Master's thesis

NTNU
Norwegian University of Science and Technology
Faculty of Engineering
Department of Civil and Environmental Engineering

Petter Jakola

Operational Lifetime of Snowplow Blades

Master's thesis in Civil and Environmental Engineering
Supervisor: Alex Klein-Paste
June 2020

NTNU
Norwegian University of
Science and Technology

mesta

Petter Jakola

Operational Lifetime of Snowplow Blades

Master's thesis in Civil and Environmental Engineering
Supervisor: Alex Klein-Paste
June 2020

Norwegian University of Science and Technology
Faculty of Engineering
Department of Civil and Environmental Engineering

NTNU
Norwegian University of
Science and Technology

Abstract

Snowplow blades are consumables in snow plowing operations and replaced several times during a winter season due to wear. In an economic perspective, a blade type with long operational lifetime and high utilization degree is preferable. However, too much wear on the blades may cause damages to the plow, resulting in costly repairs. By comparing observed wear and maximum theoretical wear the utilization degree of snowplow blades is estimated. An estimation of operational lifetime for the snowplow blade is found from utilization degree and wear rate in mm/km. This may help contractors and operators evaluate different types of snowplow blades in a cost-benefit analysis.

This project is carried out in collaboration with the Norwegian contractor Mesta AS Trondheim. Following one of their snowplow trucks on the highway E6 during the 2019/2020 winter season. Wear is measured on two types of snowplow blades (Nordic Combi Double and Steel/polyurethane). A total of 6800 km was plowed, resulting in five worn out, or for some other reason replaced snowplow blade sets.

Operational lifetime for blades given in plowing distance is found to be 1803 km for Nordic Combi Double blades and 788 km for Steel/polyurethane blades. Wear rates of 0.034 mm/km for Nordic Combi Double and 0.054 mm/km for Steel/polyurethane are calculated, resulting in a greater potential for Nordic Combi compared to Steel/polyurethane. It is also found that a utilization degree of a set of 70-90 % is possible depending on blade type.

Around 25 factors which influence expected lifetime are identified. Based on these identified factors, seven operational factors that effects wear and needs to be controlled in snowplow blade testing are presented.

A literature review is also included, searching for studies and literature which contains factors influencing snowplow blade wear, descriptions of test methods on snowplow blades in the field and laboratory, and published results on snowplow blade wear. Literature on tribology and wear mechanisms are also included.

Keywords: Snowplow blades, wear, winter maintenance

Sammendrag

Slitestål er forbruksvarer under snøbrøyting og blir byttet ut flere ganger i løpet av en vintersesong på grunn av slitasje. I et økonomisk perspektiv er det ønskelig med en slitestålttype med lang operasjonell levetid og høy utnyttelsesgrad, men for mye slitasje på slitestålet kan føre til skader på selve plogen og dermed dyre reparasjoner. Ved å sammenligne observert slitasje og maksimum teoretisk slitasje, er utnyttelsesgraden av slitestålet beregnet. Et estimat på operasjonell levetid på slitestålet beregnes fra utnyttelsesgraden og sliteraten gitt i mm/km. Dette kan være til hjelp når entreprenører skal vurdere ulike typer slitestål i en kost nytte analyse.

Denne oppgaven er gjennomført i samarbeid med den norske entreprenøren Mesta As Trondheim og følger en av brøytebilene deres på E6 i Trondheim, gjennom vintersesongen 2019/2020. Underveis måles slitasjen på to typer slitestål (Nordic Combi Double og Steel/polyurethane). Totalt 6800 km brøytes, som resulterer i at fem slitestålsett slites ut, eller må skiftes.

Operasjonell levetid for slitestålet gitt i plog kilometer er funnet til 1803 km for Nordic Combi Double og 788 km for Steel/polyurethane. Sliterater på 0,034 mm/km for Nordic Combi Double og 0,054 mm/km for Steel/polyurethane ble regnet ut. Noe som gir et større potensiale for Nordic Combi Double sammenlignet med Steel/polyurethane. Det ble også funnet at utnyttelsesgraden av et slitestålsett mellom 70-90 % er mulig, avhengig av slitestålttype.

Rundt 25 faktorer som kan begrense forventet levetid er identifisert. Basert på disse identifiserte faktorene, er syv operasjonelle faktorer som påvirker slitasjen og som må kontrolleres under testing av slitestål presentert.

Oppgaven inneholder også et litteratursøk som inkluderer studier og litteratur som inneholder: faktorer som påvirker slitasjen på slitestål, beskrivelser av testmetoder for slitestål, både i felt og laboratorier, samt publiserte resultater av slitasje på slitestål. Litteratur om tribologi og slitemekanismer er også inkludert i litteratursøket.

Preface

This report is the deliverable of TBA4940 Highway Engineering, Master's Thesis, and the final work in the Civil and Environmental Engineering master program at the Norwegian University of Science and Technology. The thesis is awarded with 30 credits and is written during the spring of 2020.

I would like to thank my supervisor, Professor Alex Klein-Paste at NTNU, for introducing me to the topic of snowplow blade lifetime and good guidance throughout the process.

The thesis is carried out in collaboration with Mesta AS Trondheim. I would like to thank Håvard Engen and the other employees at Mesta AS, for the positive response and enabling the project. Especially the three snowplow truck drivers for letting me experience snow plowing operations in practice.

Thanks to the Norwegian Public Road Administration for providing access to Vegvær application and weather data.

Great gratitude must also be given to my grandmother for letting me borrow her car during the data collection process, enabling me to show up on short notice during snowstorms, even in the middle of the night.

Finally, I would like to thank my family and friends for all the support during my years studying in Trondheim, and during the work with this thesis.

Trondheim, 25.06.2020

Petter Jakola

Table of content

List of Figures

List of Tables

List of Abbreviations

Norwegian terms are written in *italics.*

AADT	Annual daily traffic, *årsdøgnstrafikk*
AVL	Automatic vehicle location
Dk	Maintenance standard, *driftsklasse*
HP	Smaller section of a road. Used in NPRA system for dividing roads into smaller sections called HP, *hovedparsell*
MET	Norwegian Meteorological Institute, *Meteorologisk institutt*
NOK	Norwegian kroner, *norske kroner*
NPRA	Norwegian Public Road Administration, *Statens vegvesen*
NTNU	Norwegian University of Science and Technology, *Norges teknisk-naturvitenskapelige universitet*
Road reference	System to give exact position on a road combining road number, HP, and meter value.
Rode	Designated snow removal area
VTI	Swedish National Road and Transportation Institute

1 Introduction

1.1 Background

Snowplow blades (also called cutter edges) are consumables in snow plowing operations and replaced several times during a winter season due to wear. In an economic perspective, a blade type with long operational lifetime and high utilization degree is preferable. However, to much wear on the blades may cause damages to the plow, resulting in costly repairs. If lifetime is defined as the distance of blade usefulness, the maximum theoretical lifetime of a snowplow blade may be defined as the number of plowing kilometers before any damage is inflicted on the plow itself. Hence, operational lifetime can be defined as the distance plowed when the blade is removed due to wear. By identifying operational lifetime of snowplow blade types and using this in a cost-benefit analysis, contractors can choose the most cost-efficient blades for plowing operations. The following subsections introduces the winter maintenance field in Norway and plowing equipment.

1.1.1 Winter maintenance in Norway

The Norwegian society relies on roads for inland transportation of people and goods, where 86% of the transportation of people and 49% of freight transportation were carried out on the road network in 2018 (1). There are 95 166 km of public roads in Norway, organized into state roads (10 757 km), county roads (44 688 km), and municipal roads (39 721 km) (2). The Norwegian Public Roads Administration (NPRA), counties and municipalities are the road owners and are responsible for the public road network.

During winter, the mean temperature in most parts of Norway is below zero and most parts experiences more than 100 mm of precipitation on average through a winter (3). This combination results in lot of snow on Norwegian roads. Snow and ice on the road increases the accident risk, to reduce the number of accidents, winter maintenance measures are applied (4). To keep the roads at an acceptable standard, NPRA hires contractors to operate 106 maintenance contract areas. These contracts typically include winter maintenance tasks. Total cost of winter maintenance in 2018 was 25 billion NOK, which is around 20% of the total maintenance budget (5). The task of keeping the roads in satisfying winter conditions is so important that a disagreement between NPRA and the contractors will not stop winter maintenance operations, preventing negative consequences for any third parties. Any disagreements or economical questions will be solved consecutively or after the winter season (6).

NPRA operates with maintenance standards (Dk) A to E, where DkA is the highest and DkE is the lowest standard. The choice of maintenance standard is based on the traffic volume, AADT. Additional parameters considered when choosing maintenance standard are road type, geometry, compound of traffic, accidents, topography, climate, and weather. Maintenance standard gives type of strategy (anti-icing or winter road (7)), requirements for approved road conditions, and the measures and effort needed when a weather event occurs (8).

1.1.2 Snowplowing equipment and blades

To obtain the required road condition given by NPRA throughout the winter, contractors need equipment both for mechanical and chemical removal of snow and ice. Mechanical removing of snow is a key task in winter maintenance and is the primary method of removing snow and ice (7, 9). Usually this is done with a snowplow. During the 2018/2019 winter, contractors drove 21 713 903 plowing kilometers distributed on highways and county roads (10). This gives 380 km of plowing per km of road.

There are several types of snowplow configurations made for different snow conditions, road types and operation vehicles. Usually snowplows are mounted on trucks in Norway. Other vehicles that are used are tractors, road graders or loaders. The plow types used for roads are V-plow, single blade plow, diagonal plow, combination plow, multi-blade plow, side plow, underbody plow and rear mounted plow. There are benefits and disadvantages for each of them which decide their usage (9). For highways and county roads, diagonal or combination plows are used. In addition, a side wing plow can be used to get some extra plowing width.

Some plows are more advanced and include more hydraulic and movable parts than others. Regardless of complexity and configuration the plow typically consists of a moldboard, a counterbalance system, and blades (7). Figure 1.1 illustrates the different parts. The moldboard is the main body of the plow. It pushes, transports, and throws snow to the side. To reduce downward forces from the plow on the pavement, plows are fitted with a mechanical or hydraulic counterbalance system. Plow blades are the parts of the plow that scrape along the road surface to loosen snow and ice.

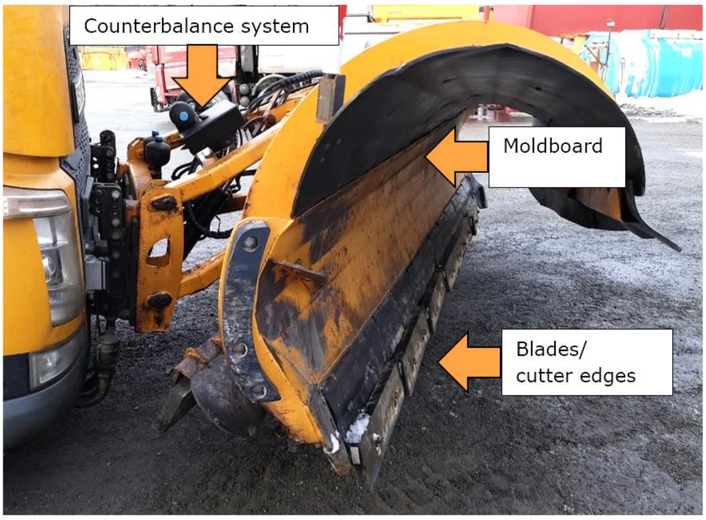


Figure 1.1: Main parts of a snowplow

The scraping process and contact with the road surface makes snowplow blades subject to wear. Because of this wear, the Norwegian contractor Mesta changes blade sets around four times during a winter season on a 22 km road section in Trondheim. The blades used are reversible, meaning that they have two sides that can be worn down before replacement (11). Knowing that there are 95 166 km of public roads in Norway, this can add up to thousands of blades for one winter season.

Choosing the right snowplow blade type might be a challenge because of the wanted material properties. The blade must have high fracture toughness to withstand impacts or shock loads from any obstructions (manholes, curb stones, bridge joints) in the road without fracturing. At the same time it must have high hardness to resist wear from the scraping process (12). These properties are contradictory since materials with high hardness often are brittle and materials with high fracture toughness have lower hardness. Blade producers must therefore compromise between material properties. Different conditions may also require different types of blades, which leads to a variety of blade types.

Types of plow blades available on the market today are standard blades made from flame hardened steel, rubber blades, carbide insert blades and high-performance blades. For high-performance blades, design and combination of materials are chosen to optimize the relation between fracture toughness and hardness. Such a design and material combination may be ceramics inserts encased in rubber and placed between steel plates. These high-performance blades typically reduce vibration and noise but have an increased investment cost.

For economic reasons, a high utilization of the blade material is preferable, which means as much as possible of the material is worn away before replacement. At the same time, it is important to keep in mind that late replacement may lead to damage on the plows moldboard resulting in costly repairs and delays (13).

Mesta usually replace all the blades at the same time. However, the utilization of blades in the same set may vary due to uneven wear on the blades. Blades may also need replacement if broken, for example by impacts with obstacles. The decision to replace is taken by the driver, usually based on a subjective evaluation. Factors such as the amount of material worn away and the weather forecast are typically considered. In advance of long-lasting heavy snowfall, it may be beneficial to ensure that blades will last the whole weather event without damaging the plow. Additionally, by replacing in advance of snowfall, unnecessary stops in plowing operations are avoided.

1.2 Objectives and research questions

The main objective of this project is to find the operational lifetime of snowplow blades used by Mesta during the 2019/2020 winter season. The research questions in this thesis are

1. **What is the operational lifetime on snowplow blades used by Mesta AS Trondheim and which factors influences expected lifetime?**
2. **How does the operational wear rate develop over time?**
3. **Which operational factors influencing wear rate needs to be controlled in plow blade testing?**

This project is initially motivated by economics and comparing cost of snowplow blade types to choose the most cost-efficient blade. However, snowplow blades are a specialized product where the consumers typically are contractors, which may have special quantity discounts from producers. Because of this, the actual costs of the blades will not be considered in this thesis.

Another topic that should be considered when choosing blade type is the clearance performance, how much snow and ice is left on the road surface after plowing (7). A poor clearance performance might increase the labor effort required to get the road surface in satisfying condition. However, clearance performance will not be addressed to limit the scope in this thesis.

2 State of the art

To get an overview of previous work done on snowplow blade wear, a "state of the art" literature review has been conducted. The objective was to find literature and studies:

- Identifying factors influencing snowplow blade wear.
- Describing test methods used to measure/predict snowplow blade wear, both in the field and laboratory.
- Containing published result on blade wear.
- Describing wear mechanisms present during snow plowing or similar situations.

Relevant literature was search for in the databases Oria, Google Scholar, Scopus, and ProQuest, using different combinations of words and terms given in Appendix A. The literature review includes "gray literature" such as reports, if they present data or information considered to be of interest to this thesis. In addition to direct search in databases, backwards and forwards "snowballing" were used from relevant articles and reports to find other citing or cited literature. Findings from the literature review are presented in the following subsections.

2.1 Factors influencing blade wear

Factors mentioned in the literature which may influence blade wear can be sorted into: material properties, operating variables, road surface, weather conditions, snow and ice characteristics, and driver or operator dependent factors. This sorting is inspired by Jacobson and Hogmark's work on road grading steels "*The tribo-technical system of the grader blade*" (14).

2.1.1 Material properties

These properties are associated with the materials used in the blades. Some of the literature mentions material properties in general by briefly mentioning or indicating that factors such as type of material, material composition, quality, and specification, influences blade wear (15-18). Other literature mentions more specific material properties, these are listed below.

Hardness

Greater hardness of the material leads to more wear resistance (12, 14, 15, 19).

Toughness

Increased toughness reduces the risk of fracture in the material (12, 14, 15, 19, 20).

Blade design

It is suggested that not only the material used in the blades, but also how they are put together and the design of the blade may influence wear (14). By placing the most wear-resistant parts in a way that fully utilizes this resistant material, it will help extend the lifetime (17).

2.1.2 Operating variables

These are variables related to the actual snowplowing operation and equipment setup.

Plowing speed

Several studies and tests suggest that the plowing speed is one of the factors influencing the wear rate (15, 16, 18, 21). During a study of snow plowing forces (20) where existing snow models were compared to fields test done in velocities 8, 16 and 24 km/h, the relationship between the force on the plow and plowing speed was found to be linear for these low speeds. Velocity is also one of the parameters which was investigated in Nixon's work *"Improved cutting edges for ice removal"* (22).

Plowing distance

The overall distance in which the plow is in contact with the road surface influence blade wear (13-15).

Blade angle

The orientation of the blade is the blade angle or operating angle and affects blade wear (15, 21). To be more specific, blade angle can be divided in rake angle, clearance angle and angle of attack as shown in Figure 2.1 and Figure 2.2. Rake angle is the angle between the position of the blade and a perpendicular line to the pavement. Clearance angle is the angle between the backside of the blade and the pavement. Angle of attack is the angle between the blade and a perpendicular line of the direction of motion.

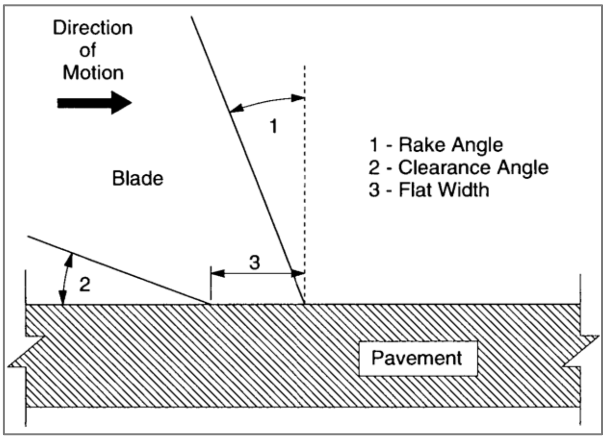


Figure 2.1: Side view of blade, illustrating rake angle and clearance angle, from Nixon (22).

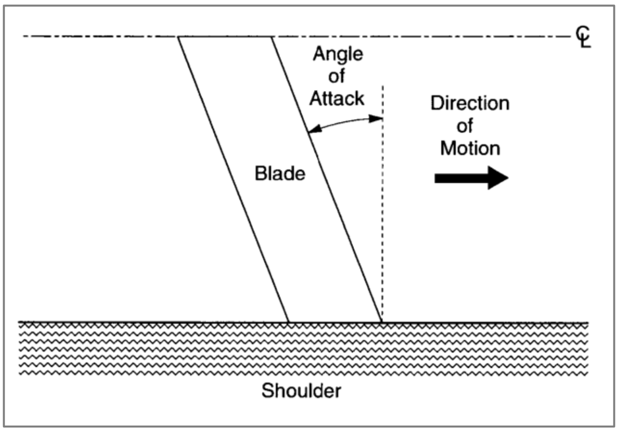


Figure 2.2: Top view of the blade, illustrating attack angle, from Nixon (22).

Position of blade on the plow

The position of the blade along the plow may give different wear on the same type of blades (15, 16, 23).

