Keweenaw Research Center

Snowmobile Trail Bump Formation Analysis, Prediction, and Modeling

Final Report
for
National Park Service - Yellowstone National Park
Planning Office
P.O. Box 168
Yellowstone Park, WY 82190

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EXECUTIVE SUMMARY

The study of the formation and geometry of snowmobile generated bumps has been of interest to snowmobile designers, groomer operators and manufacturers, and snow scientists for years. Numerous small studies have been undertaken to model this formation and to determine the mechanisms involved in mogul growth, but prior to this major study the hypotheses were mostly unproven. This report and the work that leads to it, is a start to models to predict mogul formation and geometry.

It is well known that where there are snowmobiles traveling, there will eventually be moguls. The development of these moguls is extremely important when trying to design suspensions, and also in determining the best means to groom the snow roads to minimize roughness. To complicate matters further, it appears that the suspension characteristics of snowmobiles are a major contributing factor to generation, and any alterations to the suspension, change the bumps formed. This study looks at formation in connection to weather parameters such as snow temperature, free water content, new snow, etc. It investigates present grooming practices and the differences between certain vehicles. How the snow moves and where the bumps come from is studied. How fast do the bumps form, how many snowmobiles make the snow road unbearable, along with other hypotheses made prior to the start of this test, and some that came up as it went along, are investigated.

This study is a major measurement and data analysis undertaking with the outcome being a qualitative as well as quantitative model of how bumps form. Some generalizations are as follows: 1. Bumps formed very rapidly under all weather conditions tested. 2. Bumps formed in the same locations, even over the long test period. 3. Early winter weather can have a major effect on the groomed snow roads for the entire winter. 4. Snow coaches deteriorate the snow roads differently than snowmobiles.

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INTRODUCTION

Winter visitation by vehicles within Yellowstone National Park is currently by use of either multi-passenger snow coaches or by snowmobiles. Vehicle travel is restricted to a network of snow roads within the park. These snow roads are maintained and groomed by NPS personnel and equipment. An "enjoyable" experience within the park depends highly upon the smoothness of the roads throughout the day.

The Keweenaw Research Center, KRC, was contracted by the National Park Service and Yellowstone National Park to conduct a study of snowmobile generated bump formation on the groomed snow roads within the park. This study was performed in two phases. Phase I was the development of methods to rapidly measure bump profiles and analyze them and Phase II was the field measurement of bumps under numerous scenarios on-site at Yellowstone. The final outcome of this research is recommendations for better grooming practices and ideas about traffic flow.

BACKGROUND

Winter visitation within Yellowstone National Park, as well as several other parks that experience significant snowfalls within the winter months, has grown considerably over the past decade. Snowmobile traffic into the park at the West Yellowstone entrance commonly exceeds 1000 sleds per day. Since most of these snowmobiles are headed to Old Faithful and back out by early afternoon, the majority of the vehicles pass into the park within only a few hours in the morning and come back out over a short period in mid-afternoon. This heavy traffic causes the groomed snow road to bump up quite rapidly resulting in an extremely rough ride. Roughness results in an "unpleasant" experience as well as drastically slowing traffic flow, especially on the trip back out in the afternoon. Figure 1 is a photo of some of the large numbers of snowmobiles at Old Faithful on a given day. Figure 2 shows some of the resultant bumps.

Figure 1. Snowmobiles at Old Faithful

Figure 2. Bumps on Groomed Snow Road.

Currently, grooming of the snow road is performed mostly at night. This is the safest time to groom to avoid collisions between snowmobiles and the groomer. In some cases, this is also the best time for grooming, especially if snow set up time is deemed the most important grooming parameter. If grooming is performed in early evening, as is usually the case, the groomed snow road can set up over night with very little traffic affecting the set up. Figure 3 is a photo of one of the groomers used in the park.

Figure 3. Grooming Equipment.

KRC engineers have been studying bump formation, snowmobile operation, snowmobile design, and grooming for several years. These studies have resulted in several hypotheses of how bumps form. They have also resulted in a good understanding of how grooming works and what the best scenarios for certain conditions are to achieve the best grooming results.

SCOPE OF WORK - PHASE I

KRC has been researching the formation of bumps on snowmobile trails for several years. In fact, a preliminary study to look at the problem at Yellowstone was performed prior to this current work. This background of studies in this area by KRC brought to light 2 major shortfalls within current practice.

Prior to this contract, profiles along the trail were measured using a surveyor's level, rod, and tape. This method was not only time consuming, but accuracy suffered if long distance profiles were desired. The long period required to measure a profile, an hour or more in some cases, was not conducive to studying traffic effects. For example, during a 1 hour measurement setup, 300 to 400 snowmobile passages may be missed by re-routing to the opposite lane. This was not satisfactory to this test, since the model to be developed is number of passages as related to bump growth. With this in mind, a setup to rapidly measure trail profiles was required. A method to accurately count snowmobiles was also devised for this project.

A method to analyze the data after it was collected was also devised under this phase of the contract. This method was developed from knowledge gained under previous studies and was also coupled to the new measurement system. Both of these procedures had to work together.

SCOPE OF WORK - PHASE II

Phase II of this project consists of the in-field measurement of bump formation followed by the reduction of the data collected to form a model of mogul formation and recommendations for grooming practices. An engineering team was sent to Yellowstone National Park to measure bump formation in conjunction with several other parameters. A field test procedure was determined under Phase I of this contract to get the testing started and this procedure was fine tuned on-site.

Some of the parameters to be used as variables were weather, traffic volume, vehicle type, grooming equipment used, and grooming method. Under weather parameters were the variables of air and snow temperature, wind, precipitation amount, precipitation type, snow "wetness", snow strength, and solar radiation. Traffic volumes were recorded with time so a "time of day" and bump growth per "x" snowmobiles estimate could be made. The major vehicle types for this study were snow coaches and snowmobiles with only minor attention paid to the differences between vehicles within those 2 groups. Grooming scenarios included limited tests of groomer type and method. Groomed snow road configuration in connection with grooming was also monitored.

RESULTS - PHASE I

Shortly after the contract with Yellowstone - NPS was finalized, the instrumentation needed to rapidly measure snow road profiles was rented by KRC. As mentioned previously, this equipment is known as a Geodimeter Total Station and is manufactured by Geotronics. This device is programmable and is operated by a portable PC that also acts as a data acquisition system. The measurement portion of this device records data and sends it to the computer by use of an FM radio and radio modem. For purposes of this project, a program was written to operate the system so as to get the best results for this particular application.

In general, the system consists of an electronic measurement head that sends laser signals to a prism reflector and records the time it takes for the beam to get back to the head after reflection. From this data, the distance from the head to the prism is measured. The head also records horizontal and vertical angles to the prism at the instant a distance measurement is made. The instrumentation is set up to "track" the prism as it is slowly moved along. It records at 4 Hz as it tracks. In order to get a smooth profile along the snow road, a cart was designed and fabricated and the prism was attached to it. This cart is slowly towed down the center of the snow road to take a measurement.

The way the instrumentation and the recording program were set up allows for the prism to be moved along the centerline of the snow road while recording a profile of the snow road surface.

Figures 4, 5, and 6 are photos of the measurement head, the prism reflector, and the cart with prism attached, in that order, respectively.

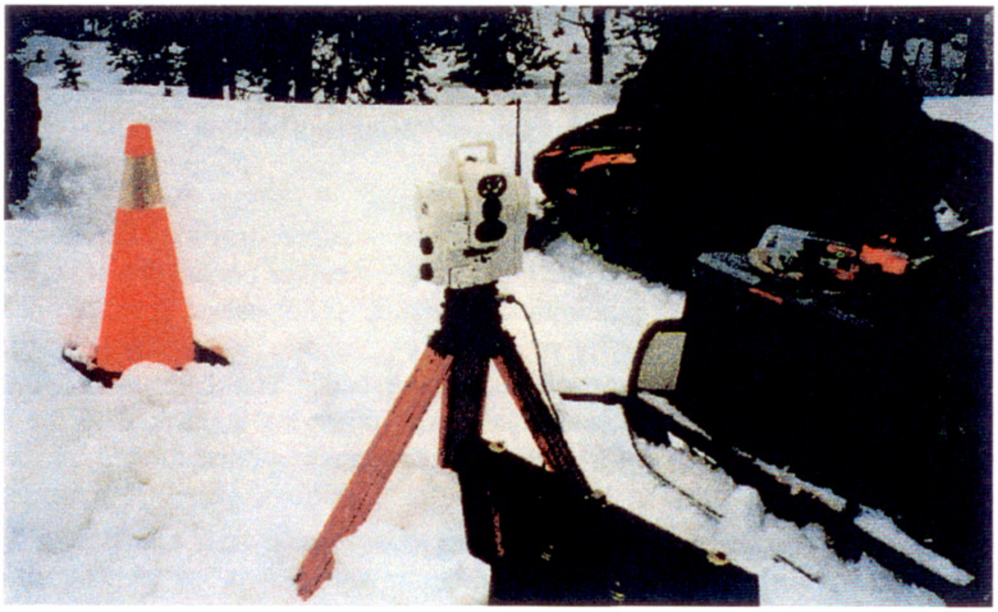

Figure 4. Bump Measurement Instrumentation.

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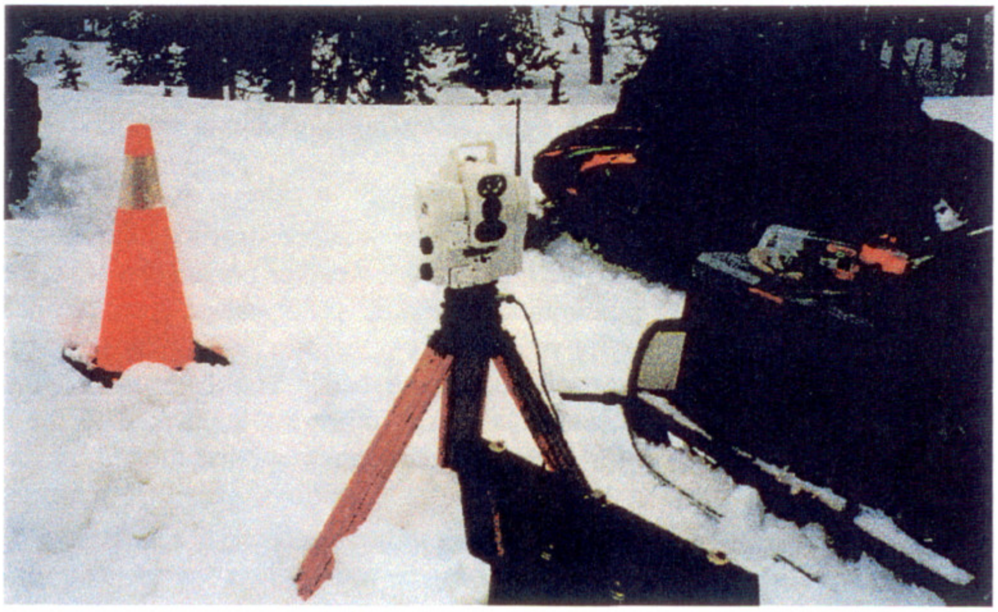

Figure 4. Bump Measurement Instrumentation.

