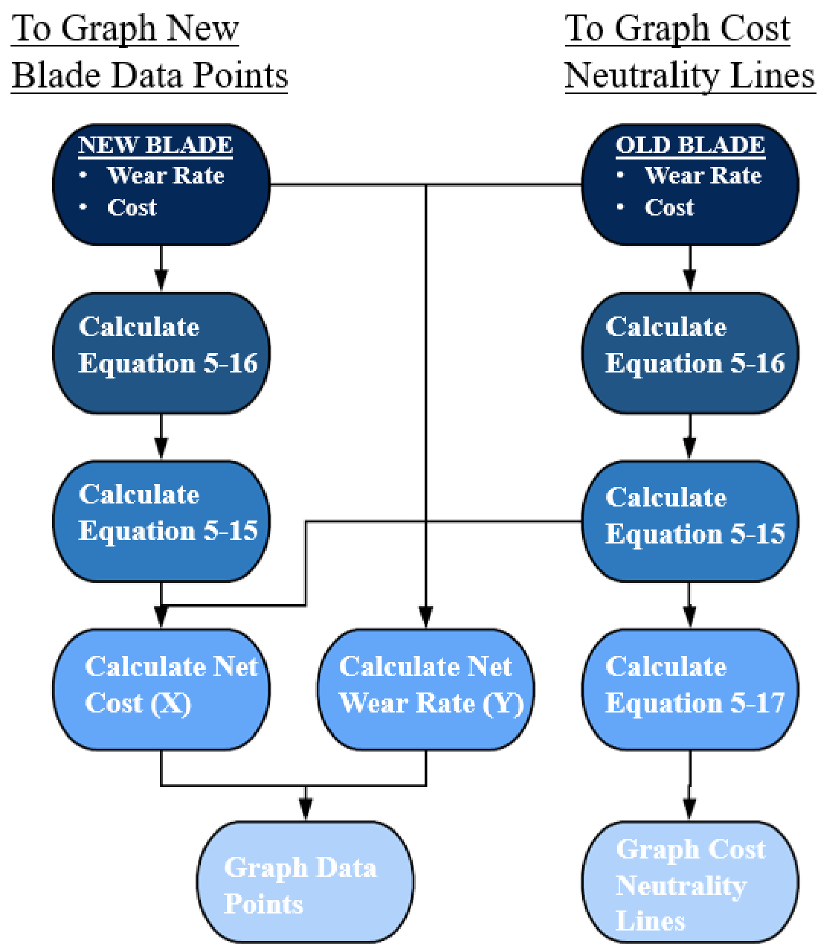

Figure 5-18: Calculating Diagram

Figure 5-18 shows a DOT how to graph an old blade for cost-neutrality line(s) and how to plot a new blade for comparison. A DOT may only have one line for cost-neutrality. Multiple lines for cost neutrality for this report come from the varying wear rates of old blades, as seen in section 5.3.2. If a DOT is comparing a new blade to an old blade within its inventory, it may have one wear rate; therefore, cost neutrality will have one line. If a DOT is comparing a new blade to historic data, from section 5.3.2, the DOT will have multiple lines for cost neutrality due to the wear rates having a standard deviation. To plot two lines for cost neutrality, the wear rates should be the average wear rate and the upper bound wear rate. This is due to the upper bound capturing the faster average wearing blade and the average capturing the common wear rate. The lower bound was not plotted due to it being a part of the “good” zone; therefore, the low bound is captured in the “good” zone. Figures 5-19 through 5-21 were created using Figure 5-18.

Figures 5-19 through 5-21 are based off the purchasing of one blade. Figure 5-19 is based off the standard carbide insert blade. The x-axis is cost difference between a new blade to an old blade. The y-axis is the wear rate in inches per 100 miles. There are two distinct lines which represent the cost neutral blades in units of cost inch per 100 miles. The expected wear and cost are the dotted and dashed lines. When the cost is less than expected, it is in the upper left of the graph, which is where the cost is negative, and the wear rate is positive. This means the cost is less than average and the anticipated wear is more than average. When the cost is more than expected, it is in the bottom right, which is where the cost is positive, and the wear rate is negative. This means the cost is more than expected and the anticipated wear should be less than expected. Therefore, anything between the dotted and dashed line is cost neutral, anything above the dotted and dashed lines are not a cost-effective purchase, and anything below the dotted and dashed lines are a cost-effective purchase.

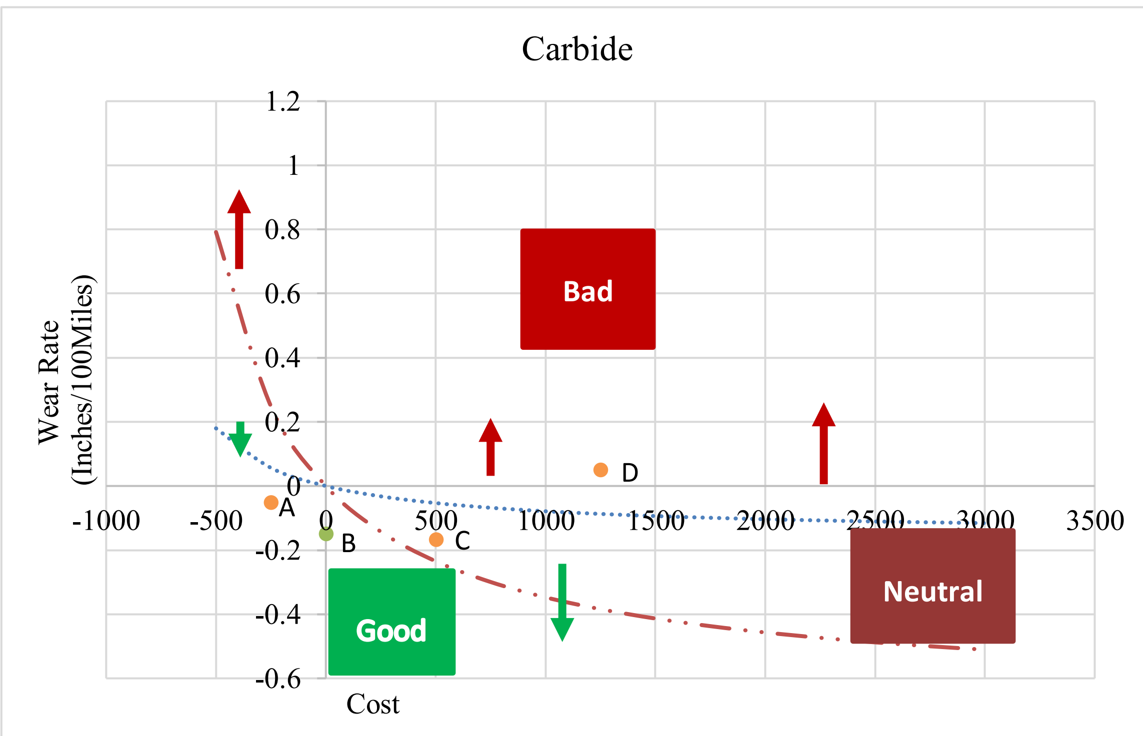

Figure 5-19: Carbide Blade Standard Wear

As seen in Figure 5-19, the x-axis is limited to -$500 to $3,000. This limitation is due to the average cost of a carbide insert blade being $900. The range in the x-axis allows for more expensive blades that historic data may not have captured and cheap blades; however, from the research capturing blade costs in Appendix B, having a blade of less than $400 for carbide insert blades is not possible. Additionally, the ranges for y-axis are estimated with probability to ensure it is possible to achieve the simulated wear rate. The research team used the average failure of the blade as 2,500 miles, as seen in Table 5-5. Using the average failure mileage, the average estimated wear never exceeds the maximum wear of 4”. This means the wear rates simulated are possible to achieve.

An example of how to use this graph is provided below. In this example, the research team provides data as if a DOT has an old blade and would like to compare it to a new blade to establish if the new blade is a cost-effective purchase. To begin, the DOT should look at Figure 5-18 and follow the steps accordingly. The steps followed for the example are seen in Table 5-9.

Table 5-9: Example One

Detailed Steps[1]	New Blade	Old Blade
Blade Details	\$1,130 $0.01 \frac{inches}{100\ miles}$	\$880 $0.015 \frac{inches}{100\ miles}$
Equation 5-16	\$35	\$35
Equation 5-15	\$1,165	\$915
Equation 5-17	NA	X[2] = 250, Y[3] = between -0.03 and -0.14 $\frac{inches}{100\ miles}$
Net Cost	X= + \$250 Y = - 0.005 $\frac{inches}{100\ miles}$	NA
Graph	Graph Data Point	Graph Cost Neutrality lines

Note: [1] The steps detailed are from Figure 5-18.
[2] The range for a carbide blade is from -\$500 to \$3,000
[3] The range for wear in the example comes from section 5.3.2.

The old blade wears at a rate of 0.015 inches/100 miles and has a capital cost of \$880. The DOT also calculated the overall cost of the blade using Equation 5-15 and 5-16. They found the cost to be \$915. Now to plot the blade the DOT utilized Equation 5-17. This creates the lines of cost neutrality for the new blade. The next step is to compare the new blade. The new blade is worn at a rate of 0.01 inches/100 miles and has an overall cost of \$1,165. To compare the blades, the DOT needs to calculate the net cost of the new blade, which is $\$1{,}165 - \$915 = \$250$. Therefore, the x-axis data point is \$250. Now to calculate the y-axis data point, the net wear needs to be calculated, which is $0.01 - 0.015 = -0.005 \frac{inches}{100\ Miles}$. Now looking at Figure 5-19, at \$250, the cost neutral wear rates are between -0.03 in/100 miles and -0.14 in/100 miles; therefore, the new blade is outside of the range of cost neutrality and in the “bad” zone. This new blade is not a cost-effective purchase.

After discussing the process of how to create the cost neutrality graphs, the research team assessed the residual data not utilized to create the graphs and example data points to show a blade in the good zone, bad zone, and the cost neutral zone. Beginning with the residual data point, as seen in Figure 5-19, the residual data point is gray and labeled “B” is below the neutral line for carbide. Therefore, this blade is a cost-effective purchase for a DOT. The blade is the same cost as the standard blade; however, it wore less than the standard meaning it is cost effective.

There are three examples of blades “tested in the field”. The research team created these example points to further assist in understanding how to use Figure 5-19. The example blades are green and labeled “A”, “C”, and “D”. The first example point is “A” and is in the “good” zone indicating that this blade wore better than standard. The actual value of this point is a blade that costs $671.41 and wore at a rate of 0.1 in/100 miles. The second example point is “C” and is within the bounds of the standard wear rate meaning it is cost neutral. The actual cost of the data point is $921.41 and wears at a rate of 0.0016 inches/100 miles. The third example point is “D” and is greater than the standard which means this blade would not be a cost-effective purchase for a DOT to make. This blade not only cost more than normal but also wore more than normal. The actual cost of the blade is $2,171 and wears at a rate of 0.2 inches/100 miles.

The next blade type that the standard graphs are created for is a carbide articulating blade as seen in Figure 5-20. The x-axis and the y-axis are the same as Figure 5-19. The lines in the graph for neutrality are represented the same as Figure 5-19. The difference in width between the two groups are the standard deviation of the two blade types are different. There is less of a standard deviation for carbide articulating blades which is why the band for neutrality is less wide.

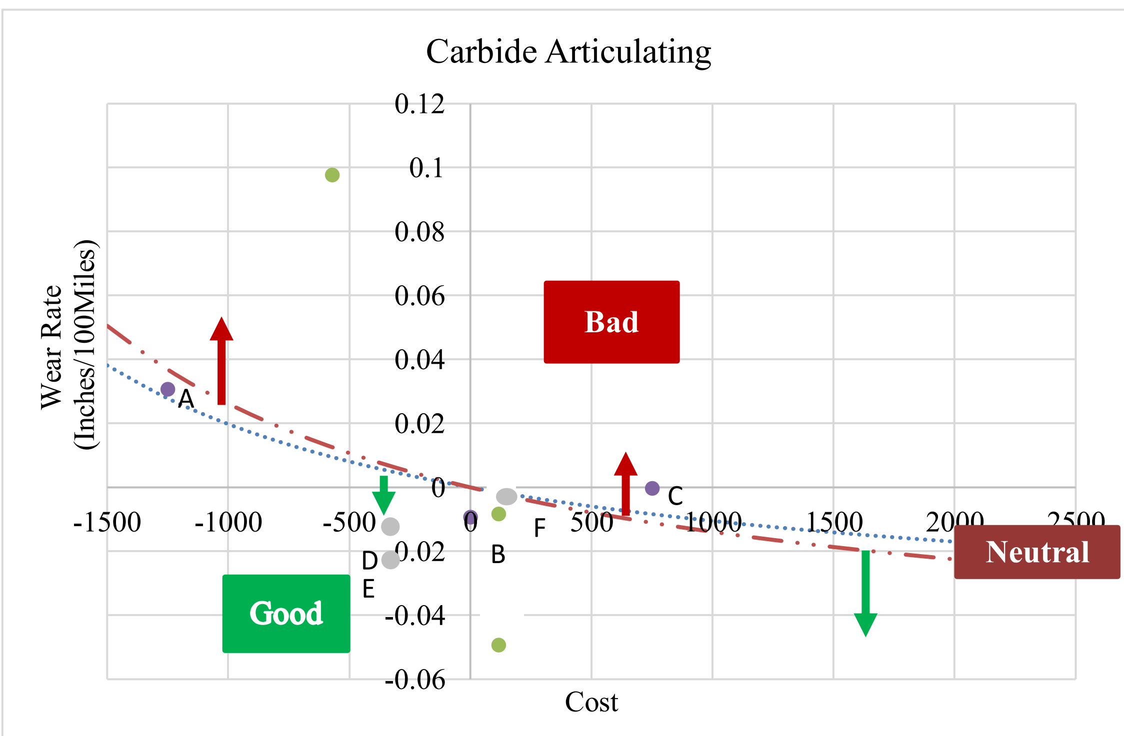

Figure 5-20: Carbide Articulating Standard Wear

The range of the x-axis is from -$1,500 to $2,500, as seen in Figure 5-20. Carbide articulating blade prices are much larger than that of carbide or steel, Figure 5-19 and 5-21 respectively. The standard price of a carbide articulating blade is $2700 which is three times as much as a carbide blade and five times as much as a steel blade. This high capital cost is what allows for a larger quantity of negative x value range. The lowest costing carbide articulating blade the research team found to be $1,800. Therefore, the low range ends at -$1,500. Additionally, the ranges for y-axis are estimated with probability to ensure it is possible to achieve the simulated wear rate. The research team used the maximum mileage on the blade as 4,000 miles, given it is the average failure for carbide blades. The wear of the blade never exceeds the maximum wear in inches of 4”. This means the wear rates simulated are possible to achieve.