Load on blade

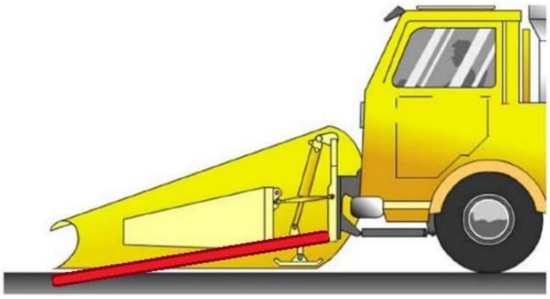
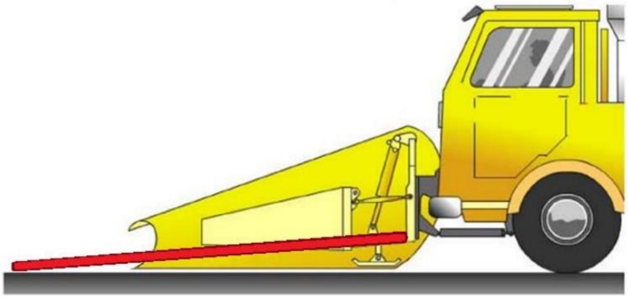
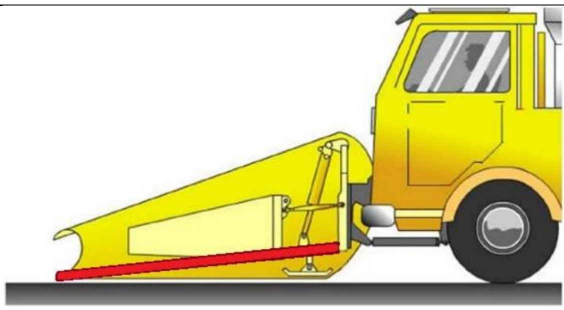
This includes vertical and horizontal forces on the blade, and are also dependent of the area of contact with the pavement (14, 15). The area of contact is related to the flat width illustrated in Figure 2.1.

The type of plow may also affect the forces acting on the blade. According to Nixon, Wei and Whelan (24), the forces on the blades are more stable when using an underbody plow where the blades are pushed down, compared to a front plow where the weight of the plow keeps the blade in contact with the pavement, which leads to more dynamic forces.

Adjustment of plow and plow mounting plate

NPRA have developed a procedure for correct adjustment of the plow and a NPRA standard for plow mounting plate settings, as a part of a textbook for winter maintenance staff. Wrong adjustments may have consequences for the load on the blades because of the line of action of plowing force (9). Too high, too low, and correct plow adjustments, and how these may affect plowing operations are described in Table 2.1. Illustrations showing the line of action of plowing force as a red line are also included in Table 2.1.

Table 2.1: Plow adjustments and consequences for line of action of plowing force.

Adjustment	**Illustrations line of action of plowing force, from NPRA textbook (9).**
Too high plow adjustment: Makes the line of action of plowing force intercept the road behind the tip of the plow. The plow may lift or "jump". This typically gets worse with increased amount of snow and higher plowing speeds, which increases risk of lost vehicle control (9).	
Too low plow adjustment: Makes the line of action of plowing force pass over and go further than the plow tip. Pushing the plow harder towards the road surface, increasing the load on the blades and risk of the truck "driving over" the plow (9).	
Correct plow adjustment: For a correct adjusted plow, the line of action of plowing force goes through the tip of the plow.	

Tire pressure
In the procedure for procedure for correct adjustment of the plow from NPRA, tire pressure is listed as a factor that needs to be controlled to achieve correct plow adjustment (9). Maintaining correct tire pressure is important to ensure correct use plow adjustment during plowing operations.

2.1.3 Road surface

Another factor mentioned as important for the wear of a plow blade is the road surface (16). There are several factors influencing the road surface.

Pavement material
Several studies mentions that the pavement material influences wear (12, 18). Bituminous asphalt and concrete are common pavement materials. Blades are worn faster on concrete pavements than bituminous asphalt (15). The condition of the pavement may also affect wear (13).

Rutting
This gives an uneven pavement surface which makes the plow lose contact with the pavement in some places, reducing the total contact surface and increasing wear rate on the areas still in contact (15).

Obstructions
Elements raised above the road surface may cause shock impacts to the blade or lift part of the blade. Examples of obstructions are manhole covers, bridge joints, curbstones, and raised pavement markings (13, 15, 25).

Snow/ice cover
Conditions where the plow scrapes bare pavement may enhance wear and are mentioned as one of the reasons for the reduced blade mileage for interstate roads compared with secondary roads in tests done by the Maine department of transportation (21). The snow cover on the road may also be affected by the road agency policy when it comes to the condition of the roadway (15) and the call-out priority (13).

2.1.4 Weather conditions

These are variables and factors mentioned in relation to weather that may influence blade wear during plowing.

Temperature
Different types of temperatures are mentioned, these include the air temperature, surface temperature and blade temperature (15). On tests conducted on Kuper Tuca SX composite blades, an early failure of the blades was experienced. The reason was melting of rubber in the blades due to heat in the blade (21).

Number of weather events
During a winter the number of snow and ice events and precipitation decides the amount of snowplowing required which will influence wear on the blades (18).

2.1.5 Snow and ice characteristics

This involve the type of material plowed, which can vary between snow, ice, or slush. Different density of snow and any abrasives or chemicals present may also affect the blade wear (15).

2.1.6 Driver

In their work, Kruse and Kirchner (15) found several indications that the person driving the snowplow truck affects the wear, and thereby the expected life time of blades. This is supported by other studies mentioning operator plowing habits and operator variability (16), as well as operator technique (18), and skill of driver (14).

2.2 Test methods on snowplow blade wear

The methods found investigating snowplow blade wear can be divided into field tests, laboratory tests, and surveys of drivers. To limit the scope, survey methods will not be included in this literature review.

2.2.1 Field test methods

In Scandinavia, the Swedish National Road and Transportation Institute (VTI) has developed test methods for different properties of snowplows in *Metodbeskrivning för plogtester* (23). In these tests two plows are used, the plow under study and a conventional reference plow for comparison. Blade wear is one of the parameters included in this method description. The wear test is conducted on a 40-50 km road section where the same truck drives back and forth at two different speeds, 40 km/h and 60 km/h. This is done for both the test plow and the reference plow. The wear is found by measuring the distance from the lower mounting holes to the lower edge of the plow blade. This is done for every blade along the plow.

Kruse and Kirchner (15) looked at the development of standardized test procedures for carbide insert plow blades. They came up with a field test where blades were tested for 300 miles, at 45 mph, with an angle of the blades of 18°. The test is conducted on dry pavement on the same route using the same driver. Blade temperature was also measured during the test using an infrared temperature measurement instrument. To find wear the height of the carbide inserts were measured before and after the test. At the end, a visual examination of the carbide inserts in the blades was conducted to look for cracks or chips.

Schneider, Crow and Holik (16) used a field test method which continuously follows plowing operations, measuring blade wear throughout a winter season (two seasons were followed in the study). The wear was measured on five different locations on the plow. The location of these measuring points on the plow are dependent on the length of the plow (11 or 12 feet). Measurements are collected together with date, time, truck number, and the name of the person who did the measurements. To collect additional data, all trucks were fitted with a digital video recorder, GPS, and an infrared vision camera. These devices collected data whenever the truck was in use. By analyzing and combining data using the program ArcGis, the start/stop time of plowing, start/stop speed when plowing, road condition, and distance plowed were found for any given time of plowing operation. Road surface types were found by looking at the plow route and position of the truck. From the collected data, wear rates were calculated.

Several other field tests have been conducted, following operators and the usage of different plow blade types, throughout one or several winter seasons (13, 18, 21, 26). Some of the studies made continuous measurements of wear on the blades following weather events (18). Others recorded hours of plowing time (13).

Various methods for determining plowing mileage have also been found in the literature. One method is to mount a wheel on the plow in a way which makes it rotate whenever the plow is down and the blades are in contact with the pavement (27). Another method is collecting reports including plow mileage, which are filled out by the drivers after weather events (21).

2.2.2 Laboratory test methods

A search for any methods testing wear on a complete blade in the laboratory was performed. In this process, VTI was asked if there have been any tests on the VTI Road Simulator investigating blade wear or wear on asphalt pavement due to snowplow blades. The VTI Road Simulator is used for wear studies on pavements and interaction between tire and pavement (28). The reply from VTI was that there have not been any tests on the simulator including snowplow blades.

Wei, Nixon and Shi (29) developed a scratch test method suitable for plow blades using a diamond intender and higher loads than previously used for the same test type. From this test they found a scratch hardness for three different types of carbide inserts blades. The scratch hardness was calculated from the normal force applied and the groove width generated. Comparing scratch hardness results with wear results from the field, they found the highest scratch hardness on the most wear resistant blades, and lowest scratch hardness on the least wear resistant blades. Even though all the carbide inserts met material specifications from manufacturers and highway maintenance agencies, the test gave different scratch hardness results (29). "*This implies that the scratch hardness correlates wear resistance of cutting edges better than indentation hardness*" (29).

Younkin (30) preformed a laboratory abrasion test on tungsten carbide inserts for snowplow blades using the test *ASTM B611, abrasive wear resistance for cemented carbides*. The test gives a volume loss in cm^3 as a measure of abrasion resistance. Five samples from three different manufacturers were tested. This is an example of an indirect test of snowplow blade components.

In their work, Kruse and Kirchner (15) tried to find or develop standardized laboratory test methods for wear on carbide inserts in snowplow blades. By looking at several standard tests from the metal industry on various material properties, they found eleven tests with potential to predict carbide inserts wear. Four of these were selected to examine: hardness, density, porosity, and grain size of carbide inserts. Three types of carbide insets were tested. Results from the laboratory seemed to give promising results compared with field test of blades with the same types of carbide inserts.

Besides the standard tests from the metal industry, Kruse and Kirchner (15) also tried to develop the scratch test from Wei, Nixon and Shi (29) and modify the ATSM B611 test used in Younkin (30) to test carbide inserts installed in blades. They found that both tests required even more development to be able to predict wear of carbide blades.

2.3 Results on snowplow blade wear

Any results on blade wear from previous studies and tests may be of interest to this thesis. This may, for example, give and impression on what to expect from different types of blades. Studies found presents wear results in several different ways: wear rate (mm/km or inches/mile), costs, plowing distance, and plowing hours until blade change. Some studies include several or a combination of these. Any cost results and studies only containing results given in cost will not be included in this literature review.

2.3.1 Wear rate

Two Swedish studies on different plow types, where the plow blades also were evaluated, have been conducted by VTI. The first VTI study, *"Miljöpligen, Meirenplogen och Mähler sidplog S45"* (31) was performed in the winter of 2009 testing three plow types. First, the Mijöplog, fitted with steel blades, was tested and compared with a reference plow with the same blade type. The test site was a public road and the surface conditions were bare asphalt in the wheel tracks and packed snow elsewhere. The wear was found to be 0.018 mm/km on average for the blades on Mijöplogen and 0.053 mm/km on average for the reference plow. A few months later during the same winter, similar testing was done for Meiren MSP 4603 also using steel blades. The test site was a public road with bare road conditions. Results were 1.7 mm/km for Meiren plow and 0.25 mm/km for the reference when looking at the overall wear of all blades along the plow. It was found from the tests that single blades experienced different wear depending on their position on the plow. The high wear rate in the Meiren plow indicated that regular steel blades may not be suitable for this type of plow.

The second VTI study *Meirinplogen* (32) was conducted in 2011 using the Meiren MSP 4603. Due to the bare road conditions during the first test in 2009 with this plow, it was decided to do another test during winter road conditions. A reference plow was also used this time. There were, however, some problems with measuring blade wear on the reference plow, so no results from the reference plow were found. For the Meiren plow the wear rate was found to be 0.008 mm/km on average, with a range of 0.00 and 0.02 mm/km depending on the blade position along the plow.

Schneider, Crow and Holik (16) studied blade wear during the 2013/2014 and 2014/2015 winter seasons. The number of trucks used in the study was 13 the first season and 20 the second season. A total of nine types or setups of blades where tested during the two seasons. Results from the study are presented as total average wear (in), total miles, wear rate (in/mile) and an equivalent standard blade ratio. The blade types and wear rates from this study are presented in Table 2.2. Another interesting thing from this study is the presentation of wear pattern over time along the plow.

Table 2.2: Type of blades and wear rate results (16).

Type of blade	First season (in/mile)	Second season (in/mile)	Both seasons (in/mile)
Carbide Single	1.16 E-03	3.27 E-03	1.89 E-03
PolarFlex	4.39 E-04	4.93 E-04	4.62 E-04
Standad	1.98 E-03	4.82 E-04	2.82 E-03
XL Classic	2.98 E-04	6.02 E-04	4.38 E-04
JOMA	4.00 E-04	-	-
Carbide Double	-	1.64 E-03	-
Double Stack	-	2.54 E-03	-
Middle Guard	-	2.57 E-03	-
No counterbalance	-	5.83 E-03	-

In the 2010/2011 winter season, Mastel (18) conducted tests to compare four different plow blade systems, where one blade set consisted of three blade sections. The tests included 85 sections of carbide steel blades, 15 sections of JOMA blades, 12 sections of Polar Flex Blades, and 6 sections of stacked carbide blades. The wear in inches was measured three places on each blade and noted in a form together with date, highway number, surface type, surface temperature, surface conditions, hours and miles plowed. There are no results giving wear in inches/mile for the different plow systems, but it may be possible to calculate from the data collected, which is presented in the report appendix. They found that the JOMA and Polar Flex lasted 3 to 4 times longer compared to carbide steel blades by comparing service life from recorded hours.

2.3.2 Distance until change

Gillis (27) studied five different types of blades used on graders and snowplows. By using a wheel mounted on the plow frame, the miles until failure was measured. Of the tested blades, carbide insert blade (2100 miles) were almost twice as durable compared with carbon blade (1200 miles), which where the second best when used for snowplowing.

A new combination blade was developed in Norway in the late nineties and tested for two winters seasons (17). This combi edge was made from three pieces of one-foot long U-shaped steels with tungsten carbide, and the U-shaped steels were encased in rubber. By using a lifetime test, the combi edge was compared with conventional scraper edges. It was found that the new combi edges lasted for 7000 km and the lifetime of conventional scraper blades was found to be 600 km.

In 2004, the Maine Department of Transportation presented results from a field comparison of traditional carbide insert blades and a new type of carbide insert blades with round isolated carbide inserts (13). The new type lasted 990 miles on average, whereas the traditional lasted 1150 on average. These result where also used as a basis for further research.

In winter 2008/2009, the Main Department of Transportation did tests on seven sets of standard carbide-insert blades, four sets of carbide-insert underbody scraper blades and two sets of Kuper Tuca SX36 (21). The blades were tested on interstate roadways (3 sets) and secondary roadways (4 sets). The average miles per set for the standard blade were 2124 for secondary roadways and 1711 on the interstate giving a total average of 1933 miles. The underbody blades lasted on average 3611 miles on secondary roads (2 sets) and 1505 miles on interstate roads (2 sets) giving a total average of 2558 miles.

In the following 2009/2010 winter season, Maine Department of Transportation experimented with three sets of Kuper Tuca SX36 snow plow blades (26). These results where compared with previous work on standard blades and measurements from previous Kuper Tuca SX tests. From this they estimated the wear life to be 3500 to 4500 miles.

A summary on JOMA blades from 2010 done by State of Ohio Department of Transportation (33) found that JOMA blades average plowing mileage varies from 3000 to 6000 depending on the location. By comparing with traditional blades used for the same locations, it was estimated that JOMA blades last 4 to 6 times longer than traditional blades. One of these comparisons looks at hours of service.

2.4 Tribology and wear mechanisms

2.4.1 Tibology in general

Tribology is defined as the science and technology of interacting surfaces in relative motion, including the study of friction, wear and lubrication (34). The book Engineering Tribology, states a definition of wear "*as the removal of material from solid surfaces as a result of mechanical actions.*" (35). The literature (35, 36) distinguishes between abrasive, erosive, cavitation, corrosive, fretting, adhesive, melting and fatigue wear mechanisms. Scanning Electron Microscopy (SEM) is a commonly used method to determine which type of wear mechanism have worn out or affected a surface (37).

In their work with road grader steel, Jacobson and Hogmark presents six tribological "*rules for reduced wear rate and failure*" (14), which also may be relevant for snowplow blade. These six rules are:

> *"Rule 1: Fight abrasive wear with decreased load (aim at small contact area)"*
> *"Rule 2: Fight abrasive wear with hardness"*
> *"Rule 3: Fight fracture with toughness"*
> *"Rule 4: Use consumable wear parts (minimize the amount of scrap)"*
> *"Rule 5: Use small exchangeable wear parts (fracture does not destroy complete scraper)"*
> *"Rule 6: Use wear resistant material only where needed (optimize the rest of the blade for toughness, scraping performance and cost)"* (14)

Further on in this literature review, the mechanisms which are found to be present during snow plowing or similar situations, will be addressed.

2.4.2 Abrasive wear

Abrasive wear occurs whenever a hard material surface slides over another material surface with the same or lower hardness. Even if the material is soft bulk it may lead to abrasive wear if it contains small hard particles (19). According to Moore (38) the energy dissipation during abrasive wear can be found as *kinetic and potential energy*, *sound* and *heat* and it is suggested that temperature changes may influence a materials wear rate in an abrasive wear situation.

An effect of high speed during abrasive wear is that weaker materials may cause wear on a harder material if the weaker material is kept cold and the stronger material is weakened by increased temperatures (19).

One can differentiate between two-body and three-body abrasive wear, depending on the conditions and interaction of the bodies involved (19, 35). In a road maintenance perspective, both are present when using a road grader blade (14). Therefore, it is likely that both are present during the similar operation, snowplowing.

Two-body abrasive wear
This type of wear occurs when two surfaces act directly on each other in a sliding motion. Two-body abrasive wear may also occur if smaller particles are rigid in a surface and another material surface slides against the particles; a typical example may be sandpaper (19). For road surfaces like asphalts abrasive elements, the aggregates, are bound to the road by bituminous binders, making the road surface into one body. When this is the case, two-body abrasive wear occurs (14). Figure 2.3 illustrates two-body abrasive wear.

Three-body abrasive wear
The other situation of abrasive wear occurs when a third body is introduced to the system as loose abrasives or particles, which are free to roll and slide in between the two surfaces (19). The effect of three-body abrasive wear is less than for two-body (14, 39). Figure 2.3 illustrates three-body abrasive wear.

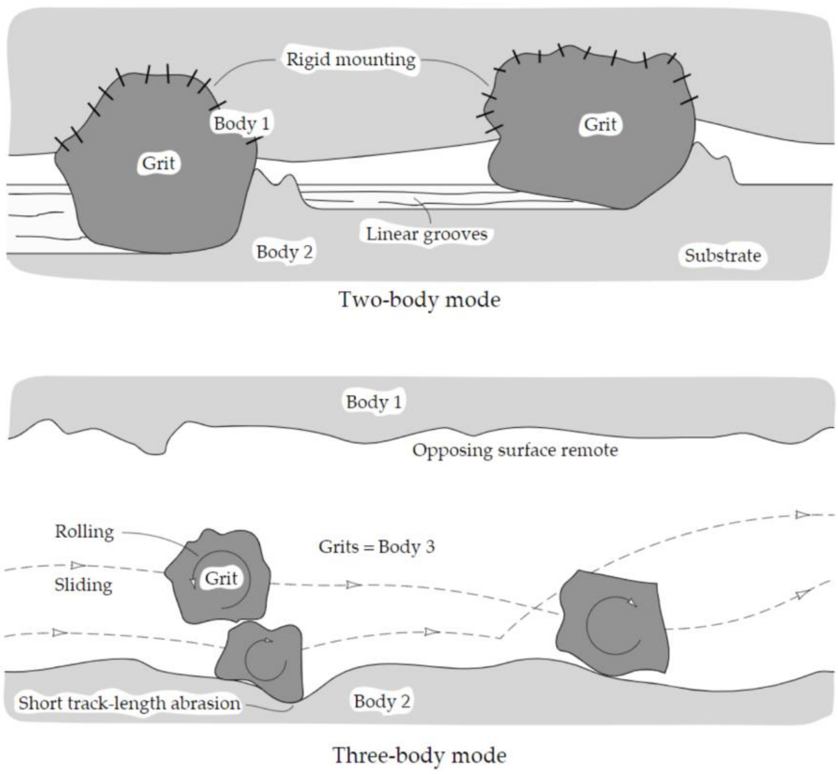


Figure 2.3: Illustration of two-body and three-body abrasive wear, from Engineering Tribology (19)

3 Method

This project is carried out in collaboration with the Norwegian contractor Mesta AS. Mesta is one of the main contractors in the winter maintenance field in Norway, operating over 40 maintenance contracts for NPRA (40). The method for this study will be a field test, continuously following Mesta during the 2019/2020 winter season, collecting data on blade wear.