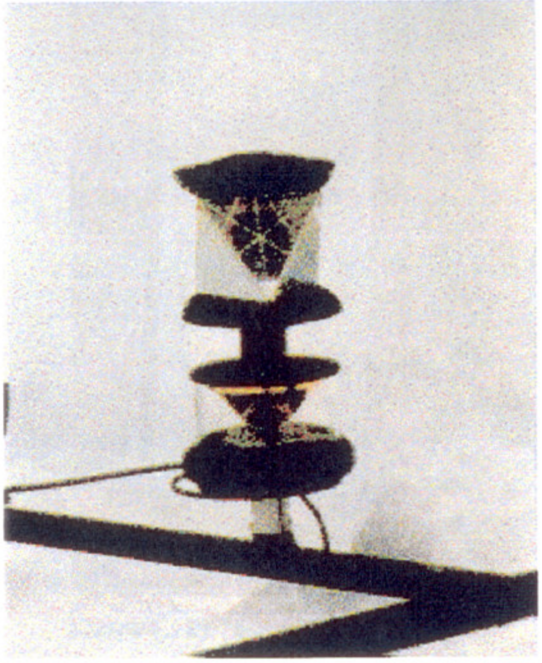

Figure 5. Reflector.

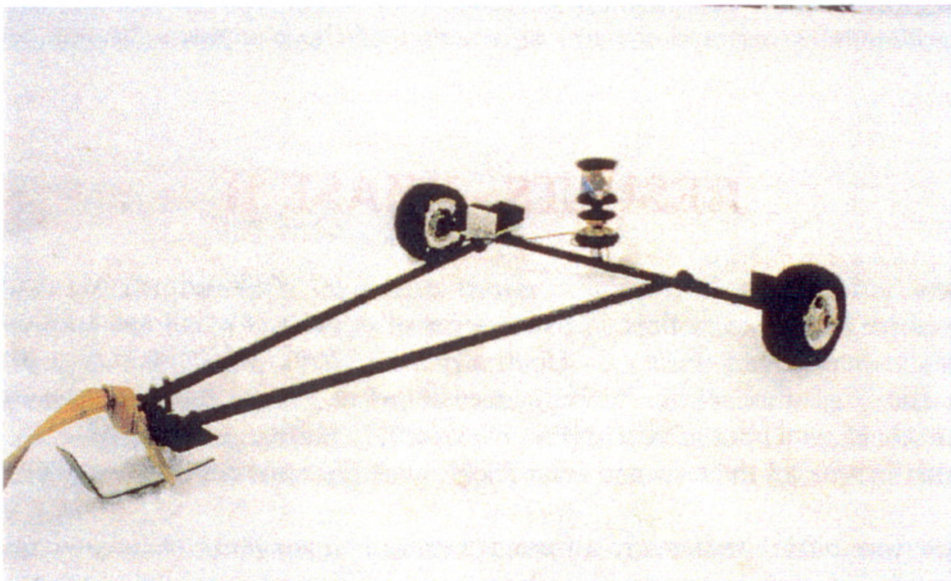

Figure 6. Profiling Cart.

Electronic trail counters were also programmed for use on-site at Yellowstone. KRC has 2 of these units that can be set up to count single lanes of traffic so as to decipher the direction of travel of snowmobiles moving on the trail. These counters record a vehicle passage number and time for every passage. From this data, the exact count at the time of each profile measurement can be determined. Figure 7 is a photo of one of these counters.

Figure 7. Electronic Trail Counter.

Concurrent with setting up and testing the electronic measurement devices, was procurement of all of the necessary equipment, supplies, and support for the field trip to Yellowstone. A test plan was developed and the equipment was loaded for the trip west. Two 1999 Arctic Cat ZL 500cc EFI snowmobiles and a sled were also a part of the equipment brought out by KRC engineers.

RESULTS - PHASE II

In early February 2000, two KRC engineers drove to West Yellowstone, MT with all of the equipment necessary to make in-field measurements of bump formation and traffic scenarios in and around Yellowstone National Park. Upon arriving at Yellowstone, a survey trip was made into the park and sites were chosen to begin measurement. A preliminary measurement setup and test was made shortly after arrival. NPS employees, in particular, Doug Madsen, was on-site and participated in most of the tests and John Sacklin was also present for several days' testing.

Measurements were made for as many different scenarios of weather, traffic, and vehicle type as possible over the test period. In general, there are 2 different sets of data that are plotted and contained as graphs within this report. All of the data collected is contained in Appendix A, "Trail Counter Data" and Appendix B "Trail Bump Profiles" at the end of this report. Some of these plots will also be contained within the body of the report while others will be referenced out of the Appendices. This section RESULTS - PHASE II contains an overview of the data collected. The section titled ANALYSIS OF RESULTS that follows is the breakdown of this data.

Figure 8 and Figure 9 are representative plots of trail counter data recorded on 2/15/2000. They were measured at the West gate and are separated into inbound and outbound numbers, where inbound is going into the park from West Yellowstone and outbound is coming out. This data has been broken into 15 minute intervals spread over a 24 hour time period. Each bar on the graph shows the number of snowmobiles passing in a certain direction within a given 15 minute period. The shape of the graphs clearly shows the periods during the day when most of the movement takes place.

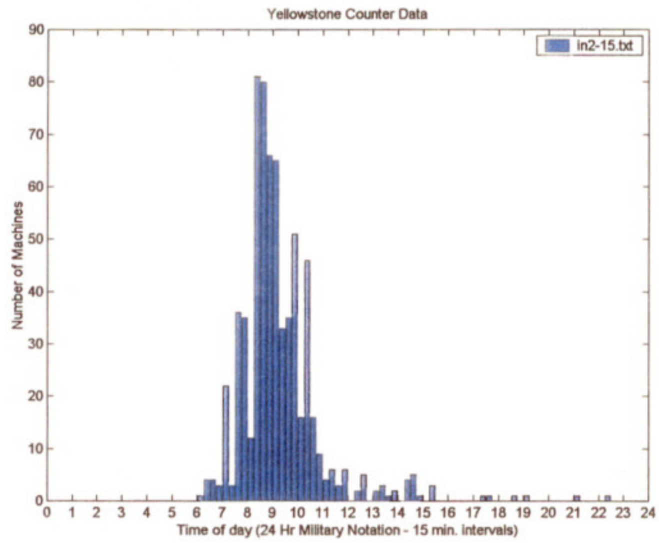

Figure 8. Trail Counter Data - Eastbound 2/15/2000.

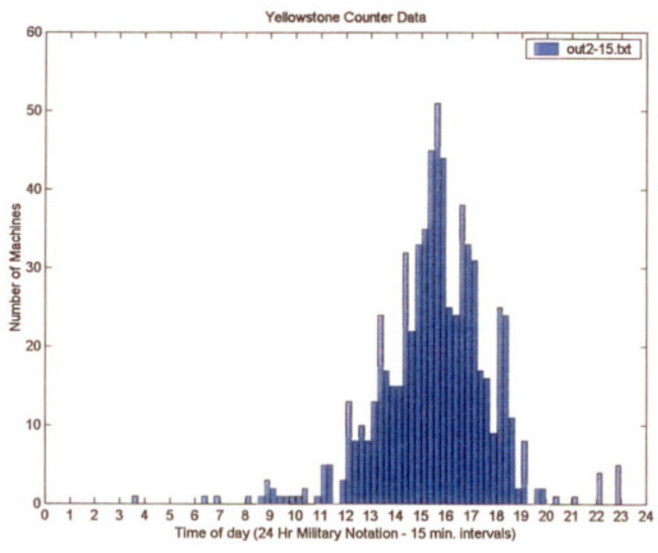

Figure 9. Trail Counter Data - Westbound 2/15/2000.

Figure 10 contains bump profiles that were also measured on 2/15/2000 in the eastbound lane. There are 3 different bump sets shown in varied colors and line types on this graph. These were measured at different times throughout the day for the same site for a single traffic direction (into the park for this case) at the West Entrance. What each of these 3 profiles is intended to show is the progression of bump growth with traffic throughout the day. These graphs will be analyzed further in the following section.

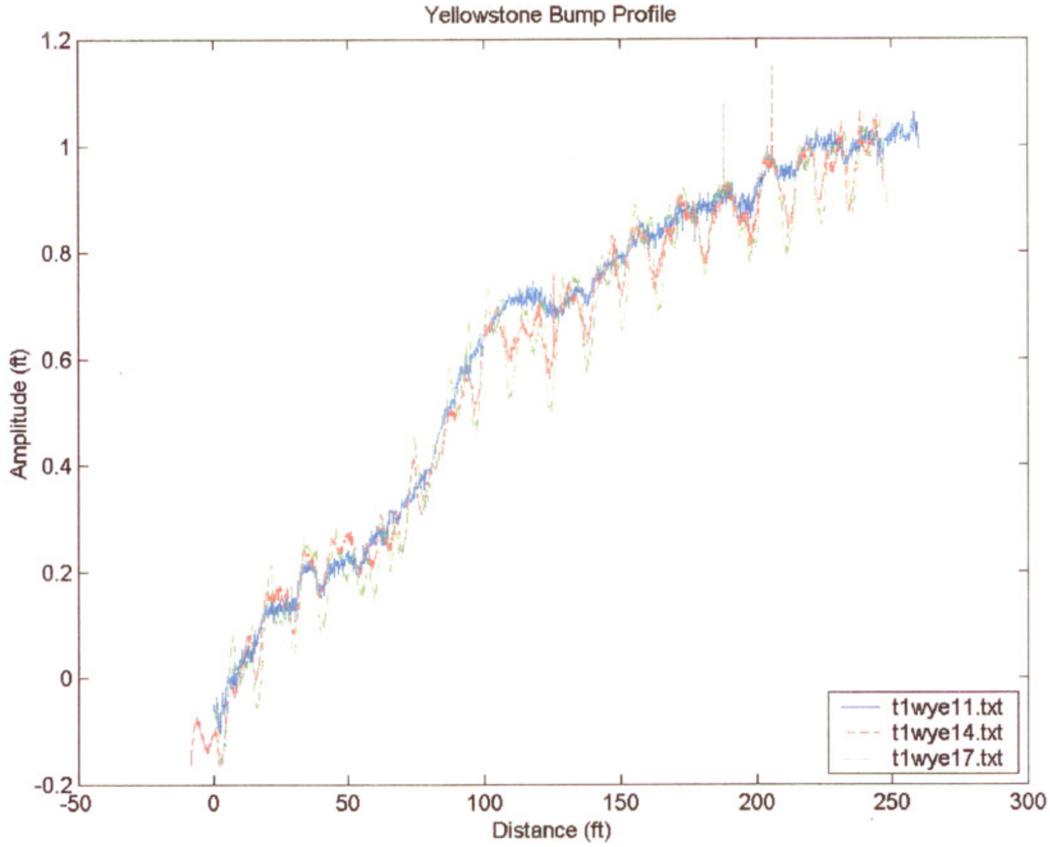

Figure 10. Bump Profiles - Eastbound 2/15/2000.

