A YELLOWSTONE SNOWROAD RUTTING INVESTIGATION;
A COMPARISON OF TRACKS VS. TIRES
AND OTHER CONTRIBUTING FACTORS

by
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A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Mechanical Engineering

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ABSTRACT

Yellowstone National Park (YNP) has been experiencing more snowroad rutting in the last ten years. Additionally, YNP has recently (winter 2013-2014) been experimenting with permitting large low-pressure tire vehicles to operate on the parks’ snowroads. To gain a better understanding of snowroad degradation, YNP employed a team of snow scientists from Montana State University. In the winter of 2015, a large scale, two year, snowroad rutting study began in YNP. Parameters pertaining to snowroad strength and the difference in impact to the snowroads between tracked and wheeled vehicles were examined. This thesis in addition to Nelson’s (2018) thesis produce a detailed overview of controllable and uncontrollable factors of maintaining and measuring impacts to the snowroads of Yellowstone National Park.

Instruments were developed to collect data in the field and in the Sub-Zero Lab at Montana State University. These instruments allowed researchers to quantify crucial differences between vehicle types and the behaviors associated with them. Once data was collected, the data was post-processed in various ways to analyze trends pertaining to snowroad strength and degradation. With the data processed and analyzed, the profilometer and hardness data proved to be the most informative on snowroad degradation tendencies, however, the other instruments helped reinforce conclusions made with the hardness and profilometer data. The process of taking subsurface measurements on vehicle pass-bys, allowed researchers to confirm that rutting is most closely tied to vehicle-surface interactions (~ top 10 cms).

It was determined that wheeled and tracked coaches can both cause ruts but by different processes. Wheeled vehicles are primarily causing ruts through compaction whereas tracked vehicles primarily cause ruts through a process of snow displacement. Ruts form from wheeled coaches but after subsequent passes the cross-sectional area of the rut tends to level off, especially when inflation pressure is decreased. While tracked vehicles’ ruts continue to grow in size after subsequent passes. Additionally, snowroad hardness was affected differently between tracks and tires. Tracks and tires at higher pressures (≥ 62 kPa) tended to more often soften the snowroad, whereas lower pressure tires (< 62 kPa) tended to harden the snowroad.
CHAPTER ONE

INTRODUCTION

Structure and Intent of Research

This thesis was written in conjunction with a Yellowstone National Park (YNP) “Snowroad Deterioration and Oversnow Vehicle Impact” technical report. This project was conducted to investigate the effects of oversnow vehicles (OSV) on the snowroads of YNP. This was an extensive, two year study on multiple parameters pertaining to road degradation in the park. Each of these parameters could permit a study alone, however this thesis is an overview of all relevant parameters pertaining to snowroad degradation in the park.

My research partner Molly Nelson and myself worked very closely throughout the duration of the project. The literature review and methods portion of this thesis were developed for Yellowstone National Park’s needs and were drawn from the report stated above. Nelson (2018) will be cited throughout the Data and Analysis section of this thesis where her contributions will add benefit. The YNP report was written as a team however for this thesis we have divided it into two separate theses.

The National Park Service (NPS) commissioned this study as part of its ongoing effort to gather scientific data to inform winter use operations. NPS policies regarding winter use in YNP have been the subject of heated debate since 1997. This controversy has only
recently settled due to compromise in the Final Rule published in 2013. The rule instituted an adaptive management plan reliant on using best available science to inform policy. As operators work under this new paradigm and suggest ideas for improved technology that will make the park cleaner and quieter, the NPS is evaluating possible new technology for potential impacts on park resources like snowroads. The quality of the snowroads can have an impact on the safety of winter operations for park visitors and staff.

Each winter, Yellowstone National Park maintains approximately 300 kilometers of snowroads to support administrative and commercial snowmobile and snowcoach (collectively, oversnow vehicles or OSVs) use in the park. Snowroads are primary mainline roads in the interior of the park which, after sufficient snowfall accumulation, are packed and groomed flat by groomers or agricultural tractors towing a leveling and grooming device. Snowcoaches have been purpose-built for oversnow driving, but are most typically vans and mid-sized shuttle buses equipped with track systems or large, low-pressure tires (LPTs) for floatation and propulsion on the snowroads (Figure 1). During the last ten years, reports from park staff and OSV operators have indicated an increase in the occurrence of ruts in the snowroads. These ruts can create dangerous driving conditions which compromise visitor experience and safety. Ruts can range in depth from a few centimeters to much deeper.
Figure 1: "Snowcoaches" range in style from purpose-built vehicles, like Bombardiers (left), to vans converted to a track system (usually "Mattracks") for the winter (center), to vans on large, LPTs for the winter (right).

The National Park Service (NPS) started studying this issue in 2012 and employed Montana State University through a Cooperative Ecosystems Studies Unit (CESU) research agreement starting in the winter of 2015-16. Faculty within the College of Engineering at MSU have a background in snow science and therefore the expertise the NPS believed was needed for this project. They also operate the MSU Subzero Research Facility, with capacity for examining snow microstructure through computerized tomography (CT) scans, producing snow for in-lab tests, and testing the mechanical properties of snow with various testing instruments. The NPS and MSU agreed on conducting two seasons of field work, during the winters of 2015-2016 and 2016-2017.

The purpose of this study is to determine the primary factors contributing to the formation of ruts in Yellowstone National Park’s snowroads and identify a suite of strategies to mitigate the phenomenon. The NPS is particularly interested in factors they can control, such grooming and the type of vehicles allowed on the road. The park’s new
rule is supposed to allow for innovative technologies that will reduce resource impacts. In the last few years YNP has been experimenting with allowing large, LPT snowcoaches. The NPS has allowed operators to experiment with these in recent years, increasing the number of LPT coaches in use in Yellowstone dramatically, starting with three in 2013-14, increasing to eight in 2014-15, over twenty in 2015-16, and finally just over 50 in 2016-17. As the park weighs whether to allow these into the future and with what constraints, they would like to understand how these vehicles impact the roads compared to tracked vehicles. While LPTs have the benefits of reduced operating noise improved fuel efficiency, and lower maintenance cost the NPS would like to understand the likelihood of LPTs damaging the roads.

Year 1 involved testing OSVs as they traveled through the park on their normal routes. A variety of testing equipment was developed during Fall 2015 specifically for this study and was used to collect data in the field. This yielded valuable information but having no opportunity to measure vehicles on repeat passes limited opportunities to isolate variables. Therefore, researchers stressed the need for a controlled setup, with the opportunity to measure numerous runs by the same vehicle and alter variables of interest. In Year 2, the NPS worked with MSU to provide a test track in Year 2 and recruited operators to bring vehicles to the track for a testing appointment in which they worked with researchers for several passes. Test methods used in Year 2 included many of those from Year 1 but also incorporated additional tests based on the results from Year 1.

This thesis describes the two-year study conducted by Montana State University (MSU) for Yellowstone National Park. Specifically, this thesis details methods, results,
and possible implications of the data. This thesis will be submitted to the park to provide additional, detailed test results and recommendations. Results will inform management policies to ensure a safer experience for visitors, NPS employees, and concessioners, increase the longevity of snowroads, and inform future designs and styles of OSVs.

**Statement of Problem**

The NPS wants to more thoroughly understand the factors that contribute to rutting so that they can mitigate factors within their control. Controllable factors include grooming practices and traffic (frequency and types of vehicles). Factors outside of administrative control include things like snowfall frequency and quantity, temperature throughout the winter, wind, and solar radiation.

This research has focused on two issues. The first, raised by the NPS’s allowance of experiments with low pressure tire (LPT) snowcoaches in the park, is whether tires impact the roads differently than tracks. Since the NPS needs to decide on the long-term policy on these tires, they need more information on possible impacts.

The second issue is what grooming practices lead to the best road conditions. Operator comments from past years have indicated that road conditions vary throughout the park. Data gathered by MSU through groomer-operator interviews and a tour through the park in 2014 (prior to the beginning of this study) have indicated that grooming practices vary across districts. The NPS would like to understand whether any changes to grooming practices could be implemented to improve road conditions throughout the park.
CHAPTER TWO

LITERATURE REVIEW

Snowroad Assessment and Maintenance

Snow as a Road Material

Snowflakes fall in many shapes and sizes and are fragile structures. As these structures accumulate, they being to bond to one another over time. This process can be expedited by disaggregation and compaction. Through these processes the crystal will very likely break down ending up with less surface area. This can be achieved by grooming, wind transport or simply taking a handful of snow and pressing it together. This process of disaggregation and compaction increases the opportunity for snow to strengthen through a process called sintering.

Ramseier and Sander (1965) found that sintering of snow is a function of temperature that is directly correlated to strengthening of snow. Colbeck (1987) defined this process by saying “crystal growth in dry snow is a process of continuous sublimation-evaporation from warmer and/or more curved surfaces and condensation on colder and/or less curved surfaces”. Basic thermodynamics dictates that water vapor moves from high to low pressures, as the water vapor is released into the air it condenses where the grains touch because the pressure is lower, due to surface curvature, at these locations. This forming and strengthening of bonds is the processes of sintering and it is directly correlated to the strengthening of the snowroad.
Abele (1990) took three snow samples of equivalent densities and allowed them to sinter for many days in a controlled laboratory environment (Figure 2). A disaggregated, compacted snow with a density of 0.5 g/cm\(^3\) (comparable to densities seen in this study) was exposed to a constant temperature of -10 °C and reached an unconfined compressive strength of 10 kg/cm\(^2\) in approximately 2-3 weeks. A sample of equivalent density was exposed to a constant temperature of -40 °C, this sample required more than 3 months for the snow to reach the same strength (Abele, 1990). This study implies that at colder temperatures a snow sample will require more time to sinter to equivalent strengths as a sample exposed to temperatures near freezing. The process of sintering does not occur at temperatures above freezing. Abele also found that snow at higher initial densities, achieved through compaction, would result in higher strengths after the sintering process.
Figure 2: Effect of time on the strength of processed snow as a function of temperature, this figure depicts that snow at temperatures closer to 0 °C is sintering to higher strengths faster than the much cooler temperatures. (Abele, 1990).

Sintering and densification can occur in an undisturbed snowpack but occur significantly faster when the snow has been agitated or disaggregated (Lee and others, 1989). As it pertains to this project, this is an important concept because by allowing grooming and traffic on the snowroads, the roads can sinter to higher strengths, faster. This process can be expedited even further by a melt-freeze event. When the temperature is above freezing the crystals will bear a slight amount of liquid water, then if the temperature drops to freezing this available water allows crystals to weld together. During warmer periods in the winter months, this can become a diurnal process of melt in the day freeze at night. The melting phase of this process can significantly weaken the
snowroad, but then ultimately makes the snowroad stronger when followed by the freeze phase.

Snow’s strength is correlated with the number and size of bonds between grains (McCallum, 2012) and this microstructure dictates how the snow will deform. Mellor (1975) describes snow as a compressible non-linear viscoelastic material which indicates that snow’s deformation greatly depends on the rate at which it is loaded. Snow takes on both elastic (as a solid) and viscous (as a fluid) behaviors when loaded in different scenarios. When subject to a load, snow undergoes an immediate recoverable deformation (elastic component) as well as a time dependent irreversible deformation, described as snow creep (viscous component) (Olagne & McClung, 1990). The stress exerted by a track or LPT snowcoach at the velocities tested in this project, exerts a load to the snow in less than ~0.1 seconds, which is within the elastic time frame for snow (Olagne & McClung, 1990). For the purpose of this study, viscous behavior was not considered a significant factor and was not examined.

The most important environmental factor influencing the quality and survival of a snowroad is temperature (Barthelemy, 1975). Diurnal temperature changes are a key player when it comes to affecting snow hardness around the park. With a relatively deep blanket of insulating snow, the ground temperature can typically be assumed to be near 0 °C. Geothermal energy maintains this temperature. In the winter months Yellowstone National Park’s ambient air temperature stays quite cold. This cool ambient temperature and radiation loss causes the snowroad surface to be much colder than the base of the snowroad. This generated temperature gradient drives a vapor pressure flux throughout
the depth of snow. With the warmer temperature near the ground, the vapor pressure is
ger higher at depth in the snowpack, which drives upward heat and water vapor fluxes. As
this happens the water vapor condenses to crystals as it moves upwards forming faceted
crystals. This process results in an overall weaker configuration of the snowpack and is
the process of temperature gradient metamorphism. In a relatively less dense
homogeneous snowpack when the temperature gradient reaches $10 \, ^\circ C/m$ or above, facet
development can begin to take hold on a snowpack (LaChapelle & Armstrong, 1977),
however, there are caveats with regards to higher snow densities (Akitaya, 1974).

Interestingly, with the snowroads being quite dense in Yellowstone (most areas
near $0.5 \, g/cm^3$) this temperature gradient metamorphism phenomenon is slightly different
than that described above. Akitaya (1974) found that a temperature gradient applied to
higher density snow can actually increase hardness over time, which is the opposite for
that of less dense snow. Based on Akitaya’s 1974 research, snow of higher densities can
be expected to strengthen when exposed to a relatively high temperature gradient where
snow of lower densities could possibly weaken when exposed to a temperature gradient.
Colbeck (1991) also conducted research on this topic and had similar conclusions. Based
on Colbeck and Akitaya’s findings most areas of the snowroads that consist of higher
density snow ($0.5 \, g/cm^3$) are expected to harden with temperature gradients; however, it
is still possible in less dense areas where there is insufficient compaction and
disaggregation for snow to become softer with an applied temperature gradient.

If snow becomes too weak and vehicles are traveling on the snowroad, rutting will
occur. Depending on temperature and traffic effects, the snowroad may deteriorate to the
point of becoming impassable. When the road regains strength, through any of the above processes, it will act to ‘lock in’ the ruts, unless the road can be smoothed and recompacted simultaneously with the regaining of strength (Lee and others, 1989). This is a unique aspect to snow as a road material, and snow as a road material is greatly affected by environmental conditions.

**Snowroad Assessments (and Factors Considered)**

Since hardness and density are the properties most indicative of snowroad loading capacity (Shoop and others, 2010), these are typically the parameters measured to assess road conditions. Since road systems can consist of many miles of multiple lanes, quick and portable testing methods can provide an advantage by allowing many tests to be taken throughout the road system.

Density is regularly collected in snow research of all kinds, including snowroad assessments. It is a straightforward measurement, requiring only the mass of a known volume of snow. Since only mass and initial volume are required to calculate the density, samples can be weighed on-site or transported from the field to the laboratory relatively simply, without a need for preserving the sample’s microstructure.

Hardness of snow is of interest as an indicator of snow strength. The strength of the snow is important in understanding how it will support vehicles. Strength can be measured in several different ways; Abele (1990) provides a good explanation of the possible methods of strength assessment in snowroads. These methods range from in-situ plate bearing tests, in which a load is applied to a plate on the surface of the snow and
displacement is measured, to laboratory compression tests of samples extracted from the road, to Rammsonde cone penetrometer in-situ measurements (Abele, 1990).

Rammsonde cone penetrometers are the most commonly used instrument to test snowroad hardness. They have the advantage of using easily portable equipment and being relatively fast and simple to use; this allows researchers to take more tests and therefore sample more points along the roads. A special version of the Rammsonde has been developed specifically for snowroad research. This version has a 30° cone instead of the original 60° cone so that it will more effectively penetrate the extremely hard snow produced through snowroad development (Lee and others, 1989).

The Rammsonde hardness measurement is so widespread in snowroad studies that standards have been established. Shoop and others (2010) cites two different sets of minimum snowroad standards that have been proposed targets for snowroad quality: Swiss Rammsonde hardness greater than 350, or Rammsonde hardness of 450 in the top 25.4 cm of snow and density of greater than 0.5 grams per cubic centimeter. Assuming that this 450 recommendation is a “Ramm hardness number” in units of kg as measured with a 60° cone, this would equate to a Ramm resistance of 4415 N. Using a correction factor of 1.56 (Shoop and others, 2010) to convert readings from a smaller, 30° cone to readings from a larger, 60° cone, a 4415 N reading from a 60° cone would equate to a reading of 2830 N with a 30° Ramm cone. Lower hardness values may not be adequate to support oversnow vehicles and so may be at risk for rutting.

Another tool commonly used in snow science to characterize snow is a shear test. However, the tools typically used for this are not suited for the hard snow encountered on
snowroads (Abele 1990). Shear testing therefore does not seem to be widely used in
snowroad characterization. The one exception found was a specialized “confined shear
strength test” developed especially for snow pavements and used by Abele (1990).

In recent years, ground-penetrating radar (GPR) has been employed to analyze
snowroads. In 2009, Lee and Wang proposed a method to correlate GPR data with
hardness as measured by a Rammsonde penetrometer. They worked on finding a
correlation by using a layer-stripping method to gain information about the individual
layers within the snowroad, and found that permittivity of the layers positively correlated
with density, which also positively correlated with hardness. In 2016, Annan and others
described use of GPR to assess the safety of winter roads by determining thickness of ice
roads. GPRs capable of measuring snowroad characteristics are promising due to their
portability and ability to take sample measurements over a large area easily.

Factors Beyond Control Influencing Snowroad Conditions

Factors not controllable by the park include weather and site characteristics (e.g.,
aspect). Analysis included these factors so that the relative influences of controllable and
non-controllable factors could be better understood. Since the formation of snowroads is
dependent on snowfall, and the metamorphism of snow is influenced by temperature
trends, weather factors are considered with respect to road conditions. Site characteristics
like elevation, slope, and aspect are widely used in snow science and avalanche research,
and will be investigated in this study to determine their relative importance on snowroad
characteristics.
In the following section, Grooming Theory and Best Practice, states grooming smaller incremental depths of fresh snow at a given time leads to a more homogeneous hardness stratigraphy throughout the depth of the road. While the NPS can send groomers out during the middle of the day in the event of prolonged snowfall, this is not always feasible due to staff schedules and heavy traffic on the roads during the middle of the day. Therefore, amount of snow groomed at a time is often linked to daily snowfall amounts. Snowfall distribution throughout the park is considered in this thesis; however, some known concepts can help predict where high snowfall areas might be located.

While elevation is often presumed to be the predominant factor affecting the distribution of snow cover, this is generally only valid “within a given elevation interval at a specific location.” This means that a higher elevation may only correspond with more snowfall within a small geographic region and over a small variation in elevation because of snowfall’s additional dependence on climate and slope, which can vary substantially over a small area (McKay & Gray, 1981). Within these constraints, higher elevation is typically linked with more snow.

Mizukami and Perica (2008) found that a snowpack with a higher mean seasonal density tends to have densification occurring at a higher rate mid-winter. Relating this to elevation, a trend of slower densification at higher elevations was demonstrated. They cite studies that have found correlation between denser newly fallen snow and warmer environments. They tracked the evolution of snow density throughout the season at various SNOTEL sites using data sets containing both snow depth and SWE values. According to the background information cited in their study, a snowpack at higher
temperature experiences densification at a faster rate than a snowpack at a lower
temperature due to the type of metamorphism predominant at warmer temperatures.
Mizukami also used site aspects to define a “Northness” characteristic (cosine of
azimuth) and “Eastness” characteristic (sine of azimuthal angle).

Wind is important in snow distribution for a couple of reasons. Combined with
slope, it can be a dominant factor in snow distribution because of how it affects the
movement of air masses over different elevations and over mountains which in turn
determines precipitation (McKay & Gray, 1981). Wind can also affect snow cover
through transporting and redistributing snow (McKay & Gray, 1981). Wind is also a
factor that has been noted to negatively impact snowroad quality and present maintenance
difficulties (Shoop and others, 2010). As seen frequently in certain windy areas in
Yellowstone, wind can cause drifts to build up on the road, making the surface uneven
and requiring more grooming to maintain a flat and discernable road surface. Conversely,
it can cause snow to blow off of the road which can leave an insufficient road base.

Aspect can impact snow cover in a variety of ways. (McKay & Gray, 1981) note
that coastal mountain ranges see the impact of aspect in: “directional flow of snowfall-
producing air masses”, “frequency of snowfall”, and “energy exchange processes
influencing snowmelt and ablation.” Sun on the south side of mountains in Yellowstone,
for example, introduces more solar energy to snow cover on these Southern aspects.

As noted in the Snow as a Road Material section, temperature is important to
snowroad quality. Temperature is not only important for the initial formation and
precipitation of snow but also snow metamorphism on the ground. This is true with
snowroads as well as the ungroomed snowpack. According to Lang and others (1997), temperature gradients in the snowroad, driven by ambient temperature, are more influential on the daily quality of a snowroad than the processing.

McClung and Schweizer (1996) have examined the short- and long-term impacts of warm temperatures on snow hardness, showing that warmer temperatures cause softer snow in the immediate, short term but ultimately harden the snow over a long-term timeframe. This hardening comes in part from increased sintering in warm snow (McClung & Schweizer, 1996), as discussed in the Snow as a Road Material section.

**Grooming Theory and Best Practice**

Oversnow vehicles have operated in Yellowstone National Park for almost seventy years. Starting with snow planes in 1949 (Figure 3), oversnow operations have transitioned over time to include snowcoaches starting in the 1950s and snowmobiles in 1963. To support these operations, the NPS constructs and maintains snowroads throughout the park each winter. Over the same decades that the NPS has maintained Yellowstone’s snowroads, collective knowledge about snowroad construction and maintenance has increased through studies in other locations throughout the world that depend on oversnow travel.
Abele (1990) provides an overview of the evolution of modern snowroads, from expansive networks of rudimentary logging roads (over 50,000 km in Canada and 70,000 km in Finland by the 1950s), to military-constructed runways in cold regions in World War II, and finally to runways and roads for Antarctic research starting in 1947. Since the advent of research in Antarctica, many studies have been conducted to increase knowledge about best practices for snowroad construction (Barthelemy, 1975; Blaisdell and others, 1998; Diemand and others, 1996; Lang and others, 1997; Lee & Haas, 1986; Lee and others, 1989; Russell-Head & Budd, 1989; Shoop and others, 2010; Shoop and others, 2014b). Shoop and others (2010) provides a good summary of the state of knowledge, incorporating many of the referenced studies.

An understanding of the snow metamorphism involved with snowroad formation helps explain the importance of different parts of the grooming procedure. According to Barthelemy (1975), the processes involved with construction and maintenance of snowroads “alter the state of natural metamorphism so that the rate at which density and
hardness increase is accelerated”. Snowroad construction and maintenance harness processes which already occur in snow in the right conditions.

Snow density and hardness are the parameters that construction and maintenance operations aim to optimize and maintain. The two main methods used for snowroad construction “processing” are disaggregation followed by compaction. These processes, in conjunction with one another, result in higher snow density and hardness. Breaking snow grains into smaller, non-uniform pieces creates thermodynamic instability, which increases the particles’ ability to bond with one another (i.e., sinter). Compaction then presses the disaggregated particles together, maximizing contact between these particles and further encouraging sintering (Barthelemy, 1975). In addition, close packing that increases contact between the grains helps distribute load throughout the snowpack (Lang and others, 1997). Effective snowroad grooming must incorporate these two components.

To achieve this processing and compaction, researchers have recommended a wide variety of equipment. Most of the relevant literature addresses the complete construction of snowroads, often starting on a deep snow or ice surface. While some of these practices may be beyond the scope of routine grooming, some of the equipment and processes used will be the same. If a deeper unconsolidated layer of snow has accumulated on the snowroad due to snowfall since the last grooming event, some methods regarding snowroad construction suggested in reviewed literature may be beneficial. Abele (1990) recommended the following construction scheme: 1) disaggregation with a tractor, harrow, and skid; 2) leveling compaction with a bulldozer and roller; 3) grading with a tractor and drag; 4) compaction finishing with a bulldozer,
roller, and smooth drag; and 5) final grading with a road grader. Russell-Head and Budd (1989) found that pneumatic-tired rollers are most effective for the snow compaction needed for construction and maintenance of snowroads (Russell-Head & Budd, 1989). Shoop and others (2010) compared rollers and drags, and found that both have different benefits. Data from this study further informed Antarctic testing of the Keweenaw Research Center “SnowPaver”, which incorporates leveling blades, a unit that mills the snow, and a vibratory compaction plate into one unit (Shoop and others, 2014a). A history of the development of this unit is available in Alger and others (2011). Lang and others (1997) tested a variety of tillers followed by a drag bar for compaction, and achieved necessary snow strengths for a snow runway. Russell-Head and Budd (1989) also noted that both the Soviets and Australians were using pneumatic-tired rollers to achieve compaction on their snowroads with success in Antarctica.

Compacting the road after each snowfall, in relatively thin layers (no more than a few centimeters), will produce the most uniform strength throughout the road profile. If compaction does not occur in this gradual manner, the entire depth of ungroomed snow should be processed and compacted all at once (Abele, 1990). If a large depth accumulates prior to the commencement of grooming, the compaction achieved will only compact to a certain depth from the top of the snowpack. According to Barthelemy (1975), “the enhancement of mechanical properties of snow” from compaction “is restricted to a limited depth below the surface”. This can be overcome by “depth processing” (digging down to the bottom of the snow and processing the entire depth) of a deep layer of ungroomed snow that has accumulated (Barthelemy, 1975), but this may
be logistically difficult. For Yellowstone, in which the snow processing equipment is mostly geared toward grooming the existing road, just processing the top layer, rather than constructing a new road in an existing snowpack, depth processing may not be possible.

After processing and compaction of the snowroad surface, the snowroad needs time to set up. According to Barthelemy (1975) “The importance of the age-hardening process in developing a trafficable surface and increasing the load-bearing capacity of a compacted snow mass cannot be overemphasized.” Shoop and others (2010) recommends that the McMurdo Station in Antarctica allow two to three weeks for age-hardening of its roads after snowroad compaction.

Some snowroad construction has involved the addition of various additives, ranging from water to sawdust (Abele, 1990). In 1989, Lee recommended more experiments with sawdust and other additives that could potentially strengthen snowroads. Lee specified that a sawdust additive had shown promise at the South Pole, where temperatures never got above freezing, but that the sawdust had not proven effective at McMurdo Station during its thawing season. In a climate in which temperatures near or above freezing are common, sawdust or other additives on the surface of the road surface can ultimately weaken the road. Debris on the road, which could include sawdust, can cause “melt holes” due to their lower albedo which absorbs solar radiation, heating the snow (Abele, 1990; Lang and others, 1997).

Russell-Head noted in 1989 that Soviets, who were the most experienced snowroad-builders at the time, seemed to have learned that compaction is more efficient
with warmer snow (though they had not published much information about their building techniques). Lee and others (1989) had drawn the same conclusion, recommending a heat treatment. Ramseier explained in 1966 that compacting snow at a high temperature (near the melting point) will lead to a higher density than compacting at a lower temperature, and that sintering near melting temperatures rapidly increases the strength of snow. However, while a higher temperature will lead to a faster rate of snow strengthening, it will result in a lower ultimate strength over a timeframe of several weeks to months (Abele, 1990).

The possibility for a rut to become frozen and preserved in a road surface due to temperature fluctuations (Lee and others, 1989) emphasizes the importance of processing any snow that has been disturbed from the flat surface during the grooming process; sintering that occurs in a rut will make the rut last longer. If processing is being achieved with a groomer’s front blade, the bottom of the blade must reach down to the bottom of the rut at a minimum to break up a rut that has formed, then re-process and compact the snow so that it will bond in a flat surface again.

While processing the snow is critical to producing a strong snowroad, “overprocessing” of the snow can counteract this relationship. Reprocessing repeatedly increases the likelihood of contaminating the snow with exhaust fumes, oil, and hydraulic fluids. Hydrocarbons present in the snowpack prevent the snow grains from sintering (Lang and others, 1997).

Beyond the groomer, all vehicles passing over the road will impact it. This is addressed in the Individual Vehicle Impacts on the Road section, but is also mentioned in
some of the studies on grooming. Shoop and others (2014b) cited tests from Canada that found that after snowroad construction and sintering, traffic can actually improve the road. Lee and Haas (1986) theorized that a buried ice layer in the McMurdo snowroad had formed from a combination of freeze-thaw cycles and traffic compaction. These observations indicate that the loading from vehicle traffic throughout the season may ultimately help to compact the road, though whether this packing could happen despite some surface damage is not discussed. Shoop and others (2010) notes that pneumatic tire rollers, used as drags in Antarctic snowroad grooming, increase density in the snowroad while disaggregating the top 10 cm of snow. This phenomenon could theoretically happen from vehicle traffic as well. Abele (1990) specifically mentions not to allow tracked vehicles on the snowroad unless they have smooth rubber tracks, and warns to avoid allowing high speeds, sudden stops, and sharp turns.

**Individual Vehicle Impacts to the Snowroad**

**Vehicle Characteristics and Impact**

Both wheeled and tracked vehicles are capable of negotiating rough terrain and obstacles that are not encountered on a typical roadway. The main difference between the two is that wheeled vehicles are typically more agile but possess higher ground pressures than tracks. Lower ground pressure is typically only an advantage in soft terrain (Laughery and others, 1990). When observing the difference between tracks and tires and their effects on snowroad quality, which is soft terrain, low ground pressure is a desirable feature of a vehicle.
Compaction of soil or snow is directly related to the magnitude of applied normal stresses. From engineering theory, a higher applied normal stress will theoretically cause more compaction of a soil that has reasonable bearing capacities. A simple method of reducing ground pressure is increasing the load bearing surface area of a track or tire. For a tire, this is achieved by decreasing inflation pressure, increasing wheel diameter or incorporating more wheels to the vehicle (Håkansson and others, 1988). Tracked vehicles have multiple bogey wheels that support the weight of the vehicle, along with the track. A vehicle equipped with four tires will have higher ground pressures than the same vehicle equipped with tracks. However, there is more to road degradation than just ground pressure. The shearing action is an important variable to explore before declaring a track or wheeled vehicle superior to one another with respect to impacts to snowroads.

Tracks and tires both have tractive “lugs” that run along the outside circumference of the track/tire. These lugs are in place to generate additional traction, which increases vehicle performance and control. In this thesis the tractive lugs on a track will be denoted as grousers, and the lugs on a tire, referred to as tread (Figure 4).

Figure 4: Left, a “Snowbuster” tracked snowcoach with a grouser, bogey wheel, and track identified. On the right an LPT vehicle is used to define the tread on a tire. These terms will be used throughout paper.
Ansorge and Godwin (2008) developed a technique that was used to determine the effects of tires and tracks on longitudinal soil movement. This study revealed that tracks caused a backward movement of the soil at or near the surface, whereas the tires tended to provoke a forward movement of the soil in the same depth range (Ansorge & Godwin, 2008). In addition to these differences, a tracked vehicle applies shear for a longer period of time, leading to increased shear displacement beneath the tracks (Ansorge & Godwin, 2008). Although the tracks are applying shear for more time they are also applying a vibration for more time, this being a benefit of disaggregating the snow and encouraging sintering (Ansorge & Godwin, 2008). For these to be accurately compared the tread and grousers must be of comparable dimensions and rigidity.

As a grouser moves around the track it must change angles at the front and rear of the track, and at intermediate bogey wheel locations, depending on the tension in the track. Less tension results in a larger relative angle change of grouser to the road surface, as the track follows the contours of the bogey wheels. As a grouser embedded in the road surface changes angles, this can cause additional deformation. The soil (or snow, extrapolating findings of the study to snowroad applications) is not only pushed backwards by the horizontal forces and the change of the lug angles, but is also lifted as the hindmost lug is lifted obliquely from the soil (Kevan, 1971). This principle pertains to tire rotation as well, however the radius of curvature of the tire or track is important to consider. A track/tire with a larger radius of curvature will decrease the angle of contact with the surface and decrease the above effect by reducing the drastic nature of the lug’s changing contact angles at the front and rear of the track/tire.
This leads to the topic of wheel diameter as it pertains to road degradation. It is widely documented in the field of terramechanics that increased wheel diameter allows a vehicle to navigate through rougher terrain with a “smoother ride”. This “smoother ride” is due to reduction in magnitude and change of direction of the reactions transmitted to the vehicle as a result of a larger diameter wheel. As it pertains to road degradation, Antille and others (2013) found that smaller width tires can reduce soil compaction provided that the contact patch area is maintained (or increased) by means of a larger tire diameter (Bekker, 1956; Håkansson and others, 1988). With the combination of performance needs, passenger comfort, and road degradation issues, a balance between wheel diameter, width and lug pattern exists for a particular vehicle mission.