3.1 Test site and plowing equipment

Test site for this study is a 22 km road section of the highway E6. Starting at Brubakkhaugen passing through Trondheim and ending at Ranheim. It is a four-lane road except for one part in the middle, which has six lanes. The designated snow removal area, called rode, also includes the highway ramps. A map of the rode is shown in Figure 3.1. The maintenance class set by NPRA is DkA, except for the most northern and southern parts which are DkB,high (41). This gives the test site an anti-icing strategy with strict requirements for approved road condition and measures implemented during weather events (8). Road surface on the test site consists of bituminous pavements of the type stone mastic asphalts (Ska) and asphalt concrete (Ab) (42). The maximum plowing speed under operation is limited to 40 km/h by regulations from NPRA (9).

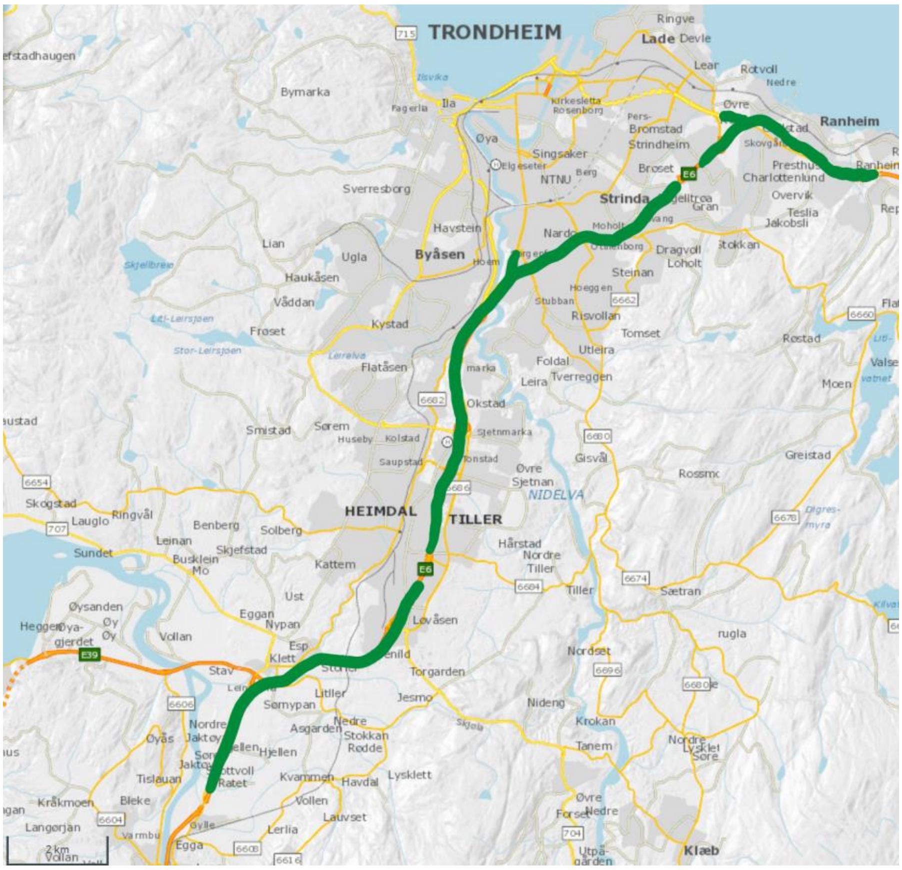


Figure 3.1: Map showing test site. Background map from vegkart.no (43).

To cover the whole width of the road and the adjoining highway ramps, five trucks in a gang plowing is used. The leading truck is one of Mestas own trucks, a Volvo FH540 8x2, while the others are operated by subcontractors. The Volvo is the truck followed in this thesis. It is equipped with a front combination plow of the type Meiren MSP 3704 LH, a wing plow and a brine spreading system, which may be in use in between plowing. Blades included in this study will be mounted on the Meiren MSP. There is room for six 2feet blades mounted with bolts on the Meiren MSP. The blades are mounted with bolts on the plow via blade holders made from polyurethane, which deforms and moves backwards when hitting obstacles (44). The equipment is shown in Figure 3.2.

Figure 3.2: Plowing equipment used. Volvo truck, Meiren MSP plow and wing plow. Blade holders are the black parts behind/ directly above the blades.

3.2 Snowplow blade types

During the 2019/2020 winter season, two types of snowplow blades were used on the Volvo truck with the Meiren MSP plow. Both blade types are reversible, meaning that they have two sides that can be worn out. The two types are Nordic Combi Double and a locally produced type which is called "Steel/polyurethane" in this thesis. Table 3.1 describes, and Figure 3.3 shows the two different types.

Table 3.1: Blade types in this study

Blade type	Description
Nordic Combi Double	Reversible blades, made out of steel plates with vulcanized rubber and ceramic cores in between (45). Blade thickness = 36 mm.
Steel/polyurethane	Locally produced reversible blades, made from steel plates with yellow polyurethane in between. These blades were produced in advance of an earlier winter season by a local producer, to be tested by Mesta. Blade thickness ≈ 47 mm.

Figure 3.3: Snowplow blades used by Mesta and tested in this thesis

3.3 Snowplow blade sets

To keep track of the blade sets, each set is given a name, which is combined by a letter (A-D) and a number 1 or 2. Each letter represents a group of six reversible plow blades. The number indicates which side of the reversible set is used, where 1 is before reversing and 2 is after reversing. For example, set C1 is the first side of group C, and C2 is the reversed side of group C. During the winter 2019-2020, a total of six set distributed on four groups where used. An overview of the blade sets in this study are presented in Table 3.2.

Table 3.2: Overview blade sets.

Set number	Blade type	Date mounted	Date replaced
A1	Nordic Combi Double	30.12.2019	26.12.2019
B1	Steel/polyurethane	26.12.2019	12.01.2020
B2	Steel/polyurethane	12.01.2020	30.01.2020
C1	Nordic Combi Double	30.01.2020	11.02.2020
C2	Nordic Combi Double	11.02.2020	17.03.2020
D1	Nordic Combi Double	17.03.2020	04.04.2020 (end measurements, D1 not replaced)

3.4 Blade position on plow

Previous studies found in the literature review have shown that different positions on the plow give different wear on the blades. For this reason, blade positions are recorded in this thesis. Inspired by VTI test method (23), and data collection sheet for blade wear given in this method, blade positions 1 to 6 for each set are defined from left to right when viewing the plow from the front. An illustration of this is presented in Appendix B.

To keep track of blades, they are engraved with numbers in the middle of both short edges, matching the position they have on the plow. These locations and engravings are chosen to minimize the risk of the numbers wearing away during plowing operations. Examples of markings are presented in Appendix B. The marking is done in a way which makes it possible to tell which side of the reversible blade is used first.

Another important thing is that the blades must be mounted in the same positions when they are reversed. Reversing and changing blades is done by the drivers, so they need to be informed about the system. Time and date of reversing and changing blade sets are also recorded.

3.5 Measurements of wear

A digital caliper with accuracy 0.03 mm is used for measuring the distance in millimeters from the lower installation holes to the lower edge of the blade. This gives two measurement points, left (L) and right (R) on each blade, and a total of twelve measurement points on the length of the plow. Measurement points are named by blade position number (1-6) and left or right side of blade, e.g. 2R (blade 2, right side) and 5L (blade 5, left side). An illustration of measuring points on a blade is presented in Appendix B.

Measurements are done before the blades are installed, during operations, and after removal. Measurement number with time and date are recorded to combine measurements with other data in further analysis. Table 3.3 contains an overview of number of measurements done for each blade set and total number of measurements. All the wear data and associated time data are logged in spreadsheets.

Table 3.3: Overview measurements

Set number	Number of measurements	Number of measurement points
A1	6	72
B1	6	72
B2	8	96
C1	5	60
C2	10	120
D1	8	96
Total	**43**	**516**

3.6 Accumulated wear

The amount for material worn away between each measurement is calculated and an average wear is found for each measurement. To figure out how the wear develops during plowing operations an accumulated wear is calculated. This is done by adding the accumulated average wear from the previous measurement, to the wear at each measurement point. Using MATLAB a boxplots showing accumulated wear versus accumulated plowing distance are made for each set. Raw data from measurements are presented in Appendix C.

3.7 Plowing data collection and processing

To be able to find the wear rate in mm/km, driving and plowing data is required. Collection of this data are done using the internal AVL system, which is used by Mesta to document and keep records of their production. Trucks are equipped with loggers and the following data is collected automatically during maintenance operations:

- **Type of production**
  Shows which equipment is in use (plow, wing plow, brine spreader, none, or a combination of these).
- **Time and date for production**
  Gives start and stop date and time for the different productions.
- **GPS location**
  Shows the location of the truck. This is shown as road reference (road number, HP and meter).
- **Distance for production**
  Kilometer driven for each type of production until type of production type is changed or the road reference is changed, typically if the truck enters a new HP.

From the AVL system, production reports containing all the information above are produced and provided from Mesta, starting at the end of November 2019 until April 2020. In addition, plowing km on the E39 highway for the Volvo truck is also provided, because the truck had to operate this road for practical operational reasons during the winter season. Appendix D presents an example how such a production report looks is Excel.

In-between each measurement the plowing kilometers is calculated by summing the distance for production, whenever the plow is included in production type. Any additional plowing kilometers from highway E39 is also added. This gives distance plowed between each measurement.

For each blade set a total plowing distance and an accumulated plowing distance are calculated. These values are presented in Appendix C.

3.8 Wear rate

Total wear rate [mm/km] for each set is calculated by dividing the total accumulated wear by the total plowing distance for each set, results are presented in Table 4.1. *Wear rate [mm/km]* for each measurement is calculated by dividing average wear for all the twelve measurement points by the plowing distance in between measurements, wear rates are also given in inches/mile. Results are presented in Appendix C.

3.9 Maximum theoretical wear and initial wear

Maximum theoretical wear can be defined as the possible wear before any damages are inflicted to the lower mounting holes or the blade holders/moldboard. In this case maximum theoretical wear is limited by the lower mounting holes. Damage to the mounting holes would make reversing of blades impossible. Because of the rake angle, maximum theoretical wear is reached when the wear on the backside of the blade reaches the lower mounting holes. At this point there will still be some material left on the front side of the blade.

Initial wear can be defined as the amount of material that needs to be worn away before full flat with is reached, this will vary depending on the rake angle and the thickness of the blade.

Figure 3.4 show a simplified cross section of the lower part of the plow and illustrates how maximum theoretical wear and initial wear is defined in this thesis. Using a rake angle of 19° and the width of the blade types, maximum theoretical wear is found to be 62.0 mm for Nordic Combi Double and 61.2 mm for Steel/polyurethane. The 19° rake angle comes from the product specification of the plow and is the angle Mesta tires to achieve when mounting the blades. However, the actual rake angle may deviate from this.

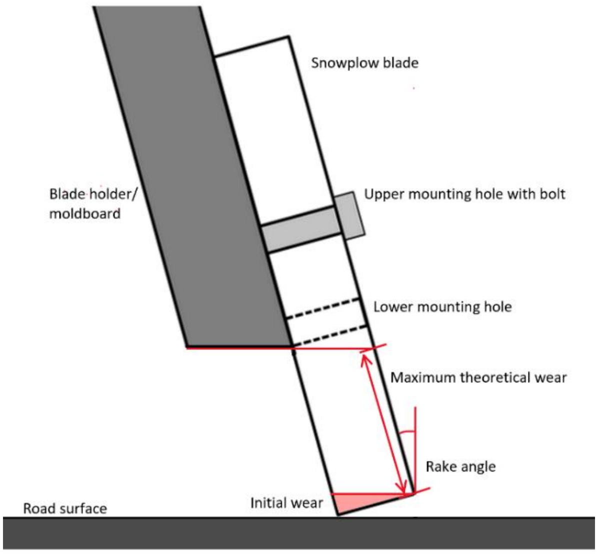


Figure 3.4: Cross section of blade. Maximum theoretical wear is marked with red double arrow, initial wear is marked by a red shaded field.

3.10 Weather data collection and processing

Information about the road surface condition is found in two ways the first one is based on weather data analyzis. Weather data includes air temperature, road surface temperature, precipitation, and relative humidity. This data is collected from weather stations on, or close to the test site. These stations are operated and owned by NPRA and Norwegian Meteorological Institute (MET). Data from NPRA weather stations are provided after contact with NPRA. Data from MET weather station are downloaded from eKlima (46), which is a service provided by MET. Figure 3.5 shows the weather station locations along the test site. Table 3.4 presents the type of data used from the weather stations and the time frequency of the data.

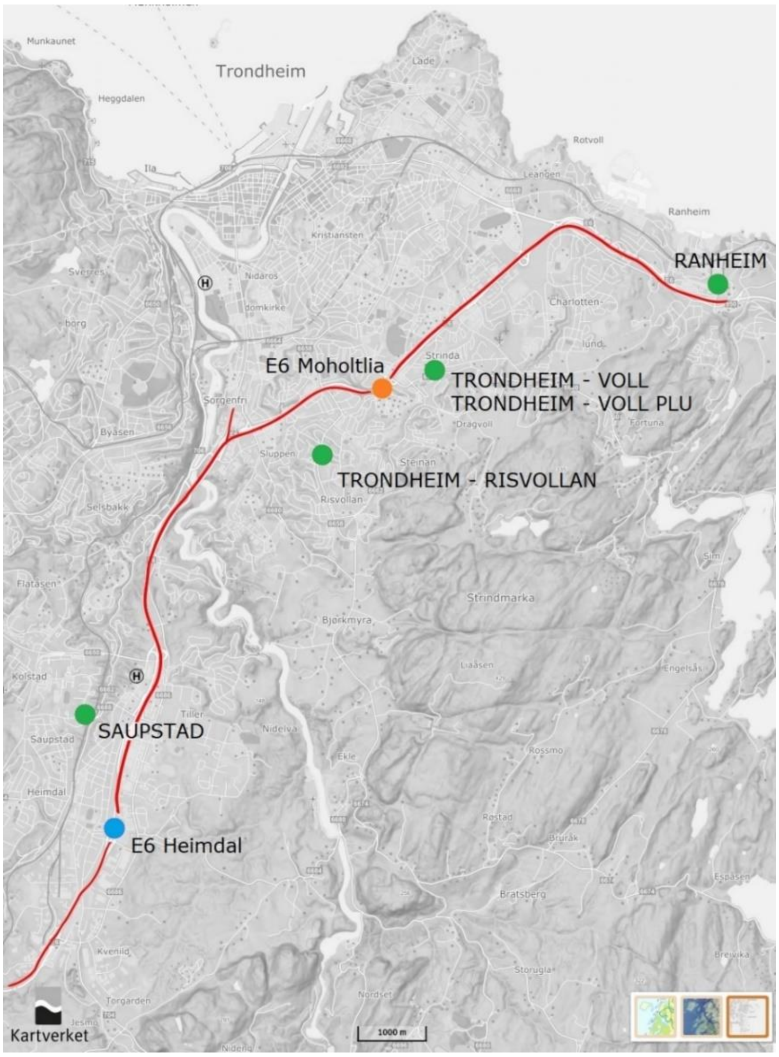


Figure 3.5: Data collection locations along the test site.
Green: MET weather station.
Orange: NPRA weather station.
Blue: Web camera, NPRA.
Background map from norgeskart.no (47).

Table 3.4: Weather stations and type of data

From	Station names	Data	Time frequency
MET	SAUPSTAD TRONDHEIM – RISVOLLAN TRONDHEIM – VOLL TRONDHEIM – VOLL PLU RANHEIM	Air temperature [°C] *(eKlima code: TA)* Precipitation (1 hour) [mm] *(eKlima code: RR_1)*	1-hour intervals
NPRA	E6 Moholtlia	Air temperature [°C] Relative humidity [%] Road surface temperature [°C]	10 min intervals

3.10.1 Precipitation as snow, from MET data

To find the precipitation as snow between measurements, air temperature and precipitation (water equivalents) from December to April, for all five MET weather stations presented in Table 3.4, are downloaded from eKlima and analyzed in excel. Using a static threshold temperature method (48), all precipitation is assumed as snow below, or equal to a threshold air temperature of 0.0 °C. The following condition is applied: if measured air temperature is above 0.0 °C at a weather station, corresponding precipitation is set to 0 mm. Afterwards, the weather station with the highest precipitation value at any given time (maximum value along the test site), is used to calculate the sum of water equivalents that have fallen as snow between each wear data measurement. Results are presented in Appendix E.

3.10.2 Road surface temperature

To find the average road surface temperature whenever the plow is lowered, data from production reports are combined with data from the NPRA weather station *E6 Moholtlia*. From production reports, the logged plowing distance is filtered out for each wear measurement. Each start time of plowing is linked to a corresponding road surface temperature. Weights are calculated as the percentage of the total plowed distance for each measurement and a weighted average is calculated for each wear data measurement. Results are presented in Appendix F.

3.10.3 Air temperature

Air temperature whenever the plow is lowered, is found by the same process as for road surface temperature in section 3.10.2. Weighted average values where the distance plowed is used as weight are presented in Appendix F.

3.10.4 Relative humidity

Relative humidity whenever the plow is lowered, is found by the same process as for road surface temperature in section 3.10.2. Weighted average values where the distance plowed is used as weight are presented in Appendix F.

3.11 Estimation of snow/ice coverage on road surface

The second method used to get information about the road surface conditions, is by an estimation of snow and ice coverage on the road surface, using picture data from the NPRA weather service *Vegvær* (49). From this service, pictures taken by the web camera *E6 Heimdalsmyra* is available. The location of the web camera is shown in Figure 3.5. Pictures from the camera are taken with 10 minutes intervals and saved in Vegvær. Appendix G shows how the Vegvær interface for web camera E6 Heimdaslmyra looks after logging in.

A total of 20 281 pictures, taken in the period 30.11.2019 – 21.04.2020 are downloaded from the Vegvær web application. On all the pictures, location, time, and date is shown in the upper left corner. Using MATLAB all the pictures are renamed so that the picture name equals the exact date and time shown on the picture.

New picture names are combined with plowing data from the production reports, to sort out the relevant pictures. If any plowing is logged between two pictures, both pictures are considered relevant.

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 3.5 presents the different coverage ranges, values, description, and example pictures. The visual assessment process is done five times to ensure a consistent assessment. The most frequently assigned value for each picture is used to interpolate a coverage value between two pictures. The estimated coverage as a function of time of passage *t,* Cov(t) is given by:

$$Cov(t) = \frac{Cov(t_1) - Cov(t_0)}{t_1 - t_0} \cdot (t - t_0) + Cov(t_0)\,, \qquad t_0 < t < t_1 \tag{3.1}$$

Subsequently a weighted average snow/ice coverage is calculated for each wear measurement, where the distance plowed between pictures are used as weights. Snow/ice coverage values for each measurement are presented in Appendix H.

Table 3.5: Snow/ice coverage on road surface

Coverage	Description/picture
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. <u>Clearly visible</u> 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. 

3.12 Linear regression

To evaluate the processed data described in section 3.10 and 3.11, together with wear rates, a linear regression data-tool in excel is used. This section gives a brief introduction to some basics in simple linear regression based on the book *Introduction to Linear Regression Analysis* (50). The focus is on interpretation of results prior to detailed descriptions of the regression calculation process.

3.12.1 Simple linear regression

Simple linear regression gives a straight-line model that shows the relationship of one single x input (regressor) and an output y (response). The general equation of a simple linear regression model is:

$$y = \beta_0 + \beta_1 x + \varepsilon \qquad (3.2)$$

Where β_0 and β_1 are regression coefficients and ε is the random error. β_0 is the intercept with y-axis and β_1 is the slope of the regression line, or the regressor coefficient.