Bump Generation by Snowmobiles

Several test sites were used to measure snowmobile generated bump formation within the park and on Forest Service land. For purposes of the rest of this report, each of these will be given a random name to make it easier to compare the results. All of the data collected is included in the two Appendices at the end of this report. Page numbering for this data will be as A-# for Appendix A and B-# for Appendix B.

Madison River Bend.

The first test section that measurements were made on is denoted as "Madison River Bend." This section is located adjacent to a turnout approximately 3 miles into the park from the West Entrance gate.

2/8/2000. Two profiles were measured in the westbound lane at this site on 2/8/2000. This was the first day of measurement with the new system and this test was the shake down of the instrumentation. 113 snowmobiles passed over the section between the 2 measurements. Counter data for this test day is on page A-1 and the profiles are plotted on page B-1.

West Gate Section.

A test section called "West Gate Section" or "Standard Test Section" was set up about 1/4 mile into the park from the West Entrance. This section was 250 feet long and was located just to the east of the service road located on the north side of the road. Baseline reference stakes were placed approximately 50 ft to the north of the centerline of the snow road and 250 feet apart at both ends of this section in the ditch alongside the road. These stakes were left in place throughout the test period to allow for comparison of profiles from day to day. Prior to each days measurements at this site, a row of cones was set down the center of the snow road to attempt to keep traffic in their own respective lane. Traffic was re-routed into the lane that was not being measured during each profiling. Figure 11 is a photo of the instrumentation setup at this site and Figure 12 shows the lane designation using cones.

Figure 11. Test Site Setup.

Figure 12. Test Lane Designation.

2/9/2000. Profiles were measured at this site on 2/9/2000. 3 separate profiles were measured throughout the day in the inbound lane and 4 in the outbound lane. Counter data for this test day is on page A-2. The 3 profiles for the inbound lane are plotted on page B-2 and the 4 westbound profiles are on page B-3.

2/11/2000. Measurements were made at this site on 2/11/2000. The counter data for this test is plotted on page A-3. Three profiles were made in the inbound lane that are plotted on page B-4 and three were also measured westbound as shown on page B-5.

2/12/2000. Profiles were measured at this site on 2/12/2000. 1 profile was measured in the eastbound lane and 2 in the westbound lane. Counter data for this test day is on page A-4. The profile in the inbound lane is plotted on page B-6 and the 2 westbound profiles are on page B-7.

2/15/2000. Measurements were made at this site on 2/15/2000 only in the inbound lane. The counter data for this test is plotted on page A-7. Seven profiles were measured in the inbound lane on this day. These are plotted on 4 separate graphs in Appendix B. The first of these is on page B-8 and is the 1st four profiles of the day. Page B-9 shows a plot of the second and third profiles, B-10 contains the last 4, and B-11 contains the first, fourth, and last profiles for the day.

2/18/2000. Three profiles were measured eastbound and 3 westbound on 2/18/2000. The counter data is plotted on page A-10. The 3 eastbound profiles are plotted on page B-12 and the westbound profiles are on page B-13. There is also a plot containing 2 eastbound and 2 westbound profiles on the same graph on page B-14.

2/19/2000. Six profiles were measured on 2/19/2000 in the inbound (eastbound) lane. Counter data is on page A-11. The first four eastbound profiles are on page B-15 in full scale. Page B-16 contains a blow-up of the middle section of the same four profiles. The 5th and 6th profiles are plotted on page B-17. B-18 is a plot of the blow up of the middle section of the 3rd through the 6th profiles.

2/23/2000. Three profiles were measured in the eastbound lane on 2/23/2000. These profiles were in conjunction with tests to compare regular grooming with the use of the "Renovator". This will be explained in a later section. The counter data for this day is on page A-15 and the plot of the 3 eastbound profiles is on page B-19.

Some other plots are contained in Appendix B for this test section as follows. Pages B-20 through B-27 are plots comparing various combinations of measurements from the tests described previously. Some of these will be used for comparison in later parts of this report.

West Gate Entrance Ramp.

2/14/2000. A profile was measured on a short section of snow road leading to the entrance gate at West Yellowstone. This is the stretch of snow road that is just outside the gate (toward the town of West Yellowstone) and carries inbound traffic. Counter data is plotted on page A-6 and the profile plot is on page B-28.

Forest Service Trail Sections.

Measurements were made on sections of trail out of the park on 2 different days.

2/14/2000. Bump profiles were measured on a section of trail from West Yellowstone headed north. 3 profiles were taken near a bridge that is alongside highway 191. Page B-29 is a plot of 2 profiles of the trail near the bridge in the 2 different lanes. Page B-30 is a plot of another piece of trail in the same vicinity. There is no counter data for these plots.

2/16/2000. Bump profiles were measured on a groomed and an un-groomed section of forest service trail on a hill near West Yellowstone. The plots for these measurements are on page B-31. There is no counter data for these plots.

Snow Movement Under Track

The movement of snow particles along the snow road surface as snowmobiles pass over a section is of interest to the mogul generation problem. Since a volume of snow needs to be moved from one place to another along the snow road to form the lows and highs of the moguls, some transport mechanism must be present. In order to monitor this, a method was devised to attempt to “track” snow particle movement in conjunction with snowmobile traffic.

To visually depict snow movement, a line of ash was placed perpendicular to the snow road transecting the traffic lane at several locations. The test was performed between 9:00 and 10:30 after the heavy morning traffic had passed on the trail inbound. At this time, the bumps were about 3 inches high. Speeds were normal or about 45 mph. The lines of dark colored ash were about 1" wide and 1/4" thick. As snowmobiles drove over these lines it was hoped that the movement of ash would depict the movement of snow particles also. The following figures are photos of this test. All of the photos shown here have the direction of travel from right to left across the page. Figure 13 is a photo of an undisturbed line of ash that is placed on top of and along the peak of a single bump. Figures 14 through 16 are 3 progressions of the same ash sample after 3, 23, and 43 snowmobile passes respectively. 3 snow coaches also passed over the sections between the last two photos. From these photos it is clear that the majority of particles are moving in the direction of travel, the particles are being "pulled" along by the snowmobile.

Figure 13. Particle Movement - Peak - No Traffic

Figure 14. Particle Movement - Peak - +3 Snowmobiles.

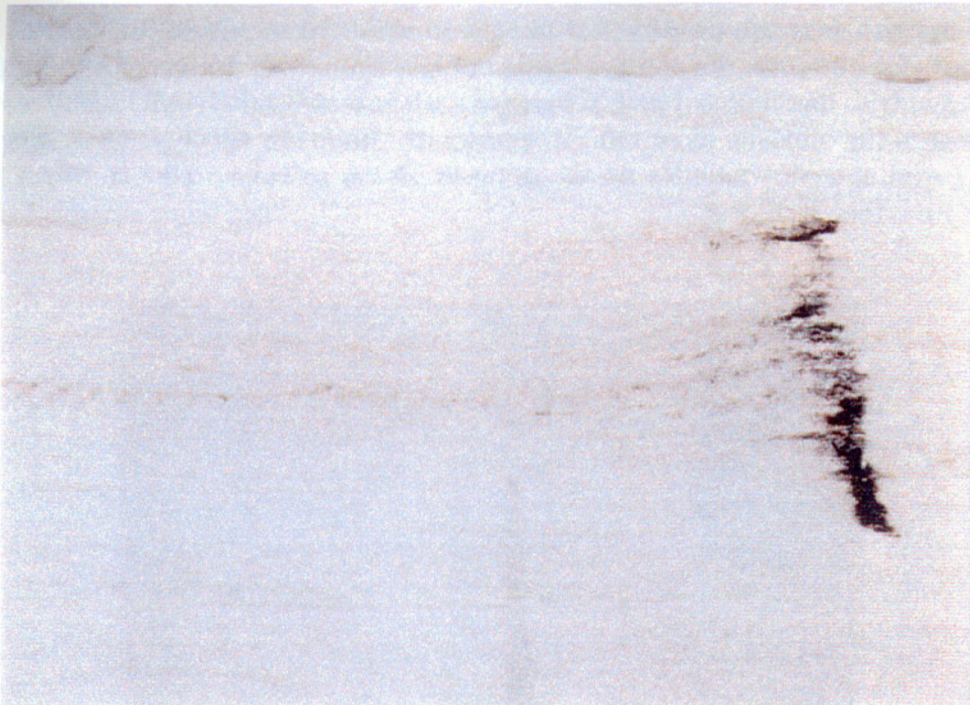

Figure 15. Particle Movement - Peak - +20 Snowmobiles.

Figure 16. Particle Movement - Peak -+20 Snowmobiles + 3 Snow Coaches.

Figures 17 through 20 are photos of the same type of test, only in this case, the ash if placed in the lowest part of a bump set, the valley, and the progression is the same. In this test, however, the ash moves in both directions. Most of the progression is in the direction of travel, but there is also movement in the opposite direction. It appears that the snow coaches move particles in the direction of travel and snowmobiles do the opposite in the troughs. This is only a hypothesis after the fact from this small test.

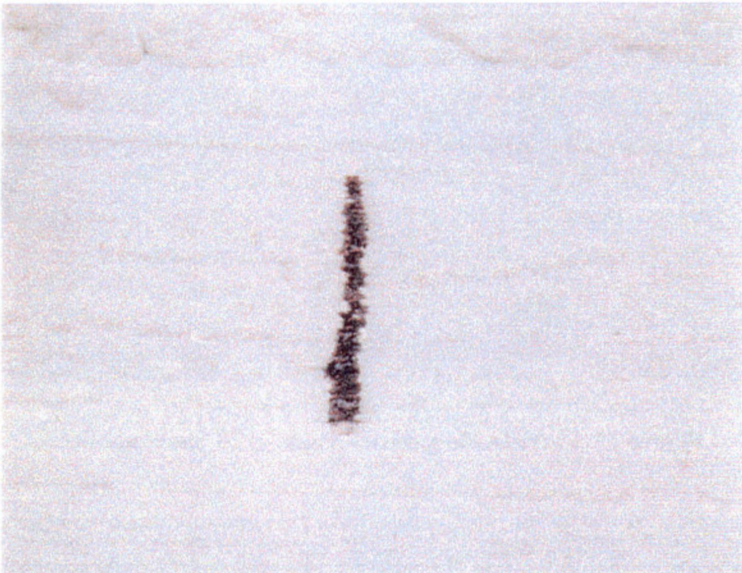

Figure 17. Particle Movement - Trough - No Traffic.

Figure 18. Particle Movement - Trough - +3 Snowmobiles.

Snow Coaches

Due to the fact that there are relatively few snow coaches that travel any given section of snow road in comparison to the number of snowmobiles, it is not possible to discern between the two when they are both traveling on the main snow road. In fact, since the number of snowmobiles is quite large in comparison to the small number of snow coaches per day, the effect of snow coaches on the overall bump formation appears to be negligible.