There are three data points as examples on the graph, they are yellow and are at locations “A”, “B”, and “C”. The first example blade is at “A” and is between the dotted and dashed lines; therefore, this blade is considered cost neutral. The blades actual cost is $2,255 and wears at a rate of 0.09 inches/100 miles. The second example point was better than expected. This data point is at “B”; therefore, this data point is considered “good”, meaning this blade is a cost-effective purchase for a DOT. It wore better than average. This data point is on the y-axis meaning it costs the same as a regular blade, which is $3,255. The difference is that this blade wore better which is a rate of 0.05 inches per 100 miles. The third example point was worse than expected. This data point is at “C”; therefore, this data point is considered “bad”, meaning this blade is not a cost-effective purchase for a DOT. They wore worse than average. This data plotted at $750, which means the blade costs $4,005, and wore at a rate of 0.059 inches/100 miles.

There are three data points from Schneider et al. 2015, which are gray and labeled as “D”, “E”, and “F”. Blade D and E are the same price; however, blade E wore better than blade D by 0.01 inches/100 miles. All three blades wore better than anticipated and would be recommended for laboratory testing.

A steel blade also created the standard graph. This is seen in Figure 5-21. The x-axis and y-axis are the same as it is noted in Figure 5-19 and 5-20. The two distinct lines in Figure 5-21 represent the cost neutrality for steel blades.

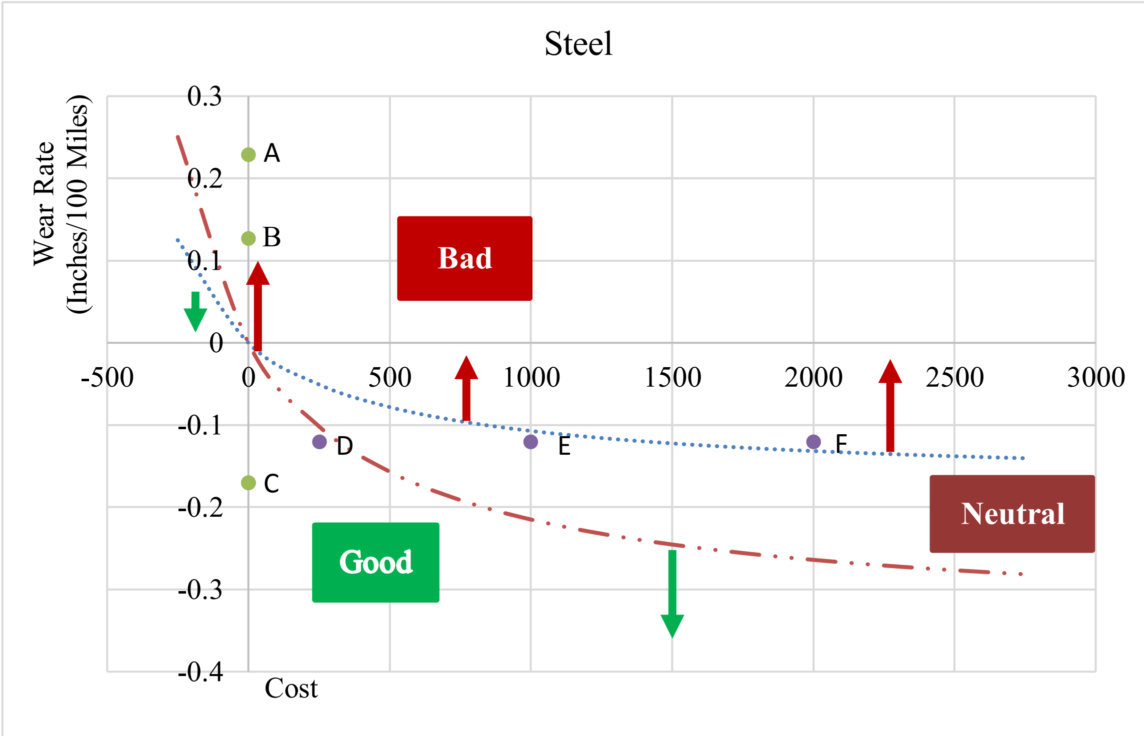

Figure 5-21: Steel Blade Standard Wear

The ranges in the x-axis are from -\$250 to \$2,500. The lower limit is due to the cost of a steel blade being so small, anything less than \$250 is not possible to achieve for a steel blade. The upper limit of \$2,500 is due to the research team not finding a steel blade that exceeds this cost. Therefore, the limits are due to what the research team has found in the current blade prices. Additionally, the ranges for y are estimated with probability to ensure it is possible to achieve the simulated wear rate. The research team used the average failure mileage on a blade as 1,500 miles, given it is the average failure mileage for steel, as seen in Table 5-5. Using the average mileage as the maximum, the wear of the blade never exceeds the maximum wear in inches of 4”. This means the wear rates simulated are possible to achieve.

As shown in Figure 5-21, the residual 25% data points of steel are plotted and are gray and labeled as “A”, “B”, and “C”. These blades are taken from the same data set which is why all are plotted vertically on the y-axis. The y-axis is the standard price of the blade. The wear rate of the plotted data points varies by 0.5 inches/100 miles. Three of the data points are above the x-axis and above the orange standard line which indicates that these blades all wear abnormally and wear faster than anticipated. The data points that are below cost the same; however, they are wearing slower than normal.

There are three example data points on Figure 5-21. These data points are yellow and are labeled as “D”, “E”. and “F”. The example blades are all worn at the same rate; however, they vary in price. Blades “D”, “E”, and “F” are considered cost-effective, cost-neutral, and not cost-effective purchases, respectively.

If a DOT is attempting to switch blade types from one blade type to another, the DOT should create the standard graph based off the old blade type and plot the new blade type. This is necessary to do to calculated cost neutrality. Though the blades are not the same material type, the variables to plot are the same; therefore, placing two different blade types on the same plot is acceptable.

5.5.4 Results

Figure 5-19 through 5-21 are the standard graphs for carbide, carbide articulating, and steel. These graphs may be replicated by DOTs to establish if a blade is a cost neutral purchase. The steel blade has the largest bound for cost neutrality, as seen in Figure 5-21. This is due to steel having the largest variability which is seen in Figure 5-5 and 5-17. Steel also allows for the greatest wear compared to carbide and carbide articulating. Additionally, the carbide articulating blade has the smallest bound for neutrality compared to carbide and steel, as seen in Figure 5-20. The carbide articulating blade has the smallest variability which is seen.

CHAPTER 6: IMPLEMENTATION OF BLADE TESTING

These are three main reasons for recommending data warehousing. First the database will provide blade data in one centralized location. This location will be comprehensive and searchable for DOTs to find blades that they are interested in testing and past research studies conducted. Being able to search previous studies will allow DOTs to find not only blade types but also regions, years, and a DOT size that reflects similar conditions.

The second purpose of data warehousing would be to educate DOTs. Data warehousing will help DOTs with guidelines and show standard methods for testing blades. The data warehousing site will provide a frequently asked questions portion where DOTs may fix faults with blades, enhance training mechanisms, or provide additional resources. Vendors of plow blades may have a forum to help improve blade discussions and education. This will allow peer exchange with respect to how they feel the blade should be optimally tested.

The last purpose of data warehousing will provide research opportunities for DOTs. Eventually DOTs have the potential to specify previous studies due to DOT size, lane miles, average winter temperature, average snowfall, and roadway material. This will allow for easy comparisons if a DOT is financially unable to test their own blades. This site will build to a point where testing may not be necessary because the research compiled is statistically significant; however, if DOTs want to test, it will further add data to solidify results and help ensure the database is up to date. In addition to being able to search the website for DOT and environmental conditions, the site could also be used to search for blade type and blade name. This will allow DOTs to see if a similar DOT has conducted a blade test and their results. DOTS will also be able to compare results of tests due to the testing protocols being consistent. When testing is the same, it allows for direct comparisons. This will further help validate the results of the studies and be able to provide definitive results. Overtime, data collection will transform from needing information to randomly testing for information. This is due to the samples over time becoming large enough to make definitive statements about the blade. After statistical significance is obtained, testing will become random and less frequent. Sampling over time may be seen in Figure 6-1 below.

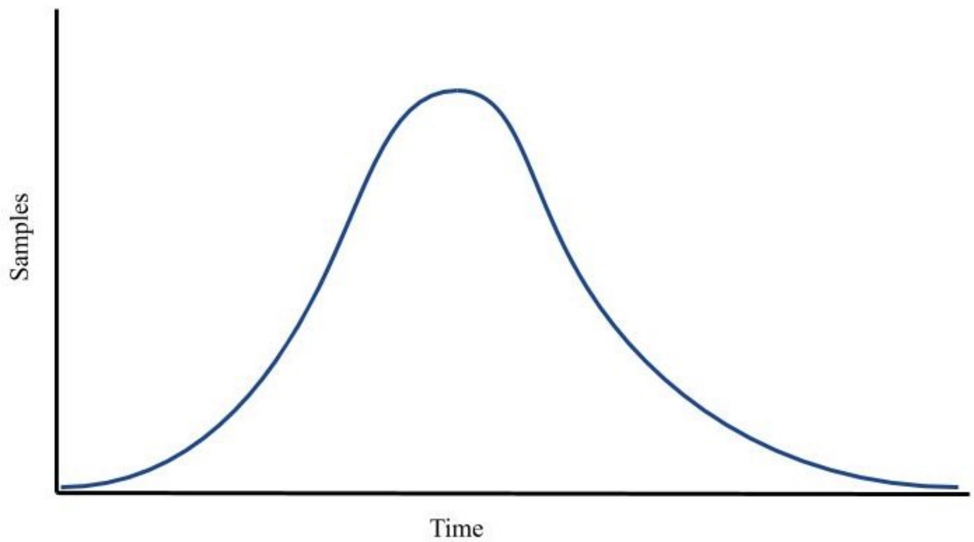

Figure 6-1: Samples over time

As seen in Figure 6-1, initially, sampling will build gradually until it hits a peak, this may be when the data hits a point of statistical significance. After the peak is arrived, the samples tested will decline rapidly.

The last benefit of data warehousing will be a DOTs ability to modify plow blade specifications. As seen in Figure 4-13, lab testing will provide specifications on high and low performance blades allowing DOTs to decipher what specifications are important for testing and what ranges are preferred. For example, from lab testing a DOT may find testing rubber for ultimate elongation is not necessary because all rubber for plow blades has the same elongations so it does not affect high and low performance; therefore, this modification will save DOTs money while testing. This is only possible through testing overtime. Additionally, vendors should be able to comment on the tests being conducted. If a vendor feels a test is inappropriate or not accurate for a product, a vendor should be able to dispute and redirect to a new test.

6.1 POTENTIAL DOWNFALLS

According to Sen et al., 2012, an important failure that occurs in data warehousing is poor data quality. To negate poor data input, the formal testing methods recommended in Chapter 4 should be followed. Utilizing the same testing methods and Clear Roads review should provide quality data if followed appropriately.

6.2 IMPLEMENTATION

The purpose of this section is to assist DOTs in implementing the standard testing protocols for field-testing, lab-testing, and cost-neutrality assessment into a data warehouse.

Field-testing is recommended to be conducted in either large-scale or small-scale. This is described in section 4.3. A DOT should consider the timeframe of testing to be able to procure the blades needed to conduct the study. Depending on how long a DOTs procurement period takes, a DOT should plan accordingly so that blades arrive before the winter season commences. However, if a DOT is attempting to track a blade that is already in its inventory, then the procurement process may be disregarded. After a season of field-testing and using the appropriate data sheets provided in Appendix C, a DOT should utilize Figures 5-3 through 5-5 to establish if the wear is normal or abnormal. These figures may be updated once more data has been collected. Figures 5-6 through 5-17 may be used if a DOT would like to assess the probability of achieving a certain mileage or wear in a season. After assessing a blade for abnormal or normal wear, a DOT should select blades for laboratory testing.

These blades selected for lab testing, as discussed in section 4.7.10.2, should be blades that either perform poorly in the field, perform well in the field, or are randomly chosen for testing. As discussed, in section 4.7.9, the lab testing is dependent on the blade type, the number of tests, and the laboratory selected to test the blades. If a blade is more than one material type, like a carbide articulating blade, then the number of tests increases which also increases the time needed to test the materials. Testing of plow blades is recommended to be conducted at the end of a winter season due to the testing methods being destructive for blade types of more than one material.

After conducting testing, using the forum recommended in Table 6-1, a DOT will be able to load information into the database which will be uploaded to the database. After the data warehousing site has been updated, a DOT will be able to utilize the cost-neutrality assessment of the blades.

6.3 DATA UPLOADING

The research team is recommending the data warehousing be implemented onto Clear Roads website. Below Table 6-1 shows the recommended method for data submittal to the data warehousing site.

Table 6-1: Plow Blade Data Warehousing Submittal

Prompt[1]	Response	Response
State and County		
Name		
Date		
Blade(s) Number Tested		
Type of Blade(s) Tested		
Name of Blade(s) and Vendor Name(s)		
How much did the blade(s) cost?		
Average Weather Temperature and Snowfall during testing		
Road Types Plowed over		
Lab Testing[2]		
Was lab testing conducted?	Yes	No
If yes, what lab conducted testing?		
If yes, are they ISO/EIC 17025 certified?	Yes	No
How many blades were tested?		
How long did results take?[3]		
How much did lab testing cost?[4]		

Reasoning for lab testing	High Performance	Low Performance
Braze		
	Ranges Expected	Ranges Achieved
Braze Composition		
Shear Strength		
Carbide		
	Ranges Expected	Ranges Achieved
Tungsten Carbide Specific Weight		
Cobalt Binder Specific Weight		
Hardness Range		
Transverse Rupture Strength		
Density		
Porosity		
Grain Size		
Rubber		
	Ranges Expected	Ranges Achieved
Ultimate Elongation 100% Modulus		
Tensile strength		
Shore a durometer		
Tear strength		
Compression Set		
Low temperature brittleness		
Steel		
	Ranges Expected	Ranges Achieved
Rockwell Hardness		
Brinell Hardness		
Material Composition		
Field Testing[5]		
Number of Trucks Used		
Miles Plowed		
Operator Review[6]		
Installation Review[7]		
Measurement Sheets[8]		
Percent Concrete/Asphalt[9]		
Bridge Joints Encountered[9]		
Average Mechanic Wage		

Note:[1] Information in this section will allow data to be searchable by weather location, mileage

[2] Lab testing is described in section 4.7.