As a wheel or track rotates and the grouser/tread is embedded in a surface, the lugs push against the soil/snow horizontally, which is partially how traction is generated (Laughery and others, 1990). When this tractive force exceeds the shearing strength of the surface, the lug will slip. When this slip occurs, it causes additional permanent deformation to the road surface. The severity of this distortion is proportional to shearing strength of the surface and the magnitude of torque produced by the track. If a tracked and wheeled vehicle are traveling at equivalent velocities, the tracked vehicle’s grousers are implanted in the surface for a longer time than a tread of a tire. This applies a shearing force to the surface for longer which can cause more soil distortion (Laughery and others, 1990).

A notable difference between tracks and tires occurs while turning a vehicle in soft terrain. When a tracked vehicle turns, one of the vehicle’s tracks must slow as the
advance of the other side pivots the vehicle about the slower track (Kevan, 1971). As a result of this “skid steer” technique for directional change, the road surface can become badly scoured from the slower track, especially as turn radius decreases. This phenomenon was not investigated but it is assumed that this scouring of the surface while turning is a disadvantage of tracked vehicles as it pertains to road degradation.

A unique benefit to LPTs is that the operator can adjust tire pressure for needs of the mission. Through discussion with operators during the study, it was gathered that operators were having improved performance with decreasing inflation pressure in their tires. Literature confirms this concept and simply put by Raper and others (1995), it is “putting more rubber on the road”. Reducing tire pressure increases the patch size of the tire in contact with the surface and increases the traction of the vehicle. Through this decrease in pressure it was also found by Raper and others (1995) that the total cross-sectional area of the road surface deformation was not affected by inflation pressure. This occurred because increased inflation pressure caused decreased rut width but increased rut depth. These two parameters tended to cancel as each affects rut area in a different manner (Raper and others, 1995).

**Soil/Off-road Surface Characteristics and Impact**

In general, vehicles are more often driving on road surfaces other than snow, so it is not surprising that most literature pertains to vehicles traveling on these other surfaces. This literature is important to relate to this project because other soils that have been studied in depth can be related to snow properties. Snow is, in many instances, more sensitive to environmental factors than soil. But many findings of soil studies are also
pertinent to snow studies. Laughery and others (1990) examined three soil types and their characteristics with respect to soil deformation (Figure 5). Laughery found that soil type B could be related to dense snow at very cold temperatures.

Figure 5: Characteristics of soil deformation for three soil types. Reprinted from Laughery and others (1990). The variable S on the x-axis represents soil distortion and on the y-axis T represents shear.

Soil A refers to a cohesionless soil, B is a cohesive soil and C a mixture of A and B. Comparing the three soil types depicts soil deformation characteristics with regards to the shearing stress. These curves were formed empirically and show the motion of soil under the plotted shear. Curve A represents a loose frictional or plastic soil such as wet
clay. For this soil the shearing strength $T_A$ is reached after the initial period of compaction, which takes place over a distance $S_A$. After this point the stress remains practically the same irrespective of any slip. Soil B consists of a dry coherent mass, dry clay or snow at very low temperatures. This soil quickly reaches its maximum shearing strength and then tapers off considerably. Curve C is a combination of the two soil types and this soil reaches its shearing strength in-between soil types A and B (Laughery and others, 1990). This figure shows that a snow at cold temperatures (soil B) will reach its shearing strength faster than the other two soil types, which indicates the highest tendency to deform from shear.

In addition to shearing tendencies, compaction is of interest when researching road degradation from vehicle traffic. Professionals throughout the soil mechanics field agree that if a higher stress is applied to a soil, more compaction will result. However, hardness and density of the material will dictate how much compaction is induced by a vehicle pass. A dense, hard road surface will resist compaction better than a relatively less-dense, soft road surface. In the two years of testing in Yellowstone it seemed that compaction was much less of a factor than shear but in soft conditions, compaction can be a large contributor to rutting.

As a vehicle moves through a deformable surface and its vertical load is high enough, it will sink. This sinking causes compaction at and just below the surface of the road and can affect performance of the vehicle. Richmond and others (1990) found that

“compaction is partially the result of vertical forces (vehicle weight) applied to the snow surface by the tire; however, it takes place along a curved path and, therefore, horizontal forces are also applied. When compaction occurs,
it can be witnessed by the presence of a rut in the snow following vehicle passage”.

In these conditions a vehicle must push through the soil on the leading edge of the tire or track; this is the concept of “bulldozing.” Bulldozing resists movement and it leaves a trench or “rut” in the wake of the vehicle’s path (Janarthanan and others, 2012). This deformation in combination with shear are the two primary causes of ruts in snow and many soil types.

A common misconception of tracks is that the weight of the vehicle is being supported by the entirety of the track’s surface area in all conditions. This is not the case in certain road surface conditions; the tracked vehicle’s weight is mainly supported by the bogey wheels on relatively stiff surfaces. The sinkage characteristics of a tracked vehicle depend on vehicle weight, track dimensions, track tension and the soil characteristics (Janarthanan and others, 2012). If the surface is extremely hard, the road experiences higher stresses due to concentration of load under the bogey wheels. In such a case, however, deformation may be limited despite the higher stresses. In the case of a softer surface, the portion of the track which is stretched between the sinking bogey wheels supports a portion of the load. This increased load-bearing surface area reduces the magnitudes of stresses seen by the road surface. In this case, deformation may be limited.

If a vehicle is exceptionally heavy, it will apply relatively high normal (perpendicular to surface) stresses which can induce more sinkage and compaction. The track’s tension contributes to how much of the track will take up load on a deformable surface. A tighter track can support more load as the bogey wheels press through the surface from vertical plastic deformation (Janarthanan and others, 2012); as this process
occurs, the track tightens further and supports even more load. Additionally, track
dimensions are important to consider for ground pressures, a larger surface area track will
distribute its load over more area which reduces pressure on the road surface. Tracks’
ground pressures are heavily reliant on soil/snow strength properties, whereas tires have a
unique advantage of controlling inflation pressure which controls load bearing surface
area independent of soil/snow characteristics.

Types of Impact: How to Measure

The Wisconsin Department of Natural Resources, in its Forest Management
Guidelines, breaks soil degradation into categories (Wisconsin Department of Natural
Resources, 2011); the two modes they define that would apply to a snowroad are
“compaction and rutting” and displacement. In snowroads, a rut—or depression in the
road surface—could form due to either compaction or removal of snow. Additionally, the
dependence of snow hardness on bonds within the snowpack means that impacts which
break bonds in the snowpack (such as treads cutting through the snow) may reduce the
snowroad’s hardness, making it easier for a vehicle to displace snow, effectively making
the road more vulnerable to rutting. Shoop and others (2014b) recognized this mode of
weakening when using surface strength measurements to determine whether “vehicle
traffic changed the snow either through compaction or by weakening through breaking
the bonds of the prepared snow surface.”

Understanding rut formation on snowroads involves understanding how snow
might be compacted, displaced, or made less hard by passing vehicles. This could involve
motion at both the snow-vehicle interface and underneath the surface of the snow as it is
compacted and moved. A variety of methods have been used previously to explore these mechanisms in studies concerning vehicle impacts on both soil and snow.

A number of studies have addressed changes to snow or soil surfaces during the passage of a vehicle. Instruments called “profile meters” or “profilometers” can measure depth, width, and total cross-sectional area of a rut and any snow piles adjacent to the rut. Raper and others (1995) employed a “profile meter” to measure both width and the “total deformed area” of ruts, compare those caused by tractor tires at different pressures. The U.S. Army Corps of Engineers Cold Regions Research and Engineering Laboratory (CRREL) has incorporated this type of instrument into several studies. Kestler and others (1999) and Affleck (2005) both used a profilometer to investigate vehicle impacts on thawing soil. Buck and others (2012) used a profilometer to examine vehicle impacts on vegetated soil. Finally, Shoop and others (2014b) applied this instrument to an Antarctic snowroad while comparing the impacts of tracked and wheeled vehicles.

Several instruments can be employed to indicate compaction caused by vehicles on a snow or soil surface. Some studies compare tire and track impacts with soil compaction to aid in vehicle selection for agricultural uses. For agricultural purposes, compaction and resultant increased density and resistance to penetration are undesirable effects as they generally result in decreased soil productivity due to reduced pore volume and size (Wisconsin Department of Natural Resources, 2011; Sutherland, 2003). For snow, however, compaction is more complicated and can have both positive and negative impacts on snowroads. Compacting snow increases its density, encouraging sintering and
making it harder. When this is localized to one set of tracks, however, it can cause ruts in the road surface.

Compaction to a road and the road’s resistance to penetration are often measured using a cone penetrometer test. As discussed in the Snowroad Assessments section, the Rammsonde penetrometer (“Ramm penetrometer”) is commonly used to measure snowroad hardness. Both 30° and 60° Ramm penetrometers have been used in snowroad studies, typically to measure overall road conditions (Lee and others, 1989; Russell-Head & Budd, 1989; Shoop and others, 2010; Shoop and others, 2014b). They have often been used in conjunction with a Clegg Impact Hammer to characterize the surface hardness of snow, both on untouched road and with regard to vehicle impacts (Lee and others, 1989; Russell-Head & Budd, 1989; Shoop and others, 2010; Shoop and others, 2014b; Shoop and others, 2014a). Tests of vehicle impacts in soils have also used a variety of cone penetrometer tests (Antille and others, 2013; Raper and others, 1995). In both snowroad and soil test, density has been measured as an indicator of compaction from grooming and/or other vehicle impact (Abele, 1990; Russell-Head & Budd, 1989; Shoop and others, 2010; Antille and others, 2013).

Beyond tests of deformation and compaction at a road’s surface, subsurface motion can indicate the impact that vehicles are having on the road. Pytka (2010) used stress-state transducers buried at depths of 10, 20, 30, and 40 cms below a snow surface to measure stresses at these depths as vehicles passed. Horn and others (2007) employed a similar stress-state-transducer setup to look at the stresses under logging vehicles on dirt logging roads. Keller and others (2002) used stress state transducers in conjunction
with displacement transducers in an agricultural field to compare subsurface stress and motion caused by rubber-tracked and wheeled tractors. Arvidsson again used this method to collect data under tracked and wheeled agricultural equipment in 2013 (Arvidsson & Keller, 2014). The stress state under a vehicle on a deformable surface provides insight into both the stress on the deformable material (snow or soil) and the motion within the soil or snowpack.

Snow scientists at Montana State University have previously used accelerometers to measure acceleration in snow during blasting for avalanche mitigation (Bones, 2012). Acceleration data can be integrated to give both velocity and displacement, though this processing can involve some error propagation (Stiros, 2008) and require correction. Yang and others (2006) provide an overview of previously proposed correction methods and the reasons behind them, and then propose an alternative correction method.

Another type of road disturbance measurement, used most typically on asphalt, is the distribution of stress at the tire-road interface. Coutermarsh and Shoop (2009) investigated this for snow and ice surfaces, using the CRREL Instrumented Vehicle to record vertical, longitudinal, and lateral/transverse forces at the tire contact patches (where the vehicle’s wheels touch the ground surface). These tests took place on a variety of snow surfaces, including packed, hardened snow. More commonly, these tests are conducted for vehicles on asphalt to test the difference in stress or force distribution in different directions for tires with different configurations (bias vs. radial, different pressures, etc.). Beer (1996) developed a measurement system specifically to determine the interface stresses in vertical, transverse, and longitudinal directions since
“tyre/pavement interface stresses is one of the most important inputs in any pavement design system”. The distribution of stress in different directions has been linked to specific types of road degradation in asphalt roads (Myers and others, 1999; Weissman, 1999).

Most Relevant Studies – Empirical Road Impact

CRREL has conducted the studies most closely related to the current study. Most recently, Shoop and others (2014b) describe a study in Antarctica in which they measured impacts from a variety of different oversnow vehicles (all on tires) making a variety of different maneuvers (turning, braking, etc.). They found that vehicles travelling at higher speeds (40 km/hr or greater) and vehicles accelerating quickly tended to cause more damage to the road in terms of rutting. They recommend the use of large, wide tires when operating wheeled coaches on the snowroads.

In 2010, Shoop and others published a study on the snowroads at McMurdo Base in Antarctica, in which they monitored snowroad conditions and related these to construction, maintenance, and traffic loading. They note that the two major routes at McMurdo are each divided into three lanes: inbound, outbound, and “construction/maintenance” or “sintering” (not used). They observed vehicle impacts based on the separation of vehicles into different lanes. They found a harder road surface in the tracked lane, but that lower in the road (20-50 cm), the tracked lane strength decreased “faster and to a lower level” than the wheeled lanes.

One study has previously been conducted to examine impacts to the snowroads in Yellowstone National Park. Alger and others (2000) examined the formation of moguls
(“bump formation”) on Yellowstone’s snowroads when traffic was predominantly snowmobiles and snowcoaches were relatively few in comparison. This study found that “the effect of coaches on the overall bump formation appears to be negligible.” However, they did investigate snowcoach impact by running a Bombardier over a stretch of road in two sets of 50 passes and measuring the profile of the snow after these passes. They found that the effect of snowcoach passes on the snowroad surface differed from that of snowmobile passes, as “the snowcoaches do tend to rut the surface parallel to the line of travel and also loosen up the surface considerably. It is uncertain whether or not this would cause problems to extended heavy use by coaches.” While the mechanism of mogul formation, which was the focus of this thesis, does not seem to apply to snowcoaches, the rutting that Alger and others noticed and predicted could potentially be a problem with increased snowcoach traffic on the roads is precisely the impetus for this study.

As discussed earlier, many of the studies relevant to this project address vehicles on a soil surface rather than snow since reducing rutting is of interest in the agricultural industry. Ansorge and Godwin (2007) used lines of talcum powder layered at known depths and widths throughout a soil pack to test deformation after passage of a tire or track. They found that for a given loading, a tire would cause more deformation in the soil than a track, with the tire causing deformation comparable to that of a track with two to three time the load. They found that using a lower tire pressure with the same load would significantly reduce the tire’s deformation and the resultant increase in soil
density, but that the low-pressure tire still caused more deformation and density increase than a track.

Antille and others (2013) tested the change in soil’s bulk density after a vehicle pass as related to tire size and inflation pressure. The main factor influencing soil displacement and density changes was found to be the initial soil density. Larger tire sizes and lower tire inflation pressures were both found to reduce soil displacement and density change. They also saw that higher-pressure tires cause more of an increase in cone penetrometer test hardness readings.

Keller and others (2002) compared tracked and wheeled tractors to determine which caused more vertical stress and associated soil compaction. They found that wheeled tractors caused significantly larger vertical soil displacement. However, they also noted that an incorrect attachment of a plow implement (or other trailer) could cause an uneven distribution of stress under the tracks; they say that tires would be less susceptible to this type of problem since tire contact area will increase in response to increased loading.

Other studies deal with frozen and thawing ground surfaces which may be more relevant to a snowroad than other soils. CRREL has investigated vehicle impacts in soils subjected to freeze/thaw (Affleck, 2005).
Overall Strategy

Since this study addressed questions about both long-term issues (i.e., evolution of the snowroads throughout the season based on grooming and other factors) and more acute impacts (i.e., comparative impacts of different vehicle types passing over the snowroad), a multi-faceted research strategy was implemented. Automatically collected data, from both existing weather stations and instruments deployed for this study (GPS units recording groomer activity and motion-sensor cameras recording traffic), provided information throughout the winter on an ongoing basis. This weather, groomer, and traffic data provided useful information on its own, and was also useful when incorporated with data collected during active field work. Active testing, involved: 1) measuring snowroad conditions throughout the park on periodic monitoring trips, and 2) analyzing the instantaneous impact of individual vehicle pass-bys on the roads. The parkwide measurements were intended to give insight into grooming, weather, and traffic pattern impacts, while the pass-by measurements would provide information on comparative road impacts from different vehicles. Figure 6 shows a conceptual framework of the project.
Figure 6: The research strategy included measurements that would provide insight into both the causal factors and resultant conditions of snowroads, on both a parkwide and an individual pass-by basis, as illustrated in this diagram.

Methods evolved from Year 1 to Year 2 as data analysis demonstrated what tests yielded the most useful results.

**Road Conditions and Grooming – Causal Factors**

Factors impacting road condition throughout the park include weather patterns, site characteristics, grooming practices, and traffic patterns (both quantity and type). Weather and grooming data were collected remotely throughout both test seasons. Traffic data was remotely collected during Year 1. Site characteristics are unchanging over the time frame of two winters, so were determined using existing maps.

**Weather Patterns**

A number of weather stations operate both within and near the park. Available weather information was gathered from Snow Telemetry (SNOTEL) sites and other types
of weather stations. This facilitated comparisons of how weather during the two testing seasons compared with weather from previous years, how weather varied throughout the park, and possibly what weather was linked to rutting, harder roads, or other trends.

Figure 7 shows locations of various types of weather stations in the park that measure snow depth, snow-water equivalent (SWE), precipitation, temperature, or more than one of these parameters. Labels denote weather stations that provided data used in this project.

Figure 7: Weather stations in Yellowstone National Park and surrounding areas provide data on snowfall, temperature, and other parameters, demonstrating how they vary throughout the park. (Map: NRCS 2016, with labels added.)
All weather data was collected through a site called Climate Analyzer, http://www.climateanalyzer.org. Climate analyzer is a website offered by Walking Shadow Ecology, the data they offer comes from the National Weather Service, The Natural Resource Conservation Service, USGS, Remote Automated Weather Stations, and The Hydrological Data System. The site allows instant access to data from all these sites in one location which allows for easier data collection.

Site Characteristics

“Site characteristics” traditionally thought to impact snowroad quality are generally unchanging on a small scale of time (i.e., two years). Elevation, aspect, and slope values have previously been calculated and are known for points throughout the park. The NPS Spatial Analysis Laboratory at Yellowstone provided this information for this project in the form of files compatible with ArcGIS software.

The range of snowroad hardness across the park changes throughout the season. Therefore, considering the dates of hardness measurements provides better insight into how site characteristics may impact the hardness between sites. As various site characteristics were graphed along with hardness readings, data was split up into date ranges. Nelson (2018) goes through the process in detail, additionally a summary of results is outlined in the Hardness vs. Site Characteristics section.

Additional characteristics, like road orientation, were calculated within ArcMap as needed.
Grooming Practices

The components of snowroad grooming include physical configurations and operational details. In winter of 2014-2015, the winter season prior to the commencement of this study, researchers who would ultimately become involved with this study and NPS staff traveled through the park to interview groomer operators and gather information on the types of groomers and grooming implements used by different park districts. While groomer operators can change their grooming attachments (drags, tillers, etc.) day-to-day, understanding the attachments available to each district and the strategies specific to each grooming district provides insight into equipment generally used by each district. Figure 8 shows a map of the major grooming districts. One additional grooming district exists on the government snowmobile road out of Mammoth, but this road is only a few miles and is not open to the public so was not considered in this study.
Figure 8: Major snowroad grooming districts in the park correspond with NPS Maintenance districts, and groomers are based out of the park's major developed areas.

To track how each groomer is used, the NPS outfitted groomers with GPS tracking devices from GPS Insight. These data loggers recorded information about each groomer at 2-minute intervals. An NPS account on the GPS Insight website provided access to all of this data. Each data point for these trackers records a time stamp, location of the groomer, speed of the groomer, distance travelled in the current trip, and distance traveled since the tracker has been installed.

During Year 1, the NPS outfitted 5 of the 6 park groomers with these GPS devices. These five groomers included the West Yellowstone agricultural tractor, the Old Faithful groomer, the Grant groomer, the Lake groomer, and the Canyon groomer. Some
of these groomers and the drag implements they use are shown in Figure 9 (Left), (Center), and (Right) and Figure 10 (Left), (Center), and (Right). The only groomer that was not tracked was the groomer that is based in Mammoth and is used only to groom the NPS employee snowmobile road, a two-mile back road that leaves the garage in Mammoth and joins the main road near Golden Gate. Due to difficulty with getting these units installed on park groomers, they were not in place in time to record any pre-season grooming information during Year 1. So, for Year 1, groomer data is only available from early January on for most groomers.

Figure 9: (Left), (Center), and (Right). Different types of groomers used in the park include (Left) an agricultural tractor in the West District, (Center) a Prinoth with a tiller attachment in the Old Faithful District, and (Right) Prinoths with various other attachments in Grant, Lake, Canyon, and North (Mammoth) Districts.

Figure 10: (Left), (Center), and (Right). Drags used in the park include a tiller in the Old Faithful District (Left) and Mogul Masters throughout the rest of the park, (Center) and (Right).
During Year 2, the Lake District received a new groomer but unfortunately its GPS was not moved to the new groomer. This resulted in a loss of Lake’s groomer data. Additionally, the Old Faithful GPS unit had a malfunction through the beginning of the season, resulting in minimal data from that groomer from the beginning of the season through February 22nd. An additional factor complicating grooming data analysis for Year 2 was that grooming equipment across the park experienced breakdowns. As the NPS worked to fix a broken groomer, they would often send another groomer to cover some of the broken groomer’s district in the meantime. This Year 2 trend prompted analysis of every groomer’s GPS data for passes by all designated test points, not just the points within the groomer’s normal district. With this method, all recorded passes by hardness test points were captured.

For Year 1, all test sites were set as “landmarks” in the GPS Insight software. This allowed extraction of all data points collected within a selected distance of each specific site. Site-specific grooming data could then be compared with road conditions and other observations. For Year 2, this analysis was done by researchers after all GPS points for each groomer throughout the season had been downloaded. The analysis in Year 2 indicated that the original “landmark” data collection from Year 1 might have missed some passes, so the same processing from Year 2 was applied to all Year 1 data in the final analysis. Grooming analysis is described in more detail in Appendix A. A summary of grooming results is provided in the Road Conditions and Grooming – Hardness section, Nelson (2018) goes over grooming methods and results in detail.
Traffic Patterns

During Year 1, motion-activated, Reconyx cameras were deployed at three of the testing sites on the main roads: along the Firehole River a few miles south of Madison Junction, near the entrance to the Virginia Cascades Road on the Norris-Canyon road, and near Kepler Cascades, east of Old Faithful. Each of these sites lies along a different popular trip route. These cameras captured and saved photos of passing traffic. Photos provided information on relative traffic loading patterns on the different road sections. Because of the assumption that traffic patterns would remain fairly similar from Year 1 to Year 2, these traffic cameras were not re-deployed in Year 2.

Road Conditions and Grooming – Condition Monitoring

During each of the seasons, a testing plan to monitor road conditions during the season was implemented. In Year 1, both NPS researchers and MSU researchers regularly monitored road conditions. NPS researchers conducted weekly testing at six predetermined test sites, with at least one test site in each of the major grooming districts. Additionally, MSU researchers conducted road condition testing during their trips to the park. During all pass-by tests, road conditions at the testing location were assessed. Researchers traveled throughout the entire park on two occasions to measure the snow depth (described in the Road Conditions – General Measurements - Depth section) and assessed road conditions at sites along the way. During Year 2, only MSU researchers collected information during trips into the park, which was not on a strict weekly basis. In this second season, pass-by tests took place at a test track in Grant Village, so condition
measurements were taken during all testing at this test track. Additionally, the second season involved two trips solely involving measurement of road conditions throughout the park.

In Year 1, NPS researchers stopped at the pre-determined test sites once per week, though not necessarily on the same day each week. Test sites were not all visited on the same day. They were provided with instructions for a testing procedure that involved recording: weather conditions at the time of testing, ambient temperature and snow surface temperature, hardness profile throughout the road depth, and snow temperature profile throughout the road depth. MSU researchers collected this same data set at each test site where pass-by testing was conducted, additionally measuring density and collecting snow samples on many occasions.

Additionally, in Year 1, two trips were conducted specifically to measure road conditions throughout the park. During these trips, researchers measured snow depth using a custom-built, Flat Earth radar sled, continually throughout the road system and stopped along the way to conduct testing similar to that from the weekly tests and to collect snow samples. The methods and use of the radar sled will be covered in detail in the Depth section below.

During Year 2, road condition assessments at both the pass-by test track and during parkwide road assessments involved taking a road hardness profile, ambient temperature, depth, and density measurements. During parkwide road assessments, snow samples were also collected at some sites.
Methods for measuring road hardness, temperature, depth, and density, as well as collecting and processing samples, are described below.

**Hardness**

A Rammsonde penetrometer was used to measure hardness throughout the depth of the snowroad at each site. The Rammsonde (Ramm) penetrometer is an instrument commonly used in snow science to characterize hardness throughout the depth of snowpack. Figure 11 shows the instrument. It consists of a cone-shaped tip, with the cone end at an angle of thirty degrees, that increases in diameter for 5.5 cm and then narrows back down, reaching a smaller diameter 10 cm from the cone tip. A rod 20 cm long is attached to this cone. Both are marked in 1.0-cm increments. A smaller-diameter rod, 30 cm long and marked at 10-cm increments, is attached to the top of that. A “hammer” fits around the smaller-diameter rod.

![Image of Rammsonde penetrometer](image)

**Figure 11:** Though various model Rammsonde penetrometers are available with different cone angles and rod lengths, the sharper cone angle of the 30° Rammsonde penetrometer, like that used in this study, is the preferable model for use on harder snow like the snowroads encountered throughout this study.

To take measurements, researchers gently set the assembled instrument on the ground and measure how far it sinks. They then place the hammer on the assembly, again marking how far it sinks. They then drop the hammer from certain heights, defined by the
10-cm increment marks, and measure how far the instrument penetrates. Standard equations translate these tests into hardness values for layers throughout the snowpack. Details on these equations and the hardness calculations are presented in Appendix B. Figure 12 shows the penetrometer in use in the field.

Figure 12: Reading the penetration depth of the Ramm penetrometer involves identifying the measurement line at snow-depth.

For each hardness reading, an average hardness was calculated for the 0 to 10 cm range, the 0 to 15 cm range, the 0 to 20 cm range, the 0 to 25 cm range, and the 0 to 30 cm range. For road sections that are less than 30 cm deep, only increments within the depth were calculated. These average values allowed comparison between the hardness readings for different test sites since they could capture many layers of different hardness with one summary number for a depth range.
Temperature

Researchers initially planned to measure temperature both in the ambient air and throughout the snowroad snowpack. In Year 1, these measurements were taken with a variety of instruments as researchers learned what did and did not work (described below). During Year 2, however, only ambient temperature was collected.

During Year 1, after testing hardness, researchers used the hole left in the snowroad from the hardness test to measure temperature throughout the depth of the road snowpack. A variety of instruments were used to take these measurements throughout the season.

Initially, a thermocouple probe (a metal rod with marks at 5-cm increments) with an Ampere reader to get temperature throughout the snowroad layers, as far down in the hardness hole as possible. From the beginning, the probe would not quite fit into the very narrow holes left behind by the hardness testing, so researchers explored better ways to deploy the temperature probe down into the snow. Then, early in the season, some readings seemed obviously incorrect. Due to the possibility of problems in the thermocouple probe wiring, the instrument was taken back to MSU and rewired. When returned to the field, however, the thermocouple once again provided questionable readings. Finally, the Ampere thermocouple reader’s temperature rating was discovered to be inadequate for the ambient temperatures encountered in the field.

An infrared (IR) thermometer initially measured temperatures on the surface of the road. A probe attachment, connected to the same instrument, measured the ambient temperature. This instrument eventually started showing problematic readings, however,
much like the thermocouple setup. This turned out to be for the same reason: ambient temperatures in the field were outside of the instrument’s rated operating environment.

After these problems surfaced throughout the season, very simple digital thermometer probes that would consistently give good readings were employed for all temperature readings. These probes, however, were only 10 cm long. This meant that obtaining temperatures throughout the depth of the road involved digging a pit instead of just sticking a probe into the hardness hole. The logistical difficulty of this process and the competing priorities during testing resulted in no such temperature profiles being measured in pits.

Due to these difficulties, most temperature readings from Year 1 are unusable. For this reason, in Year 2, the simple but reliable 10 cm-probe digital thermometers were used throughout the season. These were used to measure ambient temperature. During road condition assessments, the probe was laid on a bag of research equipment, out of the sun, until the thermometer had reached equilibrium. Readings consistently matched researcher’s expectations for ambient air temperature, lending credence to the measurements. During pass-by tests, the thermometer would be used in a similar manner to measure ambient temperature at the test site throughout the day.

Depth

During both seasons, snow depth on the roads was measured in two ways: manually and using radar. Manual readings were taken either by digging a hole to the asphalt surface and measuring its depth (for shallower snow; shown in Figure 13) or by driving a stake into the road surface until hitting the asphalt and measuring the length of
the stake driven into the snow (for deeper snow). These methods were used during both road condition assessments and pass-by testing in both field seasons.

Figure 13: Snowroad depth was checked manually at many testing locations during parkwide snowroad condition assessment trips.

While manual checking provided accurate depth readings for test sites throughout the park, these could be completed for only a small number of sites throughout the park, so provided a blunt measure of the variation in snowroad depth between districts and locations within each district.

So that a more complete picture of snowroad depth variation throughout the park could be ascertained, Flat Earth, Inc., a Bozeman-based company specializing in radar technology, provided a snow depth sensor and mount for the project. The NPS supplied the MSU team with an old snowmobile trailer, and MSU combined these to create a trailer that could be towed by a snowmobile and collect snow depth data. Flat Earth’s products had previously been used at Bridger Bowl near Bozeman, MT, and elsewhere to
measure snow depth. The trailer created for this project uses a radar instrument to take continual depth measurements as it is towed behind a snowmobile, and a GPS device to mark the location of each depth measurement.

Figure 14 shows the radar sled. In the figure, the orange equipment sticking out from the back of the sled is the location of the radar. The taller item sticking up from the trailer is a Trimble device tracking the sled’s GPS location. The yellow box houses the electronic controls and SD card where information is stored. A car battery, in a plastic bag at the front of the sled, powers the setup. This radar sled was used to record snowroad depth throughout the park on two different trips during each of the two test seasons.

Figure 14: Flat Earth, Inc., a Bozeman company, created a radar sled custom-built for this project to measure snow depth while being drug behind a park service snowmobile.
Density

Snow density readings were taken at some test sites during both pass-by test days and road-condition-assessment trips both seasons, but the method changed from Year 1 to Year 2.

During Year 1, a metal tube of known inner diameter was pushed down into the snow until the surface of the snow was at one of the lines marked on the tube. A sample bag with the date and time of the sample collection as well as which line marking had been used was prepared. Then the sample was extracted when researchers dug snow out from around the tube and slid a flat object under the sample tube so that the sample would come out intact without snow falling out the bottom. The sample was placed over the labeled bag, the flat object was slid out from under the sample, the bag was placed up around the tube, and all snow was shaken from the sample into the bag. The samples were transported to researchers’ field housing and weighed shown in Figure 15. Density of each sample was calculated as the mass divided by the volume of that sample as determined by measurements of the tube.

Due to high density snow and issues with the density tube in Year 1, a different method was employed in Year 2. A snow density testing kit, designed to capture a 100-cubic-centimeter segment of snow more quickly and uniformly than the original density tube, was incorporated into Year 2 testing. This main part of this kit consists of a metal rectangular box with a handle (Figure 16). This box has openings on the smallest sides of the rectangle so that it can be pushed into the snow and the box will fill with snow. After the box has been inserted into the snow, a sharper rectangular piece fits over the box to
seal off the open sides of the box, precisely separating the snow sample from the surrounding snow. The sample was then deposited into a Ziploc bag, which was pre-weighed, and then the bag and sample were weighed together using a spring scale included in the testing kit. Then the weight of the sample plus bag minus the weight of the empty bag gives the density in grams per cubic centimeter. A density reading was taken at all road-condition-assessment-trip sample sites except when the snow was too hard for the density tester to be inserted.