3.12.2 Coefficient of determination, R^2

In linear regressions, a coefficient of determination, R^2 is found. R^2 is a measure of how well the linear regression fits the datapoints, and can be used to explain how much of the variation in y is caused by the x input. The R^2 ranges from 0 to 1. Values close to 1 indicates that a large proportion of the variation in y can be explained by x, and $R^2=1$ is a perfect fit of the datapoints to the regression line. Whereas values close to 0 indicates that a low proportion of the variation in y can be explained by x, and $R^2=0$ indicates that the datapoints do not fit the regression line at all.

3.12.3 Significance of regression

Testing significance of regression in a simple linear regression, to see if there is a significant linear relationship between x and y, can be done through the following hypothesis testing:

$$H_0\colon \beta_1 = 0, \quad H_1\colon \beta_1 \neq 0 \qquad (3.3)$$

"Failing to reject $H_0\colon \beta_1 = 0$ implies that there is no linear relationship between x and y" (50). "*Alternatively, if $H_0\colon \beta_1 = 0$ is rejected, this implies that x is of value in explaining the variability in y"* (50).

One way of testing significance of regression is by using an analysis-of-variance (ANOVA), which calculates a test statistic F_0. An ANOVA output is provided from the excel regression tool output where F_0 is given. Using this method H_0 is rejected (there is a significant linear relationship) if:

$$F_0 > F_{\alpha,1,n-2} \qquad (3.4)$$

Where $F_{\alpha,1,n-2}$ is found from distribution table in Appendix I. In the subscript, α is a chosen value related to the confidence interval. Whereas *n* is the number of observations.

4 Results

On the E6 highway through Trondheim, Mesta AS plowed around 6800 km of road, from the start of December to early April. This resulted in five worn out, or for some reason replaced snowplow blade sets. One set in this thesis relates to one side of a reversible snowplow blade (see section 3.3). Note that Nordic Combi Double set C1 was replaced due to another reason than wear and set D1 still was operating when the wear data collection stopped. For these reasons, C1 and D1 are not included when calculating average values for Nordic Combi Double, except for total wear rate values.

Table 4.1 contains results for each set and average values for each blade type. Total wear is the average wear along the plow when the set was replaced and is used together with total plowing distance to calculate total wear rate, which also are presented in inches/mile. Assuming a rake angle of 19°, maximum theoretical wear is 62.0 mm for Nordic Combi Double and 61.2 mm for Steel/polyurethane, see section 3.9 for more details. By comparing total wear and maximum theoretical wear, a utilization degree of the blade set is found. Using total wear rate and maximum theoretical wear, a theoretical distance if 100% utilization is calculated. By subtracting total plowing distance from theoretical distance if 100 % utilization, an unused mileage is found. Unused mileage is given in km and % of theoretical distance. Reason for replacement are also presented.

Table 4.1: Wear-out results for each blade set

Set	Total Wear [mm]	Total Plowing dist-ance	Total wear rate		Utiliz-ation degree	Theoretical distance if 100 % utilization	Unused mileage	Reason for replacement
			[mm/ km]	[inch/ mile]				
Nordic Combi Double								
A1	54.72	1804 km	0.030	1.92 E-03	88.3 %	2044 km	240 km (11.7 %)	Blade 3 and 5 worn out. Blades could not be reversed, see section 4.4.2.
C1	20.52	598 km	0.034	2.18 E-03	33.1 %	1806 km	1208 km (66.9 %)	Blade 3 worn in an improper way due to broken blade holders, see section 4.4.5
C2	55.76	1801 km	0.031	1.96 E-03	89.9 %	2003 km	202 km (10.1 %)	Blade 3, 4 and 6 worn out.
D1	39.94	981 km	0.041	2.58 E-03	64.4 %	1523 km	542 km (35.6 %)	Data collection on wear stopped before reversing/ change was needed.
Avg.	55.24	1803 km	0.034*	2.09 E-03*	89.1 %	2023 km (1844 km**)	221 km (10.9 %)	
Steel/polyurethane								
B1	47.72	931 km	0.051	3.25 E-03	78.0 %	1210 km	279 km (23.0 %)	Blade 5 and 6 worn out
B2	36.68	645 km	0.057	3.60 E-03	59.9 %	1090 km	445 km (40.8 %)	Blade 5 worn out
Avg.	40.20	788 km	0.054	3.39 E-03	69.0 %	1150 km	362 km (31.5 %)	

* *C1 and D1 values are included in the average calculation of total wear rate for Nordic Combi Double.*
** *Calculated by using the total wear rate where C1 and D1 is included.*

For all sets the utilization degree in Table 4.1 is significantly lower than 100 %, varying from 33.1 % up to 89.9 % for Nordic Combi Double, and from 59.9 % up to 78.0 % for Steel/polyurethane. The reasons for change also varies, however blade number 5 was worn out in 75 % of the worn-out sets. Blade number 3 and 6 are also mentioned as worn out two times.

Total wear and total plowing distance differ for all the sets, except for A1 and C2, but the wear rate is similar for the same blade type. Comparing the two blade types, the average total wear rate for Steel/polyurethane of 0.054 mm/km is 58.82 % higher than the Nordic Combi Double value of 0.034 mm/km, indicating that Steel/polyurethane wears down faster than the Nordic Combi Double. The operational lifetime given as average total plowing distance is 1803 km for Nordic Combi Double, which is 1015 km higher than Steel/polyurethane operational lifetime of 788 km. Resulting in a 56,3 % lower plowing distance for Steel/polyurethane compared to Nordic Combi Double sets. This also supports more lifetime for Nordic Combi Double.

Nordic Combi Double have an average estimated distance if 100 % utilization of 2023 km when only considering set A1 and C2. If the average wear rate for all Nordic Combi Double sets of 0.034 mm/km is used, the theoretical distance if 100 % utilization becomes 1844 km, which is 694 km more than Steel/polyurethane. Resulting in a 37.6 % lower theoretically estimated plowing distance for Steel/polyurethane compared to Nordic Combi Double. Comparing unused mileage, the Nordic Combi Double (only A1 and C1) have less unused mileage (221 km) than Steel/polyurethane (362 km). In percent Steel/polyurethane had 20.6 % more unused mileage after the sets were worn out.

Another important result is that unexpected problems can happen during plowing operations, which might reduce the lifetime of a blade set significantly (set C1). The number of blade sets tested is too low to draw any conclusions of how often one could expect early replacement, such as C1, to occur.

4.1 Wear development and wear rate

4.1.1 Accumulated wear each set

To illustrate the wear development during plowing operations, boxplots plotting accumulated wear [mm] are made, where the boxes are plotted against plowing distance [km] on the x-axis. Plots for Nordic Combi Double and Steel/polyurethane are presented in Figure 4.1 and Figure 4.2, data is from Appendix C. The boxes show the variability of wear from twelve points along the plow for each measurement, represented by the upper and lower quartile, and upper and lower whiskers. Any outliers are marked with a red cross. Median values for each measurement are marked with a red line inside the boxes, and accumulated average values are presented with blue dots and a dotted blue line. A maximum theoretical wear line is also given at 62.0 mm for Nordic Combi and 61.2 mm for Steel/polyurethane, see section 3.9.

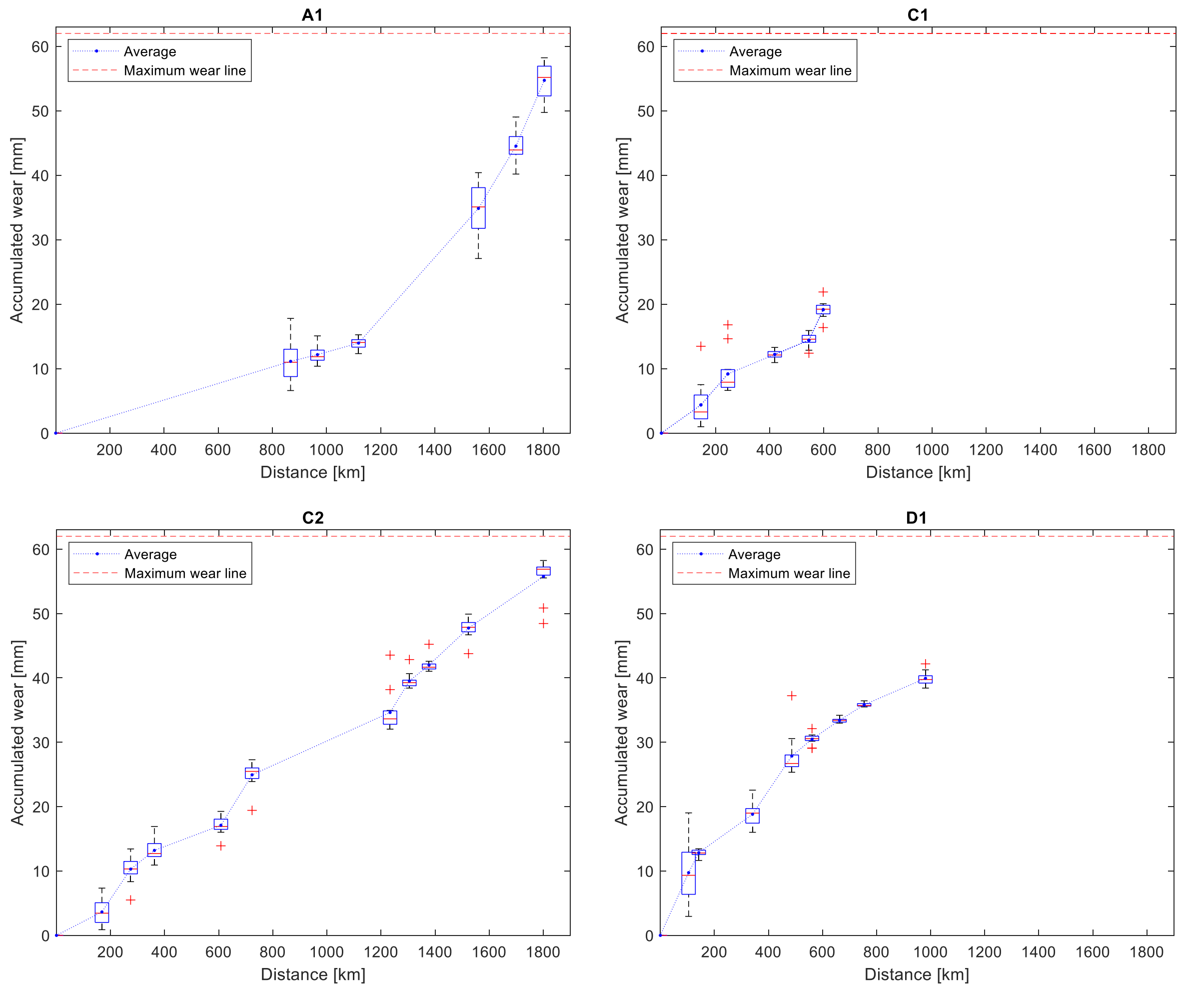


Figure 4.1: Accumulated wear Nordic Combi Double sets

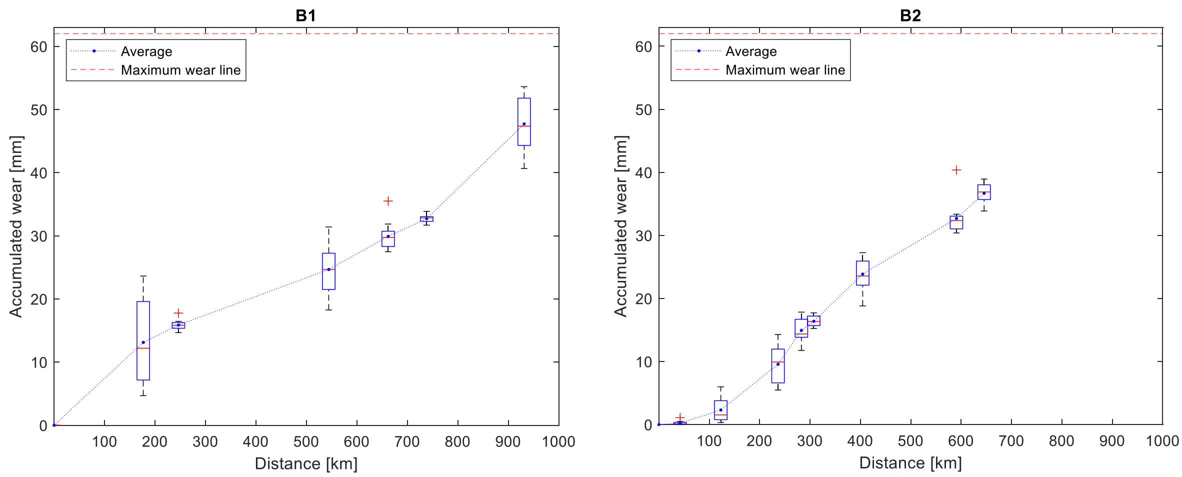


Figure 4.2: Accumulated wear Steel/polyurethane sets

The boxplots in Figure 4.1 and Figure 4.2 illustrates that the wear varies between measurements, and the angle and slope between average datapoints, which illustrates the wear rate, varies significantly. There seems to be no systematic development of the wear and wear rate during plowing operation just by looking at these plots. A more direct comparison of the sets is done in subsection 4.1.3.

Looking at the individual boxes representing each measurement, the range of the wear along the plow varies between sets, but also between measurements in the same set. For some measurements, the wear is even along the length of the plow resulting in short boxes and short whiskers, e.g. measurement number 2, 6, and 7 in set D1. Others have tall boxes and long whiskers, e.g. measurement number 1 in set D1, and measurement 1, 3 and 6 in set B1. Some outlier values are found in all the sets except for set A1.

In set B2 (Figure 4.2) the first measurement shows very little wear. This measurement was taken after only 42 km of plowing. Because of how wear is measured in this thesis (lower mounting hole to lower front edge of blade) and rake angle, a change in wear cannot be notices until the lower front edge is in contact with the asphalt. This first measurement illustrates the initial wear on the blade sets, before the full flat width is achieved.

4.1.2 Wear rate distribution

Distributions of wear rate [mm/km] for the two blade types are presented in Figure 4.3. The wear rate in these charts are the wear rate along the plow for each measurement presented in Appendix C. The values are sorted into sections of 0.02 [mm/km] to find a frequency distribution.

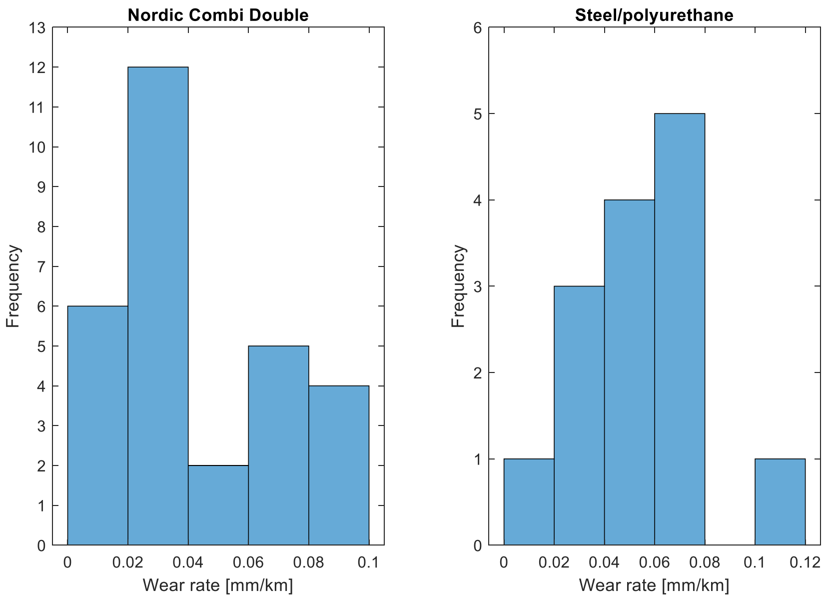


Figure 4.3: Average wear rate distributions for measurements, sorted by blade types

Figure 4.3 illustrates the variation in wear rate from the individual measurements. Supporting the observation that the wear rate varies, from section 4.1.1. The highest frequency for the Nordic Combi Double corresponds to a lower wear rate than for Steel/polyurethane. Note that there are more data points for Nordic Combi Double than for Steel/polyurethane. The highest individual wear rate value is found for Steel/polyurethane, and lies between 0.1-0.12 mm/km.

4.1.3 Accumulated wear all sets comparison

From previous subsections it is found that the development of wear varies from set to set and the type of blade. A plot that compare the sets and blade types are presented in Figure 4.4. This plot shows the development of the average accumulated wear for each set, and the blade type. The graphs are the same as in Figure 4.1 and Figure 4.2, only without boxes.

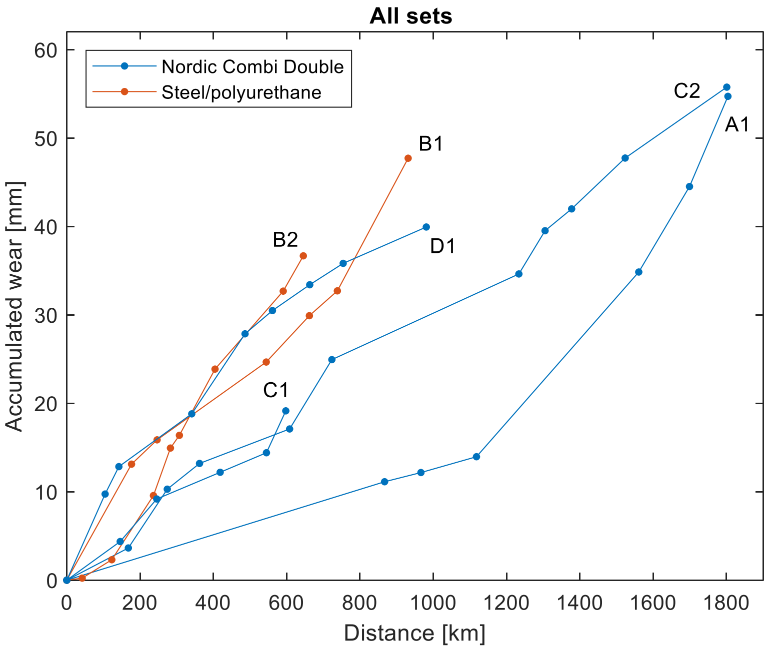


Figure 4.4: Accumulated wear all sets

From Figure 4.4 the variation in wear development between sets can be observed more clearly. The Steel/polyurethane blades seems to wear out faster than the Nordic Combi Double, with a steeper slope (higher wear rate). However, the D1 set follows the Steel/polyurethane development for the first five measurements, around 500 km. The high wear rates in the beginning of set D1 can also be observed in Appendix C, where there are tree high wear rate values in the first four measurements.

Keeping in mind that set C1 was changed for another reason than wear and the data collection was stopped before D1 required replacement, Figure 4.4 also illustrates that plowing distance (operational lifetime) is greater for Nordic Combi Double than for Steel/polyurethane.

4.1.4 Wear along plow

To see how the wear develops along the length of the plow, for the blade sets that were worn out (A1, C2, B1 and B2), the wear from each measurement is plotted as a line through the twelve individual measurement points (1L to 6R) in Figure 4.5. The visualization is inspired by *"Investigate plow blade optimization"* (16). Each line in the plots represents a measurement, where the upper line in each plot is the last measurement (set worn out), and the lower line is the first measurement in a set. For each new measurement, the increase in wear at each point on the plow, is added to the previous measurement. Note that this differs from the accumulated wear used in section 4.1.1 and 4.1.3, where the values were added to the average value from the previous measurement.

