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At the End of a Slippery Slope: A Pilot Study of Deceleration Mats for Snow Tubing

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Abstract: On-slope pilot testing of snow tubes was conducted at two ski areas in the United States to examine the effects of deceleration mats. Snow tube and rider kinematics were measured using an instrumented bodysuit and a GPS system worn by the rider. For each test, the riders descended a tubing run with minimal input and stopped in the run-out area. Snow tube and rider speeds when entering the run-out area were controlled to be approximately 9.5 m/s. Test trials were conducted with and without deceleration mats. Four deceleration mat conditions were tested, including two raised surface protuberances (ribs and projections) and two mat geometry parameters (flat and folded). The deceleration and effective coefficient of friction (COF) were determined for each trial. Data were recorded for 75 test trials with a mean (± standard deviation) speed entering the run-out area of 9.5 (±1.8) m/s. There were no significant differences in the deceleration or effective coefficient of friction between the surface protuberance conditions. The peak deceleration and effective COF for the folded mats (5.1 ± 1.6 m/s^2 and 0.26 ± 0.14) was greater than for the flat (3.3 ± 0.8 m/s^2 and 0.10 ± 0.07) and no mat (0.06 ± 0.3 m/s^2 and 0.08 ± 0.03) conditions (all $p < 0.05$). Deceleration mats in run-out areas slow snow tube riders faster than without deceleration mats. Folding the deceleration mats produced greater deceleration but did not produce significantly different kinematics for the riders.

Keywords: snow tubing; sledding; ski area design; ski area safety

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1. Introduction

Snow tubing is a recreational adventure sport in which a participant rides downhill over snow on an inflated tube. There are varying levels of sensation seeking amongst snowsports participants [1] and snow tubing allows individuals to participate in snowsports who may not otherwise be interested or capable. Though many people ride snow tubes on open, unmanaged land, a growing number of people in the USA are snow tubing at ski areas or dedicated snow tubing facilities where snow tube riders descend in lanes that are separated by berms. The lanes and berms are built and maintained using typical snow grooming equipment. According to the National Ski Areas Association Kottke report [2], there were more than 85 snow tubing hills operated by ski areas during the 2018/2019 season in the USA, with over 1.75 million customer visits.

A commercial snow tube is different from a typical consumer tire innertube. A commercial snow tube is typically a butyl rubber inflated ring torus with a fitted cover consisting of a plastic bottom and a nylon canvas top surface, with webbing handles for a rider to hold. A commercial snow tube cover can have a bottom surface that is a hard polymer (such as polyethylene or polyester) or a soft, urethane-coated vinyl.

Snow tubing operations have mechanical systems, such as a conveyor lift, that carry snow tubes and riders uphill to the top of the lanes. To descend, a snow tube rider sits in the center of the ring torus or lies chest down on the top of the snow tube and descends the hill in the tubing lane. To facilitate downhill acceleration of the snow tube and rider (due to gravity), snow tubing requires a low coefficient of friction (COF) between the snow and the bottom surface of the snow tube. At the end of the downhill section, the snow tube and rider decelerate and stop in an area called the run-out. Design of the run-out (length, slight elevation increases, deceleration assistive devices, etc.) is important because a rider (and others around the run-out area) may be at increased risk of injury if the snow tube and rider continue past the designated run-out area.

The COF between the snow and the bottom surface of a snow tube changes with snow conditions, snow types, and other environmental factors. For example, the COF would be different for fresh powder snow when compared to granular, hard packed snow. According to the scientific literature, the COF between snow and polymers (such as those found in skis and snowboards) is dependent on many factors that include the characteristics of the snow, water content of the snow, temperature, speed, etc. [3,4] The complex interactions of these variables can change quickly (within minutes) and the COF between snow and a snow tube can vary significantly over the course of a day. A change in COF will affect the speeds of snow tube riders as they descend, the speed at which they enter the run-out area, and the distance traveled in the run-out area. Because of the variability in COF for snow tubing, many ski areas in the USA use rubber deceleration mats in the run-out area to slow snow tube riders.

According to some members of the snowsports community, snow tubing deceleration mats slow snow tubes too rapidly and makes riders more likely to fall off their snow tubes (that is, destabilizing the riders). Others believe that deceleration mats do not slow snow tubes enough (if at all) and have suggested that snow tubing operators fold deceleration mats to slow better snow tubes and riders. To our knowledge there has been no scientific study of the efficacy of snow tubing deceleration mats that could help guide the design and analysis of a snow tubing park. To this end, we examined the deceleration and effective COF produced by snow tubing deceleration mats by measuring directly their effect on snow tubes riders.