Figure 15: The initial density test method involved collecting samples of known volume, saving the samples in bags, and transporting them back to the housing units to be weighted.
Figure 16: Density sampling device implemented in Year two testing, the spatula is inserted into a pit wall and the hollow square is used to trim away excess snow to insure the correct volume is obtained.

**Sampling**

During testing, snow samples were collected and transported back to the Subzero Science and Engineering Research Facility at MSU. Samples were taken at different test sites and different grooming districts throughout the course of pass-by tests. Samples were transported in coolers with snow and ice packed around them to ensure that they stayed frozen, keeping their microstructures as intact as possible. Once in the lab at MSU, the samples were placed in a cooler at -25 °C and sealed in plastic to avoid sublimation during storage.

During planning for Year 1 of this project, corers were developed for use collecting samples in this project. As researchers started taking them into the field and working with the snowroad snow, however, it was evident that the corers were not strong enough to go through the very hard snowroads, so a different sampling method was employed. Snow saws proved to be the most effective way to extract the very hard
samples. These were taken in the form of blocks of snow. Because of the ultimate difficulty of getting the samples and also the logistics of transferring samples from them to the MSU cold storage rooms in Bozeman, in both Year 1 and Year 2 only MSU collected samples, not asking the NPS researchers to collect samples during their weekly tests in Year 1. Figures 17 (Left) and (Center) show one of the corers and then a sample collected using the final method, and (Right) shows a sample packaged and ready for transport.

Figures 17: In response to field conditions encountered, snow sampling methods planned for this project transitioned from (Left) corers designed for this project to (Center) sawing samples out of the road. These were then (Right) packaged in plastic bags to avoid sample degradation.

Samples were collected with the plan of processing them using compression tests to determine their mechanical strength and properties and using computerized tomography (CT) scanning to investigate their microstructure. For testing mechanical properties, an experimental setup in the lab (Figure 18) was constructed so that a measured, uniaxial compression could be applied to a sample and the associated displacement (compression) of the top of the sample could be measured. A GeoTac GeoJac was used to apply force to the top of the sample, while a linear variable
differential transformer (LVDT) device measured downward movement at the top of the sample. During this testing, a high-speed, high-definition camera recorded a video to be analyzed by a computer program called Aramis (described in more detail later in this thesis) could analyze motion in the sample, the front of which had been flecked with black paint to facilitate particle tracking.

Figure 18: Plans for processing snow samples in the subzero lab at MSU included compression testing the samples, applying a measured force to a sample and measuring associated deformation of the sample.

The force and displacement recorded in these tests, along with the size of the sample and area over which the force is applied, could potentially give the sample material’s modulus of elasticity and Poisson Ratio.
Researchers planned to perform CT scans on snow samples that had been brought back to the lab. CT scanning produces three-dimensional imagery of the scanned sample. In snow research, CT scans can provide insight into the microstructure of the snow. The subzero labs at MSU have a CT scanner located in a cold room (Figure 19), allowing scanning to take place in a below-freezing environment at a controlled temperature.

Figure 19: The MSU Subzero Science and Engineering Research Facility includes a CT scanner in a cold room, so snow samples maintain their integrity while being scanned.
In both test seasons, individual vehicles were tested as they drove along a test track. Various measurements, described below, were taken as each vehicle passed. This information was gathered so that the relative impacts of different vehicle types and configurations could be compared. Measurable impacts included loading (vertical force on the road), subsurface disturbance (displacement and/or acceleration beneath the road surface), and surface disturbance. During each season, testing generally involved instrumentation, mostly buried in the snowroad but sometimes out above the snow, with cables transferring the gathered data to one or more computers. A tent was set up to protect the computers and keep them warm and operational. Additionally, a generator was deployed to power the electronics used in this study. During pass-bys, one or more researchers would remain in the tent, remotely controlling the testing equipment, while one or more other researchers remained outside of the tent directing the test vehicle and any other traffic, and taking additional measurements as needed. Figure 20 shows this setup in both years. General descriptions of pass-by testing conducted during Year 1 and Year 2 are provided below and followed by detailed descriptions of the testing equipment used.
Figure 20: The test setup in Year 1 (Top), on main roads throughout the park, and Year 2 (Bottom), at the Grant Village test track, were similar, but since OSV drivers shied away from driving near testing equipment. All subsurface equipment was completely buried in Year 2.
Figure 21: Year 2 testing differed from Year 1 in using a dedicated test track. In this track different lanes could be designated for different tests, and additional instrumentation (shown here in red boxes) was used.

**Year 1 Pass-by Tests – General Setup**

OSV testing during Year 1 mostly involved testing vehicles opportunistically as they were travelling through the park rather than having control of vehicles to test repeatedly. Only on the last two testing days (March 4th and 5th) of Year 1 did researchers have control over a vehicle that could be used for numerous pass-bys. As a result, Year 1 data generally only involves one pass-by from any particular vehicle on a given day.

During Year 1, test sites were set up along the snowroads already in-use in the park. During testing, researchers designated a lane for coaches to go through (marked by spray painted lines and cones and/or feathers) while being recorded. They would then stop coaches, allowing one to go through the course at a time. If this created a traffic back-up, some vehicles would be waved through without being tested.
For all of the pass-by testing, vehicle information was collected to facilitate comparison of impacts and snow disturbance associated with different vehicle characteristics. The NPS conducts a snowcoach census each year, gathering information from snowcoach operators about each of their vehicles. Therefore, comprehensive vehicle information was not collected during pass-by tests, but rather basic information about vehicles for later cross-referencing with the census.

Information collected during pass-bys included the unique identifier for the coach (company and snowcoach name or number), a photo of the coach as backup verification of the coach’s identity and basic characteristics, and the number of people on board the coach during testing.

Vehicles for which information had been collected proceeded through the test track. The research team member communicating with the snowcoach driver would communicate with the team in the tent via radio to ensure that the instruments were ready to collect data. The driver was provided with instructions on speed and/or acceleration/deceleration. In most tests, the driver was asked to drive at their regular cruising speed; in a few, they were asked to accelerate. These instructions were noted in records for each of the pass-bys. The vehicle would then drive along a previously marked line that routed it over buried load cells and right next to the camera location (surface or subsurface).

Testing days during Year 1 focused either on “surface” or “subsurface” data collection. Table 1 shows the breakdown of pass-by test data collection throughout Year 1. “Surface” data collection involved recording videos of pass-bys with a high-speed,
high-definition camera. These videos could then be studied to provide information on the nature of the interaction between the vehicle tracks or tires and the road surface.

“Subsurface” data collection involved burying the high-speed, high-definition camera in the snow in a protective box to record a high-speed series of images showing if and how the snow in the road was changing under the surface when a vehicle passed by. The snow wall adjacent to the box was flecked with black paint prior to testing to make motion detectable. Back in the lab, these videos were processed using Aramis, software that detects strain and motion in a series of images and described in more detail below.

During some test days, whether surface or subsurface analysis was taking place, an array of load cells was deployed below the road surface to measure the vertical force encountered during vehicle pass-bys.

Table 1: Year 1 field test days focused either on “Surface” or “Subsurface” data collection.

<table>
<thead>
<tr>
<th>Date</th>
<th>Day of Week</th>
<th>Location</th>
<th>Surf/Subsurf.</th>
<th>Load Cells (Y/N)</th>
<th>No. Pass-bys</th>
</tr>
</thead>
<tbody>
<tr>
<td>2016 01 15</td>
<td>Friday</td>
<td>Kepler</td>
<td>Subsurface</td>
<td>Yes</td>
<td>9</td>
</tr>
<tr>
<td>2016 01 16</td>
<td>Saturday</td>
<td>VA Cascades</td>
<td>Subsurface</td>
<td>Yes</td>
<td>15</td>
</tr>
<tr>
<td>2016 01 17</td>
<td>Sunday</td>
<td>Firehole</td>
<td>Surface</td>
<td>Yes</td>
<td>37</td>
</tr>
<tr>
<td>2016 01 28</td>
<td>Thursday</td>
<td>VA Cascades</td>
<td>Surface</td>
<td>Yes</td>
<td>5</td>
</tr>
<tr>
<td>2016 01 29</td>
<td>Friday</td>
<td>W of Sprg Crk</td>
<td>Subsurface</td>
<td>Yes</td>
<td>11</td>
</tr>
<tr>
<td>2016 01 30</td>
<td>Saturday</td>
<td>Firehole</td>
<td>Surface</td>
<td>Yes</td>
<td>6</td>
</tr>
<tr>
<td>2016 02 11</td>
<td>Thursday</td>
<td>MJ Campground</td>
<td>Surface</td>
<td>No</td>
<td>16</td>
</tr>
<tr>
<td>2016 02 12</td>
<td>Friday</td>
<td>W of Sprg Crk</td>
<td>Subsurface</td>
<td>Yes</td>
<td>18</td>
</tr>
<tr>
<td>2016 02 13</td>
<td>Saturday</td>
<td>CA S Rim Drive</td>
<td>Subsurface</td>
<td>Yes</td>
<td>13</td>
</tr>
<tr>
<td>2016 02 19</td>
<td>Friday</td>
<td>W of Kepler</td>
<td>Surface</td>
<td>No</td>
<td>2</td>
</tr>
<tr>
<td>2016 02 20</td>
<td>Saturday</td>
<td>Blanding</td>
<td>Surface</td>
<td>No</td>
<td>11</td>
</tr>
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</table>
Table 1 Continued

<table>
<thead>
<tr>
<th>Date</th>
<th>Day</th>
<th>Location</th>
<th>Surface</th>
<th>Resistance</th>
<th>No</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td>2016 02 20</td>
<td>Saturday</td>
<td>Firehole Picnic Area</td>
<td>Surface</td>
<td>No</td>
<td>19</td>
<td></td>
</tr>
<tr>
<td>2016 02 21</td>
<td>Sunday</td>
<td>Gibbon Meadows</td>
<td>Surface</td>
<td>No</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>2016 03 04</td>
<td>Friday</td>
<td>Kepler</td>
<td>Subsurface</td>
<td>Yes</td>
<td>28</td>
<td></td>
</tr>
<tr>
<td>2016 03 05</td>
<td>Saturday</td>
<td>Lewis Lake</td>
<td>Subsurface</td>
<td>Yes</td>
<td>52</td>
<td></td>
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</tbody>
</table>

Year 2 Pass-by Tests – General Setup

The “opportunistic” nature of testing in Year 1, and the associated lack of control over variables, led researchers to request a more controlled setting in Year 2. Therefore, in Year 2, the NPS worked with researchers to provide a test track and to recruit operators who would volunteer their vehicles for testing.

Researchers were provided with a test track at Grant Village, near the Grant Visitor Center (Figure 22). This stretch of road is not normally used during the winter, so was groomed especially for this study. On each of the days during which pass-by testing was conducted, one or more operators signed up to bring a snowcoach for a test period of approximately two hours. This allowed data collection for numerous runs by the same vehicle. Researchers used this opportunity to do repeat measurements with all of the controllable variables (speed, tire pressure) held constant and/or varied between runs.
As in Year 1, researchers directed test vehicles through a predefined test track under which measurement instruments were buried. In Year 2, buried instruments included a load cell array, the high-speed camera and protective box (during some tests early in the season), and an array of accelerometers. Table 2 shows the Year 2 test dates, which vehicles were tested on these dates, and at what depths the subsurface instruments were deployed. Table 3 provides further detail on the tracks or tires used by each vehicle. While ideally the instrument burial depths would have remained the same throughout the
season, early season data provided insight into what depths would work best, so depths of
testing were adjusted accordingly.

Table 2: Year 2 testing involved less vehicles per day but more repeated measurements to
validate results and more passes by each vehicle. (Abbreviations refer to: Scenic Safaris
(SS); Yellowstone Expeditions (Yell Exp); Buffalo Bus (BB); See Yellowstone (See
Yell); Bombardier (Bomb); Teton Science School (TSS)).

<table>
<thead>
<tr>
<th>Date</th>
<th>Top of Load Cell Depth (cm)</th>
<th>Accelerometer Depths (cm)</th>
<th>Vehicle(s) Tested</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/15/2017</td>
<td>10</td>
<td>NA</td>
<td>Mattracks (SS), Tires (NPS Suburban)</td>
</tr>
<tr>
<td>1/28/2017</td>
<td>8</td>
<td>5, 8, 12</td>
<td>Snowbuster (Yell Exp)</td>
</tr>
<tr>
<td>1/29/2017</td>
<td>10</td>
<td>10, 15</td>
<td>Mattracks (SS), Tires (XPR), Tires (NPS)</td>
</tr>
<tr>
<td>2/12/2017</td>
<td>20</td>
<td>10, 15, 20, 25</td>
<td>Tires (BB), Bomb (See Yell), SMs (NPS)</td>
</tr>
<tr>
<td>2/25/2017</td>
<td>20</td>
<td>10, 20, 30, 40</td>
<td>Tires (NPS)</td>
</tr>
<tr>
<td>2/26/2017</td>
<td>20</td>
<td>10, 20, 30, 40</td>
<td>Mattracks (TSS), Bomb (See Yell), Tires (NPS)</td>
</tr>
<tr>
<td>2/27/2017</td>
<td>20</td>
<td>10, 20, 30, 40</td>
<td>Tires (SS), Tires (NPS)</td>
</tr>
</tbody>
</table>

Table 3: Vehicles tested in Year 2 had a range of track and tire types.

<table>
<thead>
<tr>
<th>Date</th>
<th>Vehicle(s)</th>
<th>Type of Tracks/Tires</th>
<th>Width of Tracks/Tires cm</th>
<th>Tire Diameter cm</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/15/2017</td>
<td>SS Mattracks</td>
<td>Mattracks 150s (articulating on front, non-articulating on back)</td>
<td>41</td>
<td>NA</td>
</tr>
<tr>
<td>Date</td>
<td>Vehicle</td>
<td>Tires Model</td>
<td>Tires Size</td>
<td>Rating</td>
</tr>
<tr>
<td>------------</td>
<td>------------------</td>
<td>----------------------</td>
<td>------------</td>
<td>--------</td>
</tr>
<tr>
<td>1/28/2017</td>
<td>Snowbuster</td>
<td>Snowbuster; 6 bogey wheels, 1 drive wheel (not touching ground)</td>
<td>61</td>
<td>NA</td>
</tr>
<tr>
<td>1/29/2017</td>
<td>SS Mattracks</td>
<td>Mattracks (articulated in front, not in back; 4 wheels in front, 5 in back)</td>
<td>40.5</td>
<td>NA</td>
</tr>
<tr>
<td></td>
<td>XPR Tires</td>
<td>Alliance FloTruck 600/50R22.5 MPT; Steel Radial</td>
<td>60</td>
<td>117</td>
</tr>
<tr>
<td></td>
<td>NPS Tires</td>
<td>Michelin CargoXBib 600/50R22.5</td>
<td>60</td>
<td>117</td>
</tr>
<tr>
<td>2/12/2017</td>
<td>BB Tires</td>
<td>Nokian Country King 560/60R22.5</td>
<td>56</td>
<td>124</td>
</tr>
<tr>
<td></td>
<td>Bomb</td>
<td>Bomb</td>
<td>43*</td>
<td>NA</td>
</tr>
<tr>
<td></td>
<td>Snowmobiles</td>
<td>Snowmobile</td>
<td>not measured</td>
<td>NA</td>
</tr>
<tr>
<td>2/25/2017</td>
<td>NPS Tires</td>
<td>Michelin CargoXBib 600/50R22.5</td>
<td>60</td>
<td>117</td>
</tr>
<tr>
<td>2/26/2017</td>
<td>TSS Mattracks</td>
<td>YS3s (front and back)</td>
<td>45.6</td>
<td>NA</td>
</tr>
<tr>
<td></td>
<td>Bomb</td>
<td>Bomb</td>
<td>43</td>
<td>NA</td>
</tr>
<tr>
<td></td>
<td>NPS Tires</td>
<td>Michelin CargoXBib 600/50R22.5</td>
<td>60</td>
<td>117</td>
</tr>
</tbody>
</table>
Table 3 Continued

<table>
<thead>
<tr>
<th>Date</th>
<th>SS Tires</th>
<th>Alliance FlotMaster 381 IMP</th>
<th>620/50R22.5 IMP</th>
<th>62</th>
<th>119</th>
</tr>
</thead>
<tbody>
<tr>
<td>NPS Tires</td>
<td>Michelin CargoXBib</td>
<td>600/50R22.5</td>
<td></td>
<td>60</td>
<td>117</td>
</tr>
</tbody>
</table>

*Widths for ski/track vehicles are listed for the tracks rather than the ski.
*A width was not taken specifically on Griz's tracks, so it is assumed to be equivalent to that from Sally’s.

For each vehicle, researchers would work with the driver to define a testing plan, which involved varying the speed of the vehicle and, if the vehicle had tires, the pressure of the tires. The test plans always involved runs through the test track at a steady speed, with initial runs generally at a low speed, usually ~2 meters per second (m/s), and later runs at higher speeds, usually increased at ~4 m/s increments, until making final runs at ~11 m/s. For LPT vehicles, drivers generally did the first set of runs, ranging across all of the speeds, at a high pressure, then aired down to another typical set of running pressures for another set of testing across the different velocities. Each different tire pressure setting at which a vehicle was tested was considered to be a separate “vehicle configuration”, being considered separately from the same vehicle with different tire pressures in data analysis so that the effect of pressure on the vehicle’s impacts could be tested. Variables were adjusted and tests repeated as time allowed.

Prior to commencement of pass-bys, hardness measurements of the untouched test track were taken. After the baseline had been established, the vehicle would make 5 to 7 passes through the test area at a given speed and tire pressure, if applicable. These passes
included at least two passes through the test track over the buried instrumentation so that subsurface impacts could be measured. Then a lane would be designated for the vehicle to pass over 5 times specifically to test surface impacts. In many cases, the vehicle’s 5 passes would be in a separate, untouched lane designated for that particular vehicle’s surface passes; in other cases, in which snow conditions and/or vehicle configurations meant that passes were causing negligible surface impacts, the same instrumentation lane was used for all surface disturbance passes as well.

During the two instrumentation passes, researchers would record data from all of the buried instruments. After each set of five passes through the surface testing lane, researchers would take a profilometer reading in that lane and measure hardness in the top 10 centimeters.

The control granted by the testing setup of Year 2 allowed researchers to experiment with the comparative surface and subsurface impacts of different vehicles, and then to explore the influence that vehicle speed and variables like tire pressure can have on these impacts.

**Vehicle Loading**

Vertical forces within the snowroad were measured for each vehicle during pass-by testing. An array of twelve (LC304-500) load cells buried under the snow provided these measurements. Figure 23 shows this array. As shown, the load cells are set up in line, and a 10.5 cm by 10.5 cm metal cover goes over the top of each load cell to protect it (see Appendix C for details on these load cells).
Figure 23: The custom-built load cell array composed of twelve load cells, used to measure vertical forces in the snowroad.

Two compact data acquisition (CDAQ) units recorded data from the load cells in real-time as vehicles passed. Each CDAQ read six load cells, and fed this information into a laptop through the LabVIEW software interface. A program in LabVIEW operated the CDAQ, defining the sample rate (2,000 readings per second); starting the data acquisition process; recording the data for all channels (i.e., load cells); stopping the data recording; and saving the data in both Technical Data Management Streaming (TDMS) and comma-separated values (CSV) format. This was all controlled on a laptop computer during testing.

In the processed files, the reading at each point in time showed the force on each load cell, for a total of twelve force readings. To show the total force from each passing
track, tire, or ski, researchers calculated an additional value for each point in time equal to the sum of all the load cell forces (Figure 24). Appendix C provides more details on how the load cell data was processed.

Figure 24: Left, shows each load cell contributing force per event, on the right all the load cells are summed per each time increment to get maximum loading events.
The load cells were also used to determine exact velocities of the snowcoaches during season 2. The distance between two load-bearing points on a snowcoach was measured. Using the load events from that vehicle pass, a velocity was solved for by knowing the sample frequency (Figure 25). This distance over time measurement solved for exact velocity.

![Diagram](image)

Figure 25: (Top) the two black circles are tires (or bogey wheels) with a known distance between contact points, (Bottom) a typical tire loading pattern is shown, the left spike is from the front tire and the right spike is from the rear tire. If the maximum load is assumed to occur at the center of tire/bogey contact point, then the time between maximum loads can be correlated to the known distance to provide velocity (distance/time).
During most measurements in the field, the load cell array was set up perpendicular to the direction of vehicle travel to show force across the entire width of the track, tire, or ski. In a few tests, the load cell array was positioned parallel to the direction of traffic to determine if this would provide any other insights.

Subsurface Impacts

During Year 1 and the beginning of Year 2, subsurface deformation was measured using Aramis, an optical strain measurement program. During Year 2, an array of accelerometers was implemented to capture the similar and additional information.

Aramis is a software system manufactured by GOM, a German company. Aramis tracks points in a series of photos, analyzing how they move with respect to one another, to calculate parameters such as vertical strain, horizontal strain, and shear angle. In this study, Aramis was used to analyze series of images of pit walls within the road in order to demonstrate deformation taking place beneath the road surface.

During pass-by testing, a camera was positioned in a pit, usually facing perpendicular to the direction of traffic travel, in order to get images of a snow wall. Snowcoach drivers were asked to drive as close to this pit as they were comfortable doing so that the images would show the influences of vehicle loading as close to directly under the vehicle as possible. Because of this, the camera needed protection, and the snow wall needed support to prevent its collapse. A protective box, able to withstand the force of a snowcoach running over it, was designed and built for this purpose. The box frame has inner dimensions of 26.0 cm by 46.5 cm by 122 cm length. These dimensions were designed to provide a window into a depth ranging from immediately under the snowroad
surface to significantly beneath it and to facilitate using the camera’s field of view at a
given distance. On the end of the box, adjacent to the snow wall, a piece of Plexiglas
confined the snow and prevented its falling out into the box. Figure 26 shows this box
positioned in the snow.

![Camera box with high speed camera in place for subsurface testing.](image)

During testing, a board covered the box to prevent snow falling in onto the
camera. During some test days, snow was placed over the board so that drivers would not
see the box and shy away from approaching it. When the box was totally covered in
snow, a series of LED lights illuminated the snow wall during filming.

To calculate strain information, Aramis needs to be able to track points from
image to image to see how they move relative to one another. Snow does not naturally
have distinct optical features that would facilitate this analysis. So that Aramis would
have points to analyze, snow was speckled with black paint prior to the box being placed
into the snow pit. Black paint was diluted with water and the mixture applied to the snow
wall in a speckle-pattern. Figure 27 shows the application process and a resultant pattern.
To provide high quality images to be used in Aramis, a Fastec TS3—a high-speed, high-definition camera—was used to capture images. The camera connected to a platform in the box (Figure 26). A Gig-E cable ran from the camera to a laptop so that the camera could be armed and triggered from the laptop, meaning that no one needed to be next to the box during testing. This also allowed some remote adjustment of camera settings. For most subsurface videos, videos were saved as stacks of images, to facilitate easy processing in Aramis, and taken at a rate of 250 frames per second (fps).

In the lab at MSU, subsurface videos were analyzed in Aramis. Aramis returned a series of images with strain and other parameters calculated. This was then exported into a series of images or a video file showing how the parameter of interest varied throughout the duration of the vehicle pass-by using a color scale. Throughout Year 1, the camera setup was adjusted to improve image quality (i.e., speckling and lighting) to improve Aramis’ ability to process the images. Appendix D provides more details on these adjustments.
During Year 2, an array of Analog Devices ADXL327 small, low-power, 3-axis 2g accelerometers was implemented to measure acceleration throughout the depth of the snowroad during pass-bys. Additional information on these accelerometers can be found in Appendix E. Accelerometers measure acceleration in one or more directions, so were set up in this study to measure acceleration in three different directions. Figure 28 illustrates: vertical, “longitudinal” (in the direction of traffic), and “transverse” (horizontal and perpendicular to the direction of traffic travel) accelerations.

Accelerometer readings can be post-processed to give displacement, telling researchers how much the accelerometers are moving (in distance, mm or inches) as a vehicle passes, and whether they return to the original position after the pass. This possibility meant that accelerometer data would theoretically provide more insight into the motion detected by Aramis.

Figure 28: Accelerometers were oriented to capture vertical, longitudinal, and transverse directions. The vehicle is traveling in the same direction as the "longitudinal" arrow is pointing. Arrows are pointing in the positive direction of acceleration.
The accelerometers were buried at various depths to measure acceleration near the surface and provide information on how it differed deeper in the snowpack. Figure 29 shows the array of accelerometers as it was buried on February 12\textsuperscript{th}, 2017.

![Accelerometers in snow](image)

**Figure 29:** As demonstrated by these accelerometers deployed at the test track on February 12\textsuperscript{th}, 2017, the accelerometers were placed at a variety of known depths near the snowroad surface.

The process of digging down into the snow to place the accelerometers necessarily disrupts the state of the snow so the disturbed snow is different than the snow in the rest of the road. Researchers attempted to minimize this disruption as much as possible while placing the accelerometers. To place the accelerometers, a large pit was initially dug to allow access to a vertical wall in to which the accelerometers could be inserted. On this vertical wall, researchers dug small holes approximately 5 cm back into
the wall to attempt to get to less disturbed snow, and placed an accelerometer in the desired orientation at the back end of each hole. Snow and water were then combined to make a slush that was placed in the hole to hold the accelerometers in place and prevent them from moving as the pit next to the vertical wall was filled back in.

An accelerometer measurement kit constructed by a previous Masters student in the MSU snow science program was used to wire the accelerometers to a computer that could record the readings. This kit involved a box into which accelerometer arrays could be plugged using 15-pin connectors, a cDAQ system into which all of the accelerometer data was channeled, and then an Ethernet cable coming out that could relay the accelerometer readings to a computer through a LabView interface. Accelerometer data was saved after each pass using this program. The files were then post-processed back at MSU, as Appendix E describes in detail.

Surface Impacts

Since this study included snow disturbance on the surface of the road as well as under the surface, the Fastec camera was also used to film the surface of the snow as coaches passed. These test days usually involved a setup similar to that of subsurface testing, recording load cell data and also videos, and using the tent, generator, and heater to keep electronics warm. Passing vehicles were also stopped to get their information.

In the beginning of surface filming in Year 1, the camera was positioned on a tripod. However, a lower angle seemed to give better images of the tracks and snow displacement. Therefore, on later dates, the camera was placed inside its protective box
but on top of the snow rather than subsurface. This cut down on glare as well as providing a better viewing angle.

During pass-by tests in which vehicles were stopped for information, the vehicles would rarely go at or near normal cruising speeds once waved on to the test track. Because of the unwieldy nature of snowcoaches, drivers are hesitant to drive fast with any people or equipment on or near the road out of consideration for safety. However, since one of the questions of this study was whether snow displacement varied with speed, methods were adapted to get some videos at higher speeds. Researchers therefore conducted some tests standing by the road without a tent and not stopping the coaches (waving them on by if they stopped) and some tests hiding in trees, out of sight, attempting to film vehicles at full speed. Figure 30 shows the hidden setup, with the camera on a tripod up closer to the road and the laptop and table set up down in the trees out of view of the road.
Another variation on surface videos taken during one test day was videos taken with a head-on view of oncoming coaches. These were intended to better show how OSVs throw snow out to the sides.

These different methods of testing resulted in videos taken at a range of speeds. No test equipment was recording speeds during the pass-bys, but vehicle speeds could prove to be important during data analysis. Therefore, during Year 1, scale objects were selected or set up at each test site. These objects were placed or recorded as being at measured distances from each other and the camera. Vehicle speeds could then be calculated using the vehicles’ positions relative to these objects. For example, Figure 31 shows a frame from a pass-by where two feathers set 31 cm from each other and 2.59 m from the camera lens provided scale.
In surface videos, the distance between the feathers, the distance between the camera and the feathers, the approximate distance between the feathers and the snowcoaches, the number of frames between the snowcoach reaching the first feather and reaching the second feather, and the number of frames recorded per second can provide the approximate snowcoach speed.

In Year 2, surface videos were not taken for every pass since each vehicle did so many passes, but rather were recorded for a small sampling of the test runs at a variety of speeds. During this year, all surface videos were accompanied by subsurface tests. The distance between tires or bogey wheels on each vehicle was also measured so that the time between force spikes as measured by the load cells could be used in conjunction with the distance between tires or wheels to calculate vehicle speed.

Additionally, in both years, researchers used a profilometer (Figure 32). The NPS constructed the profilometer after a design they had seen described in papers by Rosa Affleck and Sally Shoop (Affleck, 2005; Kestler and others, 1999). Affleck lent the
original instrument to the NPS for one of their previous years of testing, and after seeing its utility the NPS constructed their own, slightly modified version. The NPS has lent the profilometer to MSU for the duration of this project.

The profilometer is ideally suited to record and quantify aberrations from a smooth road surface. Placing the profilometer vertically over any abnormality in the road (e.g., a rut or peak) and photographing it allows researchers to model a profile of the abnormality. Plans for the profilometer in this study included characterizing ruts (depth, width, etc.) by placing the profilometer across the road, as shown in Figure 32, and also investigating the “slip-stick” track phenomenon often observed on park roads by taking measurements along the length of the tracks. In Year 1, the profilometer was used to characterize instances of the slip-stick phenomenon encountered on the road. In Year 2, the profilometer was used to measure changes in the road surface after set numbers of passes by different vehicles, as discussed in the Year 2 procedure description, above.

Figure 32: A profilometer being used to measure deformations to the road surface from OSVs.
Table 4 summarizes test methods used in each year of the study.

Table 4: Year 2 involved methods refined from those of Year 1.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Year 1 Methods</th>
<th>Year 2 Methods</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Factors Impacting Roads</strong></td>
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<td></td>
</tr>
<tr>
<td>Weather</td>
<td>Weather Station Readings</td>
<td>Weather Station Readings</td>
</tr>
<tr>
<td>Grooming</td>
<td>GPS on Groomers, Equipment Inventory</td>
<td>GPS on Groomers, Equipment Inventory</td>
</tr>
<tr>
<td>Traffic Patterns</td>
<td>Traffic Cameras</td>
<td>N/A</td>
</tr>
<tr>
<td>Site Characteristics</td>
<td>GIS Files</td>
<td>GIS Files</td>
</tr>
<tr>
<td><strong>Snow Conditions throughout Park</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Depth</td>
<td>Radar Sled, Spot-checks with Rulers</td>
<td>Radar Sled, Spot-checks with Rulers</td>
</tr>
<tr>
<td>Density</td>
<td>Density Tube</td>
<td>Density Kit</td>
</tr>
<tr>
<td>Hardness</td>
<td>Rammsonde Penetrometer (weekly and research trips)</td>
<td>Rammsonde Penetrometer (research trips)</td>
</tr>
<tr>
<td>Slip-stick phenomenon</td>
<td>Profilometer</td>
<td>N/A</td>
</tr>
<tr>
<td>Snow Strength, Composition</td>
<td>Lab Analysis of Samples</td>
<td>N/A</td>
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<tr>
<td><strong>Vehicle Pass-by Impacts</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Snow State</td>
<td>Rammsonde Penetrometer, Density Tube</td>
<td>Rammsonde Penetrometer, Density Kit</td>
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<tr>
<td>Road Surface Profile</td>
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<td>Profilometer</td>
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<td>Vertical Force</td>
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</tr>
<tr>
<td>Road Sub-surface Motion</td>
<td>Aramis</td>
<td>Aramis, Accelerometers</td>
</tr>
</tbody>
</table>
CHAPTER FOUR

DATA AND DISCUSSION

Road Conditions and Grooming – Hardness

Hardness vs. Weather

To observe how weather factors contributed to snowroad hardness in the park, average monthly temperature, degree days and the percent departure from the 30 year average of precipitation were analyzed for trends. Nelson (2018) goes over this data in depth but a quick summarization is provided below.