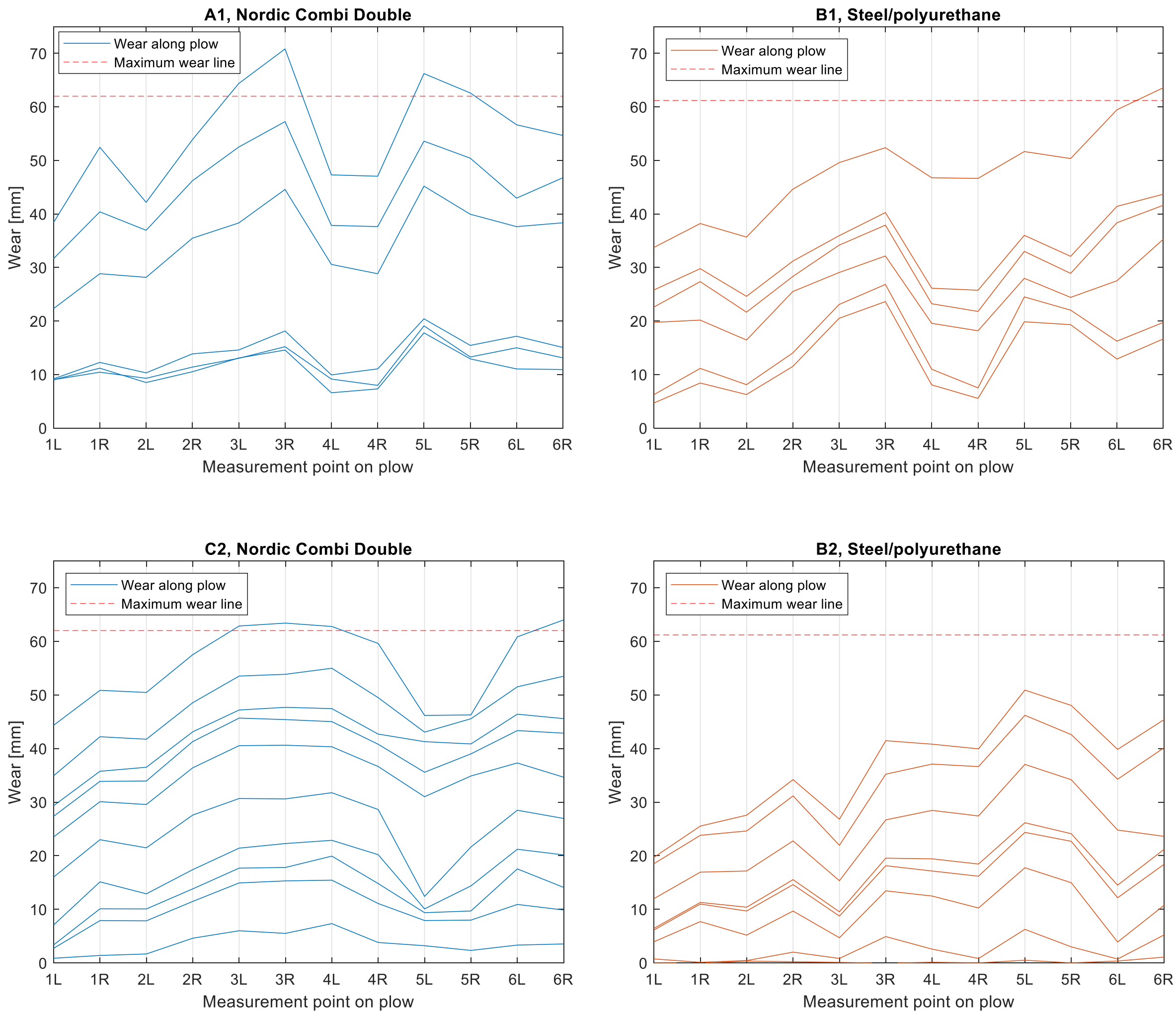


Figure 4.5: Plots of wear along plow, A1, C2, B1 and B2

From Figure 4.5 it is clearly visible that the wear differs along the length of the plow for all blade sets, depending on the blade position. For all sets except B2, the maximum theoretical wear line was passed for at least one measurement point before the set was considered worn out by one of the drivers. The lowest wear is found in position 1L for all blades, and it might be possible to spot some patterns from rutting in the road. However, the positions of rutting pattern are not consistent when all sets are compared. The difference between the maximum and minimum wear when a set is worn out are, A1 = 32.43 mm, C2 = 19.66 mm, B1 = 29.83 mm, and B2= 31.20 mm. The difference given in percent of the maximum values are, A1 = 45.8 %, C2 = 30.7 %, B1 = 46.9 %, and B2 = 61.3 %. These values indicate that Steel/polyurethane experience more uneven wear than Nordic Combi Double. However, the number of observations is to low to draw any conclusion.

4.2 Wear rate as function of weather factors

Scatter plots of wear rate for each measurement (Appendix C) versus different weather factors: precipitation as snow, road surface temperature, air temperature, and relative humidity are presented in the following subsections. Each point in the plots represent a single measurement. For each weather factor and blade type, a simple linear regression to predict wear rate based on weather factor is performed in excel. The regression lines are illustrated with dashed blue lines, and the corresponding regression equations and R^2 values are presented in the top corners. All the analyses were done with an $\alpha = 0.10$, giving a confidence level of 90 %. Using the test for significance of regression described in section 3.12.3, the significance of the regression is evaluated for each weather factor and blade type. There is a significant linear relationship if conditions in Equation 3.4 is satisfied.

4.2.1 Precipitation as snow

Using the processed precipitation data from the five MET weatherstations along the test site (Appendix E), scatter plots of wear rate [mm/km] versus precipitation as snow [water equivalents, mm] are made for each blade type. Plots are presented in Figure 4.6.

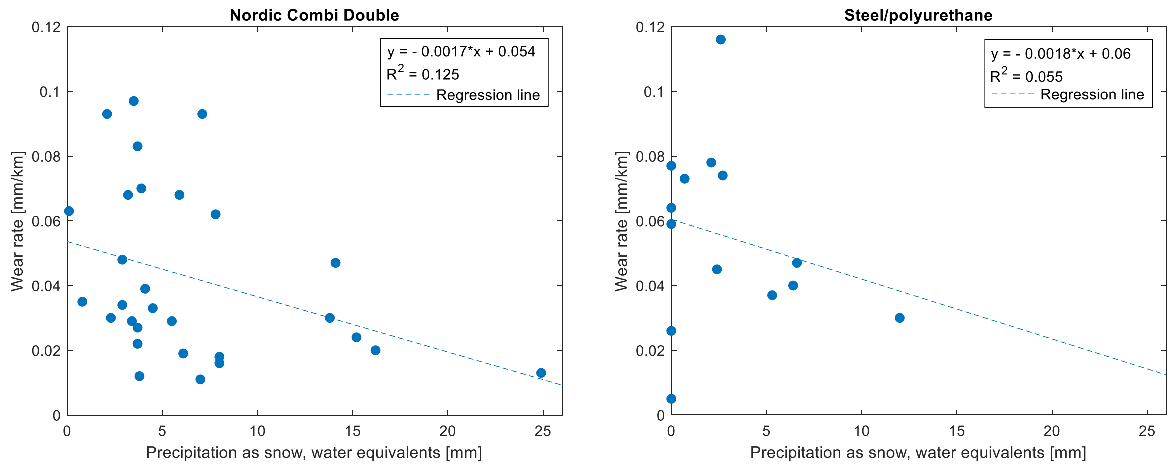


Figure 4.6: Wear rate versus precipitation as snow

In Figure 4.6 the regression lines for both blade types implies a decreased wear rate with increased amount of snow. The slopes of the regression lines are also similar.

For Nordic Combi Double the simple linear regression resulted in a significant regression equation $(F_0(1,27) = 3.840,\ p < .060)$ with a precipitation coefficient of -0.0017, intercept value of 0.054, and R^2 of 0.125. This implies that a linear relationship exists between wear rate [mm/km] and the amount of precipitation as snow [mm]. The R^2 value indicates that 12.5 % of the variation in wear rate on Nordic Combi Double can be explained by the amount of precipitation as snow.

For Steel/polyurethane the simple linear regression resulted in a non-significant regression equation $(F_0(1,12) = 0.691,\ p < .422)$ with a precipitation coefficient of -0.0018, intercept value of 0.06, and R^2 of 0.055. The non-significant linear regression indicates that there is no certain linear relation between wear rate and precipitation as snow for the collected data on Steel/polyurethane.

4.2.2 Road surface temperature

Scatter plots of wear rate [mm/km] versus road surface temperature [°C] for the two blade types are presented in Figure 4.8. Road surface temperature data comes from the NPRA weather station *E6 Moholtlia* (Appendix F).

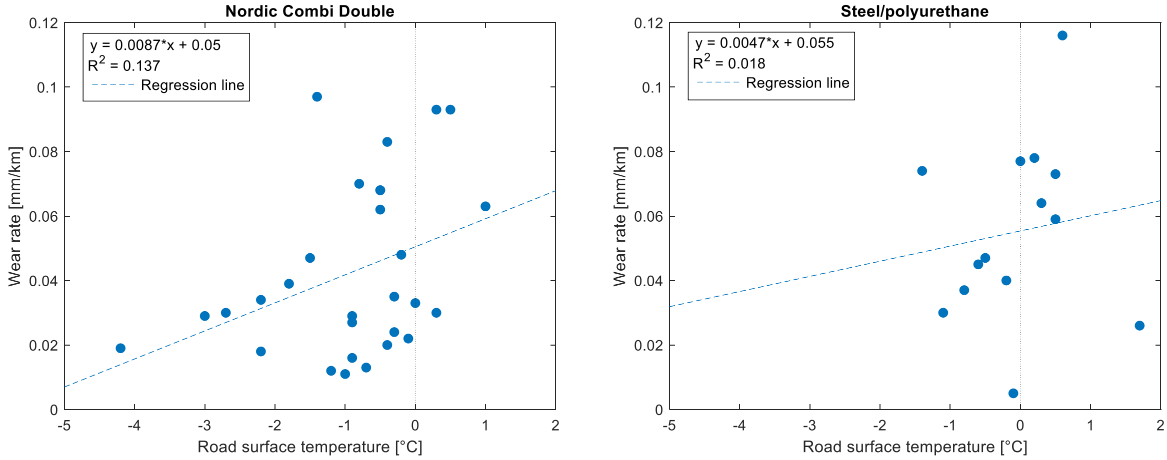


Figure 4.7: Wear rate versus road surface temperature

In Figure 4.7 the regression lines for both blade types indicates an increased wear rate with higher road surface temperatures.

For Nordic Combi Double the simple linear regression resulted in a significant regression equation ($F_0(1,27) = 4.276,\ p < .049$) with a road surface temperature coefficient of 0.0087, intercept value of 0.05, and R^2 of 0.137. This implies that a linear relationship exists between wear rate [mm/km] and road surface temperature [°C]. The R^2 value indicates that 13.7 % of the variation in wear rate on Nordic Combi Double can be explained by road surface temperature.

For Steel/polyurethane the simple linear regression resulted in a non-significant regression equation ($F_0(1,12) = 0.219,\ p < .648$) with a road surface temperature coefficient of 0.0047, intercept value of 0.055, and R^2 of 0.018. The non-significant linear regression indicates that there is no certain linear relation between wear rate and road surface temperature for the collected data on Steel/polyurethane.

4.2.3 Air temperature

Scatter plots of wear rate [mm/km] versus air temperature [°C] for the two blade types are presented in Figure 4.8. Air temperature data comes from the NPRA weather station *E6 Moholtlia* (Appendix F).

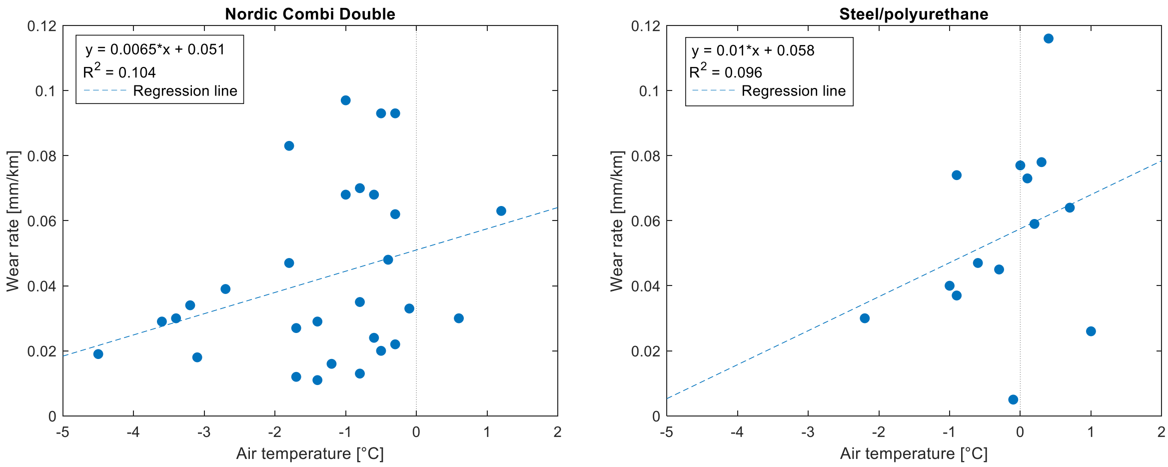


Figure 4.8: Wear rate versus air temperature

In Figure 4.8 the regression lines for both blade types indicates an increased wear rate with higher air temperatures.

For Nordic Combi Double the simple linear regression resulted in a significant regression equation ($F_0(1{,}27) = 3.120,\ p < .089$) with an air temperature coefficient of 0.0065, intercept value of 0.051, and R^2 of 0.104. This implies that a linear relationship exists between wear rate [mm/km] and air temperature [°C]. The R^2 value indicates that 10.4 % of the variation in wear rate on Nordic Combi Double can be explained by air temperature.

For Steel/polyurethane the simple linear regression resulted in a non-significant regression equation ($F_0(1{,}12) = 1.269,\ p < .282$) with an air temperature coefficient of 0.01, intercept value of 0.058, and R^2 of 0.096. The non-significant linear regression indicates that there is no certain linear relation between wear rate and air temperature for the collected data on Steel/polyurethane.

4.2.4 Relative humidity

Scatter plots of wear rate [mm/km] versus relative humidity [%] for the two blade types are presented in Figure 4.9. Relative humidity data comes from the NPRA weather station *E6 Moholtlia* (Appendix F).

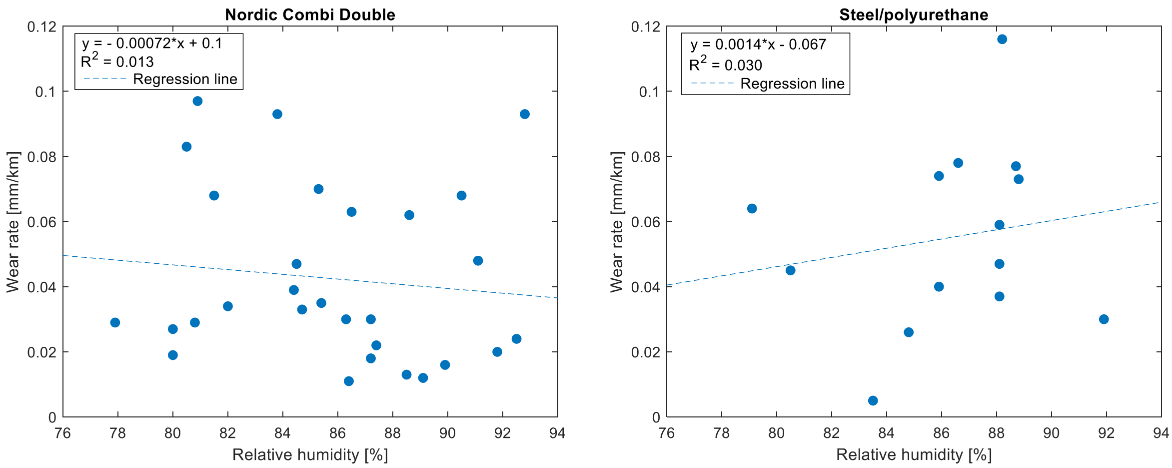


Figure 4.9: Wear rate versus relative humidity

In Figure 4.9 the regression lines indicate opposite effects of relative humidity on wear rate for the two blade types. The points are also relatively scattered.

For Nordic Combi Double the simple linear regression resulted in a non-significant regression equation $(F_0(1{,}27) = 0.349,\ p < .559)$ with a relative humidity coefficient of -0.00072, intercept value of 0.1, and R^2 of 0.013. The non-significant linear regression indicates that there is no certain linear relation between wear rate and relative humidity for the collected data on Nordic Combi double.

For Steel/polyurethane the simple linear regression resulted in a non-significant regression equation $(F_0(1{,}12) = 0.371,\ p < .554)$ with a relative humidity coefficient of 0.0014, intercept value of 0.067, and R^2 of 0.030. The non-significant linear regression indicates that there is no certain linear relation between wear rate and relative humidity for the collected data on Steel/polyurethane. These results suggest that the relative humidity have a low impact on the wear rate.

4.3 Wear rate as function of snow/ice coverage

To look for any correlation between wear rate [mm/km] and estimated snow/ice coverage [%], scatter plots of wear rates [mm/km] (Appendix C) and estimated snow/ice coverage (Appendix H) for the two blade types are presented in Figure 4.10. Each point represents a single measurement. For each blade type a simple linear regression to predict wear rate based on snow/ice coverage is performed in excel. The regression lines are illustrated with dashed blue lines, and the corresponding regression equations and R^2 values are presented in the top right corners. As for the weather factors in the previous section, the analyses were done with an α = 0.10, giving a confidence level of 90 %. Using the test for significance of regression described in section 3.12.3, the significance of the regression is evaluated for each weather factor and blade. There is a significant linear relationship if conditions in Equation 3.4 is satisfied.

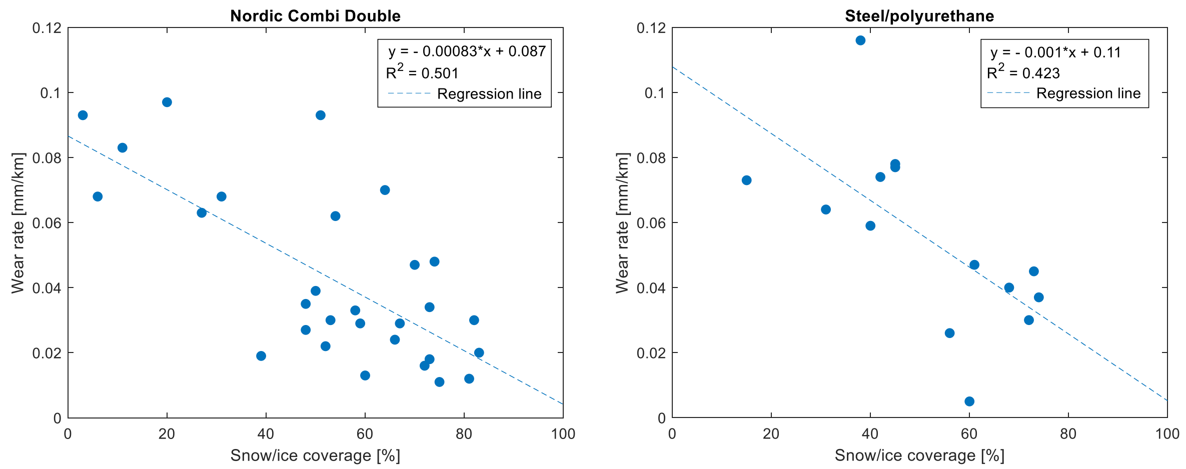


Figure 4.10: Wear rate versus snow/ice coverage

In Figure 4.10 the regression lines for both blade types indicates a decreased wear rate with increased snow/ice coverage. For Nordic Combi Double the simple linear regression resulted in a significant regression equation $(F_0(1{,}27) = 27.063,\ p < .000)$ with a snow/ice cover coefficient of -0.00083, intercept value of 0.087, and R^2 of 0.501. For Steel/polyurethane the simple linear regression resulted in a significant regression equation $(F_0(1{,}12) = 8.783,\ p < .012)$ with a snow/ice cover coefficient of -0.001, intercept value of 0.11, and R^2 of 0.423. Note that if α =0.05, corresponding to a 95 % confidence level, the regressions for both blade types would still be significant.