2. Materials and Methods

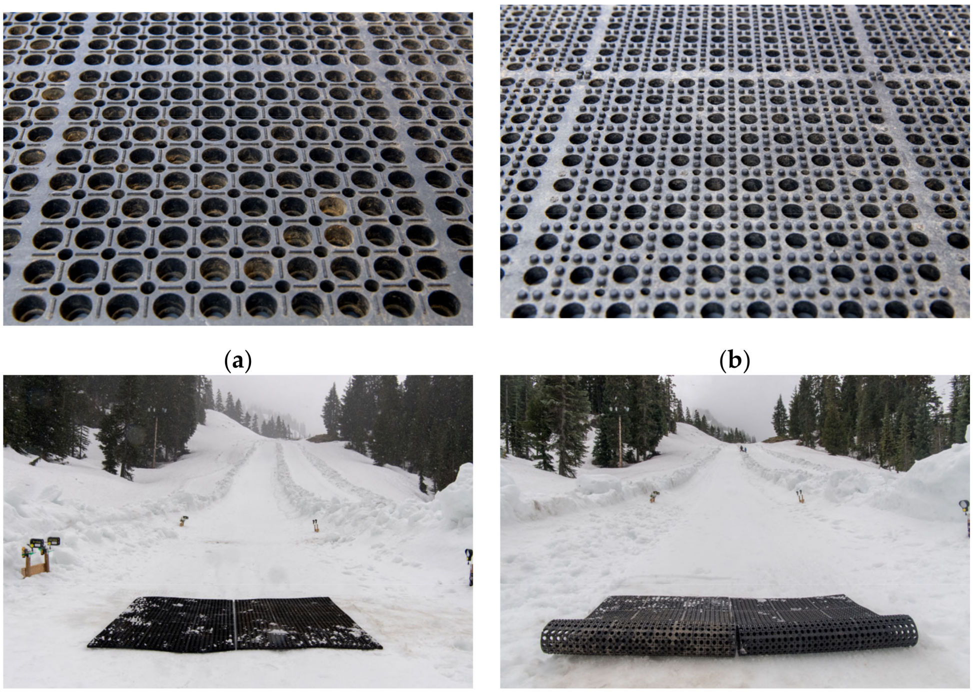
On-slope testing was conducted at two ski areas in the USA: Stevens Pass in Skykomish, WA, USA and Mammoth Mountain in Mammoth Lakes, CA, USA. Four male participants took part in the study (mean $\pm$ standard deviation: 27 $\pm$ 8 years old; 83.2 $\pm$ 17.4 kg; 181 $\pm$ 4 cm) and rode commercially available snow tubes on 5.5-meter (18 feet) wide tubing lanes constructed with horizontal (less than 1.0° slope) run-outs, as measured with a 1.8 m digital level in the area of interest. Before taking part in the study, all procedures were explained to each participant and informed consent was obtained as approved by the Institutional Review Board at Guidance Engineering and Applied Research.

2.1. Test Equipment

Participant kinematics and body motions were measured using an instrumented body suit (MVN Link, Xsens Technologies, Enschede, The Netherlands) containing 17 inertial measurement units (IMUs) that were worn under snowsport clothing. Each IMU contained a tri-axial set of linear accelerometers (range: $\pm$160 m/s^2; noise: 0.003 m/s^2/$\sqrt{\text{Hz}}$), angular rate sensors (range: $\pm$2000 °/s; noise: 0.05°/s/$\sqrt{\text{Hz}}$), and magnetometers. The data from each sensor were recorded at 240 Hz and processed using the Xsens MVN Studio BIOMECH software package. The output from this system included kinematics (acceleration and angular rate components) of the body segments and the center of mass (COM) location. In addition to the kinematic body suit, the participants were also instrumented with a GPS system that measured global position near the thoracolumbar spine and speed at 5 Hz (G2X Extreme Data Logger, Racepak, Rancho Santa Margarita, CA, USA); the GPS unit also had a set of linear accelerometers (range: $\pm$98.1 m/s^2; noise: 0.005 m/s^2) that recorded at 100 Hz. These additional sensors were placed in a vest that did not disturb the snow tube rider; see Figure 1.