In an attempt to determine the scenario of bump formation and snow road degradation caused only by snow coaches, a special snow road section was set up off of the main snow road on a side road near the West Yellowstone entrance. This piece of road was groomed 3 days prior to the proposed test and allowed to set up and sinter. On the day of testing, 2/17/2000, a Bombardier snow coach was brought to the test site and driven over the specially made snow road. Figure 21 is a photo of this vehicle on the snow road.

Figure 21. Snow Coach on Test Snow Road.

The snow coach was driven over the same section of groomed snow road for 50 laps and the profile was re-measured and the before and after profiles are given on page B-33. A second 50 laps was then made over the same section. This profile is also plotted on page B-33. A second test lane was set up at this same location and measurements were made on the same interval. The plots of these 3 profiles are given on page B-34.

To show how rutting was formed parallel to travel direction, a cross-section of the snow road was profiled. This is given on page B-35.

Figure 24. Bombardier Snow Coach.

Controlled Snowmobile Tests

On 2/21/2000 a controlled snowmobile test was performed on the same groomed road as the snow coach testing. These tests were run on a section that had not been previously trafficked by the coaches. Profiles after 0, 50, and 100 passes of the 1999 Arctic Cat ZL 500 EFI snowmobiles at 45 mph were measured in both lanes and are plotted on pages B-36 and B-37.

Renovator Tests

A comparison was made between normal grooming and use of the Yellowstone Track Systems, YTS "Renovator" on the snow road section near the entrance at West Yellowstone. This test was to determine if the "Renovator" could cut through the frozen bumps and leave a smoother snow road. The Renovator is a front mounted grooming system designed to cut deeply into hard-packed snow road surfaces to remove any old bumps and then re-smooth the surface.

Three profiles were measured in the eastbound lane at the West Entrance Site on 2/23/2000. This stretch of snow road was groomed using the normal equipment of NPS as it isusually done. The counter data for this day is on page A-15 and the plot of the 3 eastbound profiles is on page B-19. The "Renovator" was brought onto the snow road and a short section was groomed using this equipment. This piece of snow road was located between the West Entrance gate and the test section (not within the test section). Page B-38 contains profiles this piece of snow road on the same schedule (after same approximate # of snowmobiles) as the test section profile of page B-19.

Figure 25 is a photo of the Renovator system.

Figure 25. Renovator Grooming System

Cross - Park Surveys

On 3 separate occasions snowmobile trips were made into the park to visually assess bump formation and to look for bumps that were not specific to test sections. Some general observations were made during these trips.

Since the heaviest traffic is from the West Entrance to Old Faithful, this stretch is by far the roughest. Other areas of heavy traffic get rough within the park, but not as badly and as frequently as the West to Old Faithful route. This stretch starts to bump up rapidly after about 10:00 when inbound traffic starts to get heavy. The snow road starts out to be roughest in the inbound lane but gets rough across the entire snow road as riders move to the opposite (wrong direction) lane looking for smoother snow road. By the time most of the traffic starts to come back out of the park down this section, the ride is extremely uncomfortable. This scenario is, in general, a daily occurrence.

Outside of this section of the park snow road system, the roughness is generally not as severe. However, there can be rough sections, dependant upon the number of snowmobiles coming in from other entrances. Bumps tend to grow more rapidly on corners, hills, and at intersections. This is, however, also dependant on traffic volume. This difference in the traffic volume is most noticeable when continuing east past the entrance into Old Faithful. On certain days the snow road only a mile or so to the east past the turnoff is nearly smooth.

A visual survey was made between West Thumb and Old Faithful. Several snow coaches were travelling west on this route. Snowmobile traffic was light so the majority of snow road disturbance was from snow coaches only. In this instance, there was little or no bumpiness present. The snow road was quite rutted and the snow was loosened by the tracks on these vehicles. From this observation, it appeared that snow coaches will deteriorate the snow road in a manor quite different from snowmobiles. Ruts that run in parallel with the snow road will predominate. These may become difficult to travel through with heavier traffic volumes. This is consistent with the controlled snow coach test results.

Figure 26 is a photo of bumps on the inside of a corner.

Figure 26. Bumps on Corner.

Sound Measurements

Secondary to the scope of work for the mogul generation study, KRC engineers measured pass-by noise of both snowmobiles and snow coaches. Internal noise and vibration measurements were also made in the Bombardier Snow Coach. This data will be passed on to NPS if and when it is analyzed, since this was not an item of the contract, this may not be looked at for a while.

ANALYSIS OF RESULTS

There are several factors believed to be the cause of bump growth and which affect the rate at which the trail becomes uncomfortably bumpy. Of these factors, snow and traffic conditions are the major contributors. These two items can be broken down to get an understanding of how moguls form. The following is an investigation of these major contributors and their components.

Snow and Trail Properties

The strength of the trail surface controls the rate of growth of moguls. Some of the snow properties that affect the stability of the trail, and its strength, are density, wetness, temperature, crystal size, snow age, and so on. Although weather impacts the physical properties of the snow on the trail in a number of ways, this study will focus on the two most important meteorological parameters, newly fallen snow and temperature. Figure 27 contains the snowfall data taken from the weather station at West Yellowstone and its affect on snow depth over the same period. New snow has substantially different properties than that of snow that has been on the ground for any period of time. In general, it increases the overall thickness of the trail, it initially will vary from very wet to very dry, it usually has a low density and little strength, and it tends to be moved around the trail surface quite easily. Figure 28 is a graph of the air temperature from the West Yellowstone recording station during the period of this testing. This temperature can be used to estimate the snow temperature and the relative degree of "wetness" in the snow.

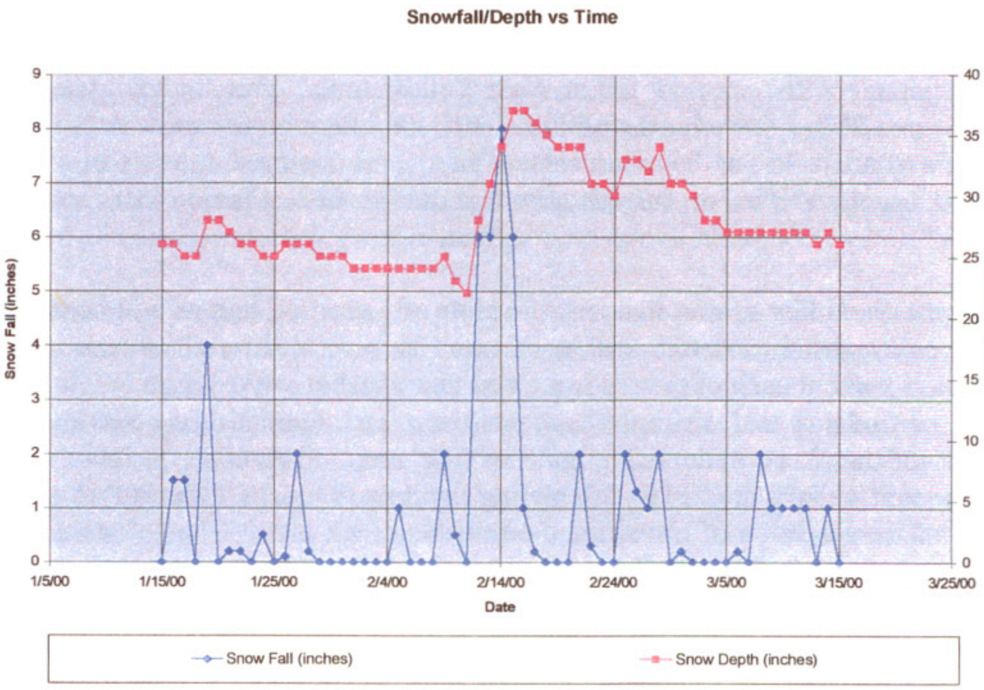

Figure 27. Snowfall and Snow Depth at West Yellowstone.

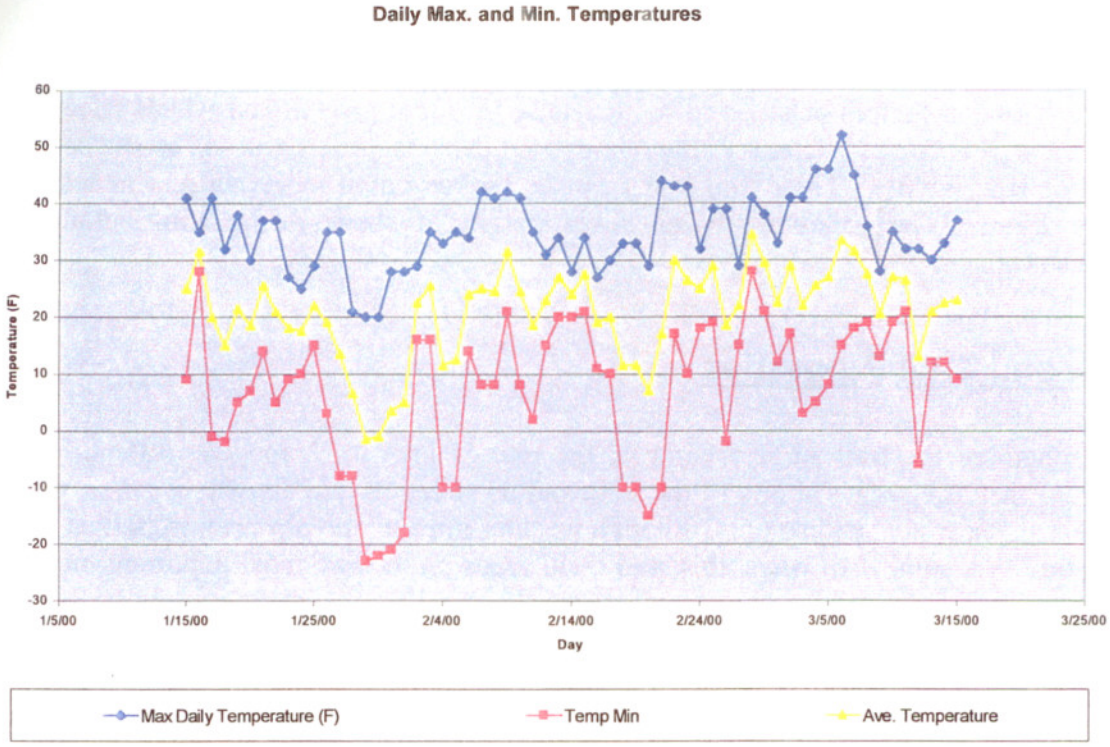

Figure 28. Air Temperature at West Yellowstone.

The snowfall data contained in Figure 27 shows that one major snowfall event occurred during the test period. This "large" snow event happened between 2/12 and 2/15. Over this 4 day period, approximately 26" of snow fell at West Yellowstone. This snowfall was fairly constant at between 6" and 8" per day over the period. The total effect on the snow depth over these days was a net gain of about 15" at the measurement site. This occurred at a rate of approximately 4" per day. This major snow event was the only time during the test period that enough snow fell to affect the trail surface condition to any great extent.