This implies that a linear relationship exists between wear rate [mm/km] and snow/ice coverage [%]. Increased amounts of snow/ice on the road reduces the wear rate of the plow blades. The R^2 values indicates that 50.1 % of the variation in wear rate on Nordic Combi Double and 42.3 % of the variation in wear rate on Steel/polyurethane can be explained by snow/ice coverage.

Comparison of the two methods for evaluating road surface condition (this section and section 4.2), shows that snow/ice coverage can explain difference in wear rates significantly better than the individual weather factors. Some trials on finding a multiple linear regressions equation, where several of the weather factors are included were done, to investigate if this could improve the weather data results. However, the snow/ice coverage was still significantly better.

4.4 Observations during operations

This section presents observations that have been made during the wear data collection process. Some are directly related to why blade sets were changed; others are more general observations.

4.4.1 Incorrect mounting of blades

Nordic Combi Double set A1 was first mounted incorrect, using the lower mounting holes instead of the upper. By using the lower holes, the distance from the bolts to the lower edge of the blade is around 73-74 mm. Using the upper holes, the distance from the bolts to the lower edge of the blade is around 103-104 mm, adding 30 mm of possible wear. For the Steel/polyurethane blades, the difference between using the upper and lower mounting holes would also be around 30 mm. Incorrect mounting of blades could therefore reduce the possible wear with 30 mm, or 48-49 % depending on blade type.

4.4.2 Blades worn down too far

For set A1 blade number 3 and 5 were worn down all the way until the backside of the lower mounting holes were damaged. Figure 4.11 shows the backside of the mounting holes where there is very little, or no steel material left for mounting when reversing the blades. These holes were supposed to be the upper mounting holes when the blades were to be reversed into what should have been set A2. Instead of reversing set A1 it was replaced with set B1. Leaving an unused blade set (A2) useless.

Figure 4.11: Damaged mounting holes, from blades worn down too far

4.4.3 Failing bolts

Two failures of mounting bolts during plowing operations have been observed. Resulting in the blade hanging down on one side as shown in Figure 4.12. Bolt failures occurred:

> 21.01.2020 set B2 measurement 2, bolt in position 6L failed.
> 24.02.2020 set C2 measurement 4, bolt in position 5L failed.

The effect on the wear of the failing bots can be found by looking at the individual measurement points on the plow. For both cases, reduced wear can be observed in Figure 4.5. The measured wear is low for these points compared with the sounding points.

Figure 4.12: Bolt failed set B2, position B6L

4.4.4 Bended blade

After an impact with a curbstone around 12.01.2020 blade number 6 became bent because of damages to the blade holders. This condition affected blade number 6 in set B2 and C1 before the blade holders were replaced. Figure 4.13 shows how blade 6 is pointing slightly more outwards on the left side compared to the rest of the plow. Resulting in lower rake angles for blade 6 in set B1 and C1.

Figure 4.13: Bended blade, due to damaged blade holders

4.4.5 Broken blade holders

Blade holders behind blade number 3 failed 05.02.2020. The result was that blade 3 in set C1 was pushed down and dragged along the surface while plowing, instead of cutting. Figure 4.14 shows how the situation was for blade 3 until the blade holders were replaced. When the blade holders were replaced blade 3 was useless, and much material was worn away on this blade in an improper way, compared to the others. Therefore, the entire set had to be revered.

Figure 4.14: Broken blade holders

4.4.6 Steel chipping

On some blades, chucks of steel have been lost. Expecially in the front of the plow (blade position 6) were several of the sets experienced rounded corners. But steel chipping was also observed other places in the middle of the plow, as snow in Figure 4.15. Steel chipping is likley caused from impact with obstructions in the road. However, steel chipping did not seem to influence the wear rate in any way, and no limitations on blade life were observed due to steel chipping in this thesis.

Figure 4.15: Steel chipping on Nordic Combi Double in one of the center plow positions

4.4.7 Steel buckling

Throughout the winter, steel was often observed to curl in frot of the lower edge of the blades. However, the amount and thickness varied. Figure 4.16 presents some example pictures, one where blades are mounted on the plow, and one after a blade is removed after both sides are used. The bucling is plastic deformation of the steel, which might occure when temperature rises and softes the materal, resulting in a flow of material under the preasure of the blade forces (51), and is likely caused by excessive heat generation from the scraping process. This steel buckling effect might not influence the wear rate directly. It will probably influence the plowing results because of a "ski tipp effect", which pushes the plow over the snow, compressing, instead of scraping and removing snow and ice. However, the heat that causes the steel buckling might increase the blade temperature, which influence wear rate (38) and the blade lifetime (15). This was experienced in an another study on Kuper Tuca SX composite blades, where an early failure of the blades occurred due to heat, which caused the rubber in the blades to melt (21).

Figure 4.16: Steel buckling on blades

4.5 Factors influencing blade lifetime

4.5.1 Factors from litterature review

A summary of the factors influencing blade wear, which was identified in the literature review, are presented in Table 4.2. Because these factors influence blade wear, they also influence expected lifetime of snowplow blades. Factors are sorted into five categories, with sub factors. This sorting is inspired by Jacobson and Hogmark's work on road grading steels "*The tribo-technical system of the grader blade*" (14). For more details about the factors, see section 2.1.

Table 4.2: Summary of factors identified in literature review, influencing blade lifetime

Category	Sub factor	Source
Material properties (15-18)	Hardness	(12, 14, 15)
	Toughness	(12, 14, 15, 20)
	Blade design	(14, 17)
Operating variables	Plowing speed	(15, 16, 18, 21)
	Plowing distance	(13-15)
	Blade angle	(15, 21)
	Load on blade	(14, 15)
	Position of blade	(15, 16, 23)
	Plow adjustment	(9)
	Tire pressure	(9)
Road surface (16)	Pavement material	(12, 13, 15, 18)
	Rutting	(15)
	Obstructions	(13, 15, 25)
	Snow cover	(15, 21)
Weather conditions	Air temperature	(15)
	Surface temperature	(15)
	Number of weather events	(18)
	Precipitation	(18)
Snow and ice characteristics	Material plowed	(15)
	Snow density	(15)
	Abrasives or chemicals	(15)
Driver or operator dependent factors (15)	Operator variability	(16)
	Operator technique	(18)
	Skill of driver	(14)

4.5.2 Factors from conversations with Mesta

Factors that have been addressed in conversations with Mesta employees, which may influence wear and lifetime of snowplow blades (in addition to the ones listed in Table 4.2) are: use of skid shoes or support wheels, use of slush blades, and amount of brine stored in the truck (with a full brine tank, 14 m^3 of brine is added to the weight of the truck). All these factors may influence the load on the snowplow blades.

Other operator dependent factors were also discussed in relation to of the observations mentioned in section 4.4. Failing bolts, bended and broken blade holders, and steel chipping, are results of impacts with obstructions in or along the road surface. Whereas incorrect mounting of blades and blades worn down too far, are driver or operator dependent factors.

5 Discussion

5.1 Operational liftetime of snowplow blades

In Table 4.1 operational lifetime for blades given in plowing distance are found to be 1803 km for Nordic Combi Double blades and 788 km for Steel/polyurethane blades. Wear rates was found to be 0.034 mm/km for Nordic Combi Double and 0.054 mm/km for Steel/polyurethane. Resulting in a greater potential for Nordic Combi compared to Steel/polyurethane. The reason for the difference in results for the two blade types, are most likely due to different material properties, since they were tested on the same truck, plow, and road, using the same drivers. This result was as expected by the drivers based on subjective experience from previous winter seasons. The Nordic Combi Double blades performed better than Steel/polyurethane, even though they are 11 mm thinner. A Steel/polyurethane blade with 36 mm thickness would probably wear out even faster due to increased loads when the surface area is reduced. Therefore, the material combination used in Nordic Combi Double is preferable.

By comparing the wear rates in inches/mile for the blades in this thesis, with previous results from studies on snowplow blade wear presented in Table 2.2, it can be observed that the blades in this study are among the fastest worn out blades, with 2.09 E-03 inched/mile for Nordic Combi Double and 3.39 E-03 inches/mile for Steel/polyurethane. However, the magnitude is about the same size as these previous results, in addition to the magnitude from the two Swedish studies (31, 32). This indicates that wear rate results from this thesis are reasonable.

Similarly, the operational lifetime (plowing distance before change) found can be compared with studies presenting results on distance until change in section 2.3.2. The blades in this study performed poorer than many of the other reported results. The reason for this might be that blades in this thesis plowed a lot on almost bare wet pavement due to the anti-icing strategy, whereas this was not the case for several of the previous studies, or the road conditions where not reported. Considering the Norwegian conditions, both blades lasted longer than the lifetime of conventional blades (600 km) found in *"New cutting edge for snowploughs and graders"* (17).

If the wear rate, dimensions, and rake angle for a snowplow blade type is known, the operational lifetime can be predicted. First a maximum theoretical wear must be found, and from this, an expected plowing distance for a blade set if it is worn out 100 %. In this thesis the theoretical distance if 100 % utilization was 1844 km for Nordic Combi Double and 1150 km for Steel/polyurethane. During actual plowing operations, a utilization degree of 100 % would be unrealistic to achieve, because of uneven wear along the plow and unexpected failures that may occur. The results from this thesis suggests that a utilization degree around 70-90 % and no more than 90 % are realistic utilization degrees. However, for a single blade set the utilization may be significantly. This was the case for blade set C1, which only achieved 33.1 % degree of utilization, leaving 1208 km of unused mileage. How often one could expect this to happened is not identified. Contractors and operators can use information about wear rate, dimensions of blade, rake angle, and utilization degree to predict an expected operational lifetime of a snowplow blade type. If expected operational lifetimes are known for several types of snowplow blades, the most cost-efficient blade can be chosen through a cost benefit analysis, resulting in reduced costs for the contractors.

In this thesis the wear rates for the two blade types are found from a continuous field study lasing an entire winter. This way different winter conditions experienced throughout a plowing season are included. As found when comparing snow/ice coverage on the road and wear rate, the wear rate is clearly influenced by snow/ice coverage, where more snow and ice creates a protective layer over the asphalt, reducing wear rate. Because of this, the type of maintenance strategy (anti-icing or winter road) will influence operational wear, since scraping on almost bare asphalt often occurs on anti-icing roads to obtain required conditions, especially when the "final clean up" is done before plowing ends. This is not the case for winter roads.

An alternative way of finding wear rates, and predict operational lifetime, could be a full-scale field test under worst-case conditions. From such a test, one could find the minimum expected operational lifetime for a blade type. For anti-icing maintenance strategy worst-case conditions is bare wet road. A continuous field test, such as this thesis, might give a more accurate result when predicting operational lifetime. However, results from one winter might not be representable for the upcoming winters, and this type of testing requires lots of time and labor compared to a worst-case condition test.

5.2 Factors influencing expected lifetime

There are lots of factors in snow plowing operation which may vary due to e.g. different conditions, locations, equipment, maintenance strategy, and personnel. Several factors influencing expected lifetime have been identified during the work whit this thesis. These where found in the literature review, as factors influencing blade wear (thereby influencing expected lifetime), by conversations with Mesta employees, and observations in the field during the wear data collection process.

It is hard to point out one single factor that influences expected lifetime the most, because the plowing process is complex, and all factors identified contributes in some way. There might also be additional factors influencing expected lifetime of snowplow blades, which this thesis did not manage to identify. In this thesis, factors such as plowing speed, pavement material, driver or operator dependent factors are tried to be kept as constant as possible. Using the same truck, plow, drivers, and plowing area. Since this thesis follows actual plowing operations and not a test setup, it is almost certain that these factors are not kept constant at all times. However, the main differences in the results is can be assumed to be caused by the material properties of the tested blades, and different road surface conditions.

Evaluation of road surface condition is done in two ways in this thesis, from weather data and visual assessment of surface conditions. If the two ways are compared the visual estimation of snow/ice cover gives the best results, where both blade types have a significant linear regression and 50,1 % (Nordic Combi Double) and 42,3 % (Steel/polyurethane) of the wear rate can be explained by snow/ice coverage. For weather factors, all the Steel/polyurethane sets gave non-significant regressions and significant regressions was found for all the Nordic Combi Double sets, except for relative humidity.

This implies that relative humidity is poor predictor of wear rate. The reason for the non-significant results on the Steel/polyurethane may be due to the low number of observations. There are additional reasons to why visual assessment of surface conditions should be used, prior to weather data. Actual precipitation as snow may vary, because precipitation may fall as snow in a range of air temperatures. Temperature data from the air and road surface may also give an incorrect evaluation of the surface condition, especially in locations where anti-icing strategy is used. Chemicals, such as NaCl is applied, this lowers the freezing point of water on the road (7), resulting in bare asphalt conditions for lower temperatures than 0 °C.

In conversations with Mesta, tire pressure and adjustment of the plow and counterbalance system, so that the plow position is correct, where considered very important. Plow adjustments and tire pressure can be controlled and adjusted if necessary, whereas e.g. the amount of brine in the truck varies during plowing operations, when the driver alternates between brine spraying and snow plowing. The weight contribution from the brine is considerable knowing that a full brine tank (14 m^3) adds 14 ton to the around 16-ton truck (including equipment). This results in challenges when adjusting the plow to the operating weight of the truck.

The two operator dependent factors identified from observations during wear data collection, will influence the lifetime significantly, since the amount of wearable material is reduced by 30 mm if blades are mounted incorrectly, and a whole blade side may be useless if the reversible blades are worn down too far, damaging mounting holes in a way that makes it impossible to reverse. Whether the set is going to be reversed or replaced might also influence the lifetime. One might allow more wear if the set is going to be replaced because there will be no need for intact mounting holes, since there will not be any further use of the blades. This might give slightly higher potential and longer lifetime for the second side of a reversible blade group. E.g. more potential for set C2 than C1.

Wear development clearly varies along the plow during plowing operations (Figure 4.5), and it is indicated that a more wear resistant blade type, such as Nordic Combi Double, have a more even wear along the length of the plow, than a less wear resistant blade type, such as Steel/polyurethane. This might be an additional downside of using less wear resistant blades, resulting in a lower utilization degree of the set. However, the number of tested blade sets should be higher to draw a certain conclusion.

The typical problem regarding blade lifetime, is that all the blades in a set are replaced whenever one blade for some reason require replacement. Either the blade is worn down more than the others, e.g. due to rutting, or it is somehow damaged. The other blades are then replaced, even if they still have much lifetime left. A good example of this, is how blade number 3 in set C2 was useless after the blade holders were broken (section 4.4.5). In this case the set only achieved a utilization degree of 33.1 %, leaving lots of unused mileage and lifetime in the other blades.

A solution to this problem might be to store the partly worn blades as backup. If a single blade requires replacement, it can be replaced with a blade which matches the wear on the other blades in the set. However, this will require a large stock of blades and a system to keep track of the wear on every single blade. Additionally, such a solution will increase the amount of labor for the drivers, time spent changing blades, and at the end there is no guarantee that a blade with matching wear is in stock.

There was however, one situation during the winter where partly worn blades were kept in stock. After set A1 was replaced the blades that had functioning mounting holes were kept because they still had one unused side. Some of these blades where later used in set D1 together with brand new blades. By doing this the consequence of blades worn down too far can be reduced.

5.3 Wear rate development over time

For the blade types tested in this thesis it does not seem to be any clear trend in the wear rate development, for example higher or lower wear rates towards the end or in the first part of the sets. This is best illustrated in Figure 4.4, where wear rates are represented by the slope of the lines between measurements. Looking at individual sets, one might say that A1 has an increased wear rate towards the end, and that D1 has a higher wear rate in the start, decreasing towards the end. But if all sets of the same blade type are considered one cannot draw such conclusions, since the wear rate varies a lot. However, the number of blades tested in this study is limited so a trend cannot be excluded. The only thig that is clear is that wear rates differ for the two blade types. This observed variation in wear rate is most likely caused by different material properties.

The only trend that might be assumed in the wear rate development, is a low wear rate for the first couple of kilometers, because of the initial wear until full flat width is achieved. Initial wear is caused by the rake angle, and low wear rate in the beginning can be observed in Figure 4.2 in the first measurement from set B2 which is after 42 km of plowing and in Figure 4.5, where the first measurement is barely visible.

5.4 Operational factors controlled in plow blade testing

Based on the findings in this thesis, both from the literature review and the wear data collection, a suggestion of operational factors that needs to be controlled in snowplow blade testing are listed together with comments in Table 5.1.

Additional factors such as temperature and pavement material should also be taken into consideration when making a test setup. These might be harder to control, due to weather variations and restrictions when it comes to test site, but conditions as close as possible to what the blades might encounter during actual plowing operations is preferable. The most important is that conditions and setup are the same for the blade types compared in a test. It would also be beneficial to be able to visually evaluate the road surface condition and the snow/ice coverage (if there is one) from e.g. pictures taken during testing.

Table 5.1: Operational factors influencing wear rate, that needs to be controlled in snowplow blade testing

Operational factors	Comments
Driving speed	Try to match the actual operational driving speed that the blades will encounter during plowing operations.
Plowing distance	Should at least be around 100 km, preferably even more to get good and measurable results. It was experienced that around 100 km of plowing was required to get a measurable change in wear.
Driver	Use the same driver for all the tests, to eliminate any personal preferences, habits, or technique.
Load on blades	Use the same type of equipment if several blades are tested for comparison. Ensure that the plow and counterbalance system is properly adjusted according to total weight of the truck, and tire pressure is correct. Any skid shoes, support wheels, and slush blade also need to be adjusted. Keep the weight of the truck constant during tests.
Blade angle	Use the same blade angles, both rake angle (Figure 2.1) and attack angle (Figure 2.2) if several blades are tested.
Full flat width	Ensure that initial wear is completed before testing so that the full flat width (Figure 2.1) of the blade is in contact with the road surface.
Maintenance strategy	The maintenance strategy on the site where the blades are to be used should be considered. Dependent on the maintenance strategy the worst-case condition can be decided. For anti-icing strategy this is bare wet asphalt. If tests are done under worst-case conditions, the actual lifetime can be expected to be greater than the test results suggest, resulting in a conservative estimate.

5.5 Sources of error

Initially there is an error from the digital caliper when measuring wear, because of the measurement accuracy of 0.03 mm in the caliper. When conducting the measurements, the goal is to measure perpendicular from the lower edge of the blade to the lower mounting holes (see "measuring points on blade" in Appendix B). When sitting your knees under the plow, a perfect perpendicular measurement may be hard to achieve. In addition, only one value is measured and noted for each of the twelve measuring points, to prevent delays in plowing operations. The skill of the person doing the measurements is likely improved with the increased number of times the measurement procedure is performed. All of this may affect the uncertainty and quality of the wear measurements.

The measurements of wear are done on twelve chosen points along the plow, and not the entire length of the plow. If some of these points are particularly exposed to e.g. rutting in the road, it may influence the results.

2019/2020 was the last winter season in the five-year *Trondheim Outer 2015-2020* maintenance contract, and the plowing equipment in this thesis had already been used for several winter seasons. Especially the plow was affected by many kilometers of plowing, impacts, and repairs from previous winter seasons. Because of this none of the blades where perfectly in line, and the actual rake angle deviates from the assumed 19°. Ideally a new plow would be preferable when testing snowplow blades.

Whether a blade set is worn out and need replacement, is based on subjective evaluation by the drivers. Due to practical reasons, such as available time, equipment, and upcoming weather events, the set may be changed before one of the blades reaches maximum theoretical wear. This was the case for blade B2 (Figure 4.5). These subjective evaluation by the drivers influence the final results.

5.6 Challenges and experience

In relation to this thesis, several challenges occurred and lot of experience on measuring snowplow blade wear were gathered, and the most important are presented below.