[3] Establishing a duration will eventually allow DOTs to properly estimate how much time to allot pre- or post-field testing.

[4] Cost of lab testing is important to determine because DOTs have a limited budget

[5] Field testing should be conducted as detailed in section 4.3.

[6] Operator review should be filled out as described in section 4.3.1.4 and seen in Appendix C. Operator review documentation should be uploaded into the database.

[7] Installation review should be filled out as described in section 4.3.1.4 and seen in Appendix C. Installation review documentation should be uploaded into the database.
[8] Measurement sheets should be filled out as described in section 4.3.1.4 and seen in Appendix C. Measurement sheets should be uploaded into the database.
[9] Percent concrete/asphalt and bridge joints encountered should be obtained utilizing GPS/AVL within the trucks and ArcGIS.

The first section in Table 6-1 with the heading prompt details the general location information. This information may be utilized for DOTs who would like to research tests conducted in similar locations based off weather conditions or road conditions. Additionally, this section may be utilized by DOTs who would like to test the same blade. The next section in Table 6-1 is lab testing. The information in this section is important for clarity on qualifications of the lab conducting testing. This section explains what is being tested, duration and cost of testing, and reasons for testing. Below the lab testing are the specific tests for the components within plow blades. The test descriptions and reasonings are discussed in section 4.7. The last section is field testing. Field testing as seen in Figure 4-13 may be conducted formally or informally. Formal field testing involves the standard test protocol as described in section 4.3 with large-scale and small-scale field testing. Informal field testing involves visual inspection and general concerns from personnel.

The research team recommends data warehousing be a part of the Clear Roads website. There are multiple reasons for this recommendation:

1. An established hub for winter maintenance research,
2. A recognized site for DOT research, and
3. Currently offer winter maintenance recommendations/training.

Due to Clear Roads recognition and utilization amongst DOTs, the research team feels it is the best option to house plow blade data. The Clear Roads website already houses numerous research studies conducted on winter maintenance equipment and operations. Additionally, Clear Roads already provides recommendations for DOT training.

6.4 ECONOMICS

After implementing data warehousing, the figures created in Chapter 5 will become outdated and will need to be updated to reflect not only the new data that may be added to the model but also the new costs and pay scale for the year that testing has occurred.

For a DOT to implement the standard graphs in section 5.4, the cost needs to update to current economic conditions. To update the costs associated with plow blades, DOTs must include calculation for inflation rates and the economic consumer index. The following is an example of a how a DOT may update for future calculations. This will be done by utilizing the CPI, inflation rate, purchasing power, ECI, and wage increase. The CPI, inflation rate, and purchasing power adjust the cost of the plow blade to current economic conditions, while ECI and wage increase adjust the wage of the workers to current economic conditions.

To use past data and predict future capital cost, the US inflation rate should be included in calculating costs. Below in Table 6-2, the average consumer price index for the past ten years is represented. The past ten years will be used to predict what the next ten years consumer price index will be.

Table 6-2: Yearly Average CPI

Date	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
CPI	214	218	224	229	232	236	237	240	245	251	255

Note: Data was obtained from CPI 2020.

As seen in Table 6-2, the consumer price index has been increasing over the past ten years. The consumer price index is used to calculate the inflation rate. Calculating the inflation rate from a historic year to a new year is calculated utilizing Equation 6-1.

$$Inflation\ Rate\ (\%) = \frac{CPI_{New} - CPI_{OLD}}{CPI_{OLD}} * 100$$

Equation 6-1

where,

CPI_{NEW} is the CPI for the latest year, and

CPI_{OLD} is the CPI for the previous year.

In order to predict the CPI for a year if the CPI is not available use Equation 6-2.

$$CPI_{Predicted} = TI_{10} * CPI_{OLD}$$

Equation 6-2

where,

$CPI_{Predicted}$ is the predicted CPI,

TI_{10} is the total inflation for the last 10 years, and

CPI_{Old} is the CPI data being utilized to predict the next 10 years.

The inflation rate is not a complete indicator of a value. The inflation rate indicates the decreasing in purchasing power of a dollar. Therefore, calculating purchasing power from a previous study to the latest data is the best way to establish how much it would cost to purchase an item today. CPI is used for the years to find the purchasing power of a dollar. CPI to find the power of a dollar was used to change the values of capital cost from an old date to a more recent date. Purchasing power is seen in Equation 6-3.

$$Purchasing\ Power = \frac{CPI_{New}}{CPI_{OLD}}$$

Equation 6-3

where,

CPI_{NEW} is the CPI for the latest year, and

CPI_{OLD} is the CPI for the previous year.

After calculating the purchasing power from Equation 6-3, a DOT should then multiply the purchasing power by the old blade data to reflect the current economic conditions.

To adjust personnel's hourly wage, a DOT should utilize the employment cost index. The average ECI for state and government workers is summarized for the past ten years in Table 6-3.

Table 6-3: Average ECI for State and Government Workers

Date	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
ECI	113	115	117	119	121	124	127	130	133	136	140
Note: Data was obtained from ECI 2020											

Table 6-3 displays the ECI for state and government workers. An ECI from the old data set and the new data set should be selected to adjust the wage. Equation 6-1 is utilized to calculate the wage rate increase.

$$Wage\ Rate\ (\%) = \frac{ECI_{New} - ECI_{OLD}}{ECI_{OLD}} * 100$$

Equation 6-4

where,

ECI_{NEW} is the ECI for the latest year, and

ECI_{OLD} is the ECI for the previous year.

To alter the wage rate from old data to current economic conditions, Equation 6-4 needs to be calculated. If the year of the new study does not have current ECI ratings available, the research team recommends that the DOT predicts the values using Equation 6-5.

$$ECI_{Predicted} = TI_{10} * ECI_{OLD}$$

Equations 6-5

where,

$ECI_{Predicted}$ is the predicted ECI,

TI_{10} is the total wage for the last 10 years, and

ECI_{Old} is the ECI data being utilized to predict the next 10 years.

The wage rate shows how much the ECI has changed over time; however, similar to the inflation rate and purchasing power, the wage increase needs to be calculated. The wage increase establishes the variation between the two data sets and is to be used to adjust the old cost to reflect the current economic conditions. The wage increase is calculated from the ECI with Equation 6-6.

$$Wage\ Increase = \frac{ECI_{New}}{ECI_{Old}}$$

Equation 6-6

where,

ECI_{NEW} is the most recent year data, and

ECI_{OLD} is the later year data that was being compared.

Multiplying the wage increase established in Equation 6-6 by the old wage of the worker will correct the old wage to current economic conditions.

To create the standard cost graphs, a DOT needs to convert the costs associated with plow blade and the pay rates for workers. After establishing the current conditions, a DOT will be able to implement the old blade data set into the cost benefit figures and assess if a blade is cost neutral or not.

CHAPTER 7: CONCLUSION

The goal of this project is to help DOTs reduce their costs associated with plow blades. To achieve this goal, the research team set four objectives:

1. Develop a standard field-testing protocol to determine how a blade is wearing,
2. Develop a standard lab-testing protocol to establish if a blade's properties are as expected,
3. Develop a standard protocol to assess if a blade is wearing normally or abnormally,
4. Present a method that incorporates current and future blade data into a comprehensive blade research warehouse.

The first and second objectives are met in Chapter 4, the third objective is established in Chapter 5, and the fourth objective was met in Chapter 6 of this report.

7.1 STANDARD TESTING PROTOCOLS

The field-testing protocol was created to establish standard testing conditions. This allows for easy replications as well as direct comparisons to be made. DOTs may field test utilizing small- or large-scale field environments. The research team recommends a DOT selection of blades for testing be based off current blade inventory, financial capabilities, and current vendor contracts. The trucks utilized during testing should have GPS/AVL capabilities with plow up/down capabilities. In addition to mileage being captured, the physical wear of the blade is recommended to be tracked using the measurement form seen in Figure C-1. The installation duration and personnel quantity should be captured, using the form shown in Figure C-2. There is also an incident report that may be filled out, see Table C-3 in case abrupt damage occurs to a blade.

The lab testing protocol recommends testing for each material commonly in plow blades. As discussed in Chapter 2, plow blades require a certain hardness, toughness, and strength for the blade to resist wear, fracture, and deformation. The specific properties tested of a material indicate a blade's resistance to wear, fracture, and deformation. The research team also established a tier system for testing. If possible, testing all the properties listed is recommended; however, if that is not possible, the research team recommends testing tier one of the materials. The tier system suggests testing based off predictors and costs. The first technicality is predictors which is the chemical or physical attribute being tested indicates poor qualities of other characteristics. The research team recommends tests that are less expensive in a lower tier and more expensive in a higher tier to alleviate some of the financial strain lab testing may add,

The laboratory testing methods recommended are ASTM standards. A laboratory survey was conducted to ensure the tests recommended are the most appropriate and applicable for not only the material but also the specific property desired. The ranges for properties to be tested are from vendor specification sheets and NASPO 2012. This section provides DOTs with the ability to lab test blades and understand specific properties they are seeking. Table 4-15 summarizes the NASPO 2012 contract and four different vendor's specification sheets. Table 4-15 was utilized for DOTs to have a starting point for laboratory testing; however, it is possible for DOTs to provide their own preferential ranges.

The three identified standardized abrasive wear tests (ASTM G75-15, ASTM B611-13, and ASTM G105) are likely the best possible standards to assess abrasive wear. But unfortunately, none of the testing apparatus specified in these standards allow testing standard 2-feet long plow blade elements. An exploratory lab study using a high-speed diamond saw gave promising results, but the methodology needs further development. Suggestions for improvements are discussed.

In order to accomplish preferential ranges, integration of lab and field testing is discussed below in terms of formally testing and informally testing, which is seen in Figure 4-13. A DOT may formally test blades for field testing, which is large-scale or small-scale field testing recommended. Informal testing is an option for a DOT who would like to test but does not have the time or financial ability for a full-scale field test. Statistically selecting blades is not probable for DOTs to conduct. It is a large quantity which will be a financial burden on a DOT which already has limited funds; therefore, the research team recommends testing blades based off failure-based testing, random seasonal testing, and success-based testing. Informal testing for a DOT is conducted by visual inspection or general concerns. Visual inspections should be done to see if blades are broken and worn unevenly. If the visual inspection indicates poor quality due to a bad blade, it is suggested to send the blade in for laboratory testing. The second informal testing method is general concerns which encompasses overall opinion and mileage/wear. Overall opinion may be monitored based off operator comments or mechanics comments which should work in conjunction with mileage/wear. After conducting either formal or informal field testing, a DOT should lab test high performing and low performing blades. Lab testing high performing and low performing blades will establish if a blade is a bad blade and will allow a DOT to establish its own preferred material ranges.

7.2 STANDARDIZATION OF RESULTS

The research team created standard graphs for DOTs to be able to assess mileage, wear, and cost for points of neutrality. The research team utilized data from Schneider et al. 2015 and the Idaho case study to create simulated models for DOT use. Figures 5-3 through 5-5 will provide DOTs with a standard on wear/mile to see if a blade is wearing normally or abnormally quantitively. Figures 5-3 through 5-5 establish that carbide articulating blades wear the least per mile, while steel wears the most per mile. In addition to DOTs being able to establish if a blade is wearing normally or abnormally, the research team determined what mileage or wear is possible to obtain.

Section 5.4 establishes the probability of mileage and wear that may be achieved before failure. This allows DOT to have an idea of how to expect a blade to perform in a season/ how long the blade may last in a season. The three blade types assessed are carbide, carbide articulating, and steel. Carbide blades are expected to achieve an average of 2,500 miles before failure, as seen in Table 5-5. Carbide articulating expected achieve an average of 4,000 miles before failure. Steel blades are expected to achieve an average mileage of 1,500 miles before failure, as seen in Figure 5-5. After establishing probability, the research team created graphs that DOTs may use to assess if a blade was at least a cost neutral purchase.

Section 5.5 creates equations and graphs for DOTs to utilize to create standard graphs for cost comparisons. This provides DOTs with an actual quantitative model to compare previous blade to a new blade. The Figures are 5-19 through 5-21.

7.3 DATA WAREHOUSING

There are three main reasons for recommending data warehousing. Having an increased amount of data will create higher quality graphs, will create better performance for testing and aid in rationale for new data. The data warehouse should be comprehensive and searchable for DOTs to find blades that they are interested in testing and past research studies conducted. The second purpose of data warehousing would be to educate DOTs. Data warehousing will help DOTs have guidelines and show standard methods for testing blades. The last purpose of data warehousing will provide research opportunity to DOTs. Eventually DOTs have the potential to specify previous studies due to DOT size, lane miles, average winter temperature, average snowfall, and roadway material. This will allow for easy comparisons if a DOT is financially unable to test blades. The potential benefits of data warehousing is one central location for plow blade data, consistent testing practices, potentially a large data bank for blade data, and modify plow blade specification. Over time, less data collection will be needed because variability will become so small that testing will be a want, not a need. Data warehousing may also utilize data from previous years and adjust to whatever the current economic conditions. The methodologies created in this study help provide DOTs with a tool for standard field and laboratory testing.

7.4 SUMMARY

This study provides DOTs with tools for assessing the wear of plow blades and establish quantitatively if the blade is cost-effective or at least cost neutral. This study provides DOTs with the tools to conduct their own testing. In addition to providing testing methods, it also allows for a DOT to select testing based off its financial abilities. Additionally, the study allows DOTs to assess their blades for normal and abnormal performance as well as assess if the blade is a financially viable purchase or not. The last benefit of this study is the suggestion for implementing data warehousing which will allow for DOTs access a large amount of data which will decrease the cost to a specific DOT to have statistically significant results, make definitive standard graphs for blades, and allow for future blades to be easily tested and compared to past blades.