It was found that Year 2 had a much cooler December and January and a warmer November and March than Year 1. From the literature review, Abele (1990) found that at colder temperatures it takes longer for snow to sinter and gain strength. So when there are colder temperatures present, a decrease in snowroad strengthening can be assumed.

Temperature can be quantitatively compared with hardness through a parameter called degree-days, used by Kozak and others (2002) based on the fact that “sintering increases rapidly at temperatures above -10 °C.” This degree-day parameter finds the difference between maximum temperature and -10 °C for every day with a maximum temperature over -10 °C. This adds up throughout the season. Test sites in warmer areas with higher daily maximum temperatures on most days will have higher daily degree-day values than test sites in colder areas. Degree days proved to be an interesting data set, hardness at all test sites versus degree-days since December 1\textsuperscript{st} showed that test sites having more degree days were harder (Nelson 2018).
A large difference in snowfall was present between Year 1 and Year 2. Year 2 had much more consistent snowfall and many areas saw well above the 30-year average of snowfall (Nelson 2018). Between the large difference in snowfall amounts and slightly colder temperatures in Year 2, it is unsurprising that more rutting was observed in Year 2.

**Hardness vs. Site Characteristics**

It was hypothesized that snowroads would be harder in certain locations based on their geographic location and characteristics. A few site characteristics proved to affect snowroad hardness (Table 5). These correlations were based on a relatively small data set so to insure these correlations are accurate, additional data would need to be collected and analyzed for trends.

Table 5: Elevation, aspect and slope angle were compared to snowroad hardness, possible trends in aspect and slope were present however elevation did prove to show trends. Higher elevation areas tended to have softer snowroads. These trends were compiled using a relatively small data set.

<table>
<thead>
<tr>
<th>Parameter:</th>
<th>Trend in Snowroad Hardness:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elevation</td>
<td>Higher elevation = softer roads</td>
</tr>
<tr>
<td>Aspect</td>
<td>Possible correlation</td>
</tr>
<tr>
<td>Slope</td>
<td>Possible correlation</td>
</tr>
</tbody>
</table>

Details on data presented above can be found in Nelson’s (2018) thesis.

**Hardness vs. Grooming**

The groomers in the park were rigged with GPS units to facilitate researchers tracking their movement and timing throughout their grooming routes. This data in
conjunction with weather station data from SNOTEL and NOAA as well as hardness tests on the snowroads were used to look for relationships.

Since grooming influences the road throughout the entirety of the season, the hardness average over a 20 cm depth was used for many of these comparisons to represent the overall quality of the snowroad packing (beyond just the surface). Evidence in this study, discussed in the Vehicle Pass-bys – Subsurface section, indicates that day-to-day vehicle impacts occur in the surface of the road, so the top-10-cm-hardness average is likely influenced by day-to-day operations while the top-20-cm-hardness average is less so. Therefore, 10-cm-depth average hardness were examined for most day-to-day factors (e.g., time between grooming and hardness) and 20-cm-depth average hardness were used to analyze impacts from season-wide grooming practices (e.g., average grooming speed throughout the season). A summarization of the results of these comparisons can be found in Table 6, reference Nelson (2018) for further detail.

Table 6: Parameters as they pertain to snowroad hardness. * indicates a trend that researchers believe underlying factors have skewed the trend, such as traffic, groomer type and weather. + indicates a trend that researchers believe to be inaccurate. Temperatures closer to 0 °C would have faster sintering rates in the snowroad which after time would show higher strengths near this temperature.

<table>
<thead>
<tr>
<th>Parameter:</th>
<th>Trend in Snowroad Hardness:</th>
</tr>
</thead>
<tbody>
<tr>
<td>Groomer velocity</td>
<td>Faster velocity = harder roads*</td>
</tr>
<tr>
<td>Groomer timing</td>
<td>More time after grooming = harder roads</td>
</tr>
<tr>
<td>Temperature between grooming runs</td>
<td>No obvious trend+</td>
</tr>
<tr>
<td>Snowfall accumulation between grooming runs</td>
<td>More snowfall between passes = softer roads</td>
</tr>
<tr>
<td>Hardness compared between grooming districts</td>
<td>All districts show hardening throughout season</td>
</tr>
</tbody>
</table>
Hardness vs. Traffic

In addition to grooming, traffic seemed to play a large role in hardness. Uncertainties with the unexpected results from the grooming section above can be partially answered through analyzing traffic data. It was found that road corridors with more traffic had higher hardness measurements than corridors with less traffic. This can be justified by noting that more disaggregation and compaction of the snowroad encourages faster sintering rates, which in time leads to higher hardness measurements. The traffic in this case is contributing to the compaction and disaggregation to the road in addition to the groomers. West Yellowstone district has the highest amount of traffic on an annual basis which in Figure 33 West Yellowstone district has the highest hardness readings of all other districts. Additionally, Lake district has the least amount of traffic and shows the lowest hardness readings.
Figure 33: The West Yellowstone grooming district sees the most traffic on an annual basis and the red line indicates it having the highest hardness readings. Lake district sees the least amount of traffic and hence has the lowest hardness readings.

Nelson (2018) outlines traffics contribution to hardness and some of the caveats with this data set.

Road Conditions – General Measurements

Density

While density is important in characterizing snow, it is not necessarily the best indicator of the quality of a snowroad, as discussed in the literature review. Hardness is a more telling characteristic regarding the snowroad’s resistance to penetration in the form of tracks or tires sinking into the surface. Hardness can vary widely even in snow with
similar density. This was confirmed by data collected on main roads during Year 2, as Figure 34 shows. While this limited data set shows a positive correlation between density and hardness at lower densities, at a high density the hardness can vary quite drastically. The majority of snowroad density measurements fell within the higher, 0.4-0.5 g/cm$^3$ range. Since data collected shows that a wide range of hardness can occur in this density range, density on park roads will not necessarily be a reliable indicator of the road’s hardness.

![Hardness vs. Density for 2017 Main Road Tests](image)

**Figure 34:** Average hardness in the top 10 cm of the snowroad versus density at the surface.

**Temperature**

A temperature gradient measured throughout the depth of the snowpack can provide insight into the metamorphosis of snow. As stated in the literature review and
research conducted by Akitaya (1974) and Colbeck (1991) density plays a heavy roll on how temperature gradients metamorphize snow. Ambient air temperature, which in large part drives the temperature gradient, was measured through both years and can be analyzed throughout the season from weather station data. Temperature at the ground-snow interface is generally assumed to be 0 °C, so if the ambient temperature is above or below 0 °C this drives a temperature gradient through the snowpack. So the potential impact of temperature gradient in the road is driven by the ambient temperatures, which were discussed in the Hardness vs. Weather section.

**Depth**

Snowroad depth was mapped throughout the park in Year 1 and Year 2 using the Flat Earth radar sled. Researchers were able to collect data from 1 out of 2 trips in Year 1 and 2 out of 3 trips in Year 2 (Table 7).

<table>
<thead>
<tr>
<th>Testing Dates</th>
<th>Trip Name</th>
<th>Data Collected (Y/N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year 1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Feb. 6-7, 2016</td>
<td>A</td>
<td>Y</td>
</tr>
<tr>
<td>Feb. 20-21, 2016</td>
<td>B</td>
<td>N</td>
</tr>
<tr>
<td>Year 2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dec. 17-18, 2016</td>
<td>C</td>
<td>N</td>
</tr>
<tr>
<td>Jan. 21-22, 2017</td>
<td>D</td>
<td>Y</td>
</tr>
<tr>
<td>Feb. 18-19, 2017</td>
<td>E</td>
<td>Y</td>
</tr>
</tbody>
</table>

This allowed researchers to detect any correlations between snowroad depth, hardness, and other road conditions. During radar trip A the research team experienced technical difficulties with the radar sled’s instrumentation and unfortunately, the southern portion of the park’s roads were not recorded during this testing trip (Figure 35). The
snowroad depths measured for this trip were variable. At higher elevations, the snowroads were observed to be deeper. To observe this correlation, the snow depth data can be compared to the elevation data in Figure 36. The area between Norris and Canyon and the Sylvan Pass area had depths of 0.5-1 meters, and also are among the highest-elevation areas for which snowroad depth was measured. This holds true to what researchers would expect with orographic precipitation events. An orographic precipitation event is caused by a relatively moist air mass being forced over a mountain or mountain range. As the air rises it cools and can cause it to precipitate, which allows for more precipitation at higher elevations. Higher elevation sites will also generally stay cooler which allows the area to conserve snow for longer after a snowfall event.
Figure 35: Snowroad depth for February 6th and 7th, 2016. Data limited in southern portion of park due to technical difficulties with radar sled.

During trip B there were additional issues with the radar sled and usable data was not collected. The first trip in Year 2 (trip C) was canceled due to extremely cold temperatures; temperatures were near -40 °C and snowmobiling was not advisable in these conditions.
Figure 36: Elevation data for Yellowstone National Parks’ road system.

Year 2 snowroad depth measured on trip D was consistently deeper in most areas as compared to Year 1 data. And unsurprisingly, deeper snow was found at higher elevations (Figure 37). For trip D, it was also observed that snowroad depth increased to the south, which was likely also the case in Year 1, but unfortunately the data was unavailable. During Year 2, the majority of the snow storms approached the park from the southwest, because of this, the southern areas of the park harbored deeper snowdepths. Data was collected on a second trip during Year 2 but after examination this data was deemed to be faulty and not used in analyses.
A slight trend was observed with snowroad depth and hardness: a deeper road tended to be softer (Figure 38). However, it is believed that there is more to this trend than just depth. The deeper roads were found at higher elevations which from atmospheric lapse rates it is known that under typical conditions that ambient air temperatures are colder at higher elevations. This slows the snow’s sintering rate and requires more time for the snow to sinter to higher strengths.

Figure 37: Snowroad depth for January 21st and 22nd, 2017. Higher elevation road portions hold more snow than lower elevations.
To determine compaction of the snowroads from district to district, the radar data was compared to SNODAS data throughout the park. SNODAS data provides an estimate of natural snow depth in a given area. Since this does not take into account any compaction due to grooming or other processes, this data, as compared to the snowroad radar data, allowed for a compaction calculation simply by dividing the radar data by the SNODAS data. It was found that grooming districts were seeing close to 40-60% compaction (Figure 39). Additionally, hardness was compared to percent compaction to look for a relationship, however as seen in Figure 39 no strong relationship was present.
Figure 39: Radar depth / SNODAS Depth Measurements vs hardness measurements from a radar trip taken on January 21st. Compaction measurements vary from 40% to 60%.

The SNODAS data is a coarse estimate of snow depth, so may not have provided precise enough measurements to relate compaction with hardness.

Samples – Mechanical Properties and Microstructure

Using the instrumentation designed for testing snow in the Subzero Facility at Montana State University, snow samples were brought back to the lab to be tested in uniaxial compression. The properties to be calculated from lab measurements were strain, modulus of elasticity, shearing strength and Poisson’s ratio. Researchers hoped to gather these properties because they are indicative of how snow will behave when introduced to external forces. What was found was that the processed snowroad samples were quite stiff, approaching the stiffness of ice (especially in Year 1). The tests that were performed did not produce accurate quantitative data on these properties, but what it did prove was
how stiff the samples were. With this information it is reasonable to qualitatively say that the modulus of elasticity was very high.

Additionally, there was a desire to obtain microstructure of the snowroads using the CT scanner in the subzero lab. However, as high hardness and densities were observed for the snow during field work and compression tests in the lab, the thought that CT scans would yield useful information became doubtful. The density and incompressibility of snow samples implied that structure would not be significantly different from one sample to the next. CT scanning was not used as originally planned. Instead efforts were focused on the other instrumentation and analysis needed for this thesis. This was in line with conclusions from Lang and others (1997), in which researchers concluded that the time-consuming nature of microstructure image analysis was not the most effective way to measure bond cohesion in snowroads.

Vehicle Pass-bys – Vehicle Loading

In Year 1 and Year 2, load cells showed patterns particular to types of vehicles. Figure 40, showing data from Year 1, shows the general shape of load curves for different vehicle types. The shapes associated with the different vehicle types (tires, skis with tracks, and tracks) remained consistent between testing years. Generally, LPT vehicles produce two brief but large magnitude spikes of force. Vehicles with skis and tracks, like a Bombardier or Snowbuster, generally produce a force from the skis and then distinct forces from the tracks’ bogey wheels. The magnitude of the generated ski force on the road was quite variable, even between subsequent passes. Some passes the ski
would produce large measured forces where other passes the ski force would be hardly perceptible. Mattrack vehicles sometimes show distinct bogey-wheel force spikes but the locations of the wheels are not always as clear as with a Bombardier or ski/track vehicle such as the Snowbuster. Possible reasons for this trend are due to a closer proximity of the bogey wheels on Mattracks than the Bombardiers and Snowbusters. Some tracked vehicles operating in the park had a staggered bogey wheel pattern, this pattern had the bogey wheels overlapping which can make discerning a bogey wheel load event even more difficult.

Force magnitudes between tracks and tires also differed significantly. In general, the tires would show a larger magnitude force exertion on the load cell per loading event. This trend is mainly contributed to the LPT vehicle having four contact locations versus the tracks having multiple bogey wheels, a track and or skis supporting the vehicles weight (Figure 40). Difference in gross vehicle weight (GVW) was not considered when observing differences in measured load magnitudes. For example, the Bombardiers were in general a lighter vehicle than most other coaches traveling in the park. This fact was acknowledged but the objective of this research was to determine what each individual vehicle was introducing to the snowroad regardless of GVW.
Figure 40: LPT, Bombardier, and Mattrack vehicles’ load profiles are plotted against time. The load patterns associated with these types of vehicles were consistent during Year 1 and Year 2.

LPT and tracked (either tracks with skis or tracks only) vehicles support their loads differently. Before data collection and reviewing literature, it was assumed that the tracked vehicles would support their weight uniformly across the entirety of the track. This is a common misconception of tracked vehicles. This was disproven by the load cells on all testing days for tracked vehicles. On a stiff snow surface such as a groomed snowroad in Yellowstone, the load cells revealed that certainly the bogey wheels were supporting the tracked vehicles’ weights. Different types of plots in MATLAB proved to be beneficial for observing these phenomena (Figure 41 through Figure 44). Figure 44 shows a Snowbuster’s distribution of load in space at the point in which the summed measured load was at a maximum. At this point in time a bogey wheel is directly over the load cell array, the large spike in force at load cell 7’s location represents this bogey wheel, to the left and right of it, the track is seen to be carrying significantly less vehicle
weight. In addition to either side of the bogey wheel, this trend held for the track in-between bogey wheels, reference Figure 41 and Figure 42 to observe the trend.

On a softer snowroad the track will support more load than in harder conditions due to deformation of the snow under the tracks. The bogey wheels higher concentration of load allows it to sink into the relatively soft snow which in turn causes the track in-between bogey wheels to tighten and support more load. This process increases the tracks load bearing surface area and increases the tracks’ performance in softer conditions. With regards to performance this can be an advantage for tracked vehicles in soft snow, however performance is not in the scope of this study and further research would be needed to fully explore this topic.
Figure 41: Distribution of load in time and space for a Snowbuster vehicle.
Figure 42: Distribution of load with respect to time for the same Snowbuster pass as above.
Figure 43: Load summed at each instance of time for all load cells in the load cell array for a Snowbuster.
Figure 44: Distribution of load perpendicular to traffic direction at the time in which the largest load occurred, the bogey wheel supports a large portion of vehicle weight at load cell 7’s location.

Tires have a much more uniform distribution of load within each loading event (Figure 45 through Figure 47), which is quite different than the tracked vehicles loading distributions (Figure 41 through Figure 42 and Figure 44).
Figure 45: A typical load distribution in space and time from a LPT vehicle.
Figure 46: Summing load cell measurements in time leads to large measured loads from LPT vehicles.
Figure 47: When comparing this plot to Figure 44 a large difference in the distribution of vehicle weight between tracks and tires are seen on the road is observed.

The relatively uniform distribution of load seen in Figure 47 is important to notice. The LPT vehicles were applying uniform loads on all four tires. This introduces relatively uniform compaction in the wake of the vehicle in-line with the direction of travel.

Tires had a unique difference to tracks, controlled by inflation pressure, the tire’s patch size in contact with the road, could vary, this change was relatively independent of road hardness which is the opposite of tracked vehicles. Tracks had a defined patch that was unchanged, however, the load bearing portion of the patch would change based on snowroad hardness (Figure 48). With a decrease in tire inflation pressure the patch size
increased, which increases tractive forces and distributes load over a larger area (Raper and others, 1995) (Figure 49). When a vehicle was traveling on an even surface, the vertical weight each tire supports remains constant. If vertical load remains constant and patch size increases, the stress exerted to road decreases. Similarly, when inflation pressure increased, patch size decreased, which in turn increased stress applied to the road. This phenomenon holds true to tracks as well, the difference being that the operator is not in control of the load bearing area of the track. Applied vehicle stress was not able to be calculated due to the unknown dimensions of the load bearing patch size of both tracks and tires. If this was a desired data set it could have been measured but due to the scale of the project there was no time to gather this additional data.

Figure 48: Above a tracked vehicle in hard snow, the snow is too hard to deform under the bogey wheels. Below a tracked vehicle in softer snow, deforms the snow and the process allows the track to support more vehicle weight.
Figure 49: Tire inflation greatly affected tire patch size, a tire with a lower inflation pressure had a bigger patch (left), a tire with higher pressure had a smaller patch (right). No measurements were taken to quantify patch size but this was observed empirically through high speed camera measurements.

Data collected proved that tire inflation pressures affect force magnitudes significantly. Theoretically, the overall force exerted was unchanged, however with the lower inflation pressure the force was less concentrated and distributed by a larger tire patch. This in turn reduced the instantaneous force measurements in the load cell data. Pass-by testing from Year 2 showed that as tire pressure decreased the force on the load cell would also decrease (Table 8).

Table 8: Maximum force compared to tire pressure, the maximum force is the peak force of a pass-by event. Force measurements taken at 20 cm’s below snowroad surface.

<table>
<thead>
<tr>
<th>Tire Pressure of Buffalo Bus LPT (kPa)</th>
<th>Max Force (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>48/62</td>
<td>2,020</td>
</tr>
<tr>
<td>28/34</td>
<td>1,165</td>
</tr>
<tr>
<td>14/14</td>
<td>810</td>
</tr>
</tbody>
</table>
On January 29th the snowroad was relatively stiff compared to the 26th of February. When the load plots of two Mattrack vehicles are compared on these two days it was seen that the track was supporting more load on the softer day (Figure 50). This occurred due to the bogey wheels sinking into the snowroad from vertical plastic deformation, which then allowed the track to tighten and support more vehicle load. The difference in force magnitude on this plot is irrelevant due to the load cell being placed at a deeper depth on the 29th of January. Due to a limited data set, two separate Mattrack vehicles were used in this figure, the rigidity of the two tracks were assumed to be comparable.
Figure 50: Top, on January 29th the hardness was 200 N and on the bottom figure, February 26th the hardness was 80 N. The track is supporting much more of the load on the 26th when the hardness was relatively softer. The load cell was placed at 10 cm’s below the surface on January 29th and 20 cm’s on February 26th, therefore there is a large difference in magnitude between the two plots.

When a track or LPT coach accelerated or decelerated the vehicle would rock backward or forward and would dictate how the vehicle would distribute its load to the
load cells. During an accelerating pass the vehicle would tilt back and in turn apply more force into the back set of tires/tracks. This concept held for deceleration, when slowing down the weight is transitioned forward to the front set of tracks or tires. In Year 1, this phenomenon was tested and resulted in line with researchers’ hypothesis. In addition to understanding this phenomenon, it was also important to control it in pass-by tests so that load was not significantly variant from pass to pass.

Dissipation of load through depth of snowroad was examined and results were consistent with assumptions and intuition. When the load cells were buried deeper beneath the snowroad surface, the force magnitude decreased (Table 9). This concept was intuitive but inserting the load cell deeper beneath the surface proved to have benefits. When the load cell was buried deeper in the snowroad the interference of dynamic and impact loading events was reduced. A dynamic load is simply a moving load, which can skew load magnitudes when compared to a static load. Impact loading in this context refers to the disturbance of a grouser on a track or tread of a tire striking the load cell and causing an additional loading event that is difficult to account for in terms of pass-by repeatability. During vehicle pass-by, the alignment of a grouser (tracked vehicle) or lug (wheeled vehicle) may impact sensed load. Dynamic loading may affect sensed load, but also at issue is the chance alignment of grouser/lug on a load cell versus a missed alignment case. When grousers or other lugs land perfectly positioned on the load cell plate, the load cell output will be relatively higher than for a case where the grousers/lugs straddle the load cell and a larger portion of the vehicle load is carried by the road surface.
adjacent to the load cell plate. Researchers determined that measuring load at a deeper depth (i.e., 20 cms) was the best method to collect consistent load data.

Table 9: Load testing on the NPS courier vehicle, 4 passes at similar velocities at each load cell depth were averaged to examine load dissipation at depth.

<table>
<thead>
<tr>
<th>Load cell Depth (cm)</th>
<th>Force measured (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surface</td>
<td>3,937</td>
</tr>
<tr>
<td>4</td>
<td>3,007</td>
</tr>
<tr>
<td>8</td>
<td>2,077</td>
</tr>
<tr>
<td>13</td>
<td>1,303</td>
</tr>
</tbody>
</table>

On the test track in Grant Village, pass-bys were separated into three velocity ranges for instrumentation passes; 0-5 m/s, 5-9 m/s, 9-13 m/s. These ranges were formulated based on the broad range of velocities measured. Most vehicles tested did not have calibrated speedometers to account for the large tires or tracks mounted on the vehicle, which eliminated the operators’ ability to account for velocity accurately by speedometer. So, velocities were calculated as described in the methods section (Figure 25) and grouped in the specified ranges to bring out any loading trend between the velocity ranges. For each vehicle tested, maximum loads per pass were averaged to get a single max load for each velocity range. It was found that as snowcoach velocity increased the average maximum force exerted on the load cells increased. There were outliers from this phenomenon but in general this was the trend seen (Table 10).

Mechanically, there are two possible contributing factors to consider for this result. It could be more likely that at higher velocities, vehicles are more likely to be slipping and rocking side to side and back and forth. Through these processes, additional
dynamic and impact loading events are experienced at these higher velocities, which can make repeatability of loading measurements more difficult.

Table 10: Average maximum load increasing within increasing velocity ranges for both tracks and tires, load cell was placed at 20 cm below surface for these measurements.

<table>
<thead>
<tr>
<th>Vehicle type</th>
<th>Velocity Range (m/s)</th>
<th>Load (N)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bomb</td>
<td>0-5</td>
<td>532</td>
</tr>
<tr>
<td></td>
<td>5-9</td>
<td>793</td>
</tr>
<tr>
<td></td>
<td>9-13</td>
<td>1026</td>
</tr>
<tr>
<td>Tires</td>
<td>0-5</td>
<td>2163</td>
</tr>
<tr>
<td></td>
<td>5-9</td>
<td>2656</td>
</tr>
<tr>
<td></td>
<td>9-13</td>
<td>2724</td>
</tr>
</tbody>
</table>

When a material is stressed to higher levels it deforms more than it does at lower levels. While increased weight may at times increase rutting, other factors besides weight can dominate under certain conditions. So in theory a heavier vehicle should be causing more ruts, however, the causal relationship between vehicle weight and rutting was not found to be especially strong.

**Impulse**

With no overwhelming correlation of snowcoach load distributions and road impacts, load data was post-processed in other ways to attempt to relate it to impacts to the snowroad. Considering velocity and the two relatively different modes of movement between tracks and tires, the impulse of pass-bys was examined. Impulse load is defined as a load that changes the momentum of an object; it is the integral of a force with respect to time (1).
To depict the concept of impulse as it pertains to snowroads and vehicle impact, Figure 51 shows two force vs time plots. The top plot has a smaller magnitude of force but acts over more time, on the bottom, force acts for less time but has higher magnitude force. These two plots have equal areas, hence equal impulse, but the mode in which they occurred was different.
This was examined to find the difference between tracks and tires. To compare vehicles’ impulse accurately they must have the same velocity, (Figure 52); if a vehicle is traveling faster it will act over less time which will directly affect impulse. Generally, the tracks were contributing smaller magnitude loads but acting over more time and the tires would act over less time and have higher magnitude forces. In most cases the impulse within velocity ranges between vehicles was comparable (Figure 53). It is important to notice as the velocity increases impulse decreases, which is what is to be expected with an impulse measurement.

Figure 52: Impulse from pass to pass can be compared to one another only if the vehicles are traveling at comparable velocities.
Figure 53: Within velocity ranges impulse magnitude is relatively comparable between tracks and tires.

As seen in Figure 40, tires would in almost all cases apply a higher load than a similar vehicle equipped with Mattracks. In Figure 54 a LPT coach sampled at two tire pressures, a Mattrack coach and Bombardier are tested. The tires with the highest pressure exerted the most force and the lower tire pressure exerted less force. The Mattracks and Bombardier applied even smaller maximum forces, yet all vehicles still produced relatively comparable impulses. However, the mode in which that impulse was applied was different. Tires only have four contact points where as the Mattracks have multiple bogey wheels, so more force events are applied with Mattracks. It was thought that this mode of impulse would be important in determination of load impacting road
quality. Impulse was calculated for all pass-bys from Year 1 and Year 2. Unfortunately, no obvious trends were found with impulse to road quality and rut size.

![Figure 54: Impulse vs max force, examining the impulse range of 100-300 Ns the maximum load varies between coaches.](image)

**Repeatability of Load Cell Measurements**

During Year 1, load data was collected throughout the park in hopes of gathering data from the snowcoaches on the roads they travel on every day. It proved difficult to instruct snowcoach operators to drive in a fashion that was beneficial for data collection. Additionally, the coaches were normally traveling with guests; when there was a large number of guests in the coach it could significantly alter the loads measured from coach to coach. The number of guests per snowcoach in Year 1 was accounted for by surveying passing coaches but it still added an additional parameter that made analysis difficult. These parameters were enough to make the load data variable and difficult to analyze.
Control on road conditions also provided additional difficulty in measurements. For example, if a snowcoach encountered any bump or rut before rolling over the load cell, the bump would set the vehicle into an oscillation which would skew how much force the track or tire exerted to the load cell. This would then prevent repeatability in load testing parameters from vehicle to vehicle. The test track in Year 2 was an attempt to increase repeatability and testing accuracy from pass to pass.

With experimentation of proper load cell depth in Year 1, the load cell was placed at the surface in the first few testing trips. The load cell at this depth measured some forces exceeding 200% of the load cells’ measurement capacity. Details on each load cell’s specifications can be found in the Appendix C. This contributed to the combination of dynamic and impact loading events which exerted a force the instrument was not designed to withstand. This may have caused the load cells to receive damage which causes the signal to be slightly noisier in some cases. Due to the budget of the project and time constraints, the designed load cell array could only be manufactured once, and precautions were made to not overload the load cells again.

Disturbance of the snow as the load cell was inserted into the road may have been a contributor to actual load at depth. Once the load cell was buried and packed into place, testing on the vehicles would begin. After a few passes the snow would most likely compact further and then be able to transfer load more efficiently. This could have been accounted for by taking hardness readings over the load cell after each pass. Unfortunately, due to time constraints in the field this measurement was not feasible and researchers focused on other measurements.
A program called Aramis was used to capture subsurface movement by filming a pixelated snowroad pit wall (Figure 26 and Figure 27). This technique in snow has been used by other snow researchers, however they conducted tests on snow of much lower hardness. The snow of lower hardness took a much smaller load to cause deformation that Aramis could detect. Aramis can measure very small deformations yet wasn’t presenting researchers with any subsurface measurements. By applying large loads to the snowroad with OSVs and only seeing very small deformations near the surface, Aramis data proved to researchers that snowroad deformation under OSVs in this project was primarily only occurring near the surface. Many alterations to the Aramis instrumentation setup were carried through in hopes of gathering reliable data, however all efforts proved unsuccessful and an array of accelerometers was designed in order to collect subsurface deformation data. Nelson (2018) outlines the processes involved with Aramis and the data collected from it in detail.

Accelerometers

Accelerometer measurements provided the insight into the subsurface motion that Aramis did not. Accelerometers, like the load cells, provide raw readings of voltage, and processing converts this raw data into g’s of acceleration. The data can then be numerically integrated to provide velocity and displacement measurements. As discussed in the literature review, error propagates through this processing. Various methods have
been developed to correct some of the known problems with accelerometer data, and one of these was used in the processing for this project as described in Appendix E. However, the initial errors and extensive correction processing of the velocity and displacement data render their values less certain. Therefore analysis focused primarily on the accelerations; velocity and displacement numbers were considered secondarily.

Similar to the load data, the accelerometer data showed patterns particular to types of vehicles. LPTs would show two distinct spikes in acceleration where the Mattracks and ski/track vehicles would show multiple spikes associated with each bogey wheel/ski. This was what researchers expected, however no overwhelming trend was observed between acceleration magnitudes between tracks and tires.

It was determined after post-processing all accelerometer data that the three main factors determining acceleration magnitudes were vehicle velocity, tire inflation pressure and depth of accelerometer. Higher vehicle velocities tended to introduce higher accelerations to the snowroad, especially tracks, lower tire pressures also tended to have smaller acceleration magnitudes. Depth was the most interesting result, acceleration closer to the snowroad surface always had higher acceleration magnitudes than accelerometers at shallower depths. These smaller magnitude accelerations are telling of less deformation (displacement) at depth. For an in-depth discussion of accelerometer processing and analysis reference Nelson (2018).
Vehicle Loading vs. Subsurface Impacts

The desire to obtain mechanical properties of the snowroads was of interest so that researchers could track the snows behavior after vehicle passes, temperature changes, grooming effects and any other parameters based on the circumstance. Attempts were made both in the field and in the lab to obtain these properties, however quantifying properties such as stress, strain and modulus of elasticity were not able to be obtained. However, researchers were able to look at more primitive measurements such as measured load to magnitude of acceleration, found by adding up the three components of acceleration in their respective directions (and using the Pythagorean Theorem), at depth (Figure 55). The trend is not overwhelmingly obvious but as load increases, acceleration increases which is expected of any material.
Figure 55: Maximum force measured by the load cells showed a positive correlation with total magnitude of acceleration. These data points come from overall maximum acceleration encountered in each direction for a given vehicle on a given day throughout Year 2. Load cell readings here are split into groups by bury depth on the day of testing.

As seen in the Accelerometers section, measured accelerations were much less at depth. Solving for displacements by numerical integration techniques from these small accelerations allowed for high error, this was due to a high noise to signal ratio. Due to the high error with displacement calculations, it was determined that the best method was to use the crude data for analysis. Using the raw accelerations and load measured at depth, trends like Figure 55 were found, however were often contradicted by further testing days. These trends were stimulating however it seemed that these trends were uncoupled with rutting and changing road conditions. Attempts to correlate measured accelerations with rutting were unsuccessful, and few repeatable trends could be
identified. This unpredictability resulted in shelving the testing procedure in favor of other testing strategies.

Vehicle Pass-bys – Surface Impacts

Quantified (Year 2 Methods)

The profilometer and Rammsonde penetrometer measured the surface impacts of the snowroads for this project. These instruments were rudimentary, reliable, and compiled the most dependable data. These tools allowed researchers to measure rut dimensions and hardness of the snow next to and in the vehicle path so that rut size and hardness could be quantified. Load, acceleration, profile, and hardness, among other data, were collected from pass-bys. The profilometer and hardness data would help to quantify if any of the other measurements contributed to rut evolution and snowroad hardness. Unfortunately, with Year 1's testing strategy the profilometer and Rammsonde penetrometer were not able to be used after each pass of a snowcoach. This was due to traffic delay and there not being a noticeable change in rut dimension from a single pass of a snowcoach. The use of a test track in Year 2 allowed a coach to pass through the instrumentation multiple times and for these surface measurements to be taken.