Throughout the remainder of this analysis, the plots of measured bumps will be referenced out of the appendices as well as inserted within this text in several different forms. The graphs are coded to indicate where each of the readings was taken and at approximately what time and date. For the first part of this analysis, only data sets from the "Standard Test Section" located about 1/4 mile east of the West Yellowstone gate will be used. The code on these data sets are as follows: The first 4 digits are "T1wy" depicting that test site. The fifth digit is either an "e" or a "w", this gives the direction of travel for the trail lane measured. The "e" stands for eastbound traffic and the "w" is westbound. The direction of travel on the "e" graphs is from left to right and for the "w" graphs it is right to left. The numbers at the end of each code coincide with the date the measurement was made. A description of each graph and data set will be made each time data is used.

Figure 29 contains several plots of measured bumps that were made throughout the test period. These were all measured in the eastbound lane at the "Standard Test Site."

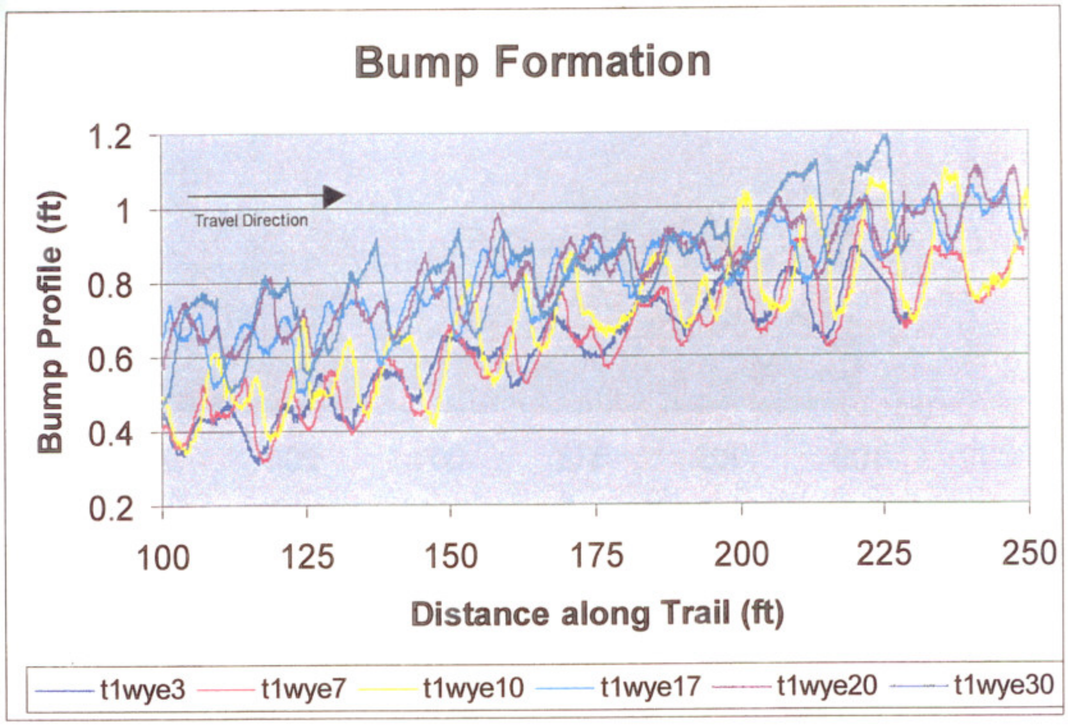

Figure 29. Bump Formation over Test Period.

The data for "t1wye3" was measured on 2/9 at 15:00, "t1wye7" on 2/11 at 13:10, "t1wye10" on 2/12 at 11:50, "t1wye17" on 2/15 at 13:30, "t1wye20" on 2/18 at 12:27, and "t1wye30" on 2/23 at 13:38. All of the plots in this graph contain the last measurement taken on each of these days in the eastbound lane. This is after the major amount of traffic has passed this section headed into the park (east). This also depicts the "maximum" bump height in this lane for the day, since very little additional traffic passes this section eastbound after about 1:30. Traffic volume data can be found for each of these days in Appendix A at the end of this report.

This set of bump profiles does not show much in the way of trends, but does show how the trail "height" changes throughout the test period. Further investigation gives the results of Figures 30 and 31. Figure 30 contains plots of three tests performed prior to the major snow event mentioned previously. These are the first three plots contained in Figure 29. It is clear from looking at this graph that the bumps formed for the 3 different days occur in almost the same spot. Keeping in mind that the trail is groomed nightly, this shows that the "old" bumps have not been groomed out of the trial totally, and that they reappear in the same place over and over.

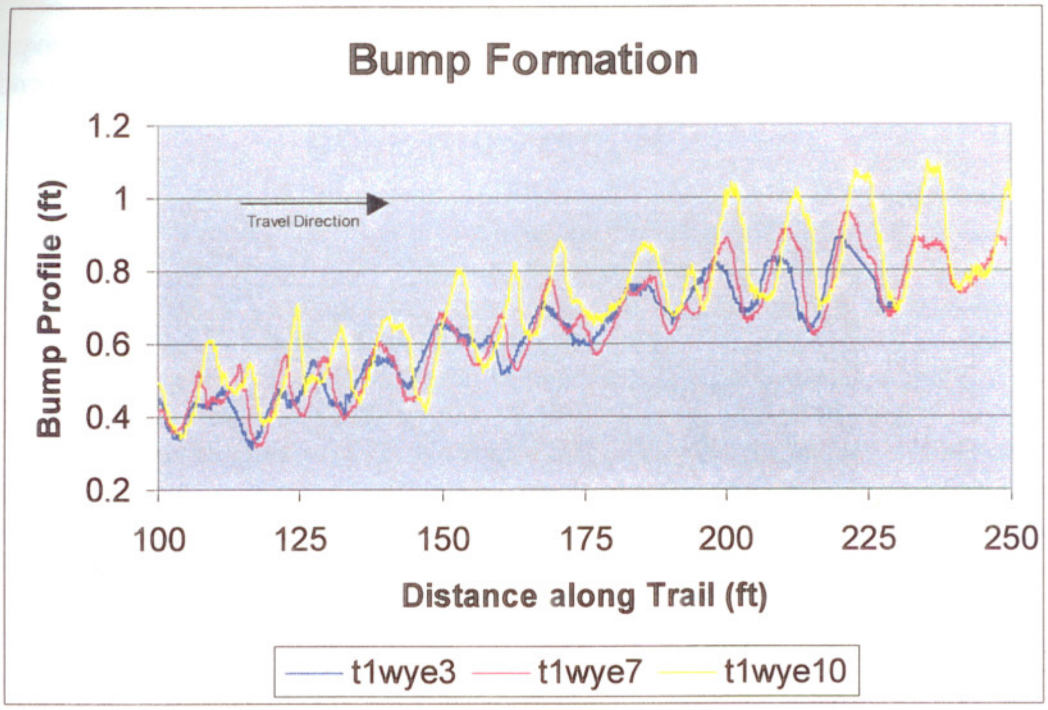

Figure 30. Bump Formation Early in the Test Period.

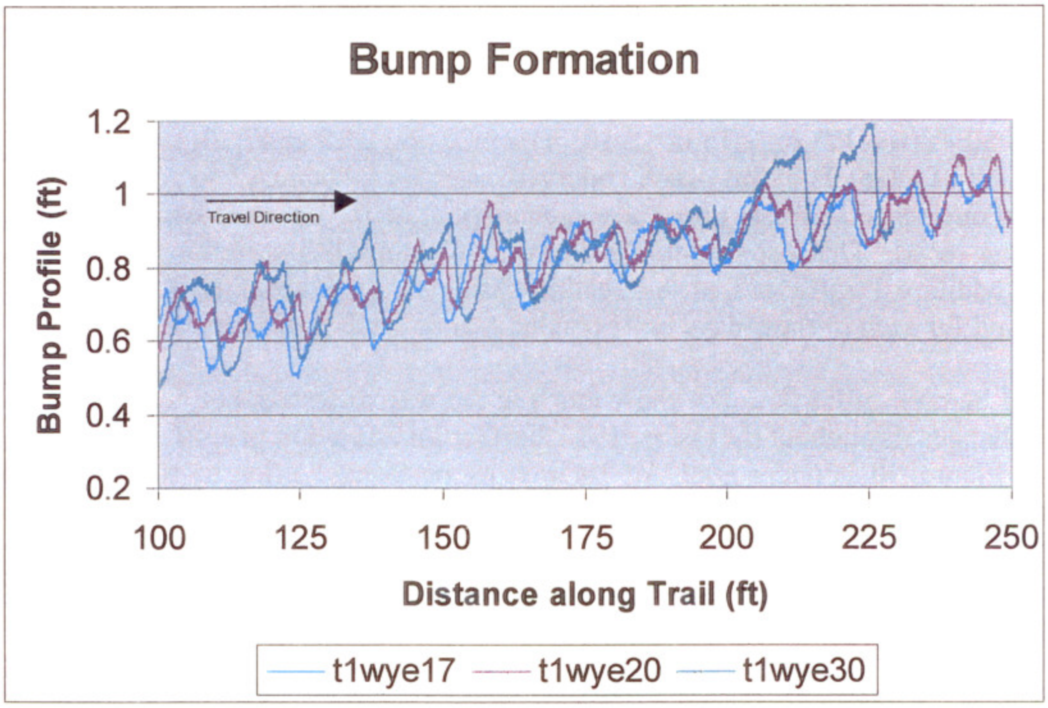

Figure 31. Bump Formation Late in the Test Period.

This is supported by previous work by the authors that bumps form rapidly when there is any surface abnormality on the trail, a bump or a dip. The tops of the old bumps create such a roughness.

Furthermore, the "low" spots of the bumps are filled with loose snow after grooming, and this snow is easily moved out and onto the top of a growing bump to accelerate the process. Figure 31 contains three tests performed after the large snow events. These data sets show the same progression as the earlier 3. It is apparent from these two figures that the troughs are growing much more rapidly (getting deeper) than the peaks get higher. This supports the fact that the snow "groomed" into the low spots does not get compacted as well. Attempts to measure differences between the strength of the snow in the troughs compared to the peaks were made on several occasions during the test period. No major differences could be seen. It is thought that this is because the bumps generated on this trail never get very big and that this "soft" layer is usually only 2", or so, thick. The Rammsonde used to measure strength is not designed to measure on these thin layers. Overall, the trail base was very hard.

It also appears from these sets of data that the bump peaks and troughs may be moving slightly in the direction of travel of the snowmobiles. This is possible, and probable, when the mechanics of snow movement is thrown into the analysis. This movement is only slight, however.

Looking back at Figure 29 it is difficult to assess whether or not the bumps over the whole period, before and after the heavy snow, tend to be forming back in the same places. There are some that appear to be following this trend, but others that don't. It will take further investigation over a longer period of time to determine if after a large snow event the trail is "healed" or the old bumps come back to affect the new ones. In any event, this data shows that the "old" bumps must be totally cut out to eliminate their affect on new growth.