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APPENDIX A:
STATE AND MUNICPALITY GENERAL INFORMATION

Table A-0-1: Detailed Types of Plows by State

Responsive States	Front	Underbelly	Tow	Wing	Other[1]	Unsure
Alaska						
Arizona	■			■		
Connecticut	■	■	■	■		
Delaware	■		■	■		
Idaho	■		■	■		
Indiana	■	■	■	■		
Iowa						
Kansas	■		■	■		
Maine	■	■		■		
Maryland	■		■	■		
Massachusetts	■		■	■		
Michigan						
Minnesota						
Montana	■	■	■	■		
New Hampshire						
New Mexico						■
North Dakota					■	
Ohio	■	■	■	■		
Oregon	■	■		■		
Pennsylvania	■			■		
Rhode Island						
Utah	■		■			
Vermont	■	■	■	■		
Washington						
West Virginia	■			■		
Wisconsin	■	■	■	■		
Wyoming	■		■	■		

Note: A summarized version of this information is available in Table 3-5.

[1] North Dakota uses graders.

Table A-0-2: Detailed Types of Plows by Municipality

Responsive Municipalities	Front	Underbelly	Tow	Wing	Other	Unsure
California- District 3	■			■		
Boise, Idaho	■	■				
Portland, Maine						■
Detroit, Michigan	■	■				
Kansas City, Missouri	■			■		
Oklahoma City, Oklahoma	■					
Omaha, Nebraska	■			■		
Portland, Oregon	■	■				
Salem, Oregon	■			■		
Syracuse, New York	■			■		

Note: A summarized version of this information is available in Table 3-5.

Table A-0-3: Detailed Blade Material Currently Used by State

Responsive States	Carbide	Steel	Rubber	Poly	Other[1]	Unsure
Alaska						
Arizona		■		■		
Connecticut						
Delaware		■				
Idaho		■				
Indiana	■	■				
Iowa						
Kansas		■				
Maine	■					
Maryland		■			■	
Massachusetts		■				
Michigan						
Minnesota						
Missouri	■	■				
Montana		■				
New Mexico						
North Dakota		■				
Ohio						
Oregon		■			■	
Pennsylvania	■					
Rhode Island						
Utah	■	■				
Vermont		■	■			
Washington						
West Virginia		■				
Wisconsin						■
Wyoming	■					

Note: A summarized version of this information is available in Table 3-5.
[1] Other is rubber ceramic.

Table A-0-4: Detailed Blade Material Currently Used by Municipality

Responsive Municipalities	Carbide	Steel	Rubber	Poly	Other[1]	Unsure
California- District 3		■				
Boise, Idaho	■					
Portland, Maine						■
Detroit, Michigan		■		■		
Oklahoma City, Oklahoma		■	■			
Omaha Nebraska		■	■			
Salem, Oregon		■	■			
Portland, Oregon		■	■			
Syracuse, New York		■	■			

Note: A summarized version of this information is available in Table 3-5.

[1] Other is rubber ceramic.

Table A-0-5: Detailed Manufacturers by State

Responsive Contacts	Built Blades	Chemung	Ironhawk	Kennametal	Kueper	Mudder	Nordic	JOMA	Winter Equipment	Volk	Unsure
Alaska											
Arizona								■			
Connecticut			■		■			■		■	
Delaware								■			
Idaho											■
Indiana								■			
Iowa								■			
Kansas		■		■	■					■	
Maine					■	■					■
Maryland											■
Massachusetts					■			■			
Michigan											
Minnesota											
Montana											■
New Hampshire											
New Mexico											■
North Dakota											■
Ohio					■			■	■		
Oregon			■					■			■
Salem, Oregon											■
Pennsylvania								■			
Rhode Island											
Utah		■	■	■	■			■	■		
Vermont	■	■	■		■		■		■	■	
Washington											
West Virginia					■			■			

Wisconsin		
Wyoming	■	■

Note: A summarized version of this information is in Table 3-5.

Table A-0-6: Detailed Manufacturers by Municipality

Responsive Contacts	Kueper	JOMA (Winter Equipment)	Winter Equipment	Volk	Steel Sales Inc.	Northern Supply	Unsure
California- District 3							■
Boise, Idaho	■		■	■			
Portland, Maine							■
Detroit, Michigan							■
Kansas City, Missouri							■
Oklahoma City, Oklahoma			■	■			
Omaha, Nebraska		■					
Portland, Oregon			■				
Salem, Oregon							
Syracuse, New York					■	■	

Note: Summarized version of this information is in Table 5-4.

Table A-0-7: State Plow and Blade

Contact	GPS/AVL	Plow Up/ Down[2]	Plow Type	Blade Vendor	Blade Material
Alaska[1]	No Response	No Response	No Response	No Response	No Response
Arizona	Yes	Yes	Front, Wing	JOMA	Articulating Rubber Carbide, Polymer, Steel
Connecticut[1]	No	N/A	Front, Underbelly, Tow, Wing	No Response	No Response
Delaware	Yes	Yes	Front, Tow, Wing	JOMA	Articulating Rubber Carbide, Steel
Idaho	Yes	Yes	Front, Tow, Wing	Kueper, Valk, Winter Equipment	No Response
Indiana	No	N/A	Front, Underbelly, Tow, Wing	JOMA	Articulating Rubber Carbide, Steel
Iowa[1]	Yes	Yes	Front, Underbelly, Tow, Wing	JOMA, Kueper, Valley	Articulating Rubber Carbide, Rubber Ceramic, Steel
Kansas	No	N/A	Front, Tow, Wing	Chemung (Evolution Edges), Valk	Steel with Carbide inserts
Maine	No	N/A	Front, Underbelly, Wing	Unsure	Carbide
Maryland	Yes	No	Front, Tow, Wing	Kueper, Mudder	Rubber Ceramic, Steel
Massachusetts	Yes	No	Front, Tow, Wing	Kueper, Valley	Steel
Michigan[1]	Yes	No Response	Underbelly, Tow, Wing	No Response	No Response

Minnesota[1]	Yes	No Response	Front, Wing, Tow	No Response	No Response
Montana	Yes	Yes	Front, Underbelly, Tow, Wing	Unsure	Steel with Carbide inserts
New Hampshire[1]	Yes	No Response	Front	No Response	No Response
New Mexico	No	N/A	No Response	No Response	No Response
North Dakota	Yes	No	No Response	No Response	Steel
Ohio[1]	Yes	Yes	Front, Underbelly, Wing	Winter Equipment, JOMA, Valley	Steel with carbide
Oregon	No	No	Front, Underbelly, Tow, Wing	Ironhawk, JOMA	Steel, Steel with Poly Coating
Pennsylvania	Yes	No	Front, Tow, Wing	JOMA, Other	Articulating Rubber Carbide
Rhode Island[1]	Yes	No Response	Front, Wing	No Response	No Response
Utah	Yes	Yes	Front, Tow	Chemung (Evolution Edges), Ironhawk, JOMA, Valley, Winter Equipment	Articulating Rubber Carbide, Carbide, Steel
Vermont	Yes	Yes	Front, Underbelly, Tow, Wing, Double Wing	Built Blades, Chemung, Ironhawk,	Rubber and Steel

				Kueper, Nordic, Valk, Winter Equipment, Valley Blades	
Washington[1]	Yes	No Response	No Response	No Response	No Response
West Virginia	Yes	No	Front, Wing	JOMA, Kueper, Valley	Steel
Wisconsin	Yes	Yes	Front, Underbelly, Tow, Wing	No Response	Articulating Rubber Carbide, Carbide, Steel
Wyoming	Yes	No	Front, Tow, Wing	JOMA, Kennametal, Kueper	Articulating Rubber Carbide, Carbide,

Note: [1] States that are a part of the technical panel.
[2] This is a feature that is associated with having a GPS/AVL system needed for research.

Table A-0-8: Municipality Plow and Blade

Contact	GPS/AVL	Plow Up/Down[1]	Plow Type	Blade Vendor	Blade Material
District 3-California	No	N/A	Front, Wing	No Response	Steel
Boise, Idaho	Yes	Yes	Front, Underbelly	Unsure	Unsure
Portland, Maine	Yes	Unsure	Front, Underbelly	Unsure	Unsure
Detroit, Michigan	Yes	No	Front, Underbelly	Unsure	Polymer
Kansas City, Missouri	Yes	Yes	Front, Wing	Unsure	Steel with Carbide inserts
Oklahoma City, Oklahoma	Yes	No	Front	Winter Equipment	Carbide, Rubber, Steel
Salem, Oregon	Yes	Yes	Front	Unsure	Rubber, Plastic Hybrids
Omaha, Nebraska	Yes	Yes	Front, Wing	Multiple- JOMA	Steel, Rubber
Portland, Oregon	Yes	Yes	Front, Underbelly	Winter Equipment	Steel, Rubber
Syracuse, New York	Yes	Unsure	Front, Wing	Steel Sales Inc., Northern Supply, Chemung Supply Corp	Steel, Rubber

Note: [1] This is a feature that is associated with having a GPS/AVL system needed for research.

APPENDIX B:
VENDORS

Table B-0-1: Phase One Blade Vendor List 1

Blade Materials	Blade Manufacturers	Blade	Blade Application	Study
Articulating	Evolution Edges	TXS		
	Ironhawk	Lake Effect		
		Interlocking Carbide Blade		
	Kueper	GK5	Front	
		Tuca SX Wave	Front	
		Kueper XT		
	Winter Equipment	JOMA		USED
	Valley	Econoflex		
		Polarflex		
Carbide	Black Cat	Snow Shock	Front	
	Everest	Reverse-A-Cast		
		RHS Butterfly		
		RHS		
		RM		
	Henderson	Carbide Plow Blades	Front, Wing	
	Ironhawk	Ice-O-Force	Underbelly	
		Lake Effect		
	Kueper	Ceco SF Wave Front		
		Tuca SX Underbody	Underbelly	USED
	SnowDogg	Municipal Plow Carbide Plow Blades		
	SnowEx	HDV V-Plow		
	Valk	Carbide Plow Blades		
	Winter Equipment	BlockBuster	Front, Wing	USED
		Razor	Front, Wing	
		Razor XL	Front, Wing	USED
		Road Maxx	Underbelly	
Polymer	Boss Plows	DXT	Front	
		XT	Front	
	Everest	Reverse-A-Cast		
	Fisher	SD Series	Underbelly	
	Meyer	Underbody Scraper	Underbelly	
	SnowDogg	Municipal Poly Plow Blades		
	SnowEx	HDV V-Plow		
		PowerPlow		

Note: A shortened version of this table is seen in Table 3-9.

Table B-0-2: Phase 1 Blade Vendor List 2

Blade Materials	Blade Manufacturers	Blade	Blade Application	Study
Rubber	Henderson	Squeegee	Front, Wing	
	Ironhawk	Rubber Plow Blades		
	SnowDogg	Municipal Plow Rubber Plow Blades		
	SnowEx	Heavy Duty		
	Valk	Rubber Plow Blades		
	Winter Equipment	WinterFlex	Front, Wing	
		V-Plow Sytem	Front, Wing	
Stainless Steel	Boss Plows	DXT	Front	
		XT	Front	
	Buyers Products	Snowdogg VXII	Front	
	Fisher	Xtreme V	Front	
		XV2	Front	
		XLS	Wing	

Note: A shortened version of this table is seen in Table 3-9.

Table B-0-3: Phase One Blade List 3

Blade Materials	Blade Manufacturers	Blade	Blade Application	Study
Steel	Black Cat	BCB300	Front	
	Boss Plows	DXT	Front	
		EXT	Wing	
		Heavy Duty	Wing	
		XT	Front	
	Everest	OWRL		
		Reverse-A-Cast		
		RHS Butterfly		
		RHS		
		RM		
	Evolution Edges	High Carbon 1084 Steel		
	Fisher	HD2	Underbelly	
		HDX	Front	
		SD Series	Underbelly	
		Xtreme V	Front	
		XLS	Wing	
		XV2	Front	
	Ironhawk	Lake Effect		
	Meyer	Road Pro 32	Front, Wing	
		Road Pro 36	Front, Wing	
	SnoEx	HDV V-Plow	Front	
		Heavy Duty		
		PowerPlow		
		Speed Wing 8600		
	SnowDogg	36 Inch Full trip Municipal Plow		
		42 Inch Full trip Municipal Plow		
		Expressway Municipal Snowplow		
	Valk	C-1084		
		Viper		
	Western Plow	Defenser	Front	
		HTS	Front	
		Midweight	Front	
		MVP 3	Front	
		MVP Plus	Front	
		Prodigy	Wing	
		Pro-Plus HD	Front	
		Pro-Plus	Front	
		Pro-Plus Series 2	Front	
		Wide-Out, Wide-Out Xl	Front, Wing	
	Winter Equipment	BlockBuster Victory	Front, Wing	USED

	Common Sense	Front
	Patriot	Front
	V Plow System	Front, Wing

Note: A shortened version of this table is seen in Table 3-9.

Table B-0-4: Narrowed down Vendor List

Blade Material	Blade Manufacturers	Blade	Blade Application	Study
Articulating	Evolution Edges	TXS		
	Ironhawk	Lake Effect		
		Interlocking Carbide Blade		
	Kueper	GK5	Front	
		Tuca SX Wave	Front	
		Kueper XT		
	Winter Equipment	JOMA		USED
	Valley	Econoflex		
		Polarflex		
Carbide	Ironhawk	Ice-O-Force	Underbelly	
		Interlocking Carbide Blade		
		Lake Effect		
	Kueper	Ceco SF Wave	Front	
		Kuper XT	Front	
		Tuca SX Underbody	Underbelly	
		Tuca SX Wave	Front	
	Winter Equipment	BlockBuster	Front	
		JOMA	Front	
		Razor	Front	
		Road Maxx	Front	
		Razor XL	Front	
		V Plow System	Front	
Polymer	Boss Plows	DXT	Front	
		XT	Front	
Rubber	Ironhawk	Rubber Plow Blades		
	Winter Equipment	V Plow System	Front	
		WinterFlex	Front	
Stainless Steel	Boss Plows	DXT	Front	
		XT	Front	
Steel	Boss Plows	DXT	Front	
		XT	Front	
		EXT	Wing	
		Heavy Duty	Wing	
	Evolution Edges	High Carbon 1084 Steel		
	Ironhawk	Lake Effect		
	Winter Equipment	BlockBuster Victory	Front	

Common Sense	Front
Patriot	Front
V Plow System	Front

Note: A more complete list of plow blades is available in Table B-1 through B-3

Table B-0-5: Vendor Recommended Blades

Road Type	Conditions	Boss Plows	Evolution Edges	Kueper[1]	Valley[2]	Winter Equipment
Freeway	Hardpack/Ice	Carbide, Steel	TXS, VST Poly Encased Carbide, 1084 Steel, MGK 50		Polarflex, Steel Carbide	JOMA, Razor XL
	Snow	Carbide, Steel	TXS, VST Endurance, 1084 Steel, MGK 50		Polarflex, Steel Carbide	BlockBuster Hammerhead
State Highway	Hardpack/Ice	Carbide, Steel	TXS, VST Endurance, 1084 Steel, MGK 50		Polarflex, Steel Carbide	Razor XL
	Snow	Carbide, Steel	TXS, VST Endurance, 1084 Steel, MGK 50		Polarflex, Steel Carbide	BlockBuster Hammerhead
Local Street	Hardpack/Ice	Steel/Rubber	TXS, VST Endurance, 1084 Steel, MGK 50		Polarflex, Steel Carbide	Patriot
	Snow	Steel/Rubber	TXS, VST Endurance, 1084 Steel, MGK 50		Polarflex, Steel Carbide	Razor XL

Note: Roads are assumed to all be chemically treated, and plows are assumed to be front plows.