Conducting a full-scale study over several months, following actual plowing operations have led to several unexpected problems, such as truck break downs, minor repairs on the plow, and driver illness, all limiting/influencing wear data collection. When problems occurred with the equipment, prioritizations had to be done to optimize the overall operation. Resulting in some days where the truck had to operate other contract areas and roads, such as the E39 highway.

Plowing operations are not necessary evenly distributed along the rode, height difference can for example give different conditions, especially with air temperatures around 1-0 °C. This was experienced several times during the winter, with heavy snow at Heimdal and rain at Ranheim.

To get measurable wear results, it has been experienced that approximately 80-120 km of plowing is required. If measurements are done more frequently, any measurable change in wear may not be found.

Good contact and communication with drivers have been very important. This is easy to maintain when there is continuous heavy snowfall, and harder when there are several days between snowfall, or there are small scattered snow events which may not require plowing at all.

A good way to measure the load on the blades was not found for this thesis. Some alternatives where discussed, such as using a NPRA truck weighing station, and lower the plow onto the scale. This might be a good way to do it in advance of a field test setup. However, to do this during operations takes time, planning and might give varying results depending on how much brine the truck carries. This might be a good way to do it in advance of a field test setup.

At the end, everything boils down to efficiency and economics in actual plowing operations. For instance, the bended blades due to damages on the blade holders (section 4.4.4), were not repaired because of the cost of new blade holders and the age of the plow. It was considered more efficient to continue operations and avoid costly repairs on the plow, since the plowing results still were good. But when the blade holders broke (section 4.4.5) repairs were required, and new blade holders had to be ordered.

6 Conclusion

The operational lifetime given in plowing kilometers for the two snowplow blade types used by Mesta in Trondheim during winter 2019/2020 are found to be: 1803 km for Nordic Combi Doble and 788 km for the Steel/polyurethane. Resulting in 56.3 % lower operational lifetime for the Steel/polyurethane compared with Nordic Combi Double.

Using total wear, total plowing distance (operational lifetime), theoretical maximum wear, and total wear rate; a degree of utilization, theoretical distance if 100 % utilization, and unused mileage of the blade set can be found. In actual plowing operations a utilization degree of 100 % would be unrealistic to assume, due to different wear along the plow and damages that may occur on the plow and blades during plowing. A more realistic utilization degree is found to be around 70-90 % depending on blade type. This can be used for estimations of expected operational lifetime of snowplow blade types in a cost benefit analysis. However, the utilization degree might be even lower for single blade sets, due to unexpected incidents.

Around 25 factors that influence wear rate have been identified, these factors will also influence the expected lifetime of snowplow blades. Factors are identified from previous studies on snowplow blades, and during the work with this thesis. From these factors, seven operational factors influencing wear rate, that needs to be controlled in snowplow blade testing are identified and presented.

Except from low wear rates for the first couple of plowing kilometers, due to initial wear when a new blade set is mounted, no trends in the wear rate development were found. The wear rate development varied on the different blade sets, likely because of the variation in road surface conditions during the winter.

When evaluating road surface conditions, it was found that a visual assessment of snow/ice coverage [%] from pictures, is preferable to analyzing weather data from weather stations. A significant correlation between the wear rate [mm/km] and snow/ice coverage [%] on the road were found for both blade types, where an increased amount of snow reduces the wear rate. Dependent of blade type 50.1 % and 42.3 % of the variation in wear rate can be explained by snow/ice coverage.

7 Further research

Testing of more blades in the same way, by continuous measurements throughout the plowing season for upcoming winters, would always be of interest to increase the number of blade sets tested. Especially testing and comparing a more standard flame hardened steel blade with the Nordic Combi Double. A drawback of this type of testing is the amount of labor and time required.

A full-scale test setup, testing the same blade types for some hundred kilometers under worst-case conditions (bare wet asphalt) could be performed, and results on wear rate could be compared with results from this thesis. If such a test setup gives promising results more blade types could be included and compared.

A simple initial laboratory test setup can be made to cut into/wear the blade types used in this thesis. By comparing results from the laboratory with the field results in this thesis, an evaluation whether such a laboratory test has the potential to predict blade lifetime can be done. If results are promising, further development of a standardized procedure for snowplow blade lifetime testing can be done.

This type of initial laboratory test setup was originally intended as part of this thesis but was postponed due to limited laboratory access when NTNU campus was closed because of corona virus. If everything goes as planned, an initial laboratory test will be performed on samples from set B1, B2, C1 and C2 at NTNU during summer 2020.

References

1. Statistics Norway. Domestic transport 2020 [Available from: https://www.ssb.no/en/transport-og-reiseliv/statistikker/transpinn].

2. Statistics Norway. Statistikkbanken: Samferdsel i kommuner og fylkeskommuner 2019 [Available from: https://www.ssb.no/statbank/table/11842/].

3. Norsk Klimaservicesenter. Klimanormaler - Normalkart temperatur 1985-2014, Normalkart nedbør 1985-2014 [Available from: https://klimaservicesenter.no/faces/desktop/article.xhtml?uri=klimaservicesenteret/Klimanormaler].

4. Alena Høye, Torkel Bjørnskau, Anna Arvidsson. 2.6 Vinterdrift av veger: Transportøkonomisk institutt; 2013 [Available from: https://tsh.toi.no/doc644.htm].

5. Norwegian Public Roads Administration. Vinterdrift 2019 [Available from: https://www.vegvesen.no/fag/veg+og+gate/drift+og+vedlikehold/Vinterdrift].

6. Mesta AS. Conversation with Mesta 13.12.2019.

7. Klein-Paste A, Dalen R. The Fundamentals of Plowing, Anti-icing, De-icing and Sanding. Sustainable Winter Road Operations2018. p. 82-100.

8. Norwegian Public Roads Administration. Håndbok 610 - Standard for drift og vedlikehold av riksveger 2014. [Available from: https://www.vegvesen.no/fag/veg+og+gate/drift+og+vedlikehold/Vinterdrift/snobroyting-og-rydding/_attachment/61430?_ts=146548c2c38&fast_title=H%C3%A5ndbok+R610+Standard+for+drift+og+vedlikehold+av+riksveger].

9. Norwegian Public Roads Administration. Textbook for Winter Maintenance Staff 2018. [Available from: https://www.vegvesen.no/_attachment/2365449/binary/1270205?fast_title=Oppl%C3%A6ring+i+vinterdrift+for+operat%C3%B8rer+SVV+rapport+673+%2827+MB%29.pdf].

10. Norwegian Public Roads Administration. Material use for winter maintenance for the 2018/19 season. Roads Department; 2019.

11. Mesta AS. Meeting with mesta 16.09.2019.

12. Nixon W, editor Factors for Consideration in Selecting Snowplow Cutting Edges. International Conference on Winter Maintenance and Surface Transportation Weather, Coralville, Iowa; 2012.

13. Thompson B. Field testing of alternative carbide edge snow plow blades:[technical memorandum]. Maine. Dept. of Transportation; 2004.

14. Jacobson S, Hogmark S, Bo T. Tribological testing of traditional road-grading steels leading to the evolution of new road-preparation concepts. Wear. 1989;130(1):151-65.

15. Cameron G. Kruse LAK. Development of Standardized Test Procedures for Carbide Insert Snowplow Blade Wear. Wisconsin Department of Transportation; 2010.

16. Schneider W, Crow M, Holik WA. Investigate plow blade optimization. 2015.

17. Ingulstad A, editor Winter maintenance - New cutting edge for snowploughs and grades. XTH PIARC International winter road congress 16-19 March 1998 in Luleaa, Sweden; 1998.

18. Mastel A. Evaluation of Snow Plow Blade Systems. 2011.

19. Stachowiak GW, Batchelor AW. Chapter 11 - Abrasive, Erosive and Cavitation Wear. In: Stachowiak GW, Batchelor AW, editors. Engineering Tribology (Fourth Edition). Boston: Butterworth-Heinemann; 2014. p. 525-76.

20. Kempainen A, Milacic D, Osborne MD, Olson WW. Modelling and testing snow ploughing forces on trucks. [St. Helier, Jersey] :1998. p. 472.

21. Colson S. Evaluation of alternative snow plow cutting edges. 2009.

22. Nixon WA. Improved cutting edges for ice removal. 1993.

23. Möller S, Gabrielsson G. Metodbeskrivning för plogtester: Statens väg-och transportforskningsinstitut; 2010.

24. Nixon WA, Wei Y, Whelan AE. Field Measurements of Ice Scraping Loads on Front Mounted Plow Blades. Iowa Institute of Hydraulic Research, College of Engineering, University of Iowa; 1997.

25. Nixon WA, Frisbie TR, Chung C-H. Field testing of new cutting edges for ice removal from pavements. Transportation Research Record. 1993(1387).

26. Colson S. Evaluation of the Kuper-Tuca SX36 snow plow cutting edges. Maine. Dept. of Transportation; 2010.

27. Gillis H, Zollars J. MOTOR GRADER AND SNOWPLOW CUTTING EDGE DURABILITY STUDY. FINAL REPORT. 1993.

28. VTI. VTI Road Simulator - [Available from: https://www.vti.se/en/Research-areas/Air-pollution-and-quality/VTI-Road-Simulator/].

29. Wei Y, Nixon WA, Shi Z. Evaluation of wear resistance of snow plow blade cutting edges using the scratch test method. West Conshohocken, Pa.1998. p. 527.

30. Younkin K. A LABORATORY EVALUATION OF TUNGSTEN CARBIDE INSERTS FOR SNOWPLOW BLADES. FINAL REPORT. Iowa Department of Transportation; 1996.

31. Möller S, Gabrielsson G. Miljöplogen, Meirenplogen och Mähler sidoplog S 45: test av egenskaper hos tre nya plogtyper2010.

32. Möller S, Gabrielsson G. Meirenplogen: kompletterande mätningar av buller, bränsleförbrukning och slitage på plogskär2011.

33. State of Ohio Department of Transport. JOMA Plow Blade Evaluation. 2010.

34. Bijwe J. Chapter 17 - Multifunctionality of nonasbestos organic brake materials. In: Friedrich K, Breuer U, editors. Multifunctionality of Polymer Composites. Oxford: William Andrew Publishing; 2015. p. 551-72.

35. Rabinowicz E. Friction and wear of materials. 2nd ed. ed. New York: Wiley; 1995.

36. Stachowiak GW, Batchelor AW. Chapter 1 - Introduction. In: Stachowiak GW, Batchelor AW, editors. Engineering Tribology (Fourth Edition). Boston: Butterworth-Heinemann; 2014. p. 1-10.

37. Stachowiak GW, Batchelor AW, Stachowiak GB. 8 - Surface Micrography and Analysis. In: Stachowiak GW, Batchelor AW, Stachowiak GB, editors. Experimental Methods in Tribology. 44: Elsevier; 2004. p. 165-220.

38. Moore MA. A preliminary investigation of frictional heating during abrasive wear. Wear. 1971;17(1):51-8.

39. Gahr K-HZ. Chapter 4 Classification of Wear Processes. In: Gahr K-HZ, editor. Microstructure and Wear of Materials 10: Elsevier; 1987. p. 80-131.

40. Mesta AS. Vi er Mesta - [Available from: http://www.mesta.no/om-mesta/vi-er-mesta].

41. Norwegian Public Roads Administration. Vegkart - Objekttype: Vinterdriftsklasse 2019 [Available from: https://www.vegvesen.no/nvdb/vegkart/v2/#kartlag:geodata/hva:(~(farge:'0_0,id:810))/@275404,7036856,10].

42. Norwegian Public Roads Administration. Vegkart - Objekttype: Vegdekke 2019 [Available from: https://www.vegvesen.no/nvdb/vegkart/v2/#kartlag:geodata/hva:(~(farge:'0_0,id:241))/@273025,7038293,10].

43. Norwegian Public Roads Administration. Vegkart 2019 [Available from: https://vegkart-2019.atlas.vegvesen.no/#kartlag:geodata/@600000,7225000,3].

44. MEIREN ENGINEERING. Patented blade holders [Available from: https://meiren.ee/en/patented-blade-holders/].

45. Nordic Roads. Nordic Combi Double - [Available from: https://nordicroads.as/produktark-og-kataloger/nordic-combi-double/].

46. Norwegian Meteorological Institute. eKlima [Available from: http://sharki.oslo.dnmi.no/portal/page?_pageid=73,39035,73_39101&_dad=portal&_schema=PORTAL].

47. Kartverket. norgeskart.no [Available from: https://www.norgeskart.no/].

48. Kienzle SW. A new temperature based method to separate rain and snow. Hydrological Processes: An International Journal. 2008;22(26):5067-85.

49. Norwegian public Roads Administration. Vegvær 2014 [Available from: https://www.vegvesen.no/fag/trafikk/Vaerdata].

50. Douglas CM, Elizabeth AP, Analysis GGVSMTATLR, Fifth E, Anne GR. Introduction to Linear Regression Analysis. US: US: Wiley; 2012.

51. Klocke F, Eisenblätter G, Krieg T. Machining: Wear of Tools. In: Buschow KHJ, Cahn RW, Flemings MC, Ilschner B, Kramer EJ, Mahajan S, et al., editors. Encyclopedia of Materials: Science and Technology. Oxford: Elsevier; 2001. p. 4708-11.

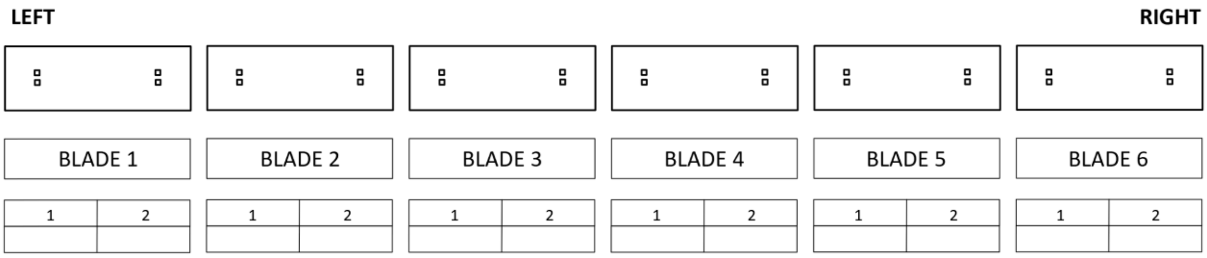
Appendix

Appendix A: Words and terms used in search of literature

Words and terms			
slitestål	brøyteplog	vinterdrift	slitasje
brøyteskjær	brøytebil	winter maintenance	nedsliting
plogskjær	snøplog	vedlikehold	wear
plogskär	plog	brøyt	wear resistance
skjær	snow plow	brøyting	wear mechanisms
skjærestål	snowplow	snow removal	wear rate
blad	plow*	road maintenance	lifetime
skär	snow plough	maintenance	life
blade	snowplough	winter	durability
cutting edge	plough*		
cutter edge	plow truck		tribology
scraper blade	grader		tribolog*
räumleisten			
rubber blade			damage
steel blade			scrape
snow removing blade			scour
			abrade
			abrasion
			high speed
			friction
			steel
			pavement
			ceramic

Appendix B: Blade position system and measuring points

POSITION SYSTEM, FRONT VIEW:



MEASURING POINTS ON BLADE:

Figure to the left shows measuring points 1 (Left) and 2 (Right) for a single blade. From lower installation holes (bottom corners furthest from blade center) to the lower edge of the blade.

PICTURES SHOWING MARKED BLADES:

Appendix C: Wear and plowing distance raw data, wear rate

Nordic Combi Double			Plowing distance [km]		Accumulated wear [mm]													Avg. wear	Wear rate	Wear rate
Set	**#**	**Date and time**	**Distance**	**Accumulated**	**1L**	**1R**	**2L**	**2R**	**3L**	**3R**	**4L**	**4R**	**5L**	**5R**	**6L**	**6R**	**Average**	**each # [mm]**	**[mm/km]**	**[inch/mile]**
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

Appendix D: Production report example

Samproduksjon / Analyserapport

Kontrakt: Trondheim Ytre
Periode: 08.12.2019 14:00:00-09.12.2019 07:00:00
Rapportdat 11.12.2019 14:21