By quantifying the surface disturbance (i.e., rut formation) of interest to the NPS, these surface measurements provide the dependent variable. All factors contributing to road quality can be compared to these measurements to determine their relative impacts. This led researchers to focus on the surface measurement tools and used this data as a foundation for all other measurements.
Using the profilometer data, a displacement area of a rut was calculated. This provided a scalar value to score rut severity based on a two-dimensional area of a rut. It was found that both tracks and tires can form ruts in conditions that permit rutting both of which can be of equal severity. However, it was discovered that once tires form a rut, a point would come where the rut would not significantly increase in dimension. On the contrary, tracks would form a rut and continue to increase the rut size after more passes (Figure 56). Due to vehicle testing time constraints, a relatively limited dataset was collected for each testing day, so it is unknown if this trend would hold with many more passes. Nevertheless, with the data that was collected, this trend did hold for almost all testing days.

Figure 56: The orange dots in this plot depict the area displaced after 5 passes from each snowcoach. The first vehicle tested was a LPT Buffalo Bus coach, the second was a Bombardier.
Tire pressure proved to have an effect on rut size; tires of higher pressure can produce an initial rut but if tire pressure is decreased, the rate at which the rut formed decreased (Figure 57). This was the case in most scenarios on the test track in Grant.

Figure 57: Tire pressure affecting rut dimensions, the tire at 76/62 kPa causes an initial rut then inflation pressure is decreased and the rate at which the rut is forming decreases.

Area displacement was compared to impulse, maximum load, and maximum acceleration in the vertical, transverse, and longitudinal directions (Figure 28) and examined for trends. As explored in the vehicle loading section it was surprisingly found the load did not have a profound effect on rut size. This point is reiterated in Figure 58, in which the light blue dots represent maximum load measurements from passes from a Mattracks vehicle; the load remains relatively unchanged, yet the area displacement diverges. This indicates a driving factor independent of load to rut formation. The LPT tires represented by the dots after 14:00 cause an initial rut formation from a wheeled
coach with tire pressures of 55 kPa. This rut area increases only slightly after the second set of runs, from a different LPT vehicle with equal tire pressures. The tire pressure is then decreased represented by the grey and yellow dots shown before 16:48, and the area displacement levels off further.

Figure 58: Time vs maximum force vs area displaced, the dots represent load measurements from passes from a Mattracks vehicle and two LPT coaches, the area displacement is represented by the green triangles.

Figure 59 shows similar patterns to Figure 58, the LPT tires cause an initial rut and when the tire pressure decreased, the rate at which the rut was forming decreased. A Bombardier was then tested which had lower magnitude maximum forces and yet the area displacement diverged. This diverging pattern for tracked vehicles was seen in most other testing days as well. These trends indicate that rut formation is mostly dictated by a
surface interaction. The literature review and surface video observation sections go over shear concepts in detail.

Figure 59: Time vs maximum force vs area displaced, this figure shows similar trends to Figure 58.

Figure 60 shows a Scenic Safaris LPT coach tested at two tire pressures, this vehicle formed a rut but the rut doesn’t appear to be growing any larger after additional passes.
Max acceleration/displacement and impulse were analyzed in comparison to these surface measurements for all testing days from the test track in Grant, but no obvious trends were observed from these datasets. This reiterates the point that rutting is not closely tied to sub-surface interactions.

The next surface parameter analyzed was hardness; a baseline hardness measurement was taken before each new snowcoach testing period. The baseline measurement was taken in an untouched area of the test track. This measurement was used to compare hardness measurements taken in the rut in a coach’s path after five passes at a specific velocity. This was completed for tracks and tires and while the results varied, some trends did surface.
In Figure 61, five passes at 2 m/s (5 mph), 4 m/s (10 mph), 7 m/s (15 mph), and 9 m/s (20 mph) were sampled for a Mattrack vehicle. The initial 5 passes softened the snowroad as well as the first velocity increase, the third velocity increase hardened the snowroad, and the last set of 5 passes softened the snowroad. This result was unexpected and the reason for this pattern is not understood. For the LPT coach, an initial softening occurred from the first 5 passes and then after 10 more passes the snow underlying the rut hardened again.

Figure 61: This plot encompasses three parameters, rut depth, a soft layer underneath the rut and hardness underneath the soft layer represented by the graduated blue color bar. (10/10), (8,8), and (6,6) represent tire pressure in psi which can be converted to kPa; (69/69), (55/55) and (41/41).

Since the trend was not overwhelmingly obvious for all Year 2 testing days, researchers summed all events in which a track or tire (high pressure and low pressure) hardened the surface (Table 11). A discrimination between high and low-pressure tires
was described as 62 kPa (9 psi) inflation pressure and above being a high-pressure tire and below 62 kPa (9 psi) was considered to be a low-pressure tire.

Table 11: High pressure, low pressure and tracks tendencies to harden the surface. The passes that are not listed as hardening the snowroad softened it.

<table>
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<th>Hardens the Surface</th>
<th>Amount of passes</th>
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<tr>
<td>High Pressure Tires</td>
<td>≥ 62 kPa</td>
<td>≥ 9 psi</td>
<td>4</td>
</tr>
<tr>
<td>Low Pressure Tires</td>
<td>&lt; 62 kPa</td>
<td>&lt; 9 psi</td>
<td>5</td>
</tr>
<tr>
<td>Tracks</td>
<td>N/A</td>
<td></td>
<td>6</td>
</tr>
</tbody>
</table>

This data demonstrated that high-pressure tires harden the surface 40% of the time, low-pressure tires harden the surface 85% of the time and tracks harden the surface 40% of the time. This data shows high-pressure tires and tracks are equivalent in softening the road 60% of the time. Low-pressure tires appeared to be superior at hardening the snowroad surface.

Although the Rammsonde penetrometer was very reliable, there are some caveats to how this tool worked in field conditions. Snow is an extremely variable material, not only locally but spatially. Snow has the ability to retain many different mechanical properties. An example of this would be as a snowcoach or groomer drives, snow can be collected along the exterior and undercarriage of the vehicle. At some point this melted, slushy snow can slip off the coach and fall onto the snowroad which can form an irregularity from the surrounding surface. This inconsistency is then buried by new snow and groomed into the snowroad. If this location is unintentionally selected for a hardness measurement, the hardness reading would be misrepresentative of the adjacent snow hardness. A similar circumstance can arise with areas being softer due to inconsistencies
of groomer mechanics or other environmental factors such as sun/shade throughout the day. Groomers cannot completely groom a surface to be homogeneous in hardness. Because of these variances, there can be a small amount of error associated with the hardness measurements. This can also explain deviation of trends that cannot be explained through understood parameters.

**Surface Video Observations**

The high speed - high definition camera brought insight into the track and tire interactions at the surface by replaying the videos in slow motion. There was difficulty in quantifying the shear concept, so the camera was used to investigate this qualitatively. Researchers would film the coaches pass from camera angles that proved to be beneficial for observing surface interactions and the differences between the tracks and LPT interactions with the snowroad. Researchers noticed that just by watching and listening to the difference between tracks and tires as they move that there was an obvious difference between the two. After watching numerous surface videos in slow motion, it was even more evident that there was a large difference in surface interaction between tracks and tires.

Tracks in general have larger dimension grousers than tread patterns on a LPT vehicle. As these large grousers contact the snowroad some deformation will occur; the severity of this deformation will largely depend on the snowroad hardness. This can be seen by comparing a tracked vehicle and a LPT vehicle traveling at comparable velocities in sequential passes when the snowroad has the same hardness (Figure 62 and Figure 63). More often than LPT vehicles the tracks are kicking up more snow. This snow that is
being kicked up is due to a shearing load from the tractive effort of the grousers/tread of tire. Through qualitative video analysis researchers believe that tracks are causing higher shearing loads to the snowroad. This is due to the generally larger grousers on tracks than LPTs and the tracks grousers stay embedded in the road for longer which applies shearing load for more time. As discussed in the literature review, grousers embedded in the snowroad most change angles at the front and rear of the track and also as the bogey wheel travels over the grouser, this causes the grouser to move while embedded in the snow. If a tire were to have grousers of equivalent size to a tracked vehicle it is believed that the shearing loads would be comparable, but tracks would still apply shearing load for more time.

Figure 62: Screenshot of a LPT traveling approximately 4 m/s. Minimal snow displacement behind the tire as it moves.
Figure 63: Screenshot of a tracked vehicle traveling approximately 4 m/s directly after the wheeled vehicle in Figure 62. Significantly more snow being kicked up behind the vehicle

In the Vehicle Characteristics and Impact section of the literature review, numerous vehicle impact topics were covered. Due to the complexity of this project researchers were not able to collect data by instruments for all these phenomena. By use of the camera, researchers hoped to document some of these phenomena. However, due to relatively high strengths of the snowroad in Year 1 and 2 these were not able to be captured by a single vehicle pass due to these concepts having a small-scale impact per vehicle pass, for the conditions tested in Year 1 and 2. Although this was disappointing there was a lesson to be learned from this. Road degradation in Year 1 and Year 2 was generally caused from compounding vehicle effects, not a single pass. So repetition of vehicle passes significantly contributes to vehicles’ impact to the snowroad surface.
Both tracked and wheeled snowcoaches can cause ruts. Ruts form through two primary modes: snow compaction and snow displacement. When tracked vehicles form ruts, the ruts often continue to deepen with subsequent passes. When wheeled vehicles form ruts, it was found that the ruts eventually reach a point at which they stop deepening, especially if tire inflation pressure is reduced. This difference implies that tires tend to cause ruts primarily through compaction whereas tracks form ruts through snow displacement. As snow is compacted and becomes denser, its resistance to compaction increases. Each additional loading by the same vehicle will cause less compaction than in previous passes. This compaction of the road will encourage sintering, which makes the road harder. The continually increasing rut depth of tracked vehicles implies that they cause ruts primarily through snow displacement.

Data showed that the snowroad surface often hardens after the passage of a wheeled snowcoach with tires at a very low pressure (less than 62 kPa (9 psi)). Snowcoaches with tires at higher pressure and tracks more often softened the road. While this implies that tires are not uniformly causing compaction in the road, Shoop and others (2010) provides an example of tires being used for a grooming implement. In this example, the tires effectively compact deeper layers of the road but cause disaggregation
in the top 10 cm of the road. Considering data from this study together with the literature, it seems likely that tires do cause road compaction at a 10 cm depth in the snow and below, but may cause softening at the road surface, especially when running at higher inflation pressures. A softer snow surface can leave the snowroad vulnerable to snow displacement.

The scope of this study included testing vehicles on groomed, prepared snowroads. These roads are relatively hard to begin with, so compaction often does not cause a large depression in the road. On harder roads, ruts are more likely to form through snow displacement. On softer roads, compaction will cause a more substantial initial depression in the road. While the compaction can result in a harder surface, when this occurs just in one set of tracks it creates an uneven snow surface. This means that on softer roads tires may create more substantial ruts than tracks.

Also, on softer roads, a tracked vehicle sinks into the snow more fully so that the vehicle’s weight is more evenly distributed across the whole track. (On hard roads, the vehicle’s weight is concentrated at the bogey wheels.) This weight distribution will cause a tracked vehicle to cause less compaction on a soft road than a wheeled vehicle of comparable weight.

The different impacts that vehicles have on soft roads and hard roads underscores the fact that vehicles perform differently in different conditions. While vehicle performance is outside the scope of this study, existing literature and operator experience will confirm that different vehicles perform differently in certain snow conditions.
The negligible degradation and possible benefits of tires to the groomed snowroad surface indicate no reason for NPS management to prevent park snowcoach operators from running wheeled coaches. This does not take into account vehicle performance and safety, which is outside the scope of the project. However, park staff and OSV operators can weigh in on this element.

The road hardening associated with tires at lower pressures (below 62 kPa) indicates that lower pressure tires can be immediately beneficial to the roads. Additionally, lower pressure tires decrease the vertical pressure on the snowroad, likely causing compaction on softer roads and decreasing uneven road surfaces experienced in soft snow. The ability to adjust pressure not only provides snowcoach operators ability to adjust snowcoach capability when needed but can also help reduce impacts to the road.

Differences between grooming districts are correlated with weather and traffic. The occurrence of days throughout the season with maximum temperature above -10 °C increases the road strength, though only to a point. Temperatures high enough to cause snowmelt that does not refreeze would counteract this pattern. Hardness readings indicated that traffic may actually be beneficial for road hardness below the surface.

Other factors that correlate to road hardness on a parkwide scale include snowfall between grooming events, which generally corresponds with daily snowfall amounts. Grooming smaller amounts of fresh snow during each grooming run results in a more consistent quality throughout the depth of the road. Both elevation and snow depth showed a negative correlation with hardness. Both of these are also positively correlated with average daily snowfall. Grooming practices can be tailored to improve road quality
in these vulnerable areas (deeper snow depth and higher elevation) by grooming frequently and during large snowfall events if possible.

Longer “set times” (in which the snowroad surface is undisturbed after grooming) are good for the road quality, so grooming as early as possible in the evening to leave maximum time before the roads experience morning traffic is beneficial. Groomers should not leave before most traffic has left their district for the day, though, as tracks in a freshly groomed snowroad will create an uneven, hard road surface.

Existing literature shows that grooming is most effective when incorporating both disaggregation of snow particles and then compaction with a drag. Most districts use a front blade to disaggregate and a drag to compact. As long as the blade is used to adequately break up the snow surface, these are a suitable option for the grooming needs of the park. Consider incorporating both elements into all park groomers if problems are noted in the other districts.

Results from this study indicate that the current traffic in the park and grooming practices can continue to support a quality road if some basic recommendations are followed. While this study attempted to address a large variety of questions about this topic, many of the individual elements of this study can be and have been subject to multi-year studies, so this topic could be studied in much more detail. A similar study of vehicle impact on soft, ungroomed roads would be beneficial to the park in the future to provide further insight into how vehicles impact the road in different snow conditions.
The research conducted for this project fell into a broad category of a large range of factors contributing to snowroad conditions. Since the vehicle impacts to YNP’s snowroads have been isolated to primarily a surface interaction, further research should be conducted to describe these phenomena in further detail. The following paragraphs will outline recommendations on these topics.

Through the learning process of rutting being primarily driven by surface interactions, a study solely on surface interactions would greatly benefit Yellowstone National Parks OSV management program. An option of a study would be to look at grouser and track patterns on tracks and tires and also which types and dimensions would be sufficient for performance needs as well as least impact to the snowroad. This would require a detailed analysis of the different treads, grouser and tire and track dimensions. Additionally, the individual effects on the snowroads would then need to be collected. This could be completed by using a profilometer and measuring shearing strength of the surface of the snowroad before and after individual pass-bys.

This recommendation possibly permits two separate research paths, a vehicle performance path and a snowroad impact path. Both would benefit the park in gaining additional data on maintaining their snowroads and also which vehicle type is the appropriate candidate for performing in commonly encountered snow conditions in the park.

This brings forth another possible snowroad focused study, that may even precede the others. If snowroad strengths from all grooming districts could be quantified and
analyzed the most appropriate grooming and traffic specifications could be fully commented on. A sufficient grooming examination was conducted in this project but due to the many factors that needed to be examined there was a limited dataset available on grooming. A full-blown grooming study would certainly be worthwhile for the Yellowstone management team in the years to come. All of these science-based approaches to managing and understanding the livelihood of Yellowstone’s snowroads would prove beneficial to the National Park Service.
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APPENDICES
APPENDIX A

GROOMING DATA EXTRACTION AND ANALYSIS
All data from Yellowstone’s GPS Insight account for all of Year 1 and Year 2 was downloaded. This included all locations recorded on each groomer from the time the GPS units were installed through the end of grooming during Year 2. This included a reading every 2 minutes when the groomer was running. The reading included: Vehicle, VIN, Date/Time, Ignition (on/off), Max Speed, Average Speed, Instantaneous Speed, Speed Limit, Odometer, Voltage, Distance, Latitude, Longitude, “Address”, “Landmark” (for landmarks set in GPS Insight website by researchers), and “Run Time.” A few other parameters (like Maximum Acceleration) were listed but the park’s units did not have the correct instrumentation for these so they appeared blank.

Readings from each season were processed by listing all of the test sites from a given season in an Excel file, developing formulas to identify when a groomer passed one of these test sites, and using these formulas to identify groomer data points that indicated the groomer was passing a test point. In Year 1, researchers originally used a function on the GPS Insight website to set a “Landmark” at each test site and then have GPS Insight determine which points fell within a chosen distance from this landmark. This procedure worked for some test locations but gave false readings or missed readings for others. Some test sites are near an intersection, so readings on the other sections of road may appear as grooming of the test point even if the groomer did not actually come toward the test point side of the intersection. Other test sites might be located on a straightaway where the groomer goes faster than in other sections so its passes may not be picked up as close enough to the test site to register. These sites required a more tailored approach to pull out relevant groomer points. Due to this complexity and the need to examine all the raw data for accuracy of identified groomer passes, researchers ultimately developed formulas for all test sites and processed all raw data in Excel rather than relying on GPS Insight’s “Landmark” feature. Formulas were developed by trial-and-error until they seemed to capture all grooming instances for the test points.

Since the majority of points on the road are groomed nightly, formulas were calibrated until they showed nightly grooming incidents for most test locations. The locations of groomer pass-bys identified as falling near these test sites were then spot-checked to verify their accuracy. For most sites, the grooming incidents were determined either by grooming GPS points that fell within a certain proximity to the test point or by two grooming GPS points that fell on either side of the test point. Excel cell references have been replaced with abbreviations here.

Abbreviations in Formulas

TestPtLat: Latitude of the test site
TestPtLong: Longitude of the test site
GrmLat: Latitude of groomer GPS point reading
GrmLong: Longitude of groomer GPS point reading
NextGrmLat: Latitude of next chronological groomer GPS point reading
NextGrmLong: Longitude of next chronological groomer GPS point reading

Formulas

Test location on a road with east-west orientation:

=IF(OR(AND(ABS(GrmLat-TestPtLat)<=0.001784, ABS(GrmLong-TestPtLong)<=0.00254), AND(OR(AND(GrmLong<TestPtLong, NxtGrmLong>TestPtLong), AND(NextGrmLong<TestPtLong, GrmLong>TestPtLong)), OR(ABS(GrmLat-TestPtLat)<=0.003568, ABS(NxtGrmLat-TestPtLat)<=0.003568))), "Yes", "-"")

Test location on a road with north-south orientation:

=IF(OR(AND(ABS(GrmLat-TestPtLat)<=0.001784, ABS(GrmLong-TestPtLong)<=0.00254), AND(OR(AND(GrmLat<TestPtLat, NxtGrmLat>TestPtLat), AND(NxtGrmLat<TestPtLat, GrmLat>TestPtLat)), OR(ABS(GrmLong-TestPtLong)<=0.003568, ABS(NextGrmLong-TestPtLong)<=0.003568))), "Yes", "-"")

Other, unique test locations (Oth):

Grant Test Track (Year 2)

=IF(AND(ABS(GrmLat-TestPtLat)<=0.001784, ABS(GrmLong-TestPtLong)<=0.00254), "Yes", "-"")

North Rim Drive (Year 2)

=IF(AND(AND(ABS(GrmLat-TestPtLat)<=0.001784, ABS(GrmLong-TestPtLong)<=0.00762), NOT(OR(GrmLong<=110.4997, AND(GrmLat>=44.72055, GrmLong<=110.4948)))), "Yes", "-"")

Groomer passes for each individual test point for each season were extracted into an additional Excel sheet. For each groomer pass, there were often several GPS points identified as being near the test site. Researchers read through each point identified and deleted duplicates (e.g., when multiple points 2 minutes from one another had all been identified). Also, groomers generally passed the test site twice each night, once going out on their grooming run and once on the way back. Since each lane was only being groomed once, while the grooms was going in the correct direction, the later of the two passes was selected for data analysis since this was presumably when grooming for that piece of road was completed, with both lanes having been groomed. The point(s) from the earlier pass was/were deleted from the spreadsheet.
For each site, the most representative weather station was selected, based on location and similarity to the closest weather station sites. Weather stations selected for the test sites are listed in the table below. Data from the relevant weather station was extracted for November through March of the relevant season(s) and placed on the same sheet as the grooming points for that year. Table A.1 provides information on the test sites for which road hardness data was collected, the category of the road used to determine the correct Excel formula for the point, and the weather station used for that site.

Table A.1. Test locations, the categories determining which Excel formulas were used to identify groomer passes, and weather station data used for each site.

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<th>Weather Station Used</th>
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<tr>
<td>Blanding</td>
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<td>Virginia Cascades</td>
<td>44.71922</td>
<td>110.666268</td>
<td>EW</td>
<td>SNOTEL</td>
<td>Canyon</td>
</tr>
<tr>
<td>Hayden Valley</td>
<td>44.643427</td>
<td>110.457214</td>
<td>NS</td>
<td>SNOTEL</td>
<td>Canyon</td>
</tr>
<tr>
<td>Northwest of West Thumb</td>
<td>44.421705</td>
<td>110.586572</td>
<td>EW</td>
<td>SNOTEL</td>
<td>Thumb Divide</td>
</tr>
<tr>
<td>Between Norris and Mammoth</td>
<td>44.861152</td>
<td>110.736385</td>
<td>NS</td>
<td>NOAA</td>
<td>YELLOWSTONE PARK MAMMOTH, WY US</td>
</tr>
<tr>
<td>Grant Test Track</td>
<td>44.393182</td>
<td>110.557337</td>
<td>Oth</td>
<td>SNOTEL</td>
<td>Thumb Divide</td>
</tr>
</tbody>
</table>

*Indicates which Excel formula was used to identify groomer passes by this location.

Grooming and weather data for each test site was then used to calculate parameters for each site. These included: time between grooming and hardness test, temperature at the hardness test, average temperature between grooming and the hardness test, average precipitation between grooming events, average change in snow depth between grooming events, average daily precipitation, average daily change in snow depth, and average daily “degree-days” (maximum daily temperature minus -10 °C for every day on which the maximum temperature was above -10 °C).

Table A.2 shows dates for which data was available for each groomer during each year. The delay in data collection at the beginning of Year 1 was due to when the NPS was able to install the GPS devices. The data gaps in Year 2 come from malfunction of the Old Faithful Groomer GPS unit and the Lake District getting a new groomer without the GPS unit being moved from one to the other.
Table A.2. Grooming GPS data available by district and year.

<table>
<thead>
<tr>
<th>Year</th>
<th>Grooming District</th>
<th>Dates of Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Canyon</td>
<td>12/16/15-3/3/16</td>
</tr>
<tr>
<td></td>
<td>West</td>
<td>1/21/15-3/14/16</td>
</tr>
<tr>
<td></td>
<td>Old Faithful</td>
<td>12/12/15-3/14/16</td>
</tr>
<tr>
<td></td>
<td>Grant</td>
<td>12/16/15-4/1/16</td>
</tr>
<tr>
<td></td>
<td>Lake</td>
<td>12/17/15-3/28/16</td>
</tr>
<tr>
<td>2</td>
<td>Canyon</td>
<td>12/6/16-3/9/17</td>
</tr>
<tr>
<td></td>
<td>West</td>
<td>12/9/16-3/17/17</td>
</tr>
<tr>
<td></td>
<td>Old Faithful</td>
<td>2/22/16-3/13/17</td>
</tr>
<tr>
<td></td>
<td>Grant</td>
<td>11/28/16-3/17/17</td>
</tr>
<tr>
<td></td>
<td>Lake</td>
<td>NA</td>
</tr>
</tbody>
</table>
APPENDIX B

RAMMSONDE HARDNESS
The equation for hardness is stated below, the ram number (RN) was solved for first then converted to a force (RR) by the equations below.

\[
RN = T + H + \frac{n f H}{p} \\
RR = RN \times 10
\]

\(RN\) = ram number (kg)  \\
\(RR\) = ram resistance (N)  \\
\(n\) = number of blows of the hammer  \\
\(f\) = fall height of the hammer (cm)  \\
\(p\) = increment of penetration for \(n\) blows (cm)  \\
\(T\) = mass of tubes including guide rod (kg)  \\
\(H\) = mass of hammer (kg)

When the cone on the penetrometer enters the snowroad, the resistance varies due to the increasing diameter of the cone. To deal with this variance Niedringhaus (1965) developed a method to mitigate this issue. They developed a correction factor to be used in the top 10 cm’s. For the top 5 cm’s of penetration a correction factor of \(4RN\) should be used and from 5-10 cm’s a correction factor of \(1.6RN\) should be applied. Due to the importance of accurate hardness measurements in this study Niedringhaus’s correction factor was employed.
MATLAB code for processing hardness data, this file uses the correction factor stated above.

```matlab
% Hardness Processor
% See paper
% for reference on this material
clear
clc

% Define Parameters
W  = 1.0125 ; %Weight of Hammer (kg)
Q  = 1.075 ; %Weight of tube (kg)

% Select file
currentFile = uigetfile('*xlsx', 'Select file to process:');

%%% Raw Data
% Grab table of Drop #, Fall Ht, Penetration Depth Values
rdgsCols = xlsread(currentFile, 'Sheet1', 'D:F');
rdgs = rdgsCols(5:size(rdgsCols,1),:);

% Grab location and time and make graph title, output filename
 [~,~,loc] = xlsread(currentFile, 'Sheet1', 'B8');
 [~,~,time] = xlsread(currentFile, 'Sheet1', 'B5');
gtitle = [loc; time];
l = char(loc);
t = char(time);

% Find the year, month, and date from the time to put in the graph filename
if t(4)~= '/'
  y1 = 6;
  y2 = 9;
  m1 = 1;
  d1 = 3;
  d2 = 4;
else
  y1 = 5;
  y2 = 8;
  m1 = 1;
  d1 = 3;
  d2 = 3;
end

% Make the graph filename
gfilen = sprintf('%s_%s_%s_%s',t(y1:y2),t(m1),t(d1:d2),l);

% Prep Vectors for Data
DrHt       = []; %Drop Heights
NumDr      = []; %Number of Drops
```
S = []; %Penetration Depths

% Grab the columns of data from Excel hardness plots (has to be same % format) but doesn't matter how many rows...

for i = 1:size(rdgs,1)
    NumDr(i)=rdgs(i,1);
end

for i = 1:size(rdgs,1)
    DrHt(i)=rdgs(i,2);
end

for i = 1:size(rdgs,1)
    S(i)=rdgs(i,3);
end

%%% Processing

% Prep vector for hardness data
R = [];

% Now solve for Ram Hardness

% For cases where the penetration depth is the same in two subsequent % readings, assume the higher hardness for all readings at that depth. Do % that by setting the penetration for that reading (= change in depth from % last reading) equal to the difference between the current reading and the % depth reading two points earlier.

R(1)=Q ;
R(2)=Q+W ;

for i=3:length(S)
    dS = S(i)-S(i-1);
    % Then calculate R based on the dS value.
    R(i)=((W*DrHt(i)*NumDr(i))/dS)+(W+Q);
end

% Allow user to select if they would like to add the correction factors % from % http://www.dtic.mil/dtic/tr/fulltext/u2/a211588.pdf % [Lee 1989, p.8]
[sel,okay] = listdlg('PromptString', 'Use correction factors?',...
    'SelectionMode','single','ListString',{'Yes','No'}, 'InitialValue', 2);
if sel == 1
    %% Split any intervals that cross 5 so appropriate CFs can
%% be applied to the sections on either side.
for i = 1:length(S)
    if i==1 && S(i)>5
        S = [5 S];
        R = [R(i) R];
    elseif S(i)<5 && S(i+1)>5
        S = [S(1:i) 5 S(i+1:end)];
        R = [R(1:i) R(i+1) R(i+1:end)];
    end
end

%% Split any intervals that cross over 10
for i = 1:length(S)
    if i==1 && S(i)>10
        S = [10 S];
        R = [R(i) R];
    elseif S(i)<10 && S(i+1)>10
        S = [S(1:i) 10 S(i+1:end)];
        R = [R(1:i) R(i+1) R(i+1:end)];
    end
end

%% Apply correction factors
for i = 1:length(S)
    if S(i) <= 5
        R(i) = 4*R(i);
    elseif and(S(i)>5, S(i)<=10)
        R(i) = 1.6*R(i);
    end
end
gfilen = sprintf('%s_CF' ,gfilen);
end

Sff=[0 0];
for i=1:length(R)
    Sff=[Sff S(i) S(i)];
end

Rff=[0];
for i=1:length(R)
    Rff=[Rff R(i) R(i)];
end
Rff=[Rff 0];

% Make final RR values in Newtons
RffN = 10*Rff;
clf
plot(RffN,Sff)
set(gca, 'YDir', 'Reverse')
xlabel('Ram Hardness (N)')
ylabel('Depth (cm)')
title(gtitle)
Pgfilen = sprintf('%s.jpg',gfilen);
set(gcf, 'PaperUnits', 'Inches');
set(gcf, 'PaperPosition', [0 0 8.5 5.5]);
set(gca, 'fontsize', 24);
saveas(gcf, Fgfilen);

% Make matrix of values to load into Excel
SumMat = zeros(length(S), 4);
Sw0 = [0, S(1:length(S)-1)];
SumMat(:,1) = Sw0;
SumMat(:,2) = S;
SumMat(:,3) = 10*R;
SumMat(:,4) = R;

% Make matrix of orig values to go next to proc vals
OrigData = zeros(length(DrHt), 3);
OrigData(:,1) = DrHt;
OrigData(:,2) = NumDr;
OrigData(:,3) = rdgs(:,3);

% Find weighted averages to add into Excel
AvgRng = [10, 15, 20, 25, 30];
WtdAvg = [];
for i = 1:length(AvgRng)
    SumAvg = 0;
    if S(length(S)) >= AvgRng(i)
        for j = 1:length(S)
            if and(S(j)<=AvgRng(i), S(j)<=0)
                SumAvg = SumAvg + (S(j)-Sw0(j))*10*R(j);
            elseif and(S(j)>AvgRng(i), Sw0(j)<AvgRng(i))
                SumAvg = SumAvg + (AvgRng(i)-Sw0(j))*10*R(j);
            end
        end
        Avg = SumAvg/AvgRng(i);
        WtdAvg = [WtdAvg Avg];
    elseif S(length(S)) < AvgRng(i)
        WtdAvg = [WtdAvg 0];
    end
end

% Write to Excel File
xlTitle = sprintf('Proc_%s',currentFile);
hdr = [time; loc; currentFile];
WtdAvgLabels = {'Weighted Average Over', '10cm', '15cm', '20cm', '25cm', '30cm'};
hdrLabels = {'Top of Layer (depth, cm)', 'Bottom of Layer (depth, cm)', ...
    'Ramm Resistance (N)', 'Ramm Resistance (kg)', '', 'Drop Height (cm)', ...
    'Number Drops', 'Total Penetration'};
sheet = 'Sheet1';
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```javascript
xlswrite(xlTitle, hdr, sheet, 'A1');
xlswrite(xlTitle, WtdAvgLabels, sheet, 'A4');
xlswrite(xlTitle, WtdAvg, sheet, 'B5');
xlswrite(xlTitle, hdrLabels, sheet, 'A6');
xlswrite(xlTitle, SumMat, sheet, 'A7');
xlswrite(xlTitle, OrigData, sheet, 'F7');
```
APPENDIX C

LOAD CELLS
The twelve load cells that created the load cell array were LC304-500 load cells designed by Omega Engineering Inc. These load cells are designed to withstand loads of 2,225 N (500 lbs), however they are capable of withstanding loads of up to 150% of capacity. Each load cell comes with a unique specifications sheet and a calibration factor. With information from the spec sheet researchers are able to very accurately convert raw voltage readings from the load cells to a load measurement. The data is then postprocessed using various programs described below.

A LabVIEW program was created to trim the data and convert it into force (pounds or Newtons). The program trimmed the data before the first load event and after the last load event according to a set threshold (a force significant enough in magnitude to indicate a vehicle passing). The LabVIEW code was programmed to trim readings earlier than 2,000 points before the first time the threshold is reached and beyond 2,000 readings after the last time the threshold is reached. Calibration information specific to each load cell was entered to set the program to translate voltage readings from each load cell into the force represented by the voltage readings. This program saved the data in comma-separated values (CSV) format that could be opened in Excel, facilitating generation of graphs and investigation of the force data. Each load cell data file (one per pass-by) was processed using this trimming program.

Further more, once the data was saved as a .xlsx file (excel file) the data was imported into MATLAB for more involved processing techniques. MATLAB was used to make 3-dimensional plots, solve for vehicle velocity (see the Vehicle Loading methods section for details) and to solve for impulse.

With possible damage to the load cells throughout use in this project, some days the load data was quite ‘noisy’. This is not uncommon with the use of instruments in the field and there are commonly used methods to ‘smooth’ the data. The most advantageous method for researchers to smooth the data was a Savitzky-Golay filter in MATLAB. This is a built-in filter in MATLAB that smooths noisy data. It takes noisy data and increases the signal-to-noise ratio without greatly distorting the signal. This filtering method proved to be a good fit for use with this project’s occasional noisy load data. Figure 64 shows unfiltered data from Year 2 and Figure 65 shows the same data after the filter was applied.
Figure 64: A pass-by from the NPS LPT courier vehicle, the instrumentation had a high level of noise associated with the measurement.

Figure 65: The same pass-by as Figure 64, however the Savitzky-Golay filter has been applied. The noise is decreased significantly and the plot is much more discernable.
To solve for impulse, a numerical integration was carried through in MATLAB. A trapezoidal integration method was used. This method sums the area under the load curve with respect to time. The equation for this method is seen below.

\[ A_i = \frac{1}{2} (f_i + f_{i+1})h \]

\[ A_T = A_0 + A_1 + \cdots A_{N-1} \]

- \( A_i \) = incremental area
- \( f_i \) = function value at point i
- \( h \) = distance between points
- \( A_T \) = total area
MATLAB code for processing load data, this is a generic code for any of the tested vehicles.