During the period of testing, the temperature did not vary considerably. This fact makes it difficult to make any predictions on how temperature affects the formation of bumps. There was one short period, however, that the temperature fell below the average by at least a few degrees. For the period of February 18 through the 21, the low temperature fell below zero by as much as -10° F. Analysis of the bumps formed during this period does not show any measurable difference as compared to bump measurements made in the "warmer" periods. Further investigation shows that even with the relatively cold nighttime temperatures, the snow pack temperature is affected for only a short period. Figure 32 is a graph depicting the snow surface temperature as measured throughout the test period. Figure 33 is a graph similar to Figure 32, with the temperature at 10 cm depth into the trail.

This short period of time that the temperature was "cold" followed directly after the heavy snow event. This further complicates trying to decipher between the effect of snowfall and temperature as separate items.

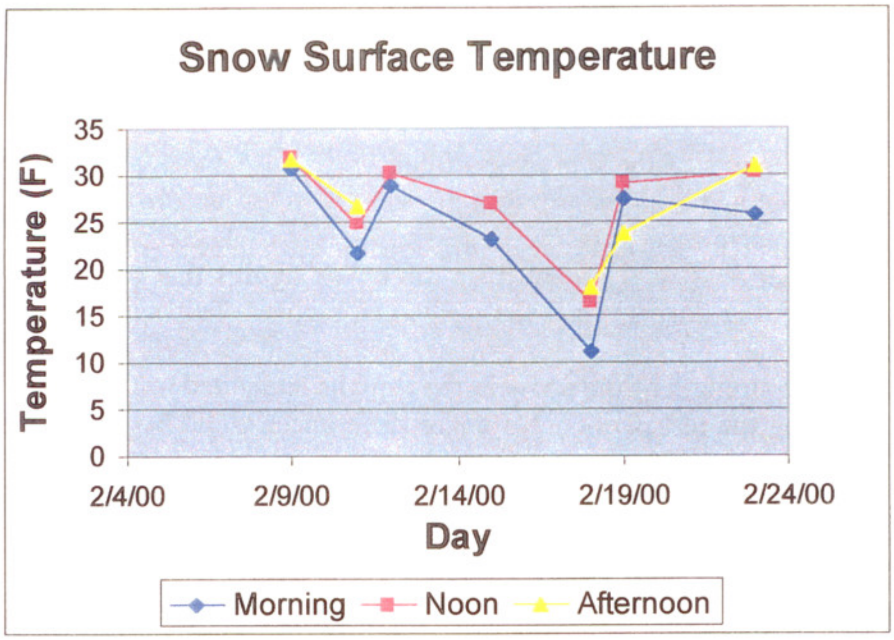

Figure 32. Snow Surface Temperature on Trail.

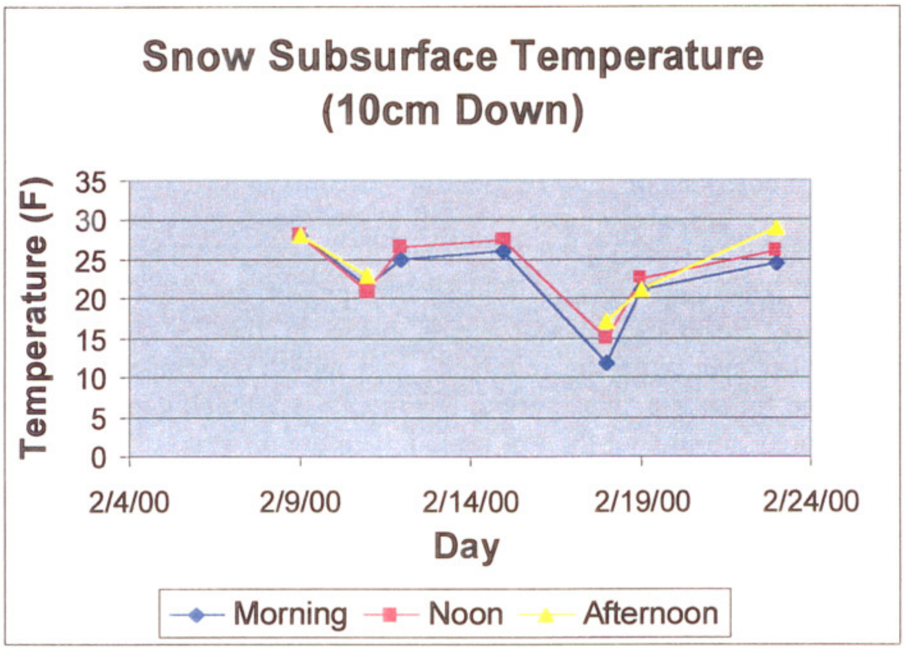

Figure 33. Snow Temperature 10 cm down from Trail Surface.

Traffic Effects

Obviously, the main reason for trail bumpiness is the presence of snowmobile traffic. The more snowmobiles that travel over a section of trail, the greater the potential for bump growth. Numerous profiles were measured over the period of this study. These are contained in plots contained in Appendix B and in part in the following analysis. Use of the traffic amounts contained in Appendix A will also be made. There will be some jumping back and forth between the Appendices and graphs contained within the body of the report.

The first question to be answered as to snowmobile generated mogul formation is "is there a standard set of bumps formed, in general?" The basic set of bumps formed on trails is a long wave that appears to have a relatively constant wavelength at specified locations. For example, an analysis of all of the profiles measured at the T1, West Yellowstone Entrance Site, show a wavelength that varies from about 11 ft to 12.5 ft. This area has well defined traffic direction lanes, and a set speed limit, 45 mph. The speed limit here tends to be adhered to quite closely. The profiles measured at the West Entrance Gate depict a much shorter wavelength, in the neighborhood of 7.5 ft. This is consistent with other measurements by the author in Michigan, and is caused by a difference in average vehicle speed. The slow speeds coming into the gate area form bumps of shorter length. The wavelength of the section crossing the bridge north of West Yellowstone is even shorter yet, 6.25 ft. Since there was only 1 measurement taken here and traffic volumes, grooming schedules, and speeds are unknown, it is difficult to give a reason for this besides the fact that the nature of the bridge crossing slows traffic and also the extreme roughness of this section keeps speeds down.

All this said, bumps tend to form a constant wavelength for a given traffic scenario. This length may vary a bit due to snow conditions, but the relatively long length and variability from section to section make it difficult to pinpoint.

The more complicated and involved variable of bump formation is the amplitude of the moguls with increased traffic volumes. Figure 34 is a plot of a section of trail at the T1 site measured on 2/15. This graph has 3 curves measured at different times during the day. It is easy to see from this set of plots that the bump amplitude grows throughout the morning period. Using the blue, relatively smooth plot (T1wye11) as a baseline, an idea of how fast bumps grow can be realized. Between the measurement of T1wye11 and the pink curve, T1wye14, there were 137 snowmobiles passing over the test section headed into the park. The curves show a rapid growth in amplitude with this number of vehicles. Between T1wye14 and T1wye17, the yellow plot, 238 more snowmobiles passed over the section.

The majority of the bump formation on this day takes place after the first 137 snowmobiles. In fact, the amplitude grows from nearly zero to between 0.2 ft (2.4 in) and 0.3 ft (3.6 in) with this number of passages. After that, the bumps become a little bigger, but not at nearly the same rate. This indicates that the bumps come to some equilibrium height after only a few vehicles and then remains fairly constant. Another interesting thing that can be seen from this graph is that the bumps seem to grow most rapidly down into the trough and the high part, the peak, doesn't seem to grow as much. This supports the idea that the "old bumps" are probably still dominant within the mogul field, the high parts are high and the lows are soft.

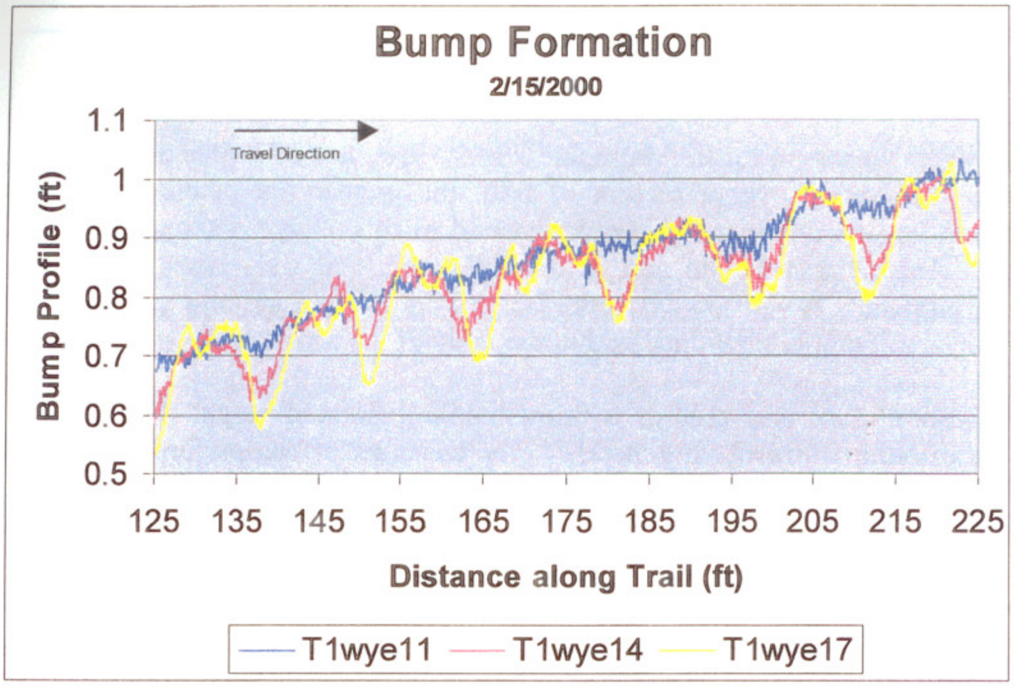

Figure 34. Bump Formation with Increased Snowmobile Traffic - 2/15/2000.

Figure 35 is a plot of a short section of trail for the same day as in Figure 34. This graph contains profiles for traffic volumes at a closer interval. The progression of the growth through time can be seen with this combination.

Figure 36 contains the profiles for the same general area on another day. The number of snowmobiles between T1wye22 and T1wye23 was 158, T1wye23 and T1wye24 was 157, T1wye24 and T1wye25 was 151. This set of profiles shows that most of the growth occurs with the first 315 vehicles. Dependant upon the bump examined (of the 3) the first 158 may not cause as much growth. It is possible that this is due to a smoother trail to start with, maybe fewer passages prior to T1wye 22 because this profile was taken at 6:30 as compared to 7:16 in the previous example, or different trail conditions. The concept of peaks growing slower than troughs is also less evident for this set. Figure 37 is a section of the same plot as Figure 36 in blown up view to give a better idea of rate of growth. The amplitude of these bumps is between 0.2 and 0.3 ft (2.4 and 3.6 inches).