mesta FÅR FOLK FRAM

	Kjøretø	Tid start	Tid stopp	Sum tid	Rode	Fylke	Kommun	Vei	HP	Fra km	Til km	Sum km	Produksjonsstatus
6				07:23:08								250,757	
217	61000006	08.12.2019 18:39	08.12.2019 18:39	00:00:07	1609 R13 E6 Sør	50	0	FV6690	3	2,964	3,008	0,044	Plog; Sideplog
218	61000006	08.12.2019 18:39	08.12.2019 18:39	00:00:03	1609 R13 E6 Sør	50	0	FV6690	4	0	0,013	0,013	Plog; Sideplog
219	61000006	08.12.2019 18:39	08.12.2019 18:39	00:00:20	1609 R13 E6 Sør	50	0	FV6690	4	0	0,172	0,172	Plog
220	61000006	08.12.2019 18:39	08.12.2019 18:40	00:00:50	1609 R13 E6 Sør	50	0	FV6690	4	0,172	0,752	0,58	Plog; Sideplog
221	61000006	08.12.2019 18:40	08.12.2019 18:45	00:05:10	1609 R13 E6 Sør	50	0	EV6	18	3,405	0	3,405	Plog; Sideplog
222	61000006	08.12.2019 18:45	08.12.2019 18:51	00:05:27	1609 R13 E6 Sør	50	0	EV6	17	3,617	0	3,617	Plog; Sideplog
223	61000006	08.12.2019 18:51	08.12.2019 18:54	00:03:34	1609 R13 E6 Sør	50	0	EV6	16	3,788	1,342	2,446	Plog; Sideplog
224	61000006	08.12.2019 18:54	08.12.2019 18:56	00:02:00	1609 R13 E6 Sør	50	0	EV6	16	1,342	0	1,342	Plog; Sideplog
225	61000006	08.12.2019 18:56	08.12.2019 18:57	00:00:52	1609 R13 E6 Sør	50	0	EV6	15	9,824	9,267	0,557	Plog; Sideplog
226	61000006	08.12.2019 18:57	08.12.2019 19:00	00:02:25	R13 Utenfor kontrakts	50	0	EV6	15	9,153	7,609	1,544	Plog; Sideplog
227	61000006	08.12.2019 19:00	08.12.2019 19:00	00:00:11	1609 R13 E6 Sør	50	0	EV6	15	9,267	9,154	0,113	Plog; Sideplog
228	61000006	08.12.2019 19:00	08.12.2019 19:00	00:00:07	R13 Utenfor kontrakts	50	0	EV6	75	32,295	32,345	0,05	Plog
229	61000006	08.12.2019 19:00	08.12.2019 19:00	00:00:02	R13 Utenfor kontrakts	50	0	FV6612	432	0,041	0,033	0,008	Plog
230	61000006	08.12.2019 19:00	08.12.2019 19:00	00:00:04	R13 Utenfor kontrakts	50	0	FV6612	432	0,033	0,065	0,032	Plog
233	61000006	08.12.2019 19:01	08.12.2019 19:01	00:00:00	R13 Utenfor kontrakts	50	0	FV6612	430	0,022	0,023	0,001	Plog
234	61000006	08.12.2019 19:01	08.12.2019 19:02	00:01:14	R13 Utenfor kontrakts	50	0	EV6	75	43	43,394	0,394	Plog
238	61000006	08.12.2019 19:04	08.12.2019 19:05	00:00:41	1609 R13 E6 Sør	50	0	EV6	15	9,383	9,824	0,441	Plog; Sideplog
239	61000006	08.12.2019 19:05	08.12.2019 19:09	00:03:46	1609 R13 E6 Sør	50	0	EV6	16	0	2,436	2,436	Plog; Sideplog
240	61000006	08.12.2019 19:09	08.12.2019 19:10	00:00:53	1609 R13 E6 Sør	50	0	EV6	81	14	14,557	0,557	Plog; Sideplog
241	61000006	08.12.2019 19:10	08.12.2019 19:10	00:00:23	1609 R13 E6 Sør	50	0	EV6	81	13	13,229	0,229	Plog; Sideplog
242	61000006	08.12.2019 19:10	08.12.2019 19:11	00:00:52	1609 R13 E6 Sør	50	0	EV6	16	3,21	3,788	0,578	Plog; Sideplog
243	61000006	08.12.2019 19:11	08.12.2019 19:16	00:05:27	1609 R13 E6 Sør	50	0	EV6	17	0	3,617	3,617	Plog; Sideplog
244	61000006	08.12.2019 19:16	08.12.2019 19:20	00:03:05	1609 R13 E6 Sør	50	0	EV6	18	0	2,051	2,051	Plog; Sideplog
245	61000006	08.12.2019 19:20	08.12.2019 19:22	00:02:02	1609 R13 E6 Sør	50	0	EV6	18	2,051	3,405	1,354	Plog; Sideplog
246	61000006	08.12.2019 19:22	08.12.2019 19:23	00:01:09	1609 R13 E6 Sør	50	0	FV6690	4	0,752	0	0,752	Plog; Sideplog
247	61000006	08.12.2019 19:23	08.12.2019 19:23	00:00:06	1609 R13 E6 Sør	50	0	FV6690	3	3,008	2,964	0,044	Plog; Sideplog
248	61000006	08.12.2019 19:23	08.12.2019 19:23	00:00:06	1609 R7 Okbas	50	0	FV6680	1	0	0,027	0,027	Plog; Sideplog
249	61000006	08.12.2019 19:23	08.12.2019 19:23	00:00:01	1609 R7 Okbas	50	0	FV6680	1	0,027	0,032	0,005	Plog
256	61000006	08.12.2019 19:25	08.12.2019 19:25	00:00:03	1609 R5 Vemax	50	0	RV706	52	0,559	0,547	0,012	Plog
257	61000006	08.12.2019 19:25	08.12.2019 19:26	00:00:41	1609 R13 E6 Sør	50	0	EV6	87	43	43,332	0,332	Plog
258	61000006	08.12.2019 19:26	08.12.2019 19:26	00:00:03	1609 R13 E6 Sør	50	0	EV6	19	0,279	0,242	0,037	Plog
259	61000006	08.12.2019 19:26	08.12.2019 19:28	00:02:11	1609 R13 E6 Sør	50	0	EV6	19	0,242	1,651	1,409	Plog
260	61000006	08.12.2019 19:28	08.12.2019 19:29	00:00:17	1609 R13 E6 Sør	50	0	EV6	89	14	14,215	0,215	Plog
261	61000006	08.12.2019 19:29	08.12.2019 19:29	00:00:02	1609 R13 E6 Sør	50	0	FV6658	400	0,037	0,022	0,015	Plog
262	61000006	08.12.2019 19:29	08.12.2019 19:29	00:00:04	1609 R13 E6 Sør	50	0	FV6658	400	0,022	0,077	0,055	Plog
263	61000006	08.12.2019 19:29	08.12.2019 19:29	00:00:23	1609 R13 E6 Sør	50	0	EV6	89	43	43,284	0,284	Plog
264	61000006	08.12.2019 19:29	08.12.2019 19:29	00:00:01	1609 R13 E6 Sør	50	0	EV6	19	2,188	2,177	0,011	Plog
265	61000006	08.12.2019 19:29	08.12.2019 19:34	00:04:59	1609 R13 E6 Sør	50	0	EV6	19	2,177	5,448	3,271	Plog
266	61000006	08.12.2019 19:34	08.12.2019 19:35	00:00:41	1609 R13 E6 Sør	50	0	EV6	19	5,448	5,9	0,452	Plog; Sideplog
267	61000006	08.12.2019 19:35	08.12.2019 19:35	00:00:01	1609 R13 E6 Sør	50	0	EV6	91	12	12,018	0,018	Plog; Sideplog

Rapport

Part of production report from 08.12.2019 to 09.12.2019 in excel containing the following information: Vehicle number, start time, stop time, rode, county, municipality, road number, HP, from km, to km, sum km, and production status (no production, plow, wing plow, and brine can be filtered).
The report also sums up total hours and total km for filtered production in the chosen time period.

Appendix E: Precipitation as snow, MET data

This appendix presents precipitation as snow between measurements, given a threshold temperature for snow at 0.0 °C.

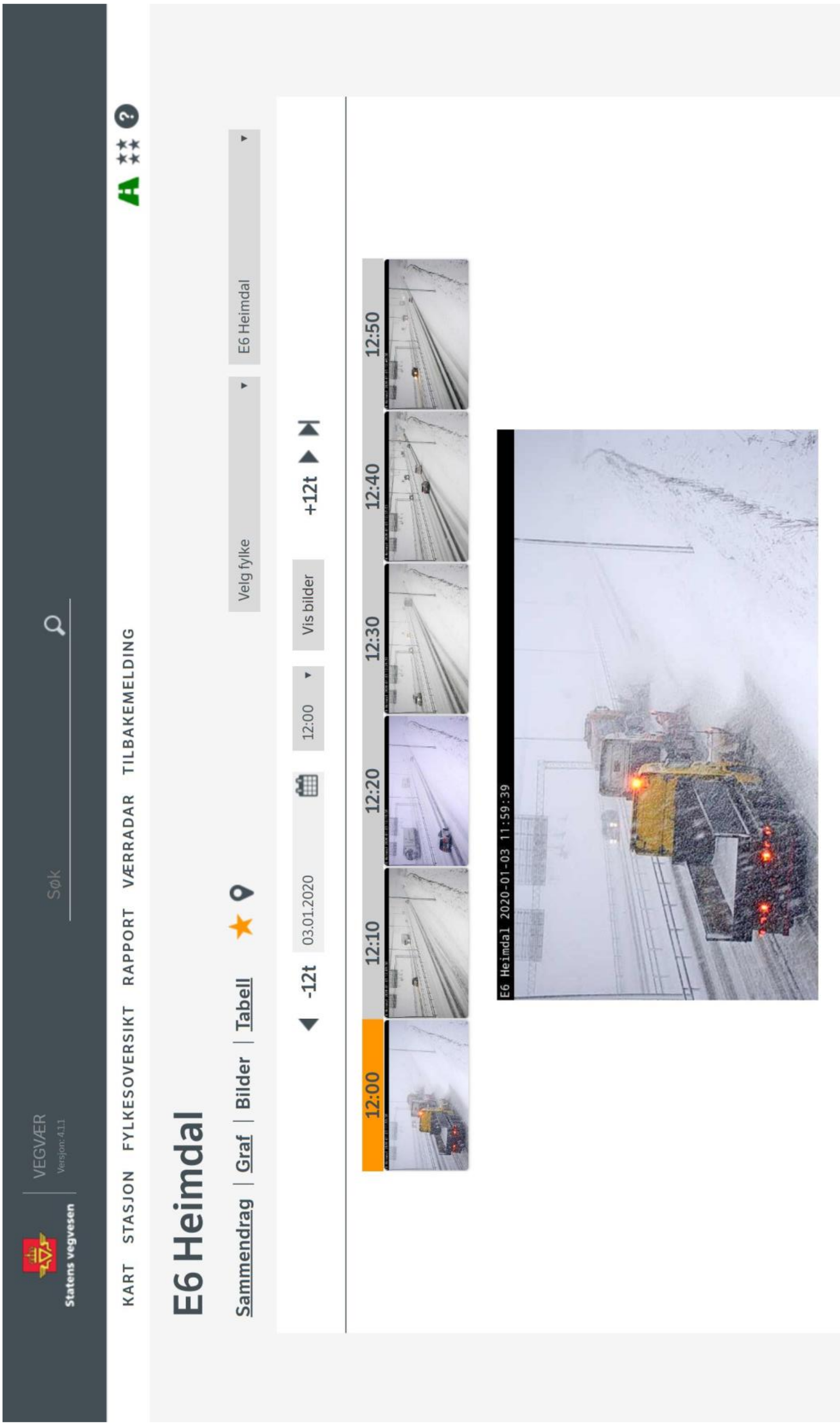
Precipitation as snow					
Nordic Combi Double			Steel/polyurethane		
Set	Measurement	Water equivalents [mm]	Set	Measurement	Water equivalents [mm]
A1	1	24.90	**B1**	1	2.70
	2	7.00		2	6.40
	3	3.80		3	12.00
	4	14.10		4	2.40
	5	3.90		5	5.30
	6	3.50		6	2.10
C1	1	2.30	**B2**	1	0.00
	2	2.90		2	0.00
	3	16.20		3	0.00
	4	15.20		4	2.60
	5	2.10		5	0.00
C2	1	3.70		6	0.00
	2	0.10		7	6.60
	3	4.50		8	0.70
	4	8.00			
	5	5.90			
	6	6.10			
	7	3.20			
	8	2.90			
	9	4.10			
	10	5.50			
D1	1	7.10			
	2	3.70			
	3	13.80			
	4	7.80			
	5	0.80			
	6	3.40			
	7	3.70			
	8	8.00			

Appendix F: Processed weather data E6 Moholtlia

This appendix presents weighted average values on road surface temperature, air temperature, and relative humidity for each measurement. Distance plowed are used as weights, see sections 3.10.2, 3.10.3 and 3.10.4.

Weather data from NPRA weather station *E6 Moholtlia*										
Nordic Combi						Polyurethane				
Set	Measu-rement	Road surface temperature [°C]	Air temp-erature [°C]	Relative humidity [%]		Set	Measu-rement	Road surface temperature [°C]	Air temp-erature [°C]	Relative humidity [%]
A1	1	-0.7	-0.8	88.5		**B1**	1	-1.4	-0.9	85.9
	2	-1	-1.4	86.4			2	-0.2	-1	85.9
	3	-1.2	-1.7	89.1			3	-1.1	-2.2	91.9
	4	-1.5	-1.8	84.5			4	-0.6	-0.3	80.5
	5	-0.8	-0.8	85.3			5	-0.8	-0.9	88.1
	6	-1.4	-1	80.9			6	0.2	0.3	86.6
C1	1	0.3	0.6	86.3		**B2**	1	-0.1	-0.1	83.5
	2	-0.2	-0.4	91.1			2	1.7	1	84.8
	3	-0.4	-0.5	91.8			3	0.3	0.7	79.1
	4	-0.3	-0.6	92.5			4	0.6	0.4	88.2
	5	0.3	-0.3	92.8			5	0.5	0.2	88.1
C2	1	-0.1	-0.3	87.4			6	0	0	88.7
	2	1	1.2	86.5			7	-0.5	-0.6	88.1
	3	0	-0.1	84.7			8	0.5	0.1	88.8
	4	-0.9	-1.2	89.9						
	5	-0.5	-1	90.5						
	6	-4.2	-4.5	80						
	7	-0.5	-0.6	81.5						
	8	-2.2	-3.2	82						
	9	-1.8	-2.7	84.4						
	10	-3	-3.6	77.9						
D1	1	0.5	-0.5	83.8						
	2	-0.4	-1.8	80.5						
	3	-2.7	-3.4	87.2						
	4	-0.5	-0.3	88.6						
	5	-0.3	-0.8	85.4						
	6	-0.9	-1.4	80.8						
	7	-0.9	-1.7	80						
	8	-2.2	-3.1	87.2						

Appendix G: Website interface Vegvær



Appendix H: Estimated Snow/ice coverage

This appendix presents weighted average values of snow/ice coverage [%] for each measurement, based on evaluation of pictures taken by *E6 Heimdalsmyra* web camera. Distance plowed is used as weights. For more details on the process see section 3.11.

Snow/ice coverage [%]

Nordic Combi Double		
Set	**Measurement**	**Weighted average value**
A1	1	60 %
	2	75 %
	3	81 %
	4	70 %
	5	64 %
	6	20 %
C1	1	53 %
	2	74 %
	3	83 %
	4	66 %
	5	3 %
C2	1	52 %
	2	27 %
	3	58 %
	4	72 %
	5	31 %
	6	39 %
	7	6 %
	8	73 %
	9	50 %
	10	59 %
D1	1	51 %
	2	11 %
	3	82 %
	4	54 %
	5	48 %
	6	67 %
	7	48 %
	8	73 %

Steel/polyurethane		
Set	**Measurement**	**Weighted average value**
B1	1	42 %
	2	68 %
	3	72 %
	4	73 %
	5	74 %
	6	45 %
B2	1	60 %
	2	56 %
	3	31 %
	4	38 %
	5	40 %
	6	45 %
	7	61 %
	8	15 %

Appendix I: Statistical Table

The statistical table below is from the book *Introduction to Linear Regression Analysis* (50). It is used for finding $F_{\alpha,1,n-2}$, when evaluating significance of regression described in section 3.12.3.

$\alpha = .10$

Nordic Combi double: $n = 29 \rightarrow n-2 = 27$
Steel/polyurethane: $n = 14 \rightarrow n-2 = 12$

Nordic Combi double: $F_{.10,1,27} = 2.90$
Steel/polyurethane: $F_{.10,1,12} = 3.18$

Percentage Points of the *F*-Distribution

$F_{.10,\nu_1,\nu_2}$

	Degrees of Freedom for the Numerator (ν_1)																		
ν_2 (Degrees of Freedom for the Denominator)	1	2	3	4	5	6	7	8	9	10	12	15	20	24	30	40	60	120	∞
1	39.86	49.50	53.59	55.83	57.24	58.20	58.91	59.44	59.86	60.19	60.71	61.22	61.74	62.00	62.26	62.53	62.79	63.06	63.33
2	8.53	9.00	9.16	9.24	9.29	9.33	9.35	9.37	9.38	9.39	9.41	9.42	9.44	9.45	9.46	9.47	9.47	9.48	9.49
3	5.54	5.46	5.39	5.34	5.31	5.28	5.27	5.25	5.24	5.23	5.22	5.20	5.18	5.18	5.17	5.16	5.15	5.14	5.13
4	4.54	4.32	4.19	4.11	4.05	4.01	3.98	3.95	3.94	3.92	3.90	3.87	3.84	3.83	3.82	3.80	3.79	3.78	2.76
5	4.06	3.78	3.62	3.52	3.45	3.40	3.37	3.34	3.32	3.30	3.27	3.24	3.21	3.19	3.17	3.16	3.14	3.12	3.10
6	3.78	3.46	3.29	3.18	3.11	3.05	3.01	2.98	2.96	2.94	2.90	2.87	2.84	2.82	2.80	2.78	2.76	2.74	2.72
7	3.59	3.26	3.07	2.96	2.88	2.83	2.78	2.75	2.72	2.70	2.67	2.63	2.59	2.58	2.56	2.54	2.51	2.49	2.47
8	3.46	3.11	2.92	2.81	2.73	2.67	2.62	2.59	2.56	2.54	2.50	2.46	2.42	2.40	2.38	2.36	2.34	2.32	2.29
9	3.36	3.01	2.81	2.69	2.61	2.55	2.51	2.47	2.44	2.42	2.38	2.34	2.30	2.28	2.25	2.23	2.21	2.18	2.16
10	3.29	2.92	2.73	2.61	2.52	2.46	2.41	2.38	2.35	2.32	2.28	2.24	2.20	2.18	2.16	2.13	2.11	2.08	2.06
11	3.23	2.86	2.66	2.54	2.45	2.39	2.34	2.30	2.27	2.25	2.21	2.17	2.12	2.10	2.08	2.05	2.03	2.00	1.97
12	3.18	2.81	2.61	2.48	2.39	2.33	2.28	2.24	2.21	2.19	2.15	2.10	2.06	2.04	2.01	1.99	1.96	1.93	1.90
13	3.14	2.76	2.56	2.43	2.35	2.28	2.23	2.20	2.16	2.14	2.10	2.05	2.01	1.98	1.96	1.93	1.90	1.88	1.85
14	3.10	2.73	2.52	2.39	2.31	2.24	2.19	2.15	2.12	2.10	2.05	2.01	1.96	1.94	1.91	1.89	1.86	1.83	1.80
15	3.07	2.70	2.49	2.36	2.27	2.21	2.16	2.12	2.09	2.06	2.02	1.97	1.92	1.90	1.87	1.85	1.82	1.79	1.76
16	3.05	2.67	2.46	2.33	2.24	2.18	2.13	2.09	2.06	2.03	1.99	1.94	1.89	1.87	1.84	1.81	1.78	1.75	1.72
17	3.03	2.64	2.44	2.31	2.22	2.15	2.10	2.06	2.03	2.00	1.96	1.91	1.86	1.84	1.81	1.78	1.75	1.72	1.69
18	3.01	2.62	2.42	2.29	2.20	2.13	2.08	2.04	2.00	1.98	1.93	1.89	1.84	1.81	1.78	1.75	1.72	1.69	1.66
19	2.99	2.61	2.40	2.27	2.18	2.11	2.06	2.02	1.98	1.96	1.91	1.86	1.81	1.79	1.76	1.73	1.70	1.67	1.63
20	2.97	2.59	2.38	2.25	2.16	2.09	2.04	2.00	1.96	1.94	1.89	1.84	1.79	1.77	1.74	1.71	1.68	1.64	1.61
21	2.96	2.57	2.36	2.23	2.14	2.08	2.02	1.98	1.95	1.92	1.87	1.83	1.78	1.75	1.72	1.69	1.66	1.62	1.59
22	2.95	2.56	2.35	2.22	2.13	2.06	2.01	1.97	1.93	1.90	1.86	1.81	1.76	1.73	1.70	1.67	1.64	1.60	1.57
23	2.94	2.55	2.34	2.21	2.11	2.05	1.99	1.95	1.92	1.89	1.84	1.80	1.74	1.72	1.69	1.66	1.62	1.59	1.55
24	2.93	2.54	2.33	2.19	2.10	2.04	1.98	1.94	1.91	1.88	1.83	1.78	1.73	1.70	1.67	1.64	1.61	1.57	1.53
25	2.92	2.53	2.32	2.18	2.09	2.02	1.97	1.93	1.89	1.87	1.82	1.77	1.72	1.69	1.66	1.63	1.59	1.56	1.52
26	2.91	2.52	2.31	2.17	2.08	2.01	1.96	1.92	1.88	1.86	1.81	1.76	1.71	1.68	1.65	1.61	1.58	1.54	1.50
27	2.90	2.51	2.30	2.17	2.07	2.00	1.95	1.91	1.87	1.85	1.80	1.75	1.70	1.67	1.64	1.60	1.57	1.53	1.49
28	2.89	2.50	2.29	2.16	2.06	2.00	1.94	1.90	1.87	1.84	1.79	1.74	1.69	1.66	1.63	1.59	1.56	1.52	1.48
29	2.89	2.50	2.28	2.15	2.06	1.99	1.93	1.89	1.86	1.83	1.78	1.73	1.68	1.65	1.62	1.58	1.55	1.51	1.47
30	2.88	2.49	2.28	2.14	2.03	1.98	1.93	1.88	1.85	1.82	1.77	1.72	1.67	1.64	1.61	1.57	1.54	1.50	1.46
40	2.84	2.44	2.23	2.09	2.00	1.93	1.87	1.83	1.79	1.76	1.71	1.66	1.61	1.57	1.54	1.51	1.47	1.42	1.38
60	2.79	2.39	2.18	2.04	1.95	1.87	1.82	1.77	1.74	1.71	1.66	1.60	1.54	1.51	1.48	1.44	1.40	1.35	1.29
120	2.75	2.35	2.13	1.99	1.90	1.82	1.77	1.72	1.68	1.65	1.60	1.55	1.48	1.45	1.41	1.37	1.32	1.26	1.19
∞	2.17	2.30	2.08	1.94	1.85	1.77	1.72	1.67	1.63	1.60	1.55	1.49	1.42	1.38	1.34	1.30	1.24	1.17	1.00

NTNU
Norwegian University of
Science and Technology

mesta