[1] Kueper representative was not comfortable recommending a blade without knowing the location of the sites; however, he is interested in being a part of the study.

[2] Valley representatives commented that dependent on the road material one of the three blades recommended would be suggested.

Table B-0-6: Vendor Survey Summary Results

Blade Manufacturers[1]	Blade Materials[2]	Blade Name	Blade Application	Study[3]
Boss Plows	Polymer	Polyurethane Plow Blades		
	Rubber	Rubber Blades		
	Steel	1080 Steel		
Evolution Edges	Articulating Carbide	TXS		
	Carbide	VST Endurance		
		VST Poly Encased Carbide		
	Rubber Ceramic	MGK 50		
	Steel	High Carbon 1084 Steel		
Ironhawk	Articulating Carbide	Lake Effect		
	Carbide	Ice-O-Force	Underbelly	
		Interlocking Carbide Blade		
	Rubber	Rubber Plow Blades		
Kueper	Carbide	Ceco SF Wave	Front	
		Kuper XT	Front	
		Tuca SX Wave	Front	X
		Tuca SX Underbody	Underbelly	X
	Rubber Ceramic	GK5		
Valley	Articulating Carbide	Econoflex		
		Polarflex	Front, Wing	X
Winter Equipment	Articulating Carbide	JOMA	Front, Wing	X
	Carbide	BlockBuster	Front, Wing	
		Razor XL	Front, Wing	
		Razor	Front, Wing	
		Road Maxx	Underbelly	
		V Plow System	Front, Wing	
	Rubber	WinterFlex	Front, Wing	
		V Plow System	Front, Wing	
	Steel	BlockBuster Victory	Front, Wing	X
		Common Sense	Front	
		Patriot	Front	
		V Plow System	Front, Wing	

Note: 1 Responsive vendor to survey.
2 Blade name and material were found through website search.
3 The “X” Denotes that the blade has been a part of a previous study.

Table B-0-7: Detailed Vendor Recommended Blades

Manufacturer	Blade Name	Material/Description	Cost
Evolution Edges	TXS	JOMA replacement	$245.00/foot
	VST Poly encased Carbide	Carbide encased in Polyurethane flexible	$181.20/foot
Kueper[1]	Kueper XT	Carbide Articulating	$84.00/foot
	Tuca SX Wave	JOMA replacement	$204.00/foot
Valley	Econoflex	JOMA replacement	$146.75/foot
	Polar Flex	Carbide Articulating	$215.00/foot
Winter Equipment	JOMA	Carbide Articulating	$285.11/foot[2]
	Razor XL	Carbide	$174.06/foot

Note: [1] Kueper representative was not comfortable recommending a blade without knowing the location of the sites; however, he is interested in being a part of the study and was comfortable with the blades the team recommended.

[2] This is pricing for a new system for JOMA; however, if purchasing a replacement for JOMA pricing would be $192.60/foot.

APPENDIX C:
TESTING PROTOCOL

Table C-0-1: Blade form

Date	Time	Truck Number	Measurement Location[1] A	B	C	D	E	Measurements Taken By	Maintenance to Blade Between Measurements

Note: Above is a cut version of the form given to Site Selected DOTs.
Blade form information is in Chapter 4 "Testing Protocol."
[1] Measurement location is available in Appendix C Figure C-1. Below the figure is a description of how the measurements are to be taken.

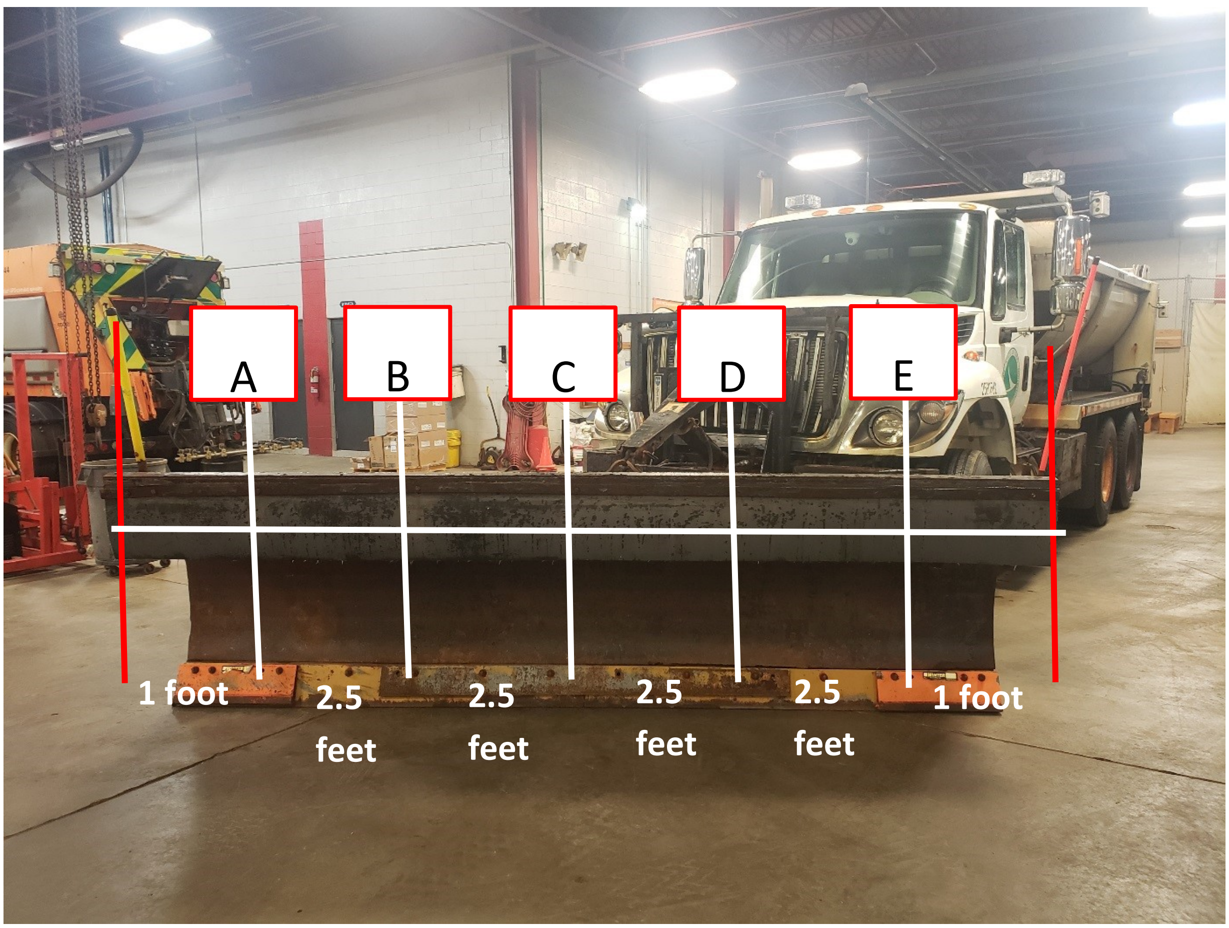


Figure C-0-1: Location of measurements along a 12-foot blade

- The Blade form is used to collect data on the physical wear of the blade see Table C-1.
- Since the blade does not wear evenly on the road, measurements at multiple locations along the blade are essential in ensuring the entire wear on the blade is captured.

- The measurements should be taken of the height of the blade in multiple locations along the blade, see Figure C-1 for the specific locations. These locations should be adjusted proportionally for an 11-foot blade.
- Measurements of the blade should be taken with a micrometer.
- Blade form should be used to note these measurements, date, time, truck number, and the counterbalance adjustment. This form is in Appendix C Table C-1.

Table C-0-2: Blade installation review

Date	Time	Truck Number	Blade Type	# of Person(s) for Installation	Tools and Equipment Used	Duration of Installation	Comment

Note: Above is a cut version of the form given to Site Selected DOTs.
Blade installation review information is in Chapter 4 "Testing Protocol."

General Information

State: ______________________________________
Garage: ____________________________________
Contact Name: ______________________________
Date: ______________________________________
Truck Number: ______________________________

Blade Specification

What blade type was used? (Place a checkmark,✓, by the blade used)

_____"Kueper XT" ____"JOMA" ____"MHL Interlocking" _____"Polarflex"

_____"Razor XL" ____"Tuca SX Wave" ____"TXS" _____"VST Poly Encase Carbide"

Operator Review (Place a checkmark,✓, on the left of the comment you agree with)

1. Noise Level

	Quiet		Moderately Quiet		Average		Above Average		Noisy

2. Clearing Ability

	Poor		Moderate		Average		Above Average		Excellent

3. Ice Clearing Ability

	Poor		Moderate		Average		Above Average		Excellent

4. Maneuverability - i.e. ability to work over bridge expansion joints, raised pavement markers, etc.

	Poor		Moderate		Average		Above Average		Excellent

5. Additional Comments about the blade:

____
____
____

Note: "Blade Type" will be filled in with the blades that have been selected by the technical panel.

Figure C-0-2: Operator review

Table C-0-3: Incident report

Date	Time	Truck Number	Blade Type	Incident[1]	Comments[2]

Note: Above is a cut version of the form given to Site Selected DOTs.
Incident report information is in Chapter 4 "Testing Protocol."

[1] The incident that occurred to damage the blade (ex. hit bridge deck, hit curb, etc.)

[2] Comments should include details of the damage to the blade (ex. there are major gashes out of blade, minor chips to middle location, etc.) and include images of the blade.

APPENDIX D:
FIELD DATA

Latitude	Longitude	Direction	Date	Time	Date_Time	Truck_Name	Op_ID	Road_Temp	Air_Temp	Speed	Distance	Mode	Blast_Pass	Granular	Gran_Rate	Gran_Lbs	Meas_Gran	Spinner	Prewet	PWet_Gals	Pwet_Rate	Meas_Pwet	WING	PLOW
42.65035	-111.70221	0.5	01/30/20	06:27:43 MST	01/30/20 06:27:43 MST	T31893		63	66	0	0.1		Normal	SALT	0	0	0	0	BRINE	0	0	0	UP	UP
42.65035	-111.70221	0.5	01/30/20	06:27:49 MST	01/30/20 06:27:49 MST	T31893		63	66	0	0		Normal	SALT	0	0	0	0	BRINE	0	0	0	UP	UP
42.65035	-111.70221	0.5	01/30/20	06:27:55 MST	01/30/20 06:27:55 MST	T31893	0751	64	66	0	0	MENU	Normal	SALT	0	0	0	0	BRINE	0	0	0	UP	UP
42.65035	-111.70221	0.5	01/30/20	06:28:01 MST	01/30/20 06:28:01 MST	T31893	0751	63	66	0	0	MENU	Normal	SALT	0	0	0	0	BRINE	0	0	0	UP	UP
42.65035	-111.70221	0.5	01/30/20	06:28:08 MST	01/30/20 06:28:08 MST	T31893	0751	63	66	0	0	AUTO	Pass	SALT	0	0	0	0	BRINE	0	0	0	UP	UP
42.65035	-111.70221	0.5	01/30/20	06:28:14 MST	01/30/20 06:28:14 MST	T31893	0751	63	66	0	0	AUTO	Pass	SALT	0	0	0	0	BRINE	0	0	0	UP	UP
42.65035	-111.70221	0.5	01/30/20	06:28:20 MST	01/30/20 06:28:20 MST	T31893	0751	63	66	0	0	AUTO	Pass	SALT	0	0	0	0	BRINE	0	0	0	UP	UP
42.65035	-111.70221	0.5	01/30/20	06:28:26 MST	01/30/20 06:28:26 MST	T31893	0751	63	66	0	0	AUTO	Pass	SALT	0	0	0	0	BRINE	0	0	0	UP	UP
42.65035	-111.70221	0.5	01/30/20	06:28:32 MST	01/30/20 06:28:32 MST	T31893	0751	63	66	0	0	AUTO	Pass	SALT	0	0	0	0	BRINE	0	0	0	UP	UP
42.65035	-111.70221	0.5	01/30/20	06:28:38 MST	01/30/20 06:28:38 MST	T31893	0751	63	66	0	0	AUTO	Pass	SALT	0	0	0	0	BRINE	0	0	0	UP	UP
42.65035	-111.70221	0.5	01/30/20	06:28:44 MST	01/30/20 06:28:44 MST	T31893	0751	62	66	0	0	AUTO	Pass	SALT	0	0	0	0	BRINE	0	0	0	UP	UP
42.65035	-111.70221	0.5	01/30/20	06:28:50 MST	01/30/20 06:28:50 MST	T31893	0751	62	66	0	0	AUTO	Pass	SALT	0	0	0	0	BRINE	0	0	0	UP	UP
42.65035	-111.70221	0.5	01/30/20	06:28:56 MST	01/30/20 06:28:56 MST	T31893	0751	60	66	0	0	AUTO	Pass	SALT	0	0	0	0	BRINE	0	0	0	UP	UP
42.65035	-111.70221	0.5	01/30/20	06:29:02 MST	01/30/20 06:29:02 MST	T31893	0751	59	66	0	0	AUTO	Pass	SALT	0	0	0	0	BRINE	0	0	0	UP	UP
42.65035	-111.70221	0.5	01/30/20	06:29:08 MST	01/30/20 06:29:08 MST	T31893	0751	59	66	0	0	AUTO	Pass	SALT	0	0	0	0	BRINE	0	0	0	UP	UP
42.65035	-111.70221	0.5	01/30/20	06:29:14 MST	01/30/20 06:29:14 MST	T31893	0751	59	66	0	0	AUTO	Pass	SALT	0	0	0	0	BRINE	0	0	0	UP	UP
42.65035	-111.70221	0.5	01/30/20	06:29:20 MST	01/30/20 06:29:20 MST	T31893	0751	59	66	0	0	AUTO	Pass	SALT	0	0	0	0	BRINE	0	0	0	UP	UP
42.65035	-111.70221	0.5	01/30/20	06:29:26 MST	01/30/20 06:29:26 MST	T31893	0751	60	66	0	0	AUTO	Pass	SALT	0	0	0	0	BRINE	0	0	0	UP	UP
42.65035	-111.70221	0.5	01/30/20	06:29:32 MST	01/30/20 06:29:32 MST	T31893	0751	59	66	0	0	AUTO	Pass	SALT	0	0	0	0	BRINE	0	0	0	UP	UP
42.65035	-111.70221	0.5	01/30/20	06:29:38 MST	01/30/20 06:29:38 MST	T31893	0751	60	66	0	0	AUTO	Pass	SALT	0	0	0	0	BRINE	0	0	0	UP	UP
42.65035	-111.70221	0.5	01/30/20	06:29:44 MST	01/30/20 06:29:44 MST	T31893	0751	60	65	0	0	AUTO	Pass	SALT	0	0	0	0	BRINE	0	0	0	UP	UP
42.65035	-111.70221	0.5	01/30/20	06:29:50 MST	01/30/20 06:29:50 MST	T31893	0751	60	65	0	0	AUTO	Pass	SALT	0	0	0	0	BRINE	0	0	0	UP	UP
42.65035	-111.70221	0.5	01/30/20	06:29:56 MST	01/30/20 06:29:56 MST	T31893	0751	28	65	0	0	AUTO	Pass	SALT	0	0	0	0	BRINE	0	0	0	UP	UP
42.65035	-111.70221	0.5	01/30/20	06:30:02 MST	01/30/20 06:30:02 MST	T31893	0751	16	65	0	0	AUTO	Pass	SALT	0	0	0	0	BRINE	0	0	0	UP	UP
42.65035	-111.70221	0.5	01/30/20	06:30:08 MST	01/30/20 06:30:08 MST	T31893	0751	18	64	0	0	AUTO	Pass	SALT	0	0	0	0	BRINE	0	0	0	UP	UP
42.65035	-111.70221	0.5	01/30/20	06:30:14 MST	01/30/20 06:30:14 MST	T31893	0751	11	62	0	0	AUTO	Pass	SALT	0	0	0	0	BRINE	0	0	0	UP	UP
42.65035	-111.70221	0.5	01/30/20	06:30:20 MST	01/30/20 06:30:20 MST	T31893	0751	15	61	0	0	AUTO	Pass	SALT	0	0	0	0	BRINE	0	0	0	UP	UP
42.65035	-111.70221	0.5	01/30/20	06:30:26 MST	01/30/20 06:30:26 MST	T31893	0751	15	60	0	0	AUTO	Pass	SALT	0	0	0	0	BRINE	0	0	0	UP	UP
42.65035	-111.70221	0.5	01/30/20	06:30:32 MST	01/30/20 06:30:32 MST	T31893	0751	15	60	0	0	AUTO	Pass	SALT	0	0	0	0	BRINE	0	0	0	UP	UP