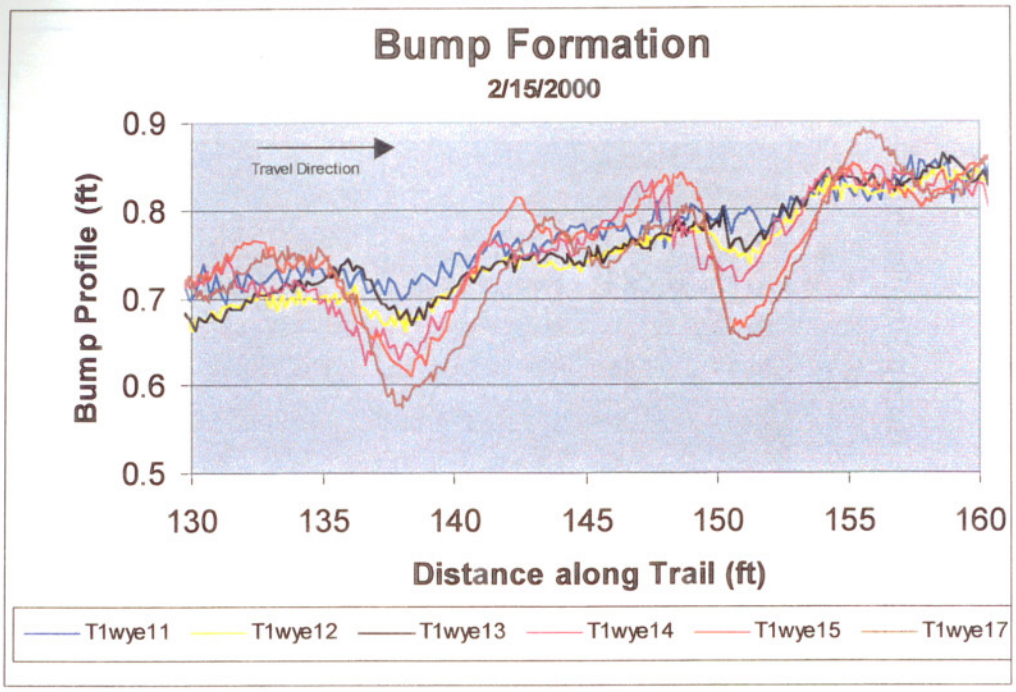

Figure 35. Bump Formation with Increased Snowmobile Traffic - 2/15/2000.

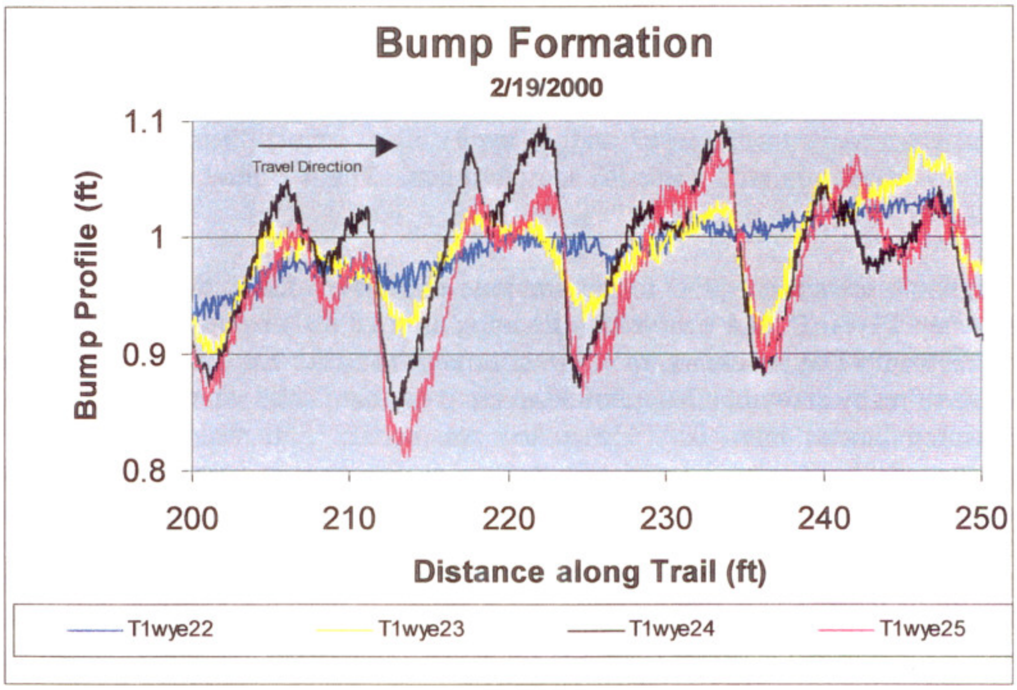

Figure 36. Bump Formation with Increased Snowmobile Traffic - 2/19/2000.

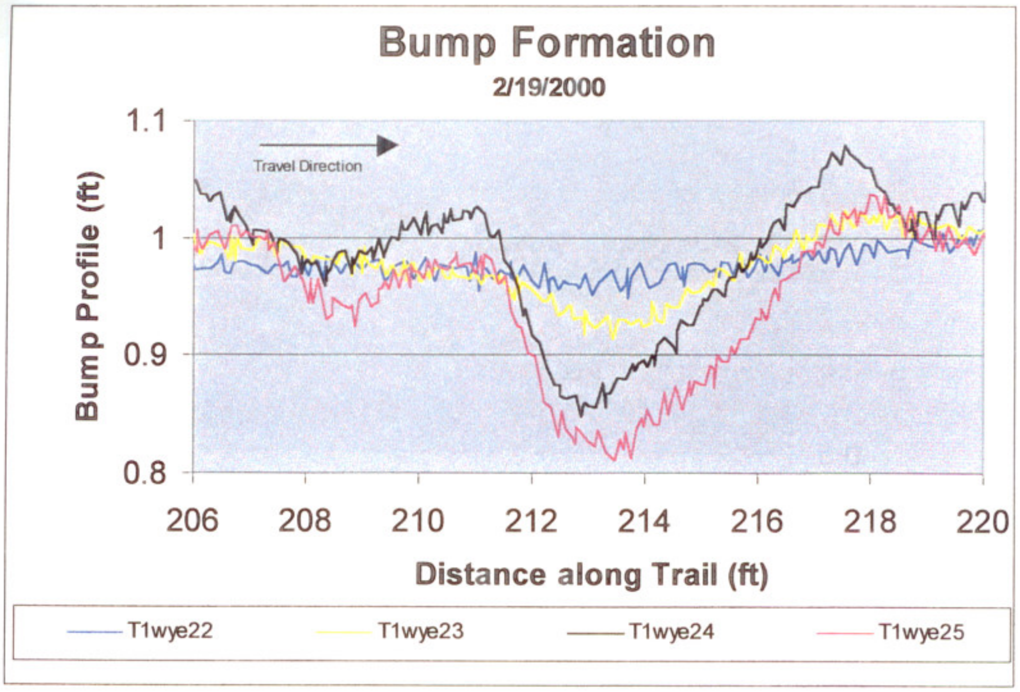

Figure 37. Bump Formation with Increased Snowmobile Traffic - 2/19/2000.

Figure 38 contains the profiles measured on 2/9/2000. The first in the sequence, T1wyeast, was not measured until 1030 on this day. This is after the heavy morning traffic has passed this section. The bumps have already been set up by this time and show up well on the graph. The number of snowmobiles passing by between T1wyeast and T1wye2 was 34 with 62 more passing between the measurement of T1wye2 and T1wye3. It is obvious from these three profiles that little or no growth occurs with these 96 snowmobiles. The amplitude of these bumps is again between 0.2 and 0.3 ft (2.4 and 3.6 inches).

Figures 39 and 40 are similar plots to the previous examples. 556 snowmobiles passed over the section between T1wye28 and T1wye29 with an additional 80 between T1wye29 and T1wye30. This was President's Day weekend, the busiest time of the year for this portion of trail. On this day there are so many snowmobiles inbound to the park that it was impossible to break the traffic to do measurements at intervals. Hence the reason that 556 sleds passed before the first measurement. Both Figures 39 and 40 show that the bumps have probably gotten to the "equilibrium" point by the second measurement. Also, there is already a bump sequence evident by the first profile. The amplitude of these bumps is on the high side of what was seen throughout the test period. They are, on average, at least 0.3 ft (3.6 in) in height. Some of the bumps in this profile also show a distinct point on the east side of each peak. This is consistent with previous works by the author that moguls in single direction lanes tend to have a "kick up" peak formed in the direction of travel.

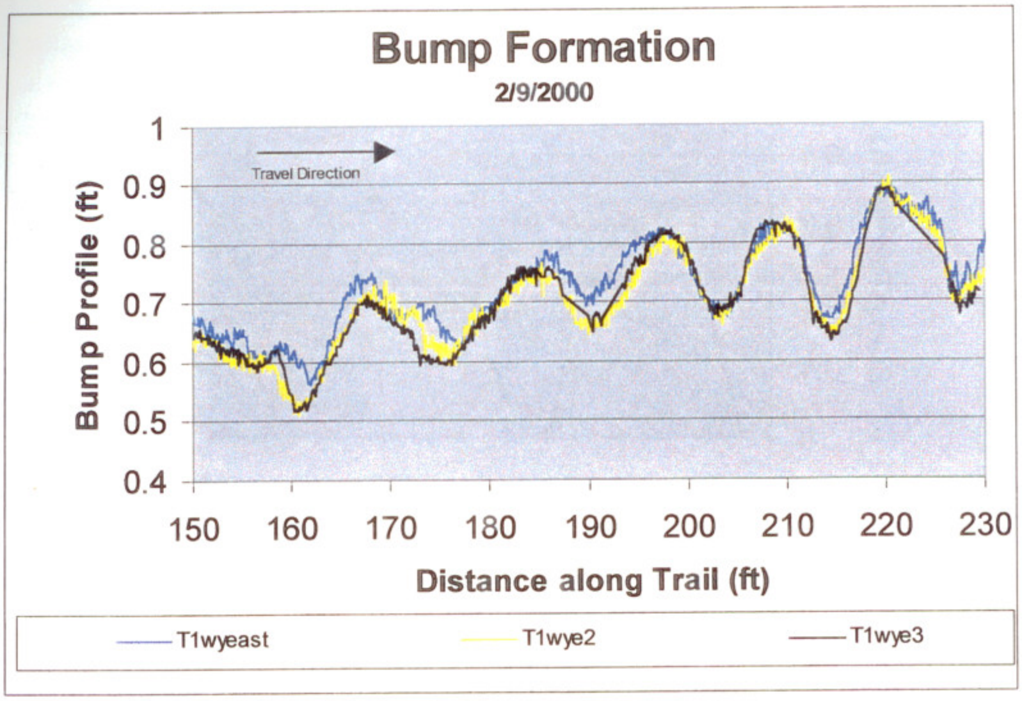

Figure 38. Bump Formation with Increased Snowmobile Traffic - 2/9/2000.