Figure 1. Participant riding position on a snow tube. The participant is wearing the kinematic body suit under his winter clothing.

Four photogates (PR1A, Alge Timing, Lustenau, Austria) were placed near the bottom of the tubing run to determine the time when the rider reached the photogate locations. Two photogates were placed 0.35 m uphill of the run-out area. The other two photogates were placed in the run-out area, with the one furthest downhill located at the uphill edge of the deceleration mats. Each deceleration mat was approximately 1.52 m long, 0.91 m wide, and 1.6 cm thick. To increase the likelihood that the snow tube would ride fully over the mats, two deceleration mats were used to span the tubing run (in the left-to-right direction); see Figure 2c,d. For the analysis, a first and second set of mats were used along the direction of travel; these sets were separated by approximately 0.3 m and 0.8 m of snow surface when the mats were flat and folded, respectively.



(**a**) (**b**)

(**c**) (**d**)

Figure 2. (**a**) Close-up view of a deceleration mat showing the "ribs" on the top surface (**b**) Close-up view of a deceleration mat showing the "projections." (Bottom row) View uphill of the tubing lane, with the first set of deceleration mats in the following conditions: (**c**) *flat*, *ribs* and (**d**) *folded*, *projections* condition. Two mats (left to right) on the tubing run were used to increase the likelihood that the snow tube would ride fully over the mats.

Data from the photogates were sampled at 2400 Hz (Nanoslice, Diversified Technical Systems, Seal Beach, CA, USA). Using the timing and the distances between photogates, the average speeds for the snow tube rider were calculated: these speeds matched well those recorded by the GPS system at the beginning of the run-out area and the speed at run-out entry presented will be from the GPS system. All systems were synchronized using remote camera triggers (Pulse II, PocketWizard USA, Shelburne, VT, USA) and impulses measured by the accelerometers of each system; synchronization allowed for the determination of kinematics at locations relative to the uphill edge of the deceleration mats. For each test trial, real-time video was recorded at 29.97 frames per second at a resolution of 1920 × 1080 (HDR-XR500V, Sony, Japan).

2.2. Test Methods

We examined two deceleration mat parameters. The first parameter was the mat geometry and the second was the mat surface in contact with the snow tube bottom. There were two deceleration mat geometry conditions tested: (1) *flat*—the mats were flat on the snow surface, and (2) *folded*—a downhill section of each mat was folded under such that between one-third and two-thirds of the mat was used in the fold and the rest of the mat remained flat on the snow surface; see Figure 2. The second mat parameter was the type of raised protuberance on the surface that faced the snow tube: (1) *ribs*—thin, linear ribs; and (2) *projections*—rounded, slightly tapered cylinders; see Figure 2.

During testing, the air temperature ranged from −1 to 13 °C and the snow temperature was 0 °C. Prior to each test, the deceleration mats were turned over (so that the side presenting to the snow tube was at the snow temperature of 0 °C) and placed in the *flat* or *folded* configuration. For each test, the participants loaded the snow tube chest down, descended the tubing lane head first, and rode over the mats (when used); the starting point was adjusted to control the speed of the rider as he entered the run-out area (target speed was 9.5 m/s). Prior to testing, the participants were asked to ride normally in the face-down configuration (that is, chest toward the snow tube—see Figure 1), to try not to slow during descent, and to keep their legs and feet off the snow and mats except to keep themselves facing straight downhill (by using lightly their feet on the snow in the descent region). Multiple test trials were conducted without mats and with mats in the four conditions related to the mat parameters (*flat* and *folded*; *ribs* and *projections*).

2.3. Data Processing and Statistical Analysis

Power spectrum densities and a residuals analysis were used to determine appropriate filter frequencies for the linear acceleration and angular rate data. The data were processed and filtered digitally to remove noise using a 4-pole, zero phase-shift Butterworth filter with a cutoff frequency of 60 Hz. All data processing was conducted in MATLAB (R2019a, MathWorks, Natick, MA, USA).

For each test trial, the parameters related to the rider kinematics were ascertained, including: resultant linear acceleration (from the pelvis accelerometers and checked with the accelerometers in the GPS unit), the peak resultant pitch over rotation rate for the axes parallel to the snow surface, and the position of the rider's center-of-mass (COM) relative to his hands (and the resultant distance). To quantify the pitch over angle, the angle between (a) the snow surface and (b) the vector between the rider's COM (or the pelvis) and his hands was determined.