Figure D-0-1: Raw GPS/AVL Data Sheet

Figure D-1 is an example of the GPS/AVL datasheet of a blade tested in the Idaho case study.

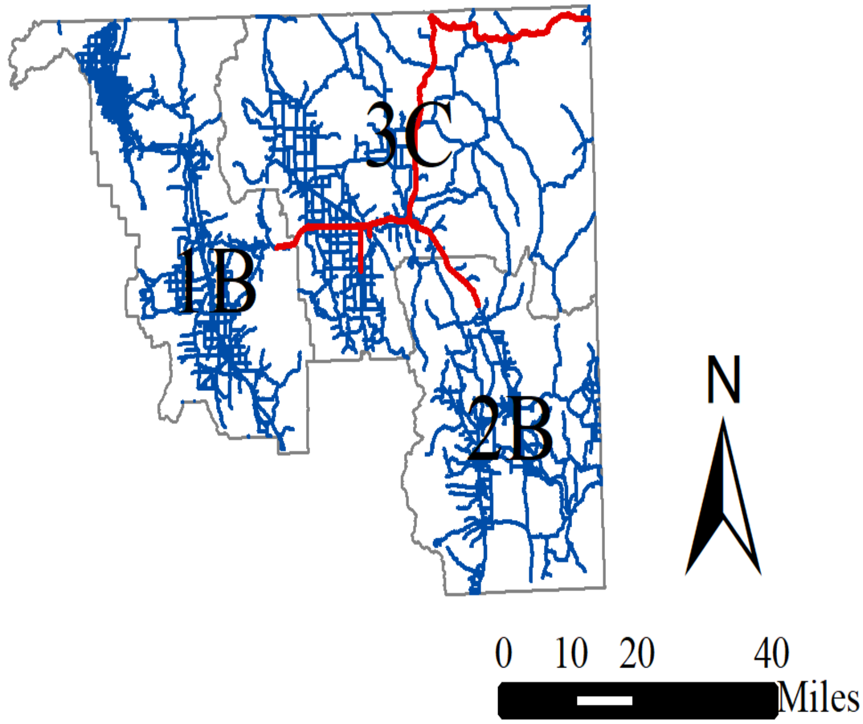


Figure D-0-2: January Soda Springs Routes

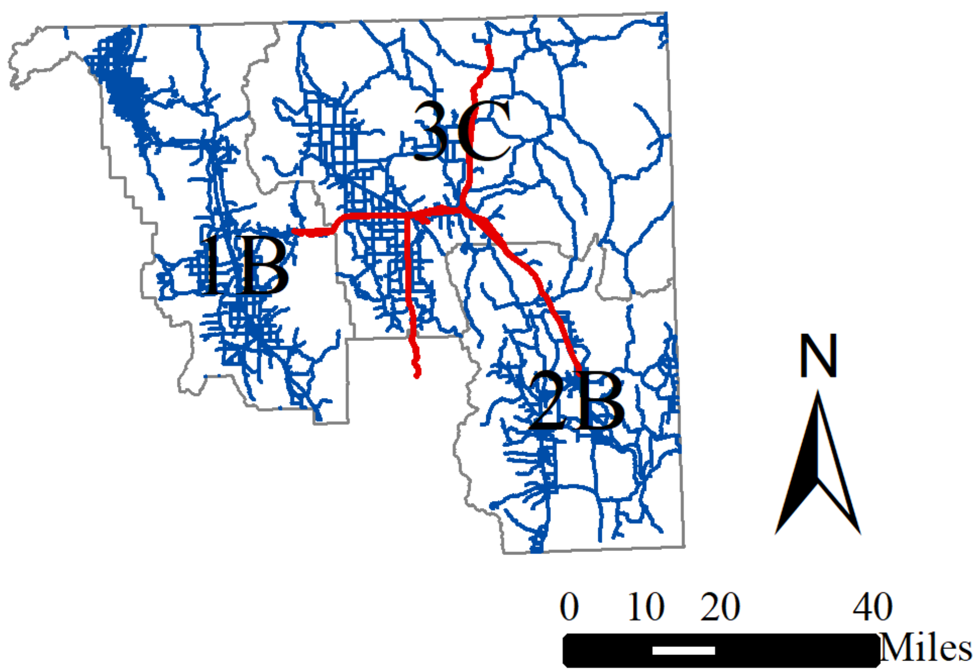


Figure D-0-3:February Routes Truck One Soda Springs

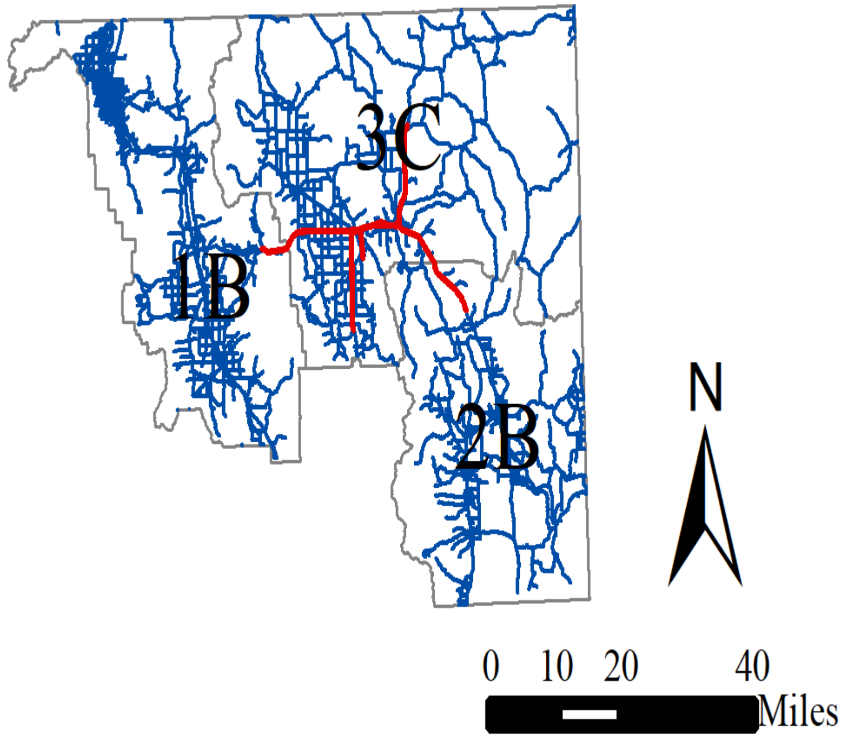


Figure D-0-4: March Routes Truck One Soda Springs

Figure D-0-5: January Truck One Route Moscow/Potlatch

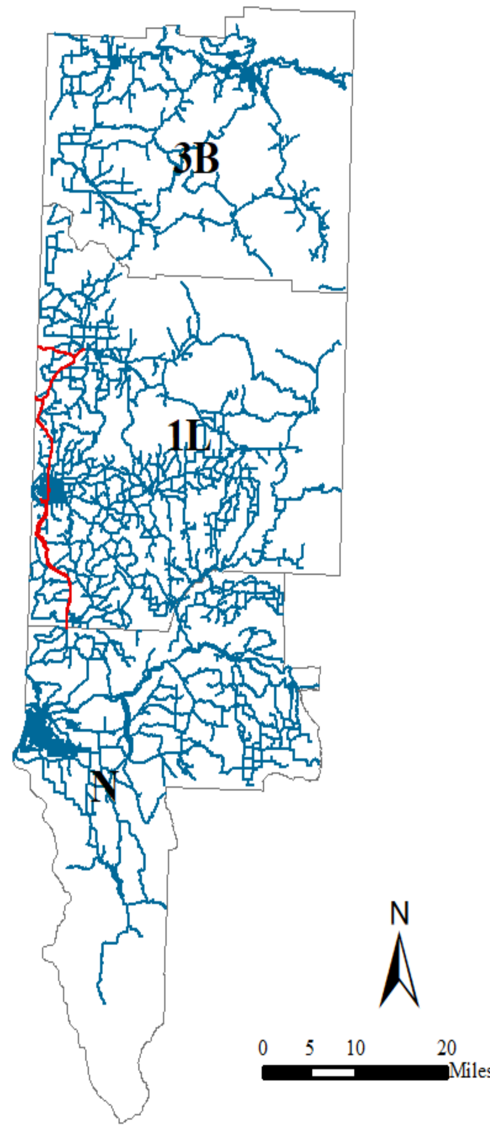


Figure D-0-6: February Truck One Route Moscow/Potlatch

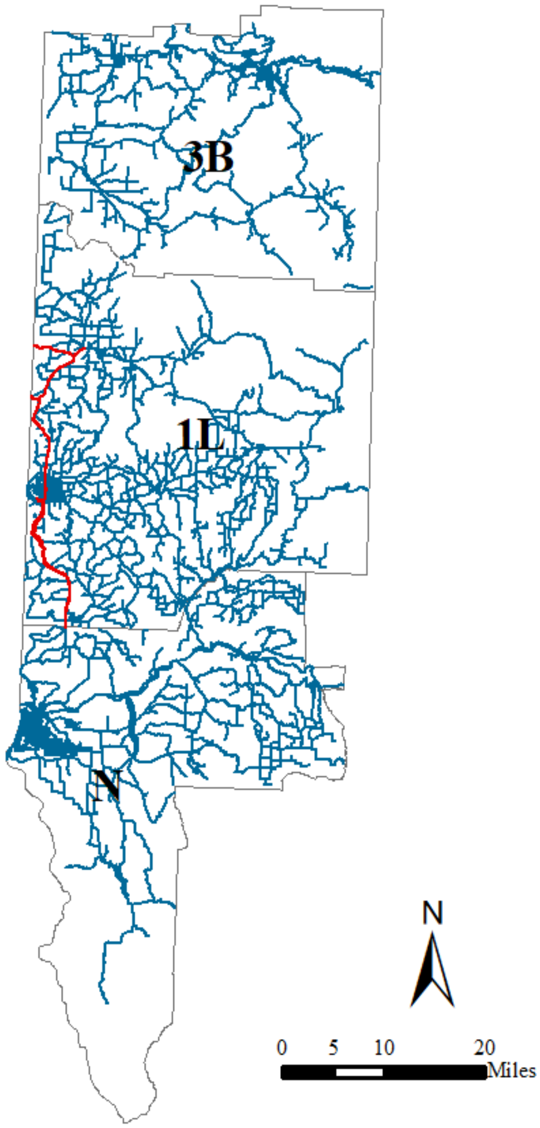


Figure D-0-7: March Route Truck One Moscow/Potlatch

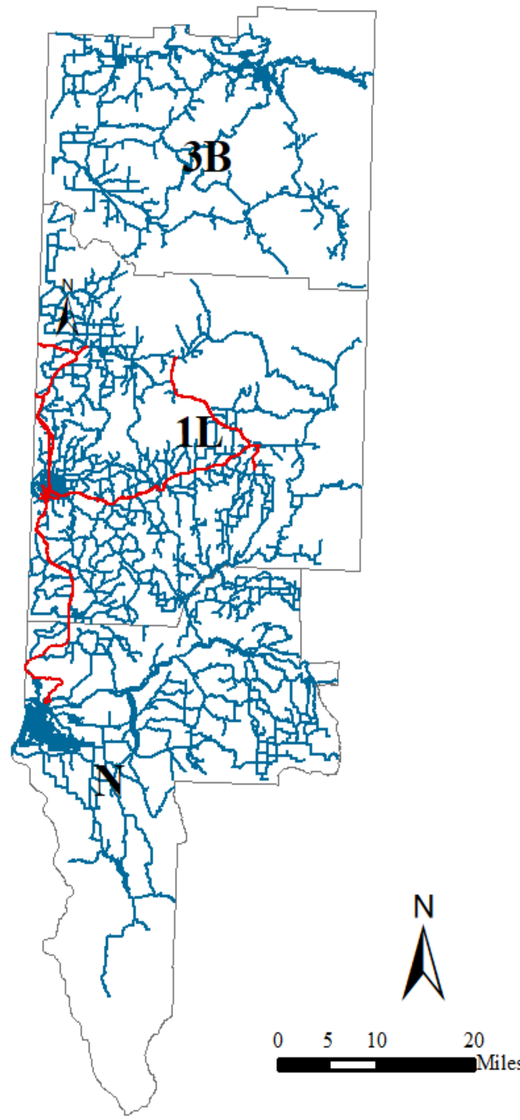


Figure D-0-8:January Route Truck Four Moscow/Potlatch

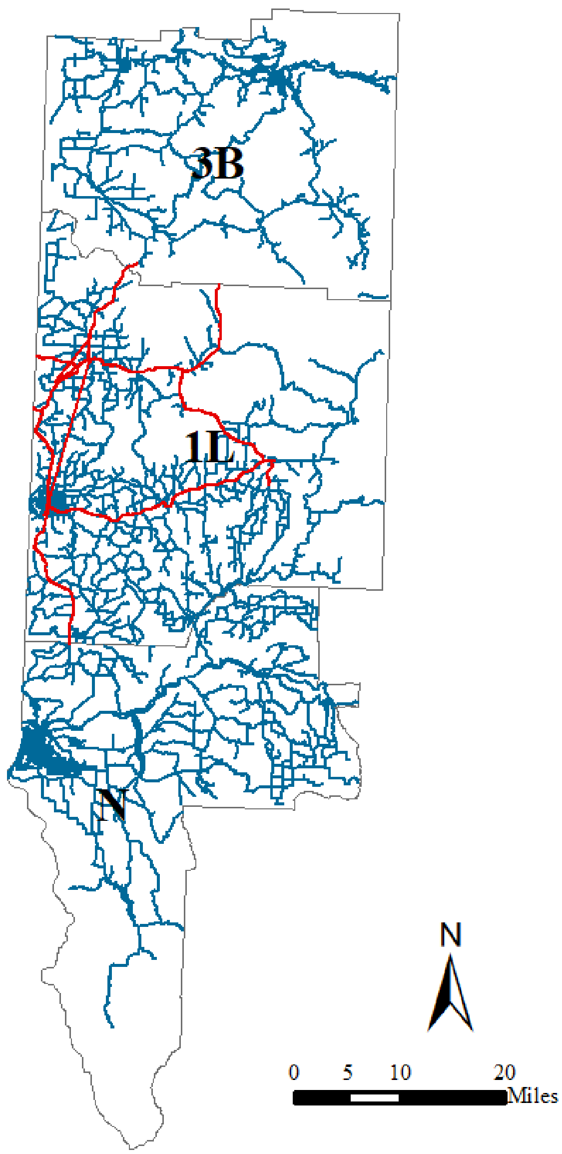


Figure D-0-9: February Routes Truck Two Moscow/Potlatch

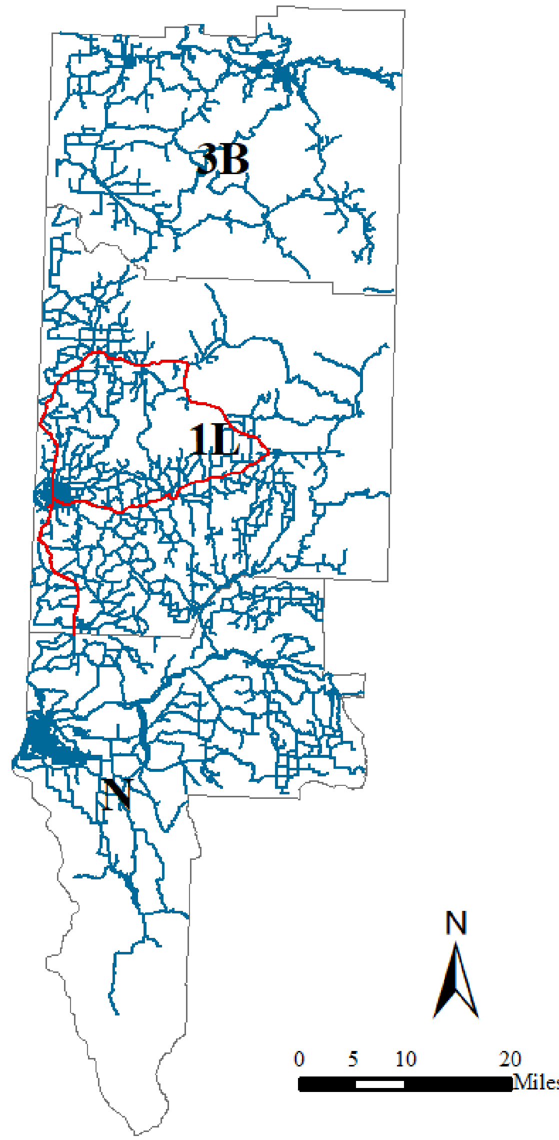


Figure D-0-10: March Routes Truck Two Moscow/Potlatch

Figure D-0-11: Raw data of the small-scale field testing.

Nordic Combi Double			Plowing distance [km]		Accumulated wear [mm]													Avg. wear each # [mm]	Wear rate [mm/km]	Wear rate [inch/mile]
Set	#	Date and time	Distance	Accumulated	1L	1R	2L	2R	3L	3R	4L	4R	5L	5R	6L	6R	Average			
A1	1	08.12.2019 14:00	867.205	867.205	9.03	11.19	8.51	10.53	13.09	14.58	6.60	7.32	17.79	12.93	11.05	10.94	11.13	11.13	0.013	8.13E-04
	2	08.12.2019 22:30	99.175	966.38	11.14	10.38	11.92	12.00	11.08	11.75	13.69	11.79	12.44	11.48	15.08	13.31	12.17	1.04	0.011	6.65E-04
	3	09.12.2019 07:00	151.582	1117.962	12.33	14.00	13.19	14.64	13.72	15.11	12.95	15.25	13.48	14.34	14.33	14.11	13.96	1.78	0.012	7.46E-04
	4	16.12.2019 11:00	442.839	1560.801	27.08	30.53	31.80	35.57	37.69	40.40	34.60	31.73	38.75	38.46	34.43	37.25	34.85	20.90	0.047	2.99E-03
	5	19.12.2019 09:00	138.506	1699.307	44.18	46.41	43.64	45.58	49.03	47.52	42.13	43.66	43.25	45.32	40.18	43.26	44.52	9.66	0.070	4.42E-03
	6	26.12.2019 11:40	104.812	1804.119	51.27	56.58	49.74	52.19	56.39	58.10	53.96	53.93	57.14	56.70	58.22	52.42	54.72	10.20	0.097	6.17E-03
C1	1	05.02.2020 14:20	145.711	145.711	3.13	4.37	1.16	3.43	7.45	13.47	2.41	0.99	2.65	2.02	3.79	7.52	4.37	4.37	0.030	1.90E-03
	2	05.02.2020 23:00	99.761	245.472	7.05	7.28	6.86	7.14	14.64	16.80	8.34	6.62	9.83	7.90	7.90	9.87	9.18	4.82	0.048	3.06E-03
	3	06.02.2020 07:25	173.055	418.527	10.94	12.65	12.34	12.85	15.24	14.52	11.76	12.10	11.80	12.11	12.12	13.29	12.65	3.46	0.020	1.27E-03
	4	06.02.2020 15:10	126.267	544.794	14.80	15.61	15.44	15.71	17.57	21.42	16.36	14.92	15.12	14.54	12.85	13.31	15.63	2.99	0.024	1.50E-03
	5	12.02.2020 12:35	52.79	597.584	21.05	23.11	20.61	20.28	20.38	22.09	20.63	20.10	21.29	19.72	17.59	19.32	20.52	4.88	0.093	5.86E-03
C2	1	13.02.2020 15:20	167.963	167.963	0.88	1.40	1.68	4.62	6.01	5.52	7.34	3.82	3.22	2.34	3.34	3.55	3.64	3.64	0.022	1.37E-03