```matlab
% MATLAB file to make load plots
% Used for Yellowstone Snowroad Project, this is a generic file that
% must be changed for various vehicles. For example, tire width, distance
% between axles and other various changes must be made for accurate
% velocities and other parameters this code solves for.

clear; clc

% Set Pass Info
% Set date of pass-bys for plot titles
Dt = '29 Jan 2017';

% Vehic = '117cmx58cm Tires, 75 kPa, 61 kPa'; Tire Dimension then
% inflation pressure.
Vehic = 'NPS Tires'; % Vehicle Type

% Track width or anything to note
Tirewidth = 60; % Centimeters
Ttl = sprintf('%s: %s', Dt, Vehic);

ConversionFile = uigetfile('*xlsx', 'Select conversion file:');
% Assign array a variable name
B = readtable(ConversionFile);
C = table2array(B);

% If data is ‘noisy’ apply Savitzky-Golay filter, this filter will
% reduce % the noise to signal ratio.
% C = sgolayfilt(C, 10, 401); % y = sgolayfilt(x, order, framelen)
% framelen must be odd
C = sgolayfilt(C, 2, 41);

% Grab Columns
loadcell1 = 4.448 * C(:, 1); % 4.448 is for newton conversions
loadcell2 = 4.448 * C(:, 2);
loadcell3 = 4.448 * C(:, 3);
loadcell4 = 4.448 * C(:, 4);
loadcell5 = 4.448 * C(:, 5);
loadcell6 = 4.448 * C(:, 6);
loadcell7 = 4.448 * C(:, 7);
loadcell8 = 4.448 * C(:, 8);
loadcell9 = 4.448 * C(:, 9);
loadcell10 = 4.448 * C(:, 10);
loadcell11 = 4.448 * C(:, 11);
loadcell12 = 4.448 * C(:, 12);
loadcellsum = 4.448 * C(:, 13);

t(1) = 1;
```
for i=1:length(loadcell1)
  t1(i)= i;  \text{\%Time for stress}
end

figure('units','normalized','outerposition',[0 0 1 1])
plot(t1,loadcellsum,'lineweight',2)
xlabel('t')
ylabel('N')
set(gca,'XTick',0:400:length(loadcell1));
PlotTitle2 = sprintf('%s; %s',ConversionFile,'Summed Load');
title(sprintf('%s; %s',ConversionFile,'load vs time'))
grid on
grid minor

% Ask user where to trim this file. i.e. Isolate wanted events.
begPromptAll = 'Enter the beginning trim value (at least 1): ';
beginAllLoad = input(begPromptAll);
endPromptAll = 'Enter the ending trim value (at least 1): ';
endAllLoad = input(endPromptAll);

loadcell1trim=   loadcell1(beginAllLoad:endAllLoad);
loadcell2trim=   loadcell2(beginAllLoad:endAllLoad);
loadcell3trim=   loadcell3(beginAllLoad:endAllLoad);
loadcell4trim=   loadcell4(beginAllLoad:endAllLoad);
loadcell5trim=   loadcell5(beginAllLoad:endAllLoad);
loadcell6trim=   loadcell6(beginAllLoad:endAllLoad);
loadcell7trim=   loadcell7(beginAllLoad:endAllLoad);
loadcell8trim=   loadcell8(beginAllLoad:endAllLoad);
loadcell9trim=   loadcell9(beginAllLoad:endAllLoad);
loadcell10trim=  loadcell10(beginAllLoad:endAllLoad);
loadcell11trim=  loadcell11(beginAllLoad:endAllLoad);
loadcell12trim=  loadcell12(beginAllLoad:endAllLoad);
loadcellsumtrim= loadcellsum(beginAllLoad:endAllLoad);

%Preallocate vectors of ones twos threes ect
one=zeros(length(loadcell1trim),1);
two=zeros(length(loadcell1trim),1);
three=zeros(length(loadcell1trim),1);
four=zeros(length(loadcell1trim),1);
five=zeros(length(loadcell1trim),1);
six=zeros(length(loadcell1trim),1);
seven=zeros(length(loadcell1trim),1);
eight=zeros(length(loadcell1trim),1);
nine=zeros(length(loadcell1trim),1);
ten=zeros(length(loadcell1trim),1);
eten=zeros(length(loadcell1trim),1);
extra=zeros(length(loadcell1trim),1);

%Create vectors of ones twos threes ect
for i=1:length(loadcell1trim)
  one(i)=1;
end
% Number of points in trimmed data
TrimmedAllLoad = endAllLoad-beginAllLoad+1;

for i=1:TrimmedAllLoad
t(i)= i;  % Time for stress
end

figure('units','normalized','outerposition',[0 0 1 1])
plot(t,loadcellsumtrim,'linewidth',2)
xlabel('t')
ylabel('N')
set(gca,'XTick',0:100:length(loadcell1));
PlotTitle2 = sprintf('%s; %s',ConversionFile,'Summed Load');
title(sprintf('%s; %s',ConversionFile,'load vs time'))
grid on
grid minor

%% Have user enter the intervals where the two maxes are located
Prompt0 = 'How many spikes are there on this plot? ';
NumSpikes = input(Prompt0);
Mmax=zeros(1,NumSpikes);
tmax=zeros(1,NumSpikes);
firstMaxbegin=zeros(1,NumSpikes);
firstMaxend=zeros(1,NumSpikes);
for i=1:NumSpikes
    Prompt1 = 'Enter beginning of first maximum interval: ';
    firstMaxbegin(i) = input(Prompt1);
    Prompt2 = 'Enter end of first maximum interval: ';
    firstMaxend(i) = input(Prompt2);
    [Mmax(i),tmax(i)] = max(loadcellsumtrim(firstMaxbegin(i):...
                              firstMaxend(i)));
end

Prompt1 = ...
'Enter the number from left to right of the 1st spike you want for velocity measurement: ';
firstspike = input(Prompt1);
Prompt2 = ...
'Enter the number from left to right of the 2nd spike you want for
velocity measurement: ';
secondspike = input(Prompt2);

tmlf = tmax(firstspike)+firstMaxbegin(firstspike);
tm2f = tmax(secondspike)+firstMaxbegin(secondspike);

%% Calculate Velocity from time interval -- UPDATE AXLES for specific
% Vehicle
timeInt = tm2f-tmlf;
timeS = timeInt/2000;
% In centimeters (Distance between front to rear bogey) or dist between
% tires
axles = 455;
Vms = axles/(100*timeS);  % Vel in meters per second
Vmih = Vms*60*60/1609.34;  % Vel in miles per hour

VelTitle = sprintf('V = %.2f m/s ', Vms);

%% Put time into seconds
tS = t/2000;

%% Plot load data in metric units
% By Load Cell, 3D Non-surface
figure(1); clf;
subplot(2,2,1);
plot3(tS,one,loadcell1trim,'linewidth',2)
hold on
plot3(tS,two,loadcell2trim,'linewidth',2)
plot3(tS,three,loadcell3trim,'linewidth',2)
plot3(tS,four,loadcell4trim,'linewidth',2)
plot3(tS,five,loadcell5trim,'linewidth',2)
plot3(tS,six,loadcell6trim,'linewidth',2)
plot3(tS,seven,loadcell7trim,'linewidth',2)
plot3(tS,eight,loadcell8trim,'linewidth',2)
plot3(tS,nine,loadcell9trim,'linewidth',2)
plot3(tS,ten,loadcell10trim,'linewidth',2)
plot3(tS,eleven,loadcell11trim,'linewidth',2)
plot3(tS,twelve,loadcell12trim,'linewidth',2)
xlabel('Time (Seconds)')
ylabel('Load Cell Number')
zlabel('Force (Newtons)')
PlotTitle1 = {'Ttl, 'Load vs. Time, by Load Cell';
title(PlotTitle1)
hold off

% Summed load plot
subplot(2,2,4)
plot(tS,loadcellsumtrim,'linewidth',2)
xlabel('Time (Seconds)')
ylabel('Force (Newtons)')
PlotTitle2 = {'Total Load vs. Time'};
title(PlotTitle2)

% Write the velocity on the summed graph at specified position
yl=ylim;
xl=xlim;
text(.05*(xl(2)-xl(1))+xl(1),.95*(yl(2)-yl(1))+yl(1),'VelTitle');

% By Load Cell, 2D
subplot(2,2,3)
plot(tS,loadcell1trim,'linewidth',2)
hold on
plot(tS,loadcell2trim,'linewidth',2)
plot(tS,loadcell3trim,'linewidth',2)
plot(tS,loadcell4trim,'linewidth',2)
plot(tS,loadcell5trim,'linewidth',2)
plot(tS,loadcell6trim,'linewidth',2)
plot(tS,loadcell7trim,'linewidth',2)
plot(tS,loadcell8trim,'linewidth',2)
plot(tS,loadcell9trim,'linewidth',2)
plot(tS,loadcell10trim,'linewidth',2)
plot(tS,loadcell11trim,'linewidth',2)
plot(tS,loadcell12trim,'linewidth',2)
xlabel('Time (Seconds)')
ylabel('Force (Newtons)')

PlotTitle3 = {'Load vs. Time, by Load Cell'};

%legend()
title(PlotTitle3)

%% Select maximums for each loads cell to create bar graph
figure('units','normalized','outerposition',[0 0 1 1])
plot(t,loadcell1sumtrim,'linewidth',2)
xlabel('t')
ylabel('N')
set(gca,'XTick',0:100:length(loadcell1trim));
PlotTitle2 = sprintf('%s; %s',ConversionFile,'Summed Load');
title(sprintf('%s; %s',ConversionFile,'load vs time'))
grid on
grid minor

Prompt3bar = 'Which spike has the highest magnitude? ';
BiggestspikeNum = input(Prompt3bar);

tForBar = firstMaxbegin(BiggestspikeNum) + tmax(BiggestspikeNum);

Mcell1  = loadcell1trim (tForBar);
Mcell2  = loadcell2trim (tForBar);
Mcell3  = loadcell3trim (tForBar);
Mcell4  = loadcell4trim (tForBar);
Mcell5  = loadcell5trim (tForBar);
Mcell6  = loadcell6trim (tForBar);
Mcell7  = loadcell7trim (tForBar);
Mcell8  = loadcell8trim (tForBar);
Mcell9  = loadcell9trim (tForBar);
Mcell10 = loadcell10trim(tForBar);
Mcell11 = loadcell11trim(tForBar);
Mcell12 = loadcell12trim(tForBar);
Mcellarray=[Mcell1  Mcell2  Mcell3  Mcell4 Mcell5 Mcell6 Mcell7 ... Mcell8 Mcell9  Mcell10 Mcell11 Mcell12];
figure(1)
subplot(2,2,2)
bar(Mcellarray)
xlim([0 13])
ylabel('Force (Newtons)')
xlabel('Load Cell Number')
Bartitle = {Ttl,'At Max Summed Load'};
title(Bartitle)

%% Information for saving Figure 1
ThreePlotName = sprintf('%sPlotsmet.jpg', ConversionFile(1:end-5));
set(gcf, 'PaperUnits', 'Inches');
set(gcf, 'PaperPosition', [0 0 17 11]);
saveas(gcf, ThreePlotName);

%% Contour plot
figure(3); clf;
loadarray=cat(2,loadcell1trim,loadcell2trim,loadcell3trim,loadcell4trim,
...loadcell5trim,loadcell6trim,loadcell7trim,loadcell8trim,loadcell9trim,
...loadcell10trim,loadcell11trim,loadcell12trim);
onestwosthrees=cat(2,one,two,three,four,five,six,seven,eight,nine,ten,
...eleven,twelve);
tarray=zeros(length(loadcell1trim),12);
for i=1:12
    tarray(:,i)=tS;
end
mesh(tarray,onestwosthrees,loadarray)
ContourPlotName = sprintf('%sContourPlot.jpg', ConversionFile(1:end-5));
set(gcf, 'PaperUnits', 'Inches');
set(gcf, 'PaperPosition', [0 0 17 11]);
xlabel('time')
ylabel('Load Cell Number')
zlabel('Force (Newtons)')
Contourtitle = {Ttl,'Surface Plot of Load Cells'};
title(Contourtitle)
saveas(gcf, ContourPlotName);
%% Solve for stress this vehicle produced
% This was an attempt to solve for stress however, through analysis
% this was not warranted as a accurate method. Additional information
% would be needed to solve for an accurate stress. This will be left
% here though in case the information is one day gathered and this code
% could be utilized.

% Area of load cell effected
Area=Tirewidth*10.16;
    % Tirewidth(4*2.54cm)=Area
% Solve for stress at each maximum load
Stress=zeros(1,NumSpikes);
for i=1:NumSpikes
    Stress(i)=Mmax(i)/Area;
    % First stress (max)  % second stress (max)
end
    % For bomb and mattracks more than two peaks

% Display stress results in command window
Stress

%% Select the Stress/Strain Excel file where you are storing
% stress/strain info.
currentFile = uigetfile( '*.xlsx', 'Select file to process:');
currentFileName = currentFile(1:end-5);

% Get the existing names of sheets in the Excel workbook.
[status,sheets] = xlsfinfo(currentFile);
sheets = [sheets 'Other'];

% Ask the user which Sheet to put the data on. If the vehicle is not
% listed yet, allow the user to select "Other". Then ask for the user
% to provide an appropriate name for the vehicle so that we can make a
% new sheet for it in the Excel file.
[sel,okay] = listdlg('PromptString', 'Select the Vehicle',
'SelectionMode', ...
'single','ListString',sheets);
if sel == length(sheets)
    vPrompt = 'Please enter the vehicle name (Snowbuster, SS Tires, etc.): ';
    Vsheet = input(vPrompt, 's');
else
    Vsheet = sheets(sel);
end

% If you will be adding to an existing sheet, read the data from that
% sheet in so you know where the blank rows start.
if sel < length(sheets)
    [num,txt,raw] = xlsread(currentFile, char(Vsheet));
    SSrows = size(txt,1)+1;
    SSaddRow = SSrows(1)+2;
StartCell = sprintf('A%d', SSaddRow);
StartDataCell = sprintf('B%d', SSaddRow); okay
StartDataCellNums = sprintf('B%d', SSaddRow+5);
else
    StartCell = 'A1';
    StartDataCell = 'B1';
    StartDataCellNums = 'B6';
end

% Find where the blank rows start and define 2 rows down as your start % point.

%% Test vals (won't be needed when plugged into bigger file)
% Vehic = 'NPS Tires';
% ConversionFile = 'NPS Tires';
% Vms = 100;
% Vmih = 5;
StressTimes = (firstMaxbegin+tmax)/2000;
% Stress = [100, 200, 300, 400, 500];

% Make Column and Row Titles
Tc = {'Vehicle'; 'File'; 'Processed'; 'Velocity (m/s)'; 'Velocity (mph)';
      'Load Time (s)'; 'Load (N)'};

% Make partial column for file ID values
Mdc = {Vehic; ConversionFile; sprintf('Processed %s', datestr(datetime('now')))); Vms; Vmih};
MdcVs = [StressTimes; Mmax];

xlswrite(currentFile, Tc, char(Vsheet), StartCell)
xlswrite(currentFile, Mdc, char(Vsheet), StartDataCell)
xlswrite(currentFile, MdcVs, char(Vsheet), StartDataCellNums)
MATLAB code for solving for impulse, many portions of this code are similar to Generic_Loadplots_Thesis code above. For additional comments reference the code above.

```matlab
%% File to go through load cell data and solve for impulse.
% This file is similar to Generic_Loadplots_Thesis however
% Impulse has been added to code

clear; clc

ConversionFile = uigetfile('*.xlsx','Select conversion file:');
B = readtable(ConversionFile);
C = table2array(B);
%Chg for real file

%Grab Columns
loadcell1= 4.448*C(:,1); %4.448 is for newton conversions
loadcell2= 4.448*C(:,2);
loadcell3= 4.448*C(:,3);
loadcell4= 4.448*C(:,4);
loadcell5= 4.448*C(:,5);
loadcell6= 4.448*C(:,6);
loadcell7= 4.448*C(:,7);
loadcell8= 4.448*C(:,8);
loadcell9= 4.448*C(:,9);
loadcell10=4.448*C(:,10);
loadcell11=4.448*C(:,11);
loadcell12=4.448*C(:,12);
loadcellsum=4.448*C(:,13);

t(1)=1;

for i=1:length(loadcell1)
    t1(i)= i; %Time for stress
end

figure('units','normalized','outerposition',[0 0 1 1])
plot(t1,loadcellsum,'linewidth',2)
xlabel('t')
ylabel('N')
set(gca,'XTick',0:400:length(loadcell1));
PlotTitle2 = sprintf('%s; %s',ConversionFile,'Summed Load');
title(sprintf('%s; %s',ConversionFile,'load vs time'))
grid on
grid minor