For each test trial, the peak acceleration over the deceleration mats was determined. For tests without deceleration mats, the peak acceleration was determined in the region where the flat deceleration mats would have been placed. In addition to the peak acceleration, the average acceleration over the deceleration mats was determined. Because the run-out regions were flat with no slope (that is, 0° slope) and there was no observable motion between the rider and tubes while traversing the deceleration mats, the effective (or average) coefficient of friction (COF) over the deceleration mat was determined using the balance of linear momentum:

$$m \times a_{\text{ave}} = -\mu_{\text{eff}} \times m \times g \tag{1}$$

that simplifies to:

$$\mu_{\text{eff}} = -\frac{a_{\text{ave}}}{g} \tag{2}$$

where μ_{eff} is the effective (average) coefficient of friction, a_{ave} is the average acceleration while in the deceleration mat region (components along the body in the direction of downhill motion), m is the mass of the rider and tube system, and g is gravity.

The data were compared between the four conditions (*folded*, *ribs*; *folded*, *projections*; *flat*, *ribs*; *flat*, *projections*). Pairwise t-tests with Bonferroni corrections (R 4.0, The R Foundation for Statistical Computing) were used to determine statistical significance; a significance level of 0.05 was used for all statistical comparisons.

3. Results

A total of 78 tests trials were performed. Data were collected for 75 tests in which the participants descended the tubing run and rode over the deceleration mats (when used); for three test trials, the data acquisition system did not record or the snow tube did not reach the run-out area. The mean ($\pm$standard deviation) speeds as the riders entered the run-out was 9.5 ($\pm$1.8) m/s with a range of 5.0 to 14.1 m/s. There was no difference in speed entering the run-out between *flat* and *folded* conditions (p = 0.24).

The deceleration was not abrupt in any test, the deceleration mats did not cause the riders to fall off the snow tubes, and there was no observable forward motion of the rider relative to the snow tube. There were no significant differences between the *ribs* and *projections* conditions across all kinematic metrics and the effective coefficient of friction (COF); see Table 1. The deceleration and COF for the *folded* condition were significantly larger than the *flat* and no mat conditions.

Table 1. Mean kinematic data (standard deviation) from the snow tube interactions with the deceleration mats during testing. The effective coefficient of friction is based on the average deceleration across the deceleration mats. The kinematic data are presented for the resultant of the components along the snow surface. There were no statistically significant differences between *ribs* and *projections* conditions; the *combined* rows include all of the *ribs* and *projections* conditions for a particular mat geometry. Bold values indicate a statistically significant difference between *flat* and *folded* conditions (p < 0.05). (*) indicates a statistically significant difference compared to the *no mat* condition (p < 0.05).

Deceleration Mat Condition	No. of Tests	Speed Entering Run-Out m/s	Peak Deceleration m/s^2	Pitch Over Rotation Rate °/sec	Change in Hand to COM Distance on Mat cm	Effective (Average) Coefficient of Friction in Mat Area
No Mat	11	8.5 (0.7)	0.6 (0.3)	–	–	0.08 (0.03)
Flat						
Ribs	11	9.7 (1.9) *	3.5 (0.6) *	12 (16)	1.4 (0.4)	0.09 (0.06)
Projections	18	9.2 (1.8) *	3.2 (0.8) **	15 (12)	1.4 (1.2)	0.11 (0.10)
Combined	29	9.4 (1.8) *	3.3 (0.8) *	13 (13)	1.4 (0.7)	0.10 (0.07)
Folded						
Ribs	17	9.7 (1.9) *	**5.1 (1.5) ***	18 (20)	**3.7 (1.5)**	**0.24 (0.13) ***
Projections	18	10.1 (1.9) *	**5.1 (1.8) ***	16 (13)	**3.7 (2.1)**	**0.28 (0.16) ***
Combined	35	9.9 (1.9) *	**5.1 (1.6) ***	17 (16)	**3.7 (1.7)**	**0.26 (0.14) ***