	2	23.02.2020 07:10	106.217	274.18	5.50	10.14	9.82	10.50	12.56	13.43	11.75	10.91	8.34	9.29	11.22	9.97	10.29	6.65	0.063	3.96E-03
	3	23.02.2020 22:05	88.012	362.192	10.92	12.49	12.51	12.63	13.05	12.80	14.77	14.01	11.75	12.00	16.92	14.51	13.20	2.91	0.033	2.09E-03
	4	24.02.2020 07:30	245.844	608.036	16.91	18.23	16.02	16.79	16.93	17.66	16.15	18.59	13.91	17.88	16.86	19.26	17.10	3.90	0.016	1.00E-03
	5	24.02.2020 17:30	115.267	723.303	26.04	24.96	25.68	27.28	26.36	25.43	25.98	25.52	19.42	24.36	24.38	23.90	24.94	7.84	0.068	4.31E-03
	6	04.03.2020 23:00	510.328	1233.631	32.43	32.04	33.02	33.76	34.80	34.95	33.51	32.96	43.54	38.18	33.76	32.63	34.63	9.69	0.019	1.20E-03
	7	12.03.2020 15:00	71.456	1305.087	38.48	38.42	39.01	39.52	39.77	39.41	39.32	38.79	39.20	38.76	40.67	42.85	39.52	4.89	0.068	4.33E-03

	8	13.03.2020 07:45	72.576	1377.663	41.50	41.40	42.09	41.34	41.03	41.81	41.95	41.42	45.22	41.37	42.58	42.23	41.99	2.48	0.034	2.16E-03
	9	13.03.2020 15:00	146.024	1523.687	47.57	48.43	47.22	47.42	48.32	48.15	49.52	48.78	43.77	46.69	47.09	49.91	47.74	5.75	0.039	2.49E-03
	10	17.03.2020 12:00	277.297	1800.984	57.16	56.40	56.46	56.70	57.08	57.29	55.53	57.85	50.86	48.45	57.07	58.24	55.76	8.02	0.029	1.83E-03
D1	1	28.03.2020 07:15	104.562	104.562	2.95	7.14	4.86	11.98	13.48	13.46	7.32	5.61	12.37	19.03	10.55	8.11	9.74	9.74	0.093	5.90E-03
	2	28.03.2020 19:00	37.55	142.112	11.64	12.55	12.80	12.77	13.45	13.09	12.55	12.80	12.57	13.38	13.41	13.07	12.84	3.10	0.083	5.23E-03
	3	29.03.2020 08:05	198.876	340.988	16.04	16.88	16.01	17.99	18.62	19.20	18.79	19.39	19.81	20.80	22.56	19.59	18.81	5.97	0.030	1.90E-03
	4	29.03.2020 20:00	145.38	486.368	25.34	26.44	25.54	26.71	26.39	26.04	26.70	28.25	27.30	27.81	30.58	37.23	27.86	9.05	0.062	3.94E-03
	5	02.04.2020 22:05	74.775	561.143	29.07	29.11	30.16	30.38	30.83	30.54	31.14	30.41	30.58	31.06	30.57	32.12	30.49	2.64	0.035	2.23E-03
	6	03.04.2020 07:00	101.829	662.972	32.99	33.03	33.44	33.37	33.43	33.63	34.19	33.72	33.39	33.49	32.97	33.25	33.41	2.92	0.029	1.82E-03
	7	03.04.2020 15:00	91.209	754.181	35.66	36.03	35.59	35.66	36.44	35.98	36.20	35.49	35.68	35.58	35.73	35.91	35.83	2.42	0.027	1.68E-03
	8	04.04.2020 07:10	226.845	981.026	39.73	39.17	38.42	39.23	40.13	39.77	39.02	40.47	39.68	40.19	41.25	42.18	39.94	4.11	0.018	1.15E-03

Steel/polyurethane			**Plowing distance [km]**		**Accumulated wear [mm]**													**Avg. wear each # [mm]**	**Wear rate [mm/km]**	**Wear rate [inch/mile]**
Set	**#**	**Date and time**	**Distance**	**Accumulated**	**B1L**	**B1R**	**B2L**	**B2R**	**B3L**	**B3R**	**B4L**	**B4R**	**B5L**	**B5R**	**B6L**	**B6R**	**Average**			
B1	1	02.01.2020 14:00	176.666	176.666	4.69	8.42	6.27	11.52	20.51	23.63	8.07	5.55	19.86	19.32	12.90	16.65	13.12	13.12	0.074	4.70E-03
	2	03.01.2020 12:15	69.748	246.414	14.67	15.85	14.96	15.64	15.70	16.33	16.04	15.08	17.77	15.83	16.46	16.21	15.87	2.76	0.040	2.51E-03