% Ask user where to trim this file.
begPromptAll = 'Enter the beginning trim value (at least 1) for all the
load cells: ';
beginAllLoad = input(begPromptAll);
endPromptAll = 'Enter the ending trim value (at least 1) for all the
load cells: ';
```
endAllLoad = input(endPromptAll);

% Enter Date the measurement was taken since we can only compare
% vehicles from same day
Dt = '5 Mar 2016';

% Vehicle Type
Vehic = 'TSS Mattracks';
Ttl = sprintf('%s: %s', Dt, Vehic);

% Trim the loadcell data from user specified inputs
loadcell1trim = loadcell1(beginAllLoad:endAllLoad);
loadcell2trim = loadcell2(beginAllLoad:endAllLoad);
loadcell3trim = loadcell3(beginAllLoad:endAllLoad);
loadcell4trim = loadcell4(beginAllLoad:endAllLoad);
loadcell5trim = loadcell5(beginAllLoad:endAllLoad);
loadcell6trim = loadcell6(beginAllLoad:endAllLoad);
loadcell7trim = loadcell7(beginAllLoad:endAllLoad);
loadcell8trim = loadcell8(beginAllLoad:endAllLoad);
loadcell9trim = loadcell9(beginAllLoad:endAllLoad);
loadcell10trim = loadcell10(beginAllLoad:endAllLoad);
loadcell11trim = loadcell11(beginAllLoad:endAllLoad);
loadcell12trim = loadcell12(beginAllLoad:endAllLoad);
loadcellsumtrim = loadcellsum(beginAllLoad:endAllLoad);

% Number of points in trimmed data
TrimmedAllLoad = endAllLoad-beginAllLoad+1;

for i=1:TrimmedAllLoad
  t(i)= i; % Time for Load
end

% Plot the trimmed summed data
figure('units','normalized','outerposition', [0 0 1 1])
plot(t,loadcellsumtrim,'linewidth',2)
xlabel('t')
ylabel('N')
set(gca,'XTick',0:100:length(loadcell1));
PlotTitle2 = sprintf('%s; %s',ConversionFile,'Summed Load');
title(sprintf('%s; %s',ConversionFile,'load vs time'))
grid on
grid minor

% Make a choice to apply the savitzky-golay filter (If very noisy apply % filter)
Choice = input('Do you want to apply the filter? Y or N: ','s')

if Choice == 'Y'
  % Apply the filter below if the data is very noisy
  loadcellsumtrim = sgolayfilt(loadcellsumtrim,2,41);
  % Plot the trimmed summed data with filter
  figure('units','normalized','outerposition', [0 0 1 1])
  plot(t,loadcellsumtrim,'linewidth',2)
xlabel('t')
ylabel('N')
set(gca, 'XTick', 0:100:length(loadcell1));
PlotTitle2 = sprintf('%s; %s', ConversionFile, 'Summed Load');
title(sprintf('%s; %s', ConversionFile, 'load vs time'))
grid on
grid minor
else
Choice == 'N'
  % If not leave as is
  loadcellsumtrim=loadcellsumtrim;
end

%% Have user enter the intervals where the two maxes are located
% Prompt0 = 'How many spikes are there on this plot? ';
NumSpikes = 2; % input(Prompt0);
Mmax=zeros(1,NumSpikes);
tmax=zeros(1,NumSpikes);
firstMaxbegin=zeros(1,NumSpikes);
firstMaxend=zeros(1,NumSpikes);
for i=1:NumSpikes

  Prompt1 = 'Enter beginning of first maximum interval: ';
  firstMaxbegin(i) = input(Prompt1);
  Prompt2 = 'Enter end of first maximum interval: ';
  firstMaxend(i) = input(Prompt2);

  [Mmax(i),tmax(i)] = max(loadcellsumtrim(firstMaxbegin(i):firstMaxend(i)));
end

% Selecting the maximums from the array you created to get velocity,
% example for a tire it would be 1 and 2. For a bomb and you knew the
% distance between the front and read bogey wheel it would be 2 and 5.
% Prompt1 = 'Enter the number from left to right of the 1st spike you
% want for velocity measurement: ';
% firstspike = 1; % input(Prompt1);
% Prompt2 = 'Enter the number from left to right of the 2nd spike you
% want for velocity measurement: ';
% secondspike = 2; % input(Prompt2);

tm1f = tmax(firstspike)+firstMaxbegin(firstspike);
tm2f = tmax(secondspike)+firstMaxbegin(secondspike);

%% Caculate Velocity from time interval -- UPDATE AXLES for Vehicle

timeInt = tm2f-tm1f;
timeS = timeInt/2000;
axles = 286;
% axles = input('Enter distance do you want to use for velocity
% calculation (in centimeters): ');
Vms = axles/(100*timeS);  % Vel in meters per second
Vmih = Vms*60*60/1609.34;  % Vel in miles per hour
VelTitle = sprintf('V = %.2f m/s ', Vms);

% Put time into seconds
tS = t/2000;

% Impulse calculation
% This filter works for always having 3 offsets 1 before the first
% event i.e tire/ ski / track, one between the first event and one
% after the last event
num_offsets=3;
%num_offsets= input('How many offsets are there on this plot? ');
for k=1:num_offsets
    Range1(k)=input('Enter beginning of range to calc Baseline: ');
    Range2(k)=input('Enter end of range to calc Baseline: ');
    Baseline(k)=mean(loadcellsumtrim(Range1(k):Range2(k)));
end
% Select Number of Loadcell ranges there are
for l=1:num_offsets
    loadranges(l)= input('Enter end of the range to apply baseline
    subtraction ');
end

% This part might be able to be more general with a loop so we don’t
% always have to have 3 offsets, with the time I have I couldn't find a
% way to put this in a loop that makes sense...
Part1=loadcellsumtrim(1:loadranges(1))-Baseline(1);
Part2=loadcellsumtrim(loadranges(1)+1:loadranges(2))-Baseline(2);
Part3=loadcellsumtrim(loadranges(2)+1:loadranges(3))-Baseline(3);

% With the baseline subtraction some values may becomes negative so we
% set them to zero
for h=1:length(Part1)
    if Part1(h)<0
        Part1(h)=0;
    else
        Part1(h)=Part1(h);
    end
end
for h=1:length(Part2)
    if Part2(h)<0
        Part2(h)=0;
    else
        Part2(h)=Part2(h);
    end
end
for h=1:length(Part3)
    if Part3(h)<0
        Part3(h)=0;
    else
        Part3(h)=Part3(h);
    end
end
% Concatenate vectors to make one large vector again, this will be the
% final vector we calculate Impulse with.
loadcellsumtrimCAT=[Part1(:); Part2(:); Part3(:)];

%Calculate impulse element wise
for i=1:length(loadcellsumtrimCAT)-1
    Impulse(i)=((loadcellsumtrimCAT(i)+loadcellsumtrimCAT(i+1))/2)*(1/2000); end
%Sum all elements of Impulse to get a total impulse from the passby.
ImpulseFinal=sum(Impulse);

plot(Impulse)

%% Select the Impulse file where you are storing the data
% info.
currentFile = uigetfile('*.xlsx', 'Select file to process:');
currentFileName = currentFile(1:end-5);

% Get the existing names of sheets in the Excel workbook.
[status,sheets] = xlsfinfo(currentFile);
sheets = [sheets 'Other'];

% Ask the user which Sheet to put the data on. If the vehicle is not
% listed yet, allow the user to select "Other". Then ask for the user
% to provide an appropriate name for the vehicle so that we can make a
% new sheet for it in the Excel file.
[sel,okay] = listdlg('PromptString', 'Select the Vehicle',
    'SelectionMode', 'single', 'ListString', sheets);
if sel == length(sheets)
    vPrompt = 'Please enter the vehicle type (Mattracks, Tires, or
Bomb): ';
    Vsheet = input(vPrompt, 's');
else
    Vsheet = sheets(sel);
end

% If you will be adding to an existing sheet, read the data from that
% sheet in so you know where the blank rows start.
if sel < length(sheets)
    [num,txt,raw] = xlsread(currentFile, char(Vsheet));
    SSrows = size(txt,1)+1;
    SSaddRow = SSrows(1)+2;
    StartCell = sprintf('A%d',SSaddRow);
    StartDataCell = sprintf('B%d',SSaddRow);okay
    StartDataCellNums = sprintf('B%d',SSaddRow+5);
else
    StartCell = 'A1';
    StartDataCell = 'B1';
    StartDataCellNums = 'B6';
end

% Find where the blank rows start and define 2 rows down as your start
% point.

%% Test vals (won't be needed when plugged into bigger file)
%Vehic = 'Snowbuster 65';
%ConversionFile = 'Snowbuster12';
%E = 100;
%M = 5;
StressTimes = (firstMaxbegin+tmax)/2000;
%Stress = [100, 200, 300, 400, 500];

% Make Column and Row Titles
Tc = {'Vehicle';'File';'Date';'Velocity (m/s)';'Velocity (mph)'...
     ;'Impulse (Ns)'};

% Make partial column for file ID values
Mdc = {Vehic; ConversionFile; Dt; Vms; Vmih;ImpulseFinal};
%MdcVs = [StressTimes; Mmax];

xlswrite(currentFile, Tc, char(Vsheet), StartCell);
xlswrite(currentFile, Mdc, char(Vsheet), StartDataCell);
%xlswrite(currentFile, MdcVs, char(Vsheet), StartDataCellNums)
Load cell data sheets, these sheets have all conversion factors and specifications for the load cells used in this project. There are two “# 1” load cells due damage to the original # 1 load cell, it was replaced with same model load cell. This change was accounted for and conversion factors were adjusted appropriately.
OMEGA ENGINEERING INC.

LOAD CELL
FINAL CALIBRATION

Job: WHM5315
Model: LC304-500
Date: 12/0/2015

0.00 - 500.00 LBS
Excitation 10.000 Vdc

Serial: 337710
Tested By: ED
Temperature Range: +60 to +160 F
Specfile: LC304

<table>
<thead>
<tr>
<th>Force (LBS)</th>
<th>Unit Data (mVdc)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>0.015</td>
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<tr>
<td>250.00</td>
<td>10.488</td>
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<tr>
<td>500.00</td>
<td>21.062</td>
</tr>
<tr>
<td>250.00</td>
<td>10.500</td>
</tr>
<tr>
<td>0.00</td>
<td>0.017</td>
</tr>
</tbody>
</table>

Change at 0.00 LBS (-INPUT to -OUTPUT)

Balance = 0.015 mVdc
Sensitivity = 21.077 mVdc/100 LBS
Input Resist = 379.30 Ohms
Output Resist = 352.80 Ohms
59K Shunt = 14.875 mVdc

Calibration Factors:
Sensitivity = 2.108 mV/V 59K Shunt = 1.488 mV/V

ELECTRICAL LEAKAGE: PASS
ELECTRICAL WIRING/CONNECTOR: RED = +INPUT (EXC)
BLACK = -INPUT (EXC)
GREEN = +OUTPUT
WHITE = -OUTPUT

This Calibration was performed using Instruments and Standards that are traceable to the United States National Institute of Standards Technology.

S/N Description Range Reference Cal Cert
3146A40859 1000 lb Reference STD 0 - 500.00 LBS C-2692 C-2592
3146A40859 HF34401A DMM UUT Unit Under Test C-2412 C-2412

Q.A. Representative: Ed Cashman Jr
Date: 12/8/2015

This transducer is tested to & meets published specifications. After final calibration our products are stored in a controlled stock room & considered in bonded storage. Depending on environment & severity of use factory calibration is recommended every one to three years after initial service installation date.

COMMENTS: FINAL TEST.

Omega Engineering Inc., One Omega Drive, Stamford, CT 06907
http://www.omega.com  email: info@omega.com  phone (800) 826-6342
**OEMGA ENGINEERING INC.**

**LOAD CELL**
**FINAL CALIBRATION**

<table>
<thead>
<tr>
<th>Force (LBS)</th>
<th>Unit Data (mVdc)</th>
<th>Normalized Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>- 0.126</td>
<td>0.000</td>
</tr>
<tr>
<td>250.00</td>
<td>10.315</td>
<td>10.441</td>
</tr>
<tr>
<td>500.00</td>
<td>20.736</td>
<td>20.862</td>
</tr>
<tr>
<td>250.00</td>
<td>10.323</td>
<td>10.449</td>
</tr>
<tr>
<td>0.00</td>
<td>- 0.129</td>
<td>0.003</td>
</tr>
</tbody>
</table>

**Balance** - 0.126 mVdc
**Sensitivity** - 20.062 mVdc
**In Resist** - 377.60 Ohms
**Out Resist** - 352.30 Ohms
**59K Shunt** - 14.849 mVdc

Change at 0.00 LBS [-INPUT to -OUTPUT]

**Calibration Factors:**
Sensitivity = 2.086 mV/V
59K Shunt = 1.485 mV/V

**ELECTRICAL LEAKAGE:** PASS
**ELECTRICAL WIRING/CONNECTOR:**
- RED = +INPUT (EXC)
- BLACK = -INPUT (EXC)
- GREEN = +OUTPUT
- WHITE = -OUTPUT

This Calibration was performed using Instruments and Standards that are traceable to the United States National Institute of Standards Technology.

<table>
<thead>
<tr>
<th>S/N</th>
<th>Description</th>
<th>Range</th>
<th>Reference</th>
<th>Cal Cert</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000lb Reference STD 0</td>
<td>0 - 500.00 LBS</td>
<td>C-2692</td>
<td>C-2692</td>
<td></td>
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<tr>
<td>3146A40659</td>
<td>HP4401A DMM</td>
<td>UUT</td>
<td>Unit Under Test</td>
<td>C-2412</td>
</tr>
</tbody>
</table>

**Q.A. Representative:** Ed Sadman Jr
**Date:** 1/21/2016

This transducer is tested to & meets published specifications. After final calibration our products are stored in a controlled stock room & considered in bonded storage. Depending on environment, & severity of use factory calibration is recommended every one to three years after initial service installation date.

**COMMENTS:** FINAL TEST.

Omega Engineering Inc., One Omega Drive, Stamford, CT 06907
http://www.omega.com  email: info@omega.com  phone (800) 826-6342
**LOAD CELL FINAL CALIBRATION**

0.00 - 500.00 LBS
Excitation 10.000 Vdc

**Calibrated:**

<table>
<thead>
<tr>
<th>Force LBS</th>
<th>Unit Data mVdc</th>
<th>Normalized Data</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.00</td>
<td>- 0.141</td>
<td>0.000</td>
</tr>
<tr>
<td>250.00</td>
<td>10.149</td>
<td>10.290</td>
</tr>
<tr>
<td>500.00</td>
<td>20.554</td>
<td>20.685</td>
</tr>
<tr>
<td>250.00</td>
<td>10.170</td>
<td>10.311</td>
</tr>
<tr>
<td>0.00</td>
<td>- 0.142</td>
<td>- 0.001</td>
</tr>
</tbody>
</table>

Balance: - 0.141 mVdc
Sensitivity: 20.695 mVdc
In Resist: 377.40 Ohms
Out Resist: 352.20 Ohms
59K Shunt: 14.877 mVdc

Change at 0.00 LBS (-INPUT to -OUTPUT)

**Calibration Factors:**

Sensitivity = 2.070 mV/V
59K Shunt = 1.468 mV/V

**ELECTRICAL LEAKAGE:** PASS
**ELECTRICAL WIRING/CONNECTOR:**
- RED = +INPUT (EXC)
- BLACK = -INPUT (EXC)
- GREEN = +OUTPUT
- WHITE = -OUTPUT

This Calibration was performed using Instruments and Standards that are traceable to the United States National Institute of Standards Technology.

<table>
<thead>
<tr>
<th>S/N</th>
<th>Description</th>
<th>Range</th>
<th>Reference</th>
<th>Cal Cert</th>
</tr>
</thead>
<tbody>
<tr>
<td>10001b</td>
<td>Reference STD 0 - 500.00 LBS</td>
<td>C-2692</td>
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<td></td>
</tr>
</tbody>
</table>

Q.A. Representative: Ed Cushman Jr.  
Date: 12/8/2015

This transducer is tested to & meets published specifications. After final calibration our products are stored in a controlled stock room & considered in bonded storage. Depending on environment & severity of use factory calibration is recommended every one to three years after initial service installation date.

COMMENTS: FINAL TEST.
**OMEGA ENGINEERING INC.**

**LOAD CELL**

**FINAL CALIBRATION**

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<tr>
<th>Force (LBS)</th>
<th>Unit Data (mVdc)</th>
<th>Normalized Data</th>
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</thead>
<tbody>
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<td>250.00</td>
<td>11.193</td>
<td>11.280</td>
</tr>
<tr>
<td>500.00</td>
<td>22.506</td>
<td>22.593</td>
</tr>
<tr>
<td>250.00</td>
<td>11.208</td>
<td>11.295</td>
</tr>
<tr>
<td>0.00</td>
<td>- 0.090</td>
<td>- 0.003</td>
</tr>
</tbody>
</table>

**Balance** = 0.087 mVdc

**Sensitivity** = 22.593 mVdc

**In. Resist** = 376.79 Ohms

**Out. Resist** = 352.10 Ohms

**59K Shunt** = 14.862 mVdc

Change at 0.00 LBS (-INPUT to -OUTPUT)

**Calibration Factors:**
- **Sensitivity** = 2.259 mV/V
- **59K Shunt** = 1.486 mV/V

**ELECTRICAL LEAKAGE:** PASS

**ELECTRICAL WIRING/CONNECTOR:**
- **RED** = +INPUT (EXC)
- **BLACK** = -INPUT (EXC)
- **GREEN** = +OUTPUT
- **WHITE** = -OUTPUT

This Calibration was performed using Instruments and Standards that are traceable to the United States National Institute of Standards Technology.

**S/N**

<table>
<thead>
<tr>
<th>Description</th>
<th>Range</th>
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<td>UUT Unit Under Test</td>
<td>C-2412</td>
<td>C-2412</td>
</tr>
</tbody>
</table>

**Q.A. Representative:** Ed Sackman Jr

**Date:** 12/8/2015

This transducer is tested to & meets published specifications. After final calibration our products are stored in a controlled stock room & considered in bonded storage. Depending on environment & severity of use factory calibration is recommended every one to three years after initial service installation date.

**COMMENTS:** FINAL TEST.

Omega Engineering Inc., One Omega Drive, Stamford, CT 06907
http://www.omega.com email: info@omega.com phone (800) 826-6342
**OMEGA ENGINEERING INC.**

LOAD CELL
FINAL CALIBRATION

0.00 - 500.00 LBS
Excitation 10.000 Vdc

<table>
<thead>
<tr>
<th>Force (LBS)</th>
<th>Unit Data (mVdc)</th>
<th>Normalized Data</th>
</tr>
</thead>
<tbody>
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<td>0.050</td>
<td>0.000</td>
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<td>250.00</td>
<td>9.419</td>
<td>9.369</td>
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<tr>
<td>500.00</td>
<td>18.891</td>
<td>18.841</td>
</tr>
<tr>
<td>250.00</td>
<td>9.447</td>
<td>9.397</td>
</tr>
<tr>
<td>0.00</td>
<td>0.052</td>
<td>0.002</td>
</tr>
</tbody>
</table>

Balance: 0.050 mVdc
Sensitivity: 18.841 mVdc
In Resist: 378.7 Ohms
Out Resist: 353.10 Ohms
59K Shunt: 14.952 mVdc

Change at 0.00 LBS (-INPUT to +OUTPUT)

Calibration Factors:
Sensitivity = 1.884 mV/V
59K Shunt = 1.495 mV/V

**ELECTRICAL LEAKAGE:** PASS
**ELECTRICAL WIRING/CONNECTOR:**
RED = +INPUT (EXC)
BLACK = -INPUT (EXC)
GRAY = +OUTPUT
WHITE = -OUTPUT

This Calibration was performed using instruments and standards that are traceable to the United States National Institute of Standards Technology.

<table>
<thead>
<tr>
<th>S/N</th>
<th>Description</th>
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<td>HK34401A</td>
<td>UUT</td>
<td>Unit Under Test</td>
<td>C-2412</td>
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</tbody>
</table>

Q.A. Representative: Ed Sackman Jr
Date: 12/8/2015

This transducer is tested to & meets published specifications. After final calibration our products are stored in a controlled stock room & considered in bonded storage. Depending on environment & severity of use factory calibration is recommended every one to three years after initial service installation date.

**COMMENTS:** FINAL TEST.

Omega Engineering Inc., One Omega Drive, Stamford, CT 06907
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OMEGA ENGINEERING INC.

LOAD CELL
FINAL CALIBRATION

0.00 - 500.00 LBS
Excitation 10.000 Vdc

Job: WHE5315
Model: LC304-500
Date: 12/8/2015
Calibrated: 0.00 - 500.00 LBS

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<td>10.562</td>
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<td>500.00</td>
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<td>21.101</td>
</tr>
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<td>250.00</td>
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<tr>
<td>0.00</td>
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Balance 0.053 mVdc
Sensitivity 21.101 mVdc
In Resist 378.90 Ohms
Out Resist 352.60 Ohms
59K Shunt 14.887 mVdc

Change at 0.00 LBS (-INPUT to -OUTPUT)

Calibration Factors:
Sensitivity = 2.110 mV/V
59K Shunt = 1.689 mV/V

ELECTRICAL LEAKAGE: PASS
ELECTRICAL WIRING/CONNECTOR:
RED = +INPUT (EXC)
BLACK = -INPUT (EXC)
GREEN = -OUTPUT
WHITE = +OUTPUT

This Calibration was performed using Instruments and Standards that are traceable to the United States National Institute of Standards Technology.

S/N 10001b Reference STD 0 - 500.00 LBS
HP34401A DMM Unit Under Test C-2692 C-2692
314644085K C-2412

Q.A. Representative: Ed Suchman Jr
Date: 12/8/2015

This transducer is tested to & meets published specifications. After final calibration our products are stored in a controlled stock room & considered in bonded storage. Depending on environment & severity of use factory calibration is recommended every one to three years after initial service installation date.

COMMENTS: FINAL TEST.

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LOAD CELL
FINAL CALIBRATION
0.00 - 500.00 LBS
Excitation 10,000 Vdc

Job: WHM5315
Model: LC304-500
Date: 12/8/2015
Calibrated: 0.00 - 500.00 LBS

Serial: 342030
Tested By: KJ
Temperature Range: +60 to +160 F
Specfile: LC304

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<td>10.729</td>
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<td>0.00</td>
<td>0.284</td>
<td>0.002</td>
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Balance = 0.286 mVdc
Sensitivity = 21.498 mVdc
In Resist = 377.5 Ohms
Out Resist = 353.00 Ohms
59K Shunt = 15.004 mVdc
Change at 0.00 LBS (-INPUT to -OUTPUT)

Calibration Factors:
Sensitivity = 2.150 mV/V
59K Shunt = 1.500 mV/V

ELECTRICAL LEAKAGE: PASS
ELECTRICAL WIRING/CONNECTOR: RED = -INPUT (EXC)
BLACK = -INPUT (EXC)
GREEN = -OUTPUT
WHITE = -OUTPUT

This Calibration was performed using Instruments and Standards that are traceable to the United States National Institute of Standards Technology.

S/N Description Range Reference Cal Cert
10001b Reference STD 0 - 500.00 LBS C-2652 C-2652
3146A40859 HP34401A CMK UTU Unit Under Test C-2412 C-2412

Q.A. Representative: El Saucedo Jr
Date: 12/8/2015

This transducer is tested to & meets published specifications. After final calibration our products are stored in a controlled stock room & considered in bonded storage. Depending on environment & severity of use factory calibration is recommended every one to three years after initial service installation date.

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OMEGA ENGINEERING INC.

LOAD CELL
FINAL CALIBRATION

0.00 - 500.00 LBS
Excitation 10.000 Vdc

Job: WMM585
Model: LC304-500
Date: 12/8/2015
Calibrated: 0.00 - 500.00 LBS

<table>
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<td>9.809</td>
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<tr>
<td>0.00</td>
<td>- 0.017</td>
<td>0.001</td>
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</tbody>
</table>

Balance - 0.018 mVdc
Sensitivity 19.679 mVdc
In Resist 377.70 Ohms
Out Resist 352.00 Ohms
59K Shunt 14.857 mVdc

Change at 0.00 LBS (-INPUT to -OUTPUT)

Calibration Factors:
Sensitivity = 1.968 mV/V  59K Shunt = 1.486 mV/V

ELECTRICAL LEAKAGE: PASS
ELECTRICAL WIRING/CONNECTOR: RED = +INPUT (EXC)
                             BLACK = -INPUT (EXC)
                             GREEN = +OUTPUT
                             WHITE = -OUTPUT

This Calibration was performed using Instruments and Standards that are traceable to the United States National Institute of Standards Technology.

S/N Description | Range | Reference | Cal Cert
1000lb Reference Std 0 - 500.00 LBS | C-2692  | C-2692
3146A40859 H034401A DMM Unit Under Test | C-2412  | C-2412

Q.A. Representative: Ed Buchanan Jr  Date: 12/8/2015

This transducer is tested to & meets published specifications. After final calibration our products are stored in a controlled stock room & considered in bonded storage. Depending on environment & severity of use factory calibration is recommended every one to three years after initial service installation date.

COMMENTS: FINAL TEST.

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OMEGA ENGINEERING INC.

LOAD CELL
FINAL CALIBRATION

0.00 - 500.00 LBS
Excitation 10,000 Vdc

Job: WHM5315
Model: LC304-500
Date: 12/8/2015

Calibrated: 0.00 - 500.00 LBS

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<th>Normalized Data</th>
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<td>10.396</td>
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<tr>
<td>0.00</td>
<td>0.147</td>
<td>0.001</td>
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</table>

Balance: 0.146 mVdc
Sensitivity: 20.850 mVdc
In Resist: 377.40 Ohms
Out Resist: 352.80 Ohms
59K Shunt: 14.933 mVdc

Change at 0.00 LBS (-INPUT to +OUTPUT)

Calibration Factors:
Sensitivity = 2.085 mV/V
59K Shunt = 1.493 mV/V

ELECTRICAL LEAKAGE: PASS
ELECTRICAL WIRING/CONNECTOR: RED = +INPUT (EXC)
BLACK = -INPUT (EXC)
GREEN = +OUTPUT
WHITE = -OUTPUT

This Calibration was performed using Instruments and Standards that are traceable to the United States National Institute of Standards Technology.

S/N: 10004
Reference STD 0 - 500.00 LBS
40400A DMM UUT Unit Under Test

Q.A. Representative: Ed Geschke Jr
Date: 12/8/2015

This transducer is tested to & meets published specifications. After final calibration our products are stored in a controlled stock room & considered in bonded storage. Depending on environment & severity of use factory calibration is recommended every one to three years after initial service installation date.

COMMENTS: FINAL TEST.

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OMEGA ENGINEERING INC.

LOAD CELL
FINAL CALIBRATION

0.00 - 500.00 LBS
Excitation: 10.000 Vdc

Job: WHM5315
Model: LC304-500
Date: 12/8/2015
Calibrated: 0.00 - 500.00 LBS

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<td>0.00</td>
<td>0.101</td>
<td>0.303</td>
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Balance: 0.098 mVdc
Sensitivity: 18.300 mVdc
In. Resist: 379.10 Ohms
Out Resist: 352.50 Ohms
59K Shunt: 14.911 mVdc
Change at 0.00 LBS (-INPUT to -OUTPUT)

Calibration Factors:
Sensitivity = 1.830 mV/V
59K Shunt = 1.491 mV/V

ELECTRICAL LEAKAGE: PASS
ELECTRICAL WIRING/CONNECTOR:
RED = +INPUT (EXC)
BLACK = -INPUT (EXC)
GREEN = +OUTPUT
WHITE = -OUTPUT

This Calibration was performed using Instruments and Standards that are traceable to the United States National Institute of Standards Technology.

S/N Description Range Reference Cal Cert
10001b Reference STD 0 - 500.00 LBS C-2692 C-2692
3146A40859 HP34401A DMK UUT Unit Under Test C-2412 C-2412

Q.A. Representative: Ed Eckman Jr
Date: 12/8/2015

This transducer is tested to & meets published specifications. After final calibration our products are stored in a controlled stock room & considered in bonded storage. Depending on environment & severity of use factory calibration is recommended every one to three years after initial service installation date.

COMMENTS: FINAL TEST.

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OMEGA ENGINEERING INC.

LOAD CELL
FINAL CALIBRATION

0.00 - 500.00 LBS
Excitation 10.00 DC

Job: WHM5315
Model: LC304-500
Date: 12/8/2015

Calibrated: 0.00 - 500.00 LBS

Serial: 342042
Tested By: ED
Temperature Range: +60 to +160 F
Specifice: LC304

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<tr>
<td>0.00</td>
<td>0.045</td>
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Balance 0.045 mVdc
Sensitivity 21.609 mVdc
In Resist 377.80 Ohms
Out Resist 353.10 Ohms
59K Shunt 14.686 mVdc

Change at 0.00 LBS (+INPUT to -OUTPUT)

Calibration Factors:
Sensitivity = 2.161 mV/V
59K Shunt = 1.987 mV/V

ELECTRICAL LEAKAGE: PASS
ELECTRICAL WIRING/CONNECTOR: RED = +INPUT (EXC)
BLACK = -INPUT (EXC)
GREEN = -OUTPUT
WHITE = -OUTPUT

This Calibration was performed using Instruments and Standards that are traceable to the United States National Institute of Standards Technology.

S/N 1003Lb Reference STD 0 - 500.00 LBS
1003Lb Reference STD 0 - 500.00 LBS
1003Lb Reference STD 0 - 500.00 LBS

Cal Cert C-2692 C-2692
C-2412 C-2412

Q.A. Representative: Ed Shearman Jr
Date: 12/8/2015

This transducer is tested to & meets published specifications. After final calibration our products are stored in a controlled stock room & considered in bonded storage. Depending on environment & severity of use factory calibration is recommended every one to three years after initial service installation date.

COMMENTS: FINAL TEST.

Omega Engineering Inc., One Omega Drive, Stamford, CT 06907
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OMEGA ENGINEERING INC.

LOAD CELL
FINAL CALIBRATION

0.00 - 500.00 LBS
Excitation 10.000 vdc

Job: WHM4986
Model: LC304-500
Date: 11/17/2015
Calibrated: 0.00 - 500.00 LBS

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Balance: - 0.082 mVdc
Sensitivity: 20.549 mVdc
In Resist: 377.00 Ohms
Out Resist: 352.00 Ohms
59K Shunt: 14.849 mVdc

Change at 0.00 LBS (-INPUT to -OUTPUT)

Calibration Factors:
Sensitivity = 2.055 mV/V
59K Shunt = 1.485 mV/V

ELECTRICAL LEAKAGE: PASS
ELECTRICAL WIRING/CONNECTOR: RED = +INPUT (EXC), BLACK = -INPUT (EXC), GREEN = +OUTPUT, WHITE = -OUTPUT

This Calibration was performed using Instruments and Standards that are traceable to the United States National Institute of Standards Technology.

S/N Description Reference Cal Cert
1001 Ref. STD 0 - 300.00 LBS C-2692 C-2692
3146A40859 HD34401A DMM UNIT Under Test C-2412 C-2412

Q.A. Representative: William Hackett Date: 11/17/2015

This transducer is tested to & meets published specifications. After final calibration our products are stored in a controlled stock room & considered in bonded storage. Depending on environment & severity of use factory calibration is recommended every one to three years after initial service instalation date.

COMMENTS: FINAL TEST.

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**Omega Engineering Inc.**

**Load Cell**

**Final Calibration**

0.00 - 500.00 LBS

Excitation 10,000 Vdc

**Job:** WHM5315  
**Model:** LC304-500  
**Date:** 12/8/2015

Calibrated: 0.00 - 500.00 LBS  
**Specfile:** LC304

<table>
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<td>250.00</td>
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<td>0.00</td>
<td>0.014</td>
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Balance: - 0.007 mVdc  
Sensitivity: 20.689 mVdc  
In Resist: 378.10 Ohms  
Out Resist: 352.70 Ohms  
59K Shunt: 14.827 mVdc  
Change at 0.00 LBS (-INPUT to -OUTPUT)

**Calibration Factors:**

Sensitivity = 2,069 mV/V  
59K Shunt = 1.483 mV/V

**Electrical Leakage:** PASS  
**Electrical Wiring/Connector:**  
RED = +INPUT (EXC)  
BLACK = -INPUT (EXC)  
GREEN = +OUTPUT  
WHITE = -OUTPUT

This Calibration was performed using Instruments and Standards that are traceable to the United States National Institute of Standards Technology.  

<table>
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<td>Unit Under Test</td>
<td>C-2412</td>
<td>C-2412</td>
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Q.A. Representative: Ed Buchanan Jr  
Date: 12/8/2015

This transducer is tested to & meets published specifications. After final calibration our products are stored in a controlled stock room & considered in bonded storage. Depending on environment & severity of use factory calibration is recommended every one to three years after initial service installation date.  
**Comments:** FINAL TEST.

Omega Engineering Inc., One Omega Drive, Stamford, CT 06907  
http://www.omega.com  email: info@omega.com  phone (800) 026-6342
APPENDIX D

ARAMIS
Throughout the first field-testing season, a variety of LED light configurations were tried in an attempt to minimize glare while maximizing light on the Plexiglas. Researchers started with “puck” type lights that could be tilted in different directions, but determined that more light was needed. LED light strips that could be turned on and off with a remote control were then added, reducing the amount of time that lights in the box were on and therefore reducing battery needs. However, these still created a slight glare that caused analysis problems in Aramis. Finally, an additional LED tube light setup was added. Experimentation with lighting setups continued into Year 2, when an LED spotlight was added.

To create visual points that Aramis could track, paint was sprayed onto the wall with spray bottles. Occasionally due to spray bottles freezing, the paint was flicked from the spray tube end onto the snow wall. Toward the end of the study, a stiff-bristled brush was dipped in paint, then its bristles flicked toward the wall to create a speckled pattern. Once paint was applied to the snow wall, it typically froze quickly so Plexiglas could be placed against it without smearing the paint.

During the last trip for pass-by testing, temperatures in the park were warmer and snow in the top several centimeters of the road had liquid in it. This meant that the paint mixed with the melted water and turned the top centimeters of snow into a uniform grey color rather than retaining the black speckles. This rendered subsurface videos taken in these conditions unusable since Aramis could not pick out points in the grey area.

Processing the images using Aramis was accomplished back at Montana State University. This involved importing all of the images from a certain pass into Aramis, having Aramis calculate a start point which it could track during the entire series, having Aramis calculate and analyze all strain, and then viewing different types of strain that Aramis calculated. For most of the videos processed, researchers planned to look at vertical (Y) strain, horizontal (X) strain, and shear angle. For some videos that Aramis was not reading properly, brightness and/or contrast were adjusted on the images.
APPENDIX E

ACCELEROMETERS
Many researchers both within the field of engineering and in other fields make use of accelerometers. Common applications include measurements of seismic activity for use by structural engineers and, more recently, measurements of physical activity for use by laypeople in activity-trackers such as FitBits and by researchers conglomerating and analyzing this data.

Accelerometers yield data on acceleration, typically expressed in gs. Integration of acceleration readings gives velocity, and a second integration gives displacement. However, this procedure results in velocity and displacement numbers that contain an implausible drifting throughout the duration of the measurement (Yang and others, 2006). There are several identified reasons contributing to this drift (Yang and others, 2006), and researchers have worked to better understand these factors (Moschas and others, 2015). In 2008, Stiros published a study on the propagation of error in these integrations. Yang and others (2006) provides an overview of these methods, and proposes a data correction procedure involving a correction curve (using a least-squares method to find the equation for the curve) and a windowed filter that corrects for long-period oscillations. Researchers often use this type of progression (least squares and then filtering) to remove noise from their data (Zhang and others, 2016), but there does not appear to be one predominant procedure for removing noise. For the current research, the method proposed by Yang et. al seems to be appropriate and effective. The method of data filtering used in this project follows the steps proposed in Yang and others (2006), except that no Fourier Transform was applied in this processing.

Data from accelerometers was collected using a cDAQ and LabView, and then processed using MATLAB. LabView created data files with in the form of large tables, with each column listing readings for one accelerometer. The accelerometer channel is listed on the top of the column and identifies which accelerometer’s readings are listed. Prior to testing, voltage readings corresponding to baseline, 1-g (gravity) readings were obtained for each axis of each accelerometer. These voltages were then used to find the gs/Volt conversion for each axis of each accelerometer.

For each day of testing, a “conversion” file was created in which the location (depth in the road; center or side of the track) of each accelerometer during testing was identified using the name of the channel on which the accelerometer was read. This file listed the conversion factors associated with each accel axis.

The MATLAB code written to process the accelerometer files imports the raw data from LabView and the conversion file for the particular testing day. MATLAB finds the correct conversion factor for each channel and associates that channel’s data with the accelerometer’s location during testing. The conversion factor is used to convert all raw voltage readings into gs. MATLAB then displays a graph of this so that the user may select approximately where the acceleration event begins and ends in the data. Points outside of this selected window are assumed to represent zero baseline. From this point;
an average of these baseline values is determined for each accelerometer and subtracted out from the other readings for that particular accelerometer. This gives the minimally-processed accelerometer readings. A filter is then applied to convert all accelerometer readings with an absolute value below 0.02 to zero. This is intended to cut down on noise seen in the accelerometer data.

The acceleration values are numerically integrated to give approximate velocity values. MATLAB then find points before the beginning and after the end of the acceleration event by looking for a certain number of zeros before and after the event. The readings between these beginning and end values then become the velocity values that need to be corrected for drift. The velocities prior to and after the event are calculated, and the slope of velocity drift based on the difference between these velocities and the time over which the event occurs is calculated. Then these slopes are subtracted out from the accelerometer readings within the event window, giving accelerometer readings that have been corrected for the common problem of drift. The MATLAB code then numerically integrates these corrected numbers once to find velocity and again to find displacement.

Corrected acceleration, velocity, and displacement data is all output into both excel sheets and graphs, and in this form data can be analyzed for insight into vehicle impacts.
MATLAB code used for accelerometer data, this code moves through accelerometer data and converts voltage to G’s of acceleration and then a numerical integration technique solves for velocity and displacement values.

```matlab
%% File to go through accelerometer files and convert
% voltages to gs, then integrate for velocity and displacement.
clear
close all
clc

%% Select files to be used in processing (accel data, conversion file)
% and pull in raw data.

% Get file with conversion numbers specific to the accels, info on
% accel location/orientation for the particular test.
ConversionFile = uigetfile('*xlsx','Select conversion file:');
B = readtable(ConversionFile);
C = table2struct(B);

% Select file to process.
currentFile = uigetfile('*xlsx','Select file to process:');
currentFileName = currentFile(1:end-5);

% Get data from Excel worksheet (tab 2)
[num,txt,raw] = xlsread(currentFile, 'Measured Data');

%% Set up header information layout to be used in processed output.
% Make cell for channel names.
Nms = {};
% Make double for conversion values used.
ConvRates = [];
% Make cell for orientation of accels.
Orients = {};
% Make cell for depth of accels.
Depths = {};
% Make cell for position of accels.
Positions = {};
% Make double for row in graph matrix.
PlotRows = [];
% Make double for column in graph matrix.
PlotCols = [];
% Make cell for positive direction description
PosDirs = {};

%% Loop through all columns and make big array with the pertinent raw
data.

% Decide on Number of Columns Needed (get rid of NAs by making their
% conversion number equal to 0).
L = 0;
for i = 1:length(txt)
% Find the conversion factor for the channel specified in the column name.
    Conv = 0;
    for j = 1:length(C)
        if strcmp(C(j).Name, txt(i))
            Conv = C(j).Conversion;
        end
    end
% Add a column for any rows with a non-zero conversion factor.
    if Conv ~= 0
        L = L+1;
    end
end

% Set up a matrix for all of the accel measurements converted to gs.
Gvals = [];

% Go through each column of raw data to find appropriate header information and, find acceleration data, and convert acceleration to gs.
for i = 1:length(txt)
    Conv = 0;
    % Find the correct header information for the channel, if not "NA".
    for j = 1:length(C)
        if strcmp(C(j).Name, txt(i))
            Nm = C(j).Name;
            Conv = C(j).Conversion;
            Orient = C(j).Orientation;
            Depth = C(j).Depth;
            Position = C(j).Position;
            PlotRow = C(j).PlotRow;
            PlotCol = C(j).PlotCol;
            PosDir = C(j).PosPoints;
        end
    end
    % Get the raw readings from the column and convert them to gs.
    if Conv ~= 0
        % Make vector of the column's raw values
        colvals = num(:,i);
        % Make a new vector of the column's converted values
        colvalsGs = colvals*Conv;
        % Add the header values for this column to the collected values.
        Nms = [Nms {Nm}];
        ConvRates = [ConvRates Conv];
        Orients = [Orients {Orient}];
        Depths = [Depths {Depth}];
        Positions = [Positions {Position}];
        Gvals = [Gvals colvalsGs];
        PlotRows = [PlotRows PlotRow];
PlotCols = [PlotCols PlotCol];
PosDirs = [PosDirs {PosDir}];
% Plot the current values
scatter(1:length(colvalsGs),abs(colvalsGs))
hold on
end
end
hold off

% Ask user where to trim this file.
begPrompt = 'Please enter the beginning trim value (at least 1): ';
begin = input(begPrompt);
endPrompt = 'Please enter the ending trim value: ';
ending = input(endPrompt);

% Number of points in trimmed data
Trimmed = ending-begin+1;

% And make a vector of time values in seconds:
Tvals = zeros(Trimmed,1);
for i = 1:Trimmed
    Tvals(i) = i;
end
Tvals = Tvals/5000;

% Make a matrix for dT values (for t(j)-t(j-1))
dTs = zeros(length(Tvals),1);
for i = 2:length(dTs)
    dTs(i) = Tvals(i)-Tvals(i-1);
end

%% Subtract Baseline out from Acceleration

% Prep for the final values
GvalsInt = zeros(Trimmed,L);
GvalsFin = zeros(Trimmed,L);

% Another for loop through columns to subtract out the baseline accel % readings
for i = 1:L

% Find average of points outside of trim area.
preData = Gvals(1:begin,i);
postData = Gvals(ending:length(Gvals),i);
allnonData = [preData; postData];
Baseline = mean(allnonData);

% Extract the values within the trim area
GvalsDataRaw = Gvals(begin:ending,i);

% Subtract out the baseline as determined by the average
GvalsData = GvalsDataRaw - Baseline;

% Add converted, normalized data into final matrix
GvalsInt(1:length(GvalsInt),i) = GvalsData;
for n = 1:length(GvalsData)
    if abs(GvalsInt(n,i)) <= 0.02
        GvalsInt(n,i) = 0;
    end
end
end

%% Find Initial Velocity Values from Acceleration

% Find the average acceleration value between i and i-1, to use for
% numeric integration
SumGi = zeros(size(GvalsInt));
SumGi(2:size(SumGi,1), :) = GvalsInt(2:size(GvalsInt,1),:)... +GvalsInt(1:size(GvalsInt,1)-1,:);
AvgGi = SumGi/2;

% Multiply each row by 9.81 and the appropriate dt to get change in
% velocity (m/s) from the previous point
VvalsChgi = zeros(size(AvgGi));
for i = 1:size(VvalsChgi,1)
    VvalsChgi(i,:) = AvgGi(i,:)*dTs(i);
end

% Use the change in velocity numbers to get the velocity at each time
VvalsUncor = zeros(size(AvgGi));
for i = 2:size(VvalsUncor,1)
    VvalsUncor(i,:) = VvalsUncor(i-1,:) + VvalsChgi(i,:);
end

% Find section that will need velocity correction based on number zeros
% desired.
% How many zeros do you want to find to decide that it's the start of
% the real acceleration?
numzers = 200;
% Make a matrix to store the beginning and end filter numbers for each
% channel.
FixRg = zeros(2,L);
for i = 1:L
    % Find the beginning and end of the section that will need correcting
    % (last 0 before action and first 0 after action)
    for n = (numzers+1):length(GvalsInt)
if (GvalsInt(n,i)~=0) && (isequal(GvalsInt(n-numzers:n-1,i),zeros(numzers,1)))
    FixRg(1,i) = n-1;
    break
end

if FixRg(1,i) == 0
    FixRg(1,i) = 1;
end

for n = (length(GvalsInt)-numzers-1):-1:1
    if (GvalsInt(n,i)~=0) && (isequal(GvalsInt(n+1:n+numzers,i),zeros(numzers,1)))
        FixRg(2,i) = n+1;
        break
    end
end

if FixRg(2,i) == 0
    FixRg(2,i) = length(GvalsInt);
end

end

% Find the slope of drift of the velocity (in G*s/s), using the
% velocity at the
% beginning and end of the acceleration range, using the range found
% above.