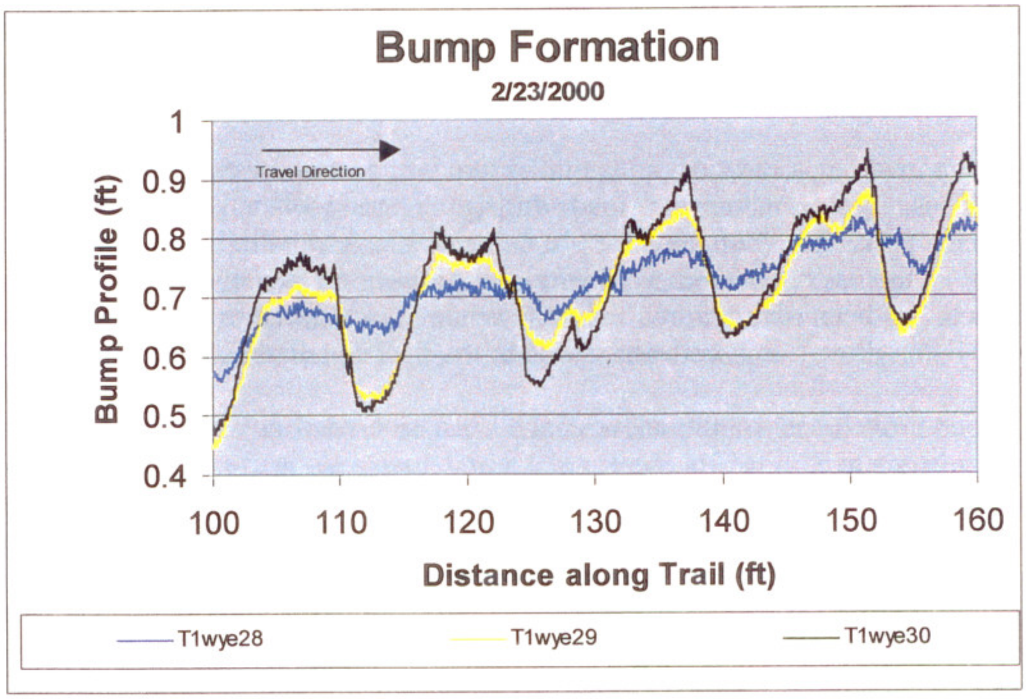

Figure 39. Bump Formation with Increased Snowmobile Traffic - 2/23/2000.

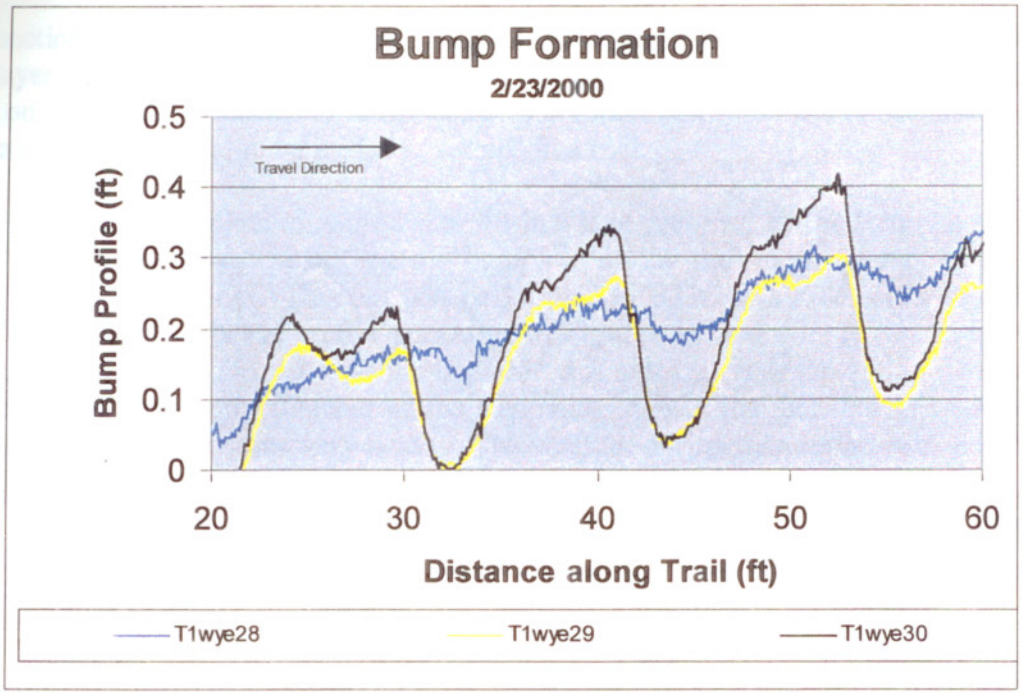

Figure 40. Bump Formation with Increased Snowmobile Traffic - 2/23/2000.

In general, the amplitudes of all of the bumps measured on the T1 sections fall into the same range. It can be seen by close examination of each profile that this varies within a single mogul field, however. Extensive analysis was made within this project to determine the effects of snow temperature on the growth. The final conclusion of this is that the bump heights very so little on average over the period that it is difficult to decipher what causes the differences.

Attempts were made on a few occasions to measure bumps in the westbound lane at T1wy in the afternoon. These measurements were made during the period when the major traffic was coming back out of the park. The plots of these are contained in Appendix B. These profiles show the same trends as the eastbound measurements, the problem is, however, that traffic for morning measurements has been diverted into this lane while inbound lane measurements are made and the resulted bump growth is affected by traffic in the opposite direction.

During the controlled test of the snow coach on a side road adjacent to the T1 site, several profiles were measured. Profiles measured longitudinally along the path of travel of the snow coach are contained in Appendix B on pages 33 and 34. These profiles show bumpiness forming along the section but there does not appear to be any distinct pattern to it. Page 35 in Appendix B contains a cross section of the same snow coach trail section. This plot shows several bumps across the trail but again there is no discernable pattern. Note that the bumps shown in this figure are not distinct track ruts, they are too close together. Also, the amplitude of these bumps is quite small. Keep in mind that this test is only a limited number of passes on a single day. The visual interpretation of this test confers that there was not really a pattern of bumpiness set up in this test. This is not to say that it will not occur over a winter period, this is unknown.
During the controlled snowmobile test on this same section of trail, passes were made using the KRC snowmobiles in an attempt to generate bumps on a newly formed trail. Pages 36 and 37 of Appendix B contain profiles from these tests. Again, there appears to be no pattern of bumps set

up in this section. This is due to the fact that the trail was groomed on top of a relatively thick old snow layer and that there were only 100 passes made. These same sorts of tests have been performed on numerous occasions at KRC, and it was found that it takes a considerable number of passes to get a mogul field to be initially "set up" in a trail.

Figure 41 contains a set of plots measured near T1 in a lane groomed by the Renovator groomer. The Renovator is designed to cut out the old bumps in an icy trail in an attempt to keep them from rapidly forming new ones. This test was performed on 2/23/2000, President's day weekend. This was during the same heavy traffic period as in Figures 39 and 40. It can be seen that a "normal" set of bumps has formed with the traffic in this section. It is the authors' opinion that this is inconclusive to the effectiveness of the Renovator due to the fact that this was a single grooming and that the traffic was very heavy. The weather during this period was also far from ideal for grooming. The temperatures were relatively warm and it had rained over the period prior to the test. It is probable that this section may need to be groomed several times to get the old bumps out and to re-build a durable trail.

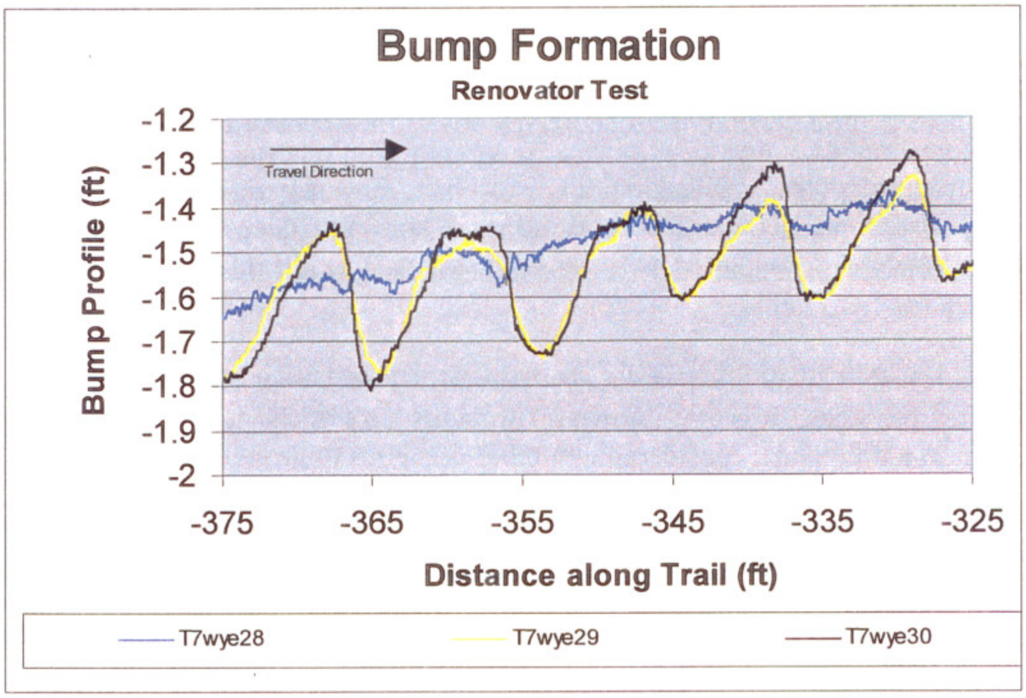

Figure 41. Bump Formation with Increased Snowmobile Traffic - Renovator 2/23/2000.

CONCLUSIONS

Probably the most important conclusion that was developed during the bump measurement portion of this study was that the bumps appear to reoccur in the same places even after nightly grooming. This justifies the thought that present grooming practice does not cut deep enough to eliminate the "signature" of old bumps. These same bumps just redevelop with traffic. There was an indication from operators that the early December weather did not help this situation, but it is still believed that the equipment has problems cutting the icy bumps. There is a slight progression of the mogul form in the direction of travel, but this does not really effect the roughness.

Roughness occurs after only a limited number of passages. The bumps seem to reach some "equilibrium" for a given section after a fixed number of snowmobiles. Bump growth has been seen to be accelerated by warm weather in other studies by the author, but this phenomena is unclear from this test. In general, warm snow does not bond well, and in turn bumps up rapidly.

Snow coaches degrade the snow road surface in a manner that is not similar to snowmobiles. It appears that there is little generation of short, choppy bumps caused by snow coaches, although this conclusion is not drawn from long periods of traffic in as large numbers as snowmobiles. Only a limited number of passes were made over the controlled section test and these bumps were not seen. The snow coaches 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.

Bumps on controlled snowmobile test did not "mature." This is probably due to a hard, icy snow road and limited passages. It is also known by previous tests of the authors that the "first" set of bumps present in a trail take a considerable number of passes to grow into any pattern.

A single test using the "Renovator" did not appear to make the surface any smoother. It is probable, however, that this test was not performed under the best conditions. The renovator was used late in the season when the snow road was extremely hard and was difficult to work. The rain and icing of the previous day made matters even worse.