	3	04.01.2020 06:30	297.822	544.236	29.38	24.89	24.21	27.34	21.84	21.18	24.45	26.54	19.34	18.26	27.15	31.40	24.67	8.80	0.030	1.87E-03
	4	04.01.2020 18:40	117.72	661.956	27.53	31.86	29.87	27.48	29.78	30.43	28.33	28.28	29.70	29.15	35.51	31.02	29.91	5.24	0.045	2.82E-03
	5	05.01.2020 06:30	76.393	738.349	33.10	32.33	32.87	32.78	31.68	32.26	32.81	33.87	32.91	33.09	32.97	31.98	32.72	2.81	0.037	2.33E-03
	6	12.01.2020 18:00	193.127	931.476	40.66	41.15	43.79	46.16	46.36	44.84	53.35	53.61	48.37	50.99	50.76	52.60	47.72	15.00	0.078	4.92E-03
B2	1	21.01.2020 15:30	41.995	41.995	0.04	-0.06	0.35	0.23	0.11	-0.06	0.14	0.01	0.51	0.01	0.36	1.09	0.23	0.23	0.005	3.43E-04
	2	21.01.2020 23:00	80.83	122.825	0.94	0.41	0.32	2.02	0.96	5.21	2.67	1.05	5.99	3.22	0.60	4.36	2.31	2.08	0.026	1.63E-03
	3	22.02.2020 06:30	113.601	236.426	5.51	9.90	7.06	9.97	6.17	10.84	12.21	11.73	13.80	14.28	5.48	7.83	9.57	7.26	0.064	4.05E-03
	4	23.01.2020 11:20	46.384	282.81	11.76	12.85	14.07	14.50	13.62	14.26	14.24	15.50	16.17	17.29	17.83	17.23	14.94	5.37	0.116	7.34E-03
	5	24.01.2020 07:05	24.424	307.234	15.26	15.24	15.65	15.87	15.73	16.35	17.21	17.21	16.74	16.36	17.29	17.72	16.38	1.45	0.059	3.75E-03
	6	24.01.2020 15:00	97.244	404.478	21.92	22.03	23.13	23.61	22.18	23.52	25.42	25.35	27.26	26.45	26.66	18.82	23.87	7.48	0.077	4.88E-03
	7	25.01.2020 07:00	186.087	590.565	30.39	30.74	31.34	32.26	30.47	32.40	32.51	33.08	33.03	32.29	33.36	40.39	32.69	8.82	0.047	3.00E-03
	8	30.01.2020 12:00	54.894	645.459	33.87	34.41	35.64	35.73	37.56	38.93	36.40	36.00	37.39	38.13	38.25	37.93	36.68	4.00	0.073	4.61E-03

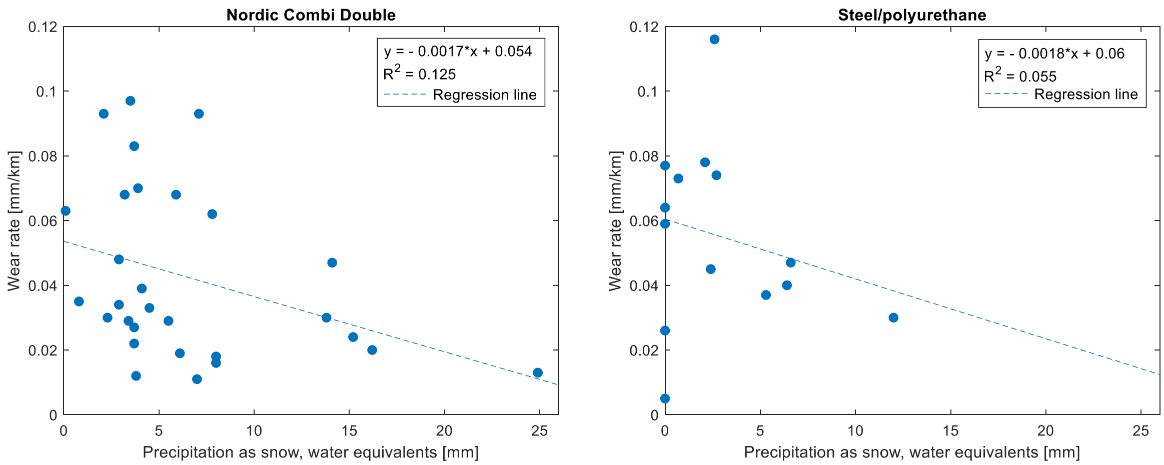


Figure D-0-12: Scatterplot of the wear rate versus the amount of fallen snow (in mm water equivalent)

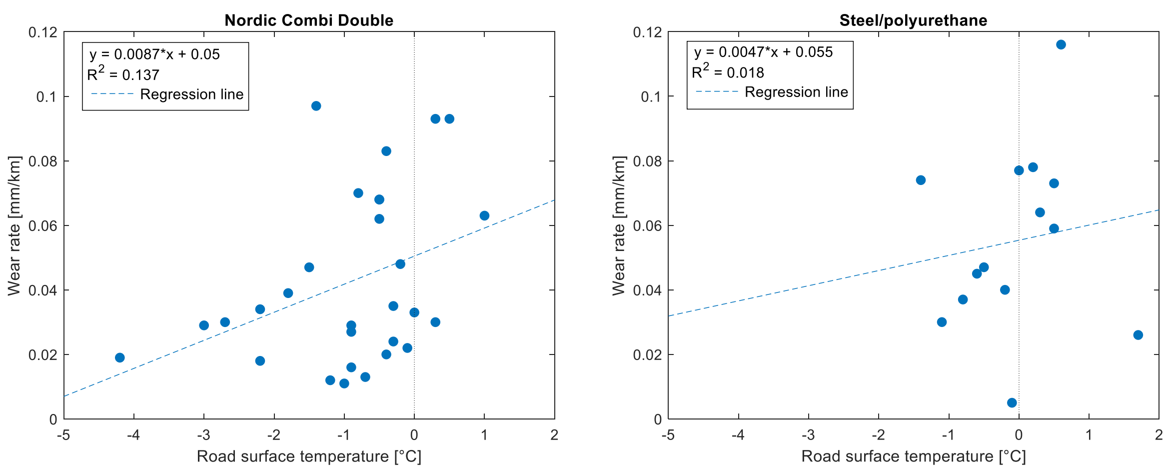


Figure D-0-13: Scatterplot of the wear rate versus the road surface temperature

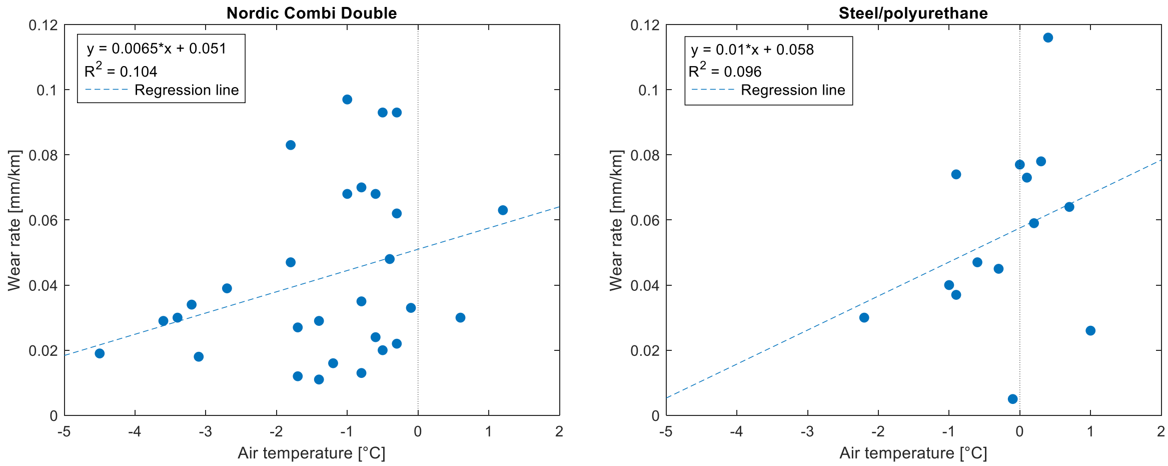


Figure D-0-14: Scatterplot of the wear rate versus the air temperature

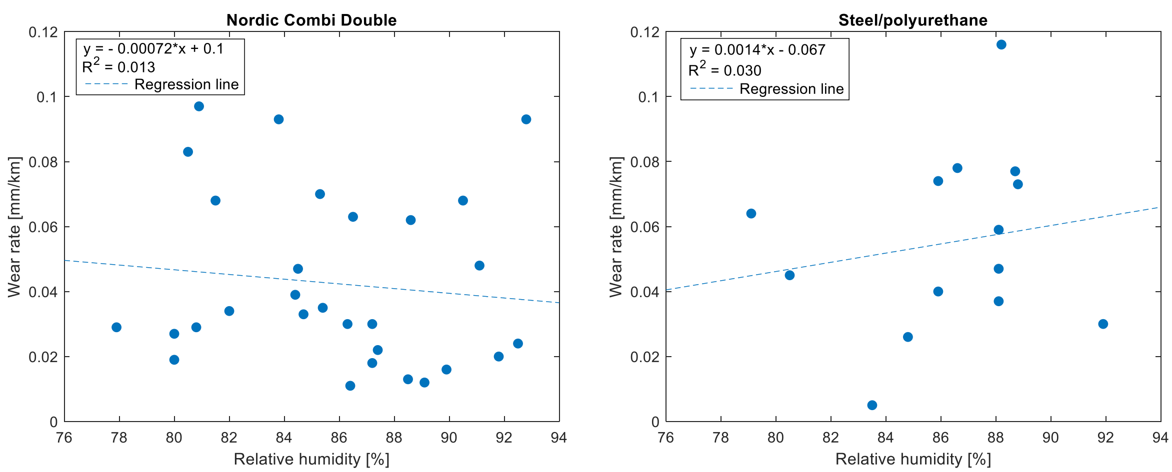
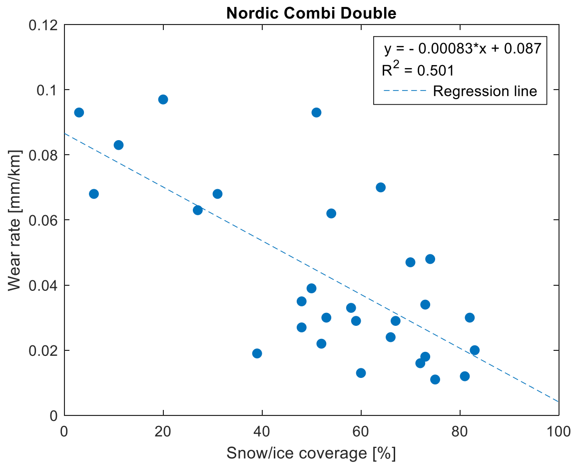


Figure D-0-15: Scatterplot of the wear rate versus the relative humidity



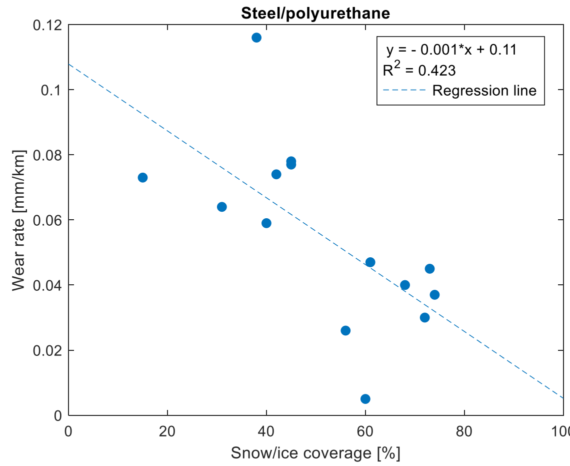


Figure D-0-16: Scatterplot of the wear rate versus the snow/ice coverage

APPENDIX E:
ASTM STANDARDS

The following sections briefly describe the ASTM and AWS standard discussed in Chapter 4. These descriptions are to provide an idea of what the ASTM standard test is and what material it should be used for. For further detail, please see the ASTM or AWS websites.

E.1 BRAZE

AWS C3.2M/C3.2:2008 is the standard method for evaluating the strength of brazed joints. (AWS 2020).

AWS C3.2M/C3.2:2008 is a standard that defines the different types of joints and how to evaluate the shear strength of that joint (AWS 2020).

AWS A5.8M standard section 9.3 notes to use ASTM Standards in Section 3, Metals Test Methods and Analytical Procedures, Volume 5, Analytical Chemistry for Metals, Ores, and Related Materials: E32 to E1724 for the testing of brazing material; therefore, the standard test of E32 is recommended for testing (AWS 2020) .

ASTM E32 defines the practices for sampling of various ferroalloys and steel additives in order to test the material for compositional specifications.(ASTM E32-15 2015).

E.2 CARBIDE

ASTM Volume 02.05, May 2020 Metallic and Inorganic Coatings; Metal Powders and Metal Powder Products contains standards for cemented carbides which is the carbide used in snowplow blades. These standards contain all information on how testing should be conducted, how specimens should be prepared, and everything needed to test the specimen for the desired specification. Below are the standards recommended in Table 2 with the standard test number and its scope as noted on the ASTM website (ASTM 2020).

ASTM B657-18 defines the testing of a cemented carbide's microstructure. The microstructure of a cemented carbide affects both the mechanical and physical properties of the material (ASTM B657-18 2018).

ASTM B294-17 details Rockwell hardness testing for indication of the cemented carbides wear resistance. (ASTM B294-17 2017)).

ASTM B406-96(2015) defines this testing method used to determine the quality of cemented carbide from sintered strength measurements. (ASTMB406-96 2015).

ASTM B311-08 is the standard for testing the density of a powder metallurgy materials for cemented carbides and for materials containing less than two percent porosity (ASTM B11-17 2017).

ASTM B276-05 defines the testing methodology to determine the apparent porosity in cemented carbides (ASTM B276-05 2015).

ASTM B930-03 is the standard test method for evaluating and accepting the measurement of grain sizes in cemented tungsten carbides (ASTM B930-03 2017).

ASTM B406-96 is the standard testing method for transverse rupture strength of cemented carbides (ASTM B406-96 2015).

E.3 RUBBER

ASTM D1456-86 details the standard test methodology for determining the elongation of a rubber at a specific stress *(ASTM D1456-86 2020).*

ASTM D412-16 is the standard testing method to evaluate tension for vulcanized rubber and thermoplastic elastomers *(ASTM D412-16 2020).*

ASTM D2240 – 15e1 details the standard test for durometer hardness *(ASTM D2240-15ei 2015).*

ASTM D624 – 00 is the standard testing method for vulcanized rubber and thermoplastic elastomers to evaluate tear strength *(ASTM D624-00 2020).*

ASTM D395 – 18 details the standard test methods for evaluating compression set of a material *(ASTM D395-18 2018).*

ASTM D2137-11 is the standard testing method to evaluate brittleness point of flexible polymers and coated fabrics *(ASTM D2137-11 2018).*

E.4. STEEL

ASTM Volume 3.01 Metals- Mechanical Testing; Elevated and Low temperature Tests; Metallography encompasses the standard testing of E10 and E18.

ASTM E18 is the standard testing methods for Rockwell Hardness for metallic materials *(ASTM E18 2020).*

ASTM E10 details the testing methodology for evaluating metallic materials for the Brinell hardness (*ASTM E10-18 2018).*

ASTM E3-11 is the standard practice for preparing a specimen for microstructure evaluation. The ways to evaluate a metal and their allows are by light optical or scanning electron microscope (ASTM E3-11 2017).

research for winter highway maintenance

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