VelChgInRg = zeros(1,L);
Slopes = zeros(1,L);
for i = 1:L
    VelChgInRg(1,i) = VvalsUncor(FixRg(2,i),i) - VvalsUncor(FixRg(1,i),i);
    Slopes(1,i) = VelChgInRg(1,i)/(Tvals(FixRg(2,i)) - Tvals(FixRg(1,i)));
end

% Now subtract these slopes out from the accelerations in the relevant
% range to get the final accelerations.

for i = 1:L
    for n = 1:length(GvalsData)
        if n <= FixRg(1,i)
            GvalsFin(n,i) = GvalsInt(n,i);
        elseif n >= FixRg(2,i)
            GvalsFin(n,i) = GvalsInt(n,i);
        else
            GvalsFin(n,i) = GvalsInt(n,i) - Slopes(1,i);
        end
    end
end
% Then Continue on to Graph Accel and Integrate

for  i = 1:L

% Plot the current values on a big sheet with room for all accels
Rws = max(PlotRows); CIs = max(PlotCols); Posit = (PlotRows(i)-1)*Cls+PlotCols(i);
subplot(Rws,Cls,Posit)
plot(Tvals, GvalsFin(:,i))
axis([0 inf -0.1 0.1])
xlabel('Time, seconds')
ylabel('Acceleration, Gs')
set(gca,'Fontsize',7)
PlotTitle1 = sprintf('%s; %s',currentFileName,char(Orients(i)));
PlotTitle2 = sprintf('%s cm Depth, Track %s',char(Depths(i)),
                      char(Positions(i)));
FinalTitle = {PlotTitle1,PlotTitle2};
title(FinalTitle)
end

PlotName = sprintf('%sAccelPlots.jpg', currentFileName);
set(gcf,'PaperUnits','Inches');
saveas(gcf, PlotName);
hold off

write acceleration data to Excel
OutFile = sprintf('%sProc', currentFileName);
sheet = 'AccelSheet';

% Make a Legend Column and put into spreadsheet
Legend = {{'Channel'}; {'ConversionRate'}; {'Depth'};
          {'Orientation'};...
          {'Position'}; {'PositivePoints'}};
xlRange = 'A1';
xlswrite(OutFile,Legend,sheet,xlRange);

% Compile all header info and put into spreadsheet
Header = [Nms; num2cell(ConvRates); Depths; Orients; Positions;
          PosDirs];
xlRange = 'B1';
xlswrite(OutFile,Header,sheet,xlRange);

% Then finally the values
xlRange = 'B7';
xlswrite(OutFile,GvalsFin,sheet,xlRange);

%% VELOCITY
% Find the average acceleration value between i and i-1, to use for
% numeric integration
SumG = zeros(size(GvalsFin));
SumG(2:size(SumG,1), :) = GvalsFin(2:size(GvalsFin,1),:).
+GvalsFin(1:size(GvalsFin,1)-1,:);
AvgG = SumG/2;

% Multiply each row by 9.81 and the appropriate dt to get change in 
% velocity (m/s) from the previous point 
VvalsChg = zeros(size(AvgG));
for i = 1:size(VvalsChg,1)
    VvalsChg(i,:) = AvgG(i,:)*9.81*dt(i);
end

% Use the change in velocity numbers to get the velocity at each time 
VvalsFin = zeros(size(AvgG));
for i = 2:size(VvalsFin,1)
    VvalsFin(i,:) = VvalsFin(i-1,:)+VvalsChg(i,:);
end

% Another for loop through columns to plot them 
for i = 1:size(VvalsFin,2)

% Plot the current values 
    Rws = max(PlotRows);
    Cls = max(PlotCols);
    Posit = (PlotRows(i)-1)*Cls+PlotCols(i);
    subplot(Rws,Cls,Posit)
    plot(Tvals, VvalsFin(:,i))
    axis([0 inf -inf inf])
    xlabel('Time, seconds')
    ylabel('Velocity, m/s')
    set(gca, 'Fontsize',7)
    PlotTitle1 = sprintf('%s; %s',currentFileName,char(Orients(i)));
    PlotTitle2 = sprintf('%s cm Depth, Track %s',... 
                       char(Depths(i)),char(Positions(i)));
    FinalTitle = {PlotTitle1,PlotTitle2};
title(FinalTitle)
    hold on
end

PlotName = sprintf('%sVelPlots.jpg', currentFileName);
% PDF attempt: PdfName = sprintf('%sPlots.pdf', currentFileName);
set(gcf, 'PaperUnits', 'Inches');
set(gcf, 'PaperPosition', [0 0 17 11]);
saveas(gcf, PlotName);
% Pdf Attempt: print(PdfName,'-dpdf','-fillpage');
hold off
close(gcf)

% Write velocity data to Excel
sheet = 'VelSheet';

% Put legend column into spreadsheet
xlRange = 'A1';
xlswrite(OutFile,Legend,sheet,xlRange);

% Put header information into spreadsheet
xlRange = 'B1';
xlswrite(OutFile,Header,sheet,xlRange);

% Then finally the values
xlRange = 'B7';
xlswrite(OutFile,VvalsFin,sheet,xlRange);

%% DISPLACEMENT

% Make a matrix for avg velocity values between i and i-1, to use for % numeric integration
SumV = zeros(size(VvalsFin));
SumV(2:size(SumV,1), :) = VvalsFin(2:size(VvalsFin,1),:);...
  +VvalsFin(1:size(VvalsFin,1)-1,:);
AvgV = SumV/2;

% Prep a matrix of values for the change in displ., then the final displ.
DvalsChg = zeros(size(VvalsFin));

% Make a vector to hold the final displacement for each channel
Dends = [];

% Multiply each row by the appropriate dt to get change in displ, and then % 1000 to make the displacement unit millimeters
for i = 1:size(DvalsChg,1)
  DvalsChg(i,1:size(DvalsChg,2)) = AvgV(i,:)*dTs(i)*1000;
end

% Use the change in disp numbers to get the disp at each time
DvalsFin = zeros(size(AvgV));
for i = 2:size(DvalsFin,1)
  DvalsFin(i,:) = DvalsFin(i-1,:)+DvalsChg(i,:);
end

for i = 1:size(DvalsFin,2)
  Dend = DvalsFin(length(DvalsFin),i);
  Dends = [Dends Dend];
end

% Another for loop through columns
for i = 1:size(DvalsFin,2)

% Plot the current values
  Rws = max(PlotRows);
 Cls = max(PlotCols);
  Posit = (PlotRows(i)-1)*Cls+PlotCols(i);
subplot(Rws,Cls,Posit)
plot(Tvals, DvalsFin(:,i))
axis([0 inf -inf inf])
xlabel('Time, seconds')
ylabel('Displacement, mm')
set(gca, 'Fontsize',7)

PlotTitle1 = sprintf('%s; %s',currentFileName,char(Orients(i)));
PlotTitle2 = sprintf('%s cm Depth, Track %s',char(Depths(i)),... char(Positions(i)));
FinalTitle = {PlotTitle1,PlotTitle2};
title(FinalTitle)
end

PlotName = sprintf('%sDispPlots.jpg', currentFileName);
% PDF attempt: PdfName = sprintf('%sPlots.pdf', currentFileName);
set(gcf, 'PaperUnits', 'Inches');
set(gcf, 'PaperPosition', [0 0 17 11]);
saveas(gcf, PlotName);
% Pdf Attempt: print(PdfName,'-dpdf','-fillpage');
hold off

% Write displacement data to Excel
sheet = 'DispSheet';

% Put legend column into spreadsheet
xlRange = 'A1';
xlswrite(OutFile,Legend,sheet,xlRange);

% Put header information into spreadsheet
xlRange = 'B1';
xlswrite(OutFile,Header,sheet,xlRange);

% Then finally the values
xlRange = 'B7';
xlswrite(OutFile,DvalsFin,sheet,xlRange);

%% Summary Data

%% Summarize Acceleration Data

% Max/min
Amax = max(GvalsFin);
Amin = min(GvalsFin);

% Switches from Pos to Neg
Aswitch = zeros(1,L);
for i = 1:L
  for n = 2:length(Tvals)
    if GvalsFin(n-1,i)<0 && GvalsFin(n,i)>=0
      Aswitch(1,i) = Aswitch(1,i)+1;
    end
  end
end
elseif GvalsFin(n-1,i)>=0 && GvalsFin(n,i)<0
    Aswitch(1,i) = Aswitch(1,i)+1;
end
end
end

%%% Summarize Velocity Data

% Max/Min
Vmax = max(VvalsFin);
Vmin = min(VvalsFin);

% Switches from Pos to Neg
Vswitch = zeros(1,L);
for i = 1:L
    for n = 2:length(Tvals)
        if VvalsFin(n-1,i)<0 && VvalsFin(n,i)>=0
            Vswitch(1,i) = Vswitch(1,i)+1;
        elseif VvalsFin(n-1,i)>=0 && VvalsFin(n,i)<0
            Vswitch(1,i) = Vswitch(1,i)+1;
        end
    end
end

%%% Summarize Velocity Data

% Max/Min
Dmax = max(DvalsFin);
Dmin = min(DvalsFin);

% Switches from Pos to Neg
Dswitch = zeros(1,L);
for i = 1:L
    for n = 2:length(Tvals)
        if DvalsFin(n-1,i)<0 && DvalsFin(n,i)>=0
            Dswitch(1,i) = Dswitch(1,i)+1;
        elseif DvalsFin(n-1,i)>=0 && DvalsFin(n,i)<0
            Dswitch(1,i) = Dswitch(1,i)+1;
        end
    end
end

Legend2 = [{'AccelMax'}; {'AccelMin'}; {'AccelSwitch'}; {'VelMax'};...
          {'VelMin'}; {'VelSwitch'}; {'DispMax'}; {'DispMin'};
          {'DispSwitch'};...
          {'DispFinal'}];

SummDat = [Amax; Amin; Aswitch; Vmax; Vmin; Vswitch; Dmax; Dmin;...
           Dswitch; Dends];

% Write displacement data to Excel
sheet = 'Sheet1';

% Put legend column into spreadsheet
xlRange = 'A1';
xlswrite(OutFile,Legend,sheet,xlRange);

% Put header information into spreadsheet
xlRange = 'B1';
xlswrite(OutFile,Header,sheet,xlRange);

% Then legend 2
xlRange = 'A7';
xlswrite(OutFile,Legend2,sheet,xlRange);

% Then finally the values
xlRange = 'B7';
xlswrite(OutFile,SummDat,sheet,xlRange);
Accelerometer data sheets, these sheets have all the used accelerometers’ specifications.
FEATURES
3-axis sensing
Small, low profile package
4 mm x 4 mm x 1.45 mm LF CSP
Low power: 350 μA typical
Single-supply operation: 1.8 V to 3.6 V
10,000 g shock survival
Excellent temperature stability
Bandwidth adjustment with a single capacitor per axis
RoHS/WEEE lead-free compliant

APPLICATIONS
Cost-sensitive, low power, motion- and tilt-sensing applications
Mobile devices
Gaming systems
Disk drive protection
Image stabilization
Sports and health devices

GENERAL DESCRIPTION
The ADXL327 is a small, low power, complete 3-axis accelerometer with signal conditioned voltage outputs. The product measures acceleration with a minimum full-scale range of ±2 g. It can measure the static acceleration of gravity in tilt-sensing applications, as well as dynamic acceleration, resulting from motion, shock, or vibration.

The user selects the bandwidth of the accelerometer using the C1, C2, and C3 capacitors at the XOUT, YOUT, and ZOUT pins. Bandwidths can be selected to suit the application with a range of 0.5 Hz to 1600 Hz for X and Y axes and a range of 0.5 Hz to 550 Hz for the Z axis.

The ADXL327 is available in a small, low profile, 4 mm x 4 mm x 1.45 mm, 16-lead, plastic lead frame chip scale package (LF CSP_1Q).

FUNCTIONAL BLOCK DIAGRAM

Figure 1.
ADXL327 PRODUCT PAGE QUICK LINKS

Last Content Update: 02/23/2017

COMPARABLE PARTS
View a parametric search of comparable parts.

EVALUATION KITS
- ADXL327 Breakout Board

DOCUMENTATION
Application Notes
- AN-1057: Using an Accelerometer for Indination Sensing
- AN-688: Phase and Frequency Response of IMEMS Accelerometers and Gyros

Data Sheet
- ADXL327: Small, Low Power, 3-Axis ±2 g Accelerometer Data Sheet

DESIGN RESOURCES
- ADXL327 Material Declaration
- PCN-PDN Information
- Quality And Reliability
- Symbols and Footprints

DISCUSSIONS
View all ADXL327 EngineerZone Discussions.

SAMPLE AND BUY
Visit the product page to see pricing options.

TECHNICAL SUPPORT
Submit a technical question or find your regional support number.

DOCUMENT FEEDBACK
Submit feedback for this data sheet.

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## REVISION HISTORY

8/09—Revision 0: Initial Version
## SPECIFICATIONS

$T_A = 25^\circ C, V_S = 3 \text{ V}, C_X = C_Y = C_Z = 0.1 \mu\text{F}$, acceleration = 0 g, unless otherwise noted. All minimum and maximum specifications are guaranteed. Typical specifications are not guaranteed.

### Table 1.

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<td></td>
<td>kHz</td>
</tr>
<tr>
<td>SELF TEST$^5$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Logic Input Low</td>
<td></td>
<td>+0.6</td>
<td></td>
<td></td>
<td>V</td>
</tr>
<tr>
<td>Logic Input High</td>
<td></td>
<td>+2.4</td>
<td></td>
<td></td>
<td>V</td>
</tr>
<tr>
<td>ST Actuation Current</td>
<td>±60</td>
<td></td>
<td></td>
<td></td>
<td>μA</td>
</tr>
<tr>
<td>Output Change at $X_{OUT}$</td>
<td>Self test 0 to 1</td>
<td>−210</td>
<td>−450</td>
<td>−850</td>
<td>mV</td>
</tr>
<tr>
<td>Output Change at $Y_{OUT}$</td>
<td>Self test 0 to 1</td>
<td>+210</td>
<td>+450</td>
<td>+850</td>
<td>mV</td>
</tr>
<tr>
<td>Output Change at $Z_{OUT}$</td>
<td>Self test 0 to 1</td>
<td>+210</td>
<td>+770</td>
<td>+1400</td>
<td>mV</td>
</tr>
<tr>
<td>OUTPUT AMPLIFIER</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Output Swing Low</td>
<td>No load</td>
<td>0.1</td>
<td></td>
<td></td>
<td>V</td>
</tr>
<tr>
<td>Output Swing High</td>
<td>No load</td>
<td>2.8</td>
<td></td>
<td></td>
<td>V</td>
</tr>
<tr>
<td>POWER SUPPLY</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operating Voltage Range</td>
<td>$V_S = 3 \text{ V}$</td>
<td>1.8</td>
<td>3.6</td>
<td></td>
<td>V</td>
</tr>
<tr>
<td>Supply Current</td>
<td>No external filter</td>
<td>350</td>
<td></td>
<td></td>
<td>μA</td>
</tr>
<tr>
<td>Turn-On Time$^6$</td>
<td></td>
<td>1</td>
<td></td>
<td></td>
<td>ms</td>
</tr>
<tr>
<td>TEMPERATURE</td>
<td></td>
<td>−40</td>
<td>+85</td>
<td></td>
<td>°C</td>
</tr>
</tbody>
</table>

1 Defined as coupling between any two axes.

2 Sensitivity is essentially ratiometric to $V_S$.

3 Defined as the output change from ambient-to-maximum temperature or ambient-to-minimum temperature.

4 Actual frequency response controlled by user-supplied external filter capacitors ($C_x, C_y, C_z$).

5 Bandwidth with external capacitors = $1/(2 \pi \times 32 \times C_x)$. For $C_x = 0.003 \mu F$, bandwidth = 1.6 kHz. For $C_x = 0.001 \mu F$, bandwidth = 500 Hz. For $C_y, C_z = 0.01 \mu F$, bandwidth = 0.5 Hz.

6 Self test response changes cubically with $V_S$.

7 Turn-on time is dependent on $C_x, C_y, C_z$ and is approximately $160 \times C_x$ or $C_y$ or $C_z + 1$ ms, where $C_x, C_y, C_z$ are in μF.
## Absolute Maximum Ratings

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acceleration (Any Axis, Unpowered)</td>
<td>10,000 g</td>
</tr>
<tr>
<td>Acceleration (Any Axis, Powered)</td>
<td>10,000 g</td>
</tr>
<tr>
<td>$V_{i}$</td>
<td>$-0.3 \text{ V to } +3.6 \text{ V}$</td>
</tr>
<tr>
<td>All Other Pins</td>
<td>Indefinite</td>
</tr>
<tr>
<td>Output Short-Circuit Duration (Any Pin to Common)</td>
<td></td>
</tr>
<tr>
<td>Temperature Range (Powered)</td>
<td>$-55^\circ \text{C to } +125^\circ \text{C}$</td>
</tr>
<tr>
<td>Temperature Range (Storage)</td>
<td>$-65^\circ \text{C to } +150^\circ \text{C}$</td>
</tr>
</tbody>
</table>

Stresses above those listed under Absolute Maximum Ratings may cause permanent damage to the device. This is a stress rating only; functional operation of the device at these or any other conditions above those indicated in the operational section of this specification is not implied. Exposure to absolute maximum rating conditions for extended periods may affect device reliability.

**ESD Caution**

ESD (electrostatic discharge) sensitive device. Charged devices and circuit boards can discharge without detection. Although this product features patented or proprietary protection circuitry, damage may occur on devices subjected to high energy ESD. Therefore, proper ESD precautions should be taken to avoid performance degradation or loss of functionality.
## PIN CONFIGURATION AND FUNCTION DESCRIPTIONS

![Figure 2. Pin Configuration](image)

### Table 3. Pin Function Descriptions

<table>
<thead>
<tr>
<th>Pin No.</th>
<th>Mnemonic</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>NC</td>
<td>No Connect (or Optionally Ground)</td>
</tr>
<tr>
<td>2</td>
<td>ST</td>
<td>Self Test</td>
</tr>
<tr>
<td>3</td>
<td>COM</td>
<td>Common</td>
</tr>
<tr>
<td>4</td>
<td>NC</td>
<td>No Connect</td>
</tr>
<tr>
<td>5</td>
<td>COM</td>
<td>Common</td>
</tr>
<tr>
<td>6</td>
<td>COM</td>
<td>Common</td>
</tr>
<tr>
<td>7</td>
<td>COM</td>
<td>Common</td>
</tr>
<tr>
<td>8</td>
<td>ZOUT</td>
<td>Z Channel Output</td>
</tr>
<tr>
<td>9</td>
<td>NC</td>
<td>No Connect (or Optionally Ground)</td>
</tr>
<tr>
<td>10</td>
<td>YOUT</td>
<td>Y Channel Output</td>
</tr>
<tr>
<td>11</td>
<td>NC</td>
<td>No Connect</td>
</tr>
<tr>
<td>12</td>
<td>XOUT</td>
<td>X Channel Output</td>
</tr>
<tr>
<td>13</td>
<td>NC</td>
<td>No Connect</td>
</tr>
<tr>
<td>14</td>
<td>Vcc</td>
<td>Supply Voltage (1.8 V to 3.6 V)</td>
</tr>
<tr>
<td>15</td>
<td>Vss</td>
<td>Supply Voltage (1.8 V to 3.6 V)</td>
</tr>
<tr>
<td>16</td>
<td>NC</td>
<td>No Connect</td>
</tr>
<tr>
<td>EP</td>
<td>Exposed pad</td>
<td>Not internally connected. Solder for mechanical integrity.</td>
</tr>
</tbody>
</table>
TYPICAL PERFORMANCE CHARACTERISTICS

N > 1000 for all typical performance plots, unless otherwise noted.

Figure 3. X-Axis Zero g Bias at 25°C, $V_i = 3$ V

Figure 6. X-Axis Self Test Response at 25°C, $V_i = 3$ V

Figure 4. Y-Axis Zero g Bias at 25°C, $V_i = 3$ V

Figure 7. Y-Axis Self Test Response at 25°C, $V_i = 3$ V

Figure 5. Z-Axis Zero g Bias at 25°C, $V_i = 3$ V

Figure 8. Z-Axis Self Test Response at 25°C, $V_i = 3$ V
ADXL327

Figure 15. X-Axis Sensitivity at 25°C, $V_c = 3\, V$

Figure 16. Y-Axis Sensitivity at 25°C, $V_c = 3\, V$

Figure 17. Z-Axis Sensitivity at 25°C, $V_c = 3\, V$

Figure 18. X-Axis Sensitivity vs. Temperature, Eight Parts Soldered to PCB, $V_c = 3\, V$

Figure 19. Y-Axis Sensitivity vs. Temperature, Eight Parts Soldered to PCB, $V_c = 3\, V$

Figure 20. Z-Axis Sensitivity vs. Temperature, Eight Parts Soldered to PCB, $V_c = 3\, V$
Figure 21: Typical Current Consumption vs. Supply Voltage

Figure 22: Typical Turn-On Time, \( V_i = 3 \text{ V} \)
\( C_i = C_1 = C_2 = 0.0007 \text{ \( \mu \)} F \)
ADXL327

THEORY OF OPERATION
The ADXL327 is a complete 3-axis acceleration measurement system. The ADXL327 has a measurement range of ±2 g minimum. It contains a polysilicon surface micromachined sensor and signal conditioning circuitry to implement an open-loop acceleration measurement architecture. The output signals are analog voltages that are proportional to acceleration. The accelerometer can measure the static acceleration of gravity in tilt sensing applications, as well as dynamic acceleration, resulting from motion, shock, or vibration.

The sensor is a polysilicon surface micromachined structure built on top of a silicon wafer. Polysilicon springs suspend the structure over the surface of the wafer and provide a resistance against acceleration forces. Deflection of the structure is measured using a differential capacitor that consists of independent fixed plates and plates attached to the moving mass. The fixed plates are driven by 180° out-of-phase square waves. Acceleration deflects the moving mass and unbalances the differential capacitor resulting in a sensor output whose amplitude is proportional to acceleration. Phase-sensitive demodulation techniques are then used to determine the magnitude and direction of the acceleration.

The demodulator output is amplified and brought off-chip through a 32 kΩ resistor. The user then sets the signal bandwidth of the device by adding a capacitor. This filtering improves measurement resolution and helps prevent aliasing.

MECHANICAL SENSOR
The ADXL327 uses a single structure for sensing the X, Y, and Z axes. As a result, the three axes sense directions are highly orthogonal with little cross-axis sensitivity. Mechanical misalignment of the sensor due to the package is the chief source of cross-axis sensitivity. Mechanical misalignment can, of course, be calibrated out at the system level.

PERFORMANCE
Rather than using additional temperature compensation circuitry, innovative design techniques ensure that high performance is built-in to the ADXL327. As a result, there is neither quantization error nor nonmonotonic behavior, and temperature hysteresis is very low (typically <3 mg over the −25°C to +70°C temperature range).
APPLICATIONS INFORMATION

POWER SUPPLY DECOUPLING

For most applications, a single 0.1 μF capacitor, Cch, placed close to the ADXL327 supply pins adequately decouples the accelerometer from noise on the power supply. However, in applications where noise is present at the 50 kHz internal clock frequency (or any harmonic thereof), additional care in power supply bypassing is required because this noise can cause errors in the acceleration measurement. If additional decoupling is needed, a 100 Ω (or smaller) resistor or ferrite bead can be inserted in the supply line. Additionally, a larger bulk bypass capacitor (1 μF or greater) can be added in parallel to Cch. Ensure that the connection from the ADXL327 ground to the power supply ground is low impedance because noise transmitted through ground has a similar effect as noise transmitted through Vss.

SETTING THE BANDWIDTH USING C1, C2, AND C3

The ADXL327 has provisions for band limiting the Xout, Yout, and Zout pins. Capacitors must be added at these pins to implement low-pass filtering for anti-aliasing and noise reduction. The 3 dB bandwidth equation is

\[ f_{3\text{dB}} = \frac{1}{(2\pi)(32 \text{ kΩ})} \times C_{\text{FB}} \times C_{1,2,3} \]

or more simply

\[ f_{3\text{dB}} = \frac{5 \mu\text{F}}{C_{1,2,3}} \]

The tolerance of the internal resistor (RFB) typically varies as much as ±15% of its nominal value (32 kΩ), and the bandwidth varies accordingly. A minimum capacitance of 0.0047 μF for C1, C2, and C3 is recommended in all cases.

Table 4. Filter Capacitor Selection, C1, C2, and C3

<table>
<thead>
<tr>
<th>Bandwidth (Hz)</th>
<th>Capacitor (μF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4.7</td>
</tr>
<tr>
<td>10</td>
<td>0.47</td>
</tr>
<tr>
<td>50</td>
<td>0.10</td>
</tr>
<tr>
<td>100</td>
<td>0.05</td>
</tr>
<tr>
<td>200</td>
<td>0.027</td>
</tr>
<tr>
<td>500</td>
<td>0.01</td>
</tr>
</tbody>
</table>

SELF TEST

The ST pin controls the self test feature. When this pin is set to Vss, an electrostatic force is exerted on the accelerometer beam. The resulting movement of the beam allows the user to test whether the accelerometer is functional. The typical change in output is -1.08 g (corresponding to -450 mV) in the X axis, +1.08 g (+450 mV) on the Y axis, and +1.83 g (+770 mV) on the Z axis. This ST pin can be left open circuit or connected to common (COM) in normal use. Never expose the ST pin to voltages greater than Vss + 0.3 V. If this cannot be guaranteed due to the system design (for instance, there are multiple supply voltages), then a low Vss clamping diode between ST and Vss is recommended.

DESIGN TRADE-OFFS FOR SELECTING FILTER CHARACTERISTICS: THE NOISE/BW TRADE-OFF

The selected accelerometer bandwidth ultimately determines the measurement resolution (smallest detectable acceleration). Filtering can be used to lower the noise floor to improve the resolution of the accelerometer. Resolution is dependent on the analog filter bandwidth at Xout, Yout, and Zout.

The output of the ADXL327 has a typical bandwidth greater than 500 Hz. The user must filter the signal at this point to limit aliasing errors. The analog bandwidth must be no more than half the analog-to-digital sampling frequency to minimize aliasing. The analog bandwidth can be further decreased to reduce noise and improve resolution.

The ADXL327 noise has the characteristics of white Gaussian noise, which contributes equally at all frequencies and is described in terms of μg/√Hz (the noise is proportional to the square root of the accelerometer bandwidth). The user should limit bandwidth to the lowest frequency needed by the application to maximize the resolution and dynamic range of the accelerometer.

With the single-pole roll-off characteristic, the typical noise of the ADXL327 is determined by

\[ \text{rms Noise} = \text{Noise Density} \times \sqrt{\text{BW} \times 1.6} \]

Often, the peak value of the noise is desired. Peak-to-peak noise can only be estimated by statistical methods. Table 5 is useful for estimating the probabilities of exceeding various peak values, given the rms value.

Table 5. Estimation of Peak-to-Peak Noise

<table>
<thead>
<tr>
<th>Peak-to-Peak Value</th>
<th>% of Time That Noise Exceeds Nominal Peak-to-Peak Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>2 x rms</td>
<td>32</td>
</tr>
<tr>
<td>4 x rms</td>
<td>4.6</td>
</tr>
<tr>
<td>6 x rms</td>
<td>0.27</td>
</tr>
<tr>
<td>8 x rms</td>
<td>0.006</td>
</tr>
</tbody>
</table>

USE WITH OPERATING VOLTAGES OTHER THAN 3 V

The ADXL327 is tested and specified at Vss = 3 V; however, it can be powered with Vss as low as 1.8 V or as high as 3.6 V. Noise that some performance parameters change as the supply voltage is varied.

The ADXL327 output is ratiometric; therefore, the output sensitivity (or scale factor) varies proportionally to the supply voltage. At Vss = 3.6 V, the output sensitivity is typically 500 mV/g. At Vss = 2 V, the output sensitivity is typically 289 mV/g.

The zero g bias output is also ratiometric; therefore, the zero g output is nominally equal to Vss/2 at all supply voltages.

The output noise is not ratiometric but is absolute in volts; therefore, the noise density decreases as the supply voltage increases. This is because the scale factor (mV/g) increases while the noise voltage remains constant. At Vss = 3.6 V, the X- and Y-axis noise density is typically 200 μg/√Hz, while at Vss = 2 V, the X- and Y-axis noise density is typically 300 μg/√Hz.
ADXL327

Self test response in g is roughly proportional to the square of the supply voltage. However, when ratiometricity of sensitivity is factored in with supply voltage, the self test response in volts is roughly proportional to the cube of the supply voltage.

For example, at $V_s = 3.6$ V, the self test response for the ADXL327 is approximately $-780$ mV for the X axis, $+780$ mV for the Y axis, and $+1330$ mV for the Z axis. At $V_s = 2$ V, the self test response is approximately $-130$ mV for the X axis, $+130$ mV for the Y axis, and $-220$ mV for the Z axis.

The supply current decreases as the supply voltage decreases. Typical current consumption at $V_s = 3.6$ V is 375 μA, and typical current consumption at $V_s = 2$ V is 300 μA.
LAYOUT AND DESIGN RECOMMENDATIONS

The recommended soldering profile is shown in Figure 25, followed by a description of the profile features in Table 6. The recommended PCB layout or solder land drawing is shown in Figure 26.

Table 6. Recommended Soldering Profile

<table>
<thead>
<tr>
<th>Profile Feature</th>
<th>Sn63/Pb37</th>
<th>Pb-Free</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Ramp Rate (T_r to T_f)</td>
<td>3°C/sec maximum</td>
<td>3°C/sec maximum</td>
</tr>
<tr>
<td>Preheat</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Minimum Temperature (T_{min})</td>
<td>100°C</td>
<td>150°C</td>
</tr>
<tr>
<td>Maximum Temperature (T_{max})</td>
<td>150°C</td>
<td>200°C</td>
</tr>
<tr>
<td>Time (T_{min} to T_{max}), t_r</td>
<td>60 sec to 120 sec</td>
<td>60 sec to 180 sec</td>
</tr>
<tr>
<td>Ramp-Up Rate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time Maintained Above Liquidus (T_i)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Liquidus Temperature (T_i)</td>
<td>183°C</td>
<td>217°C</td>
</tr>
<tr>
<td>Time (t_i)</td>
<td>60 sec to 150 sec</td>
<td>60 sec to 150 sec</td>
</tr>
<tr>
<td>Peak Temperature (T_p)</td>
<td>240°C + 0°C/−5°C</td>
<td>260°C + 0°C/−5°C</td>
</tr>
<tr>
<td>Time Within 5°C of Actual Peak Temperature (t_s)</td>
<td>10 sec to 30 sec</td>
<td>20 sec to 40 sec</td>
</tr>
<tr>
<td>Ramp-Down Rate</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Time 25°C to Peak Temperature</td>
<td>6°C/sec maximum</td>
<td>6°C/sec maximum</td>
</tr>
<tr>
<td></td>
<td>6 minutes maximum</td>
<td>8 minutes maximum</td>
</tr>
</tbody>
</table>

Figure 25. Recommended Soldering Profile

Figure 26. Recommended PCB Layout

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ADXL327

OUTLINE DIMENSIONS

ORDERING GUIDE

<table>
<thead>
<tr>
<th>Model</th>
<th>Measurement Range</th>
<th>Specified Voltage</th>
<th>Temperature Range</th>
<th>Package Description</th>
<th>Package Option</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADXL327BCPZ(^1)</td>
<td>±2 g</td>
<td>3 V</td>
<td>–40°C to +85°C</td>
<td>16-Lead LFCSPLQ</td>
<td>CP-16-5a</td>
</tr>
<tr>
<td>ADXL327BCPZ-RL(^1)</td>
<td>±2 g</td>
<td>3 V</td>
<td>–40°C to +85°C</td>
<td>16-Lead LFCSPLQ</td>
<td>CP-16-5a</td>
</tr>
<tr>
<td>ADXL327BCPZ-RL(^1)</td>
<td>±2 g</td>
<td>3 V</td>
<td>–40°C to +85°C</td>
<td>16-Lead LFCSPLQ</td>
<td>CP-16-5a</td>
</tr>
<tr>
<td>EVAL-ADXL327(^1)</td>
<td>±2 g</td>
<td>3 V</td>
<td>–40°C to +85°C</td>
<td>Evaluation Board</td>
<td>CP-16-5a</td>
</tr>
</tbody>
</table>

\(^1\) Z = RoHS Compliant Part.