When the deceleration mats were in the *folded* condition, the snow tube and rider rotated back slightly as they compressed the folded section of the mat and moved past the fold; see Figure 3d. Though the snow tube and rider rotated slightly forward (in the pitching direction) after passing the folded section, the magnitude of angle change was small (less than 7° across all tests) and not observable on the video. The average pitch forward for the COM was 6° (95% confidence interval: 4 to 7°) after the deceleration mats in the *folded* condition. For comparison, the average pitch forward was 4° (95% confidence interval: 0 to 7°) for the *flat* condition; there were no statistical differences between the two mat conditions. In some tests there was a small vertical bounce as the rider moved past the fold in the *folded* mat, but there was no difference in the vertical component of COM acceleration compared to the normal variability measured in the *flat* and *no mat* conditions. The distance between the COM and hands changed less than 7 cm while traversing the mats, with the component along the fore-aft direction changing less than 2.5 cm.

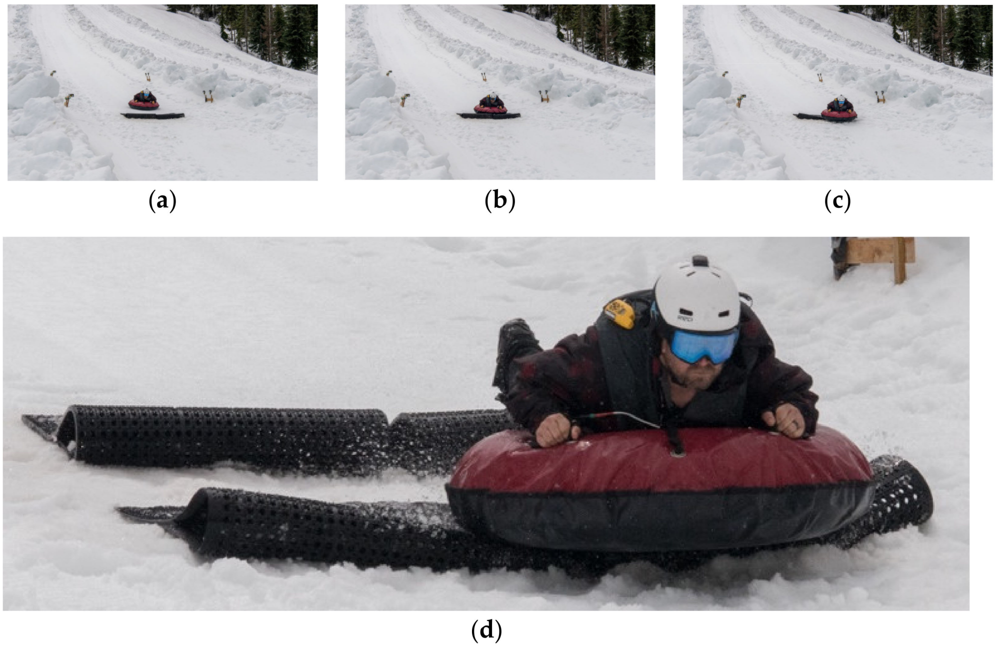


Figure 3. (**a**–**c** from **left** to **right**) Participant descending the snow tube run and traversing the deceleration mats that were in the *folded* configuration. When the deceleration mats were folded (regardless of the side—*ribs* or *projections*—presenting to the snow tube), the snow tube and rider compressed the folded section as they moved past. (**d**) Close-up of the compression of the folded portion of a deceleration mat.

4. Discussion

4.1. Measurement Values

In this study, we conducted on-slope measurements of snow tubing to analyze the effects of deceleration mats in the run-out area of a snow tubing lane. We found that deceleration mats were effective at slowing snow tubes and riders when compared to not having deceleration mats; the mats increased the peak deceleration by a factor of 5 for the *flat* condition and almost 8 for the *folded* condition compared to the *no mat* condition. Consistent with this, the effective (average) COF increased with deceleration mat use and was amplified when the mats were in the *folded* configuration. Though the deceleration increased significantly with mat use in our tests, it did not cause the riders to become unstable or fall off the snow tubes. Traversing the deceleration mats did not produce observable movement between the riders and snow tubes (from the video) and we measured less than 2.5 cm of fore-aft motion between the rider and snow tube when traversing and exiting the deceleration mats. Deceleration mats slow but do not destabilize riders.

The measurements in this study agreed well with data published on friction between other materials and snow. It was expected that the effective coefficient of friction (COF) for the snow tubes on the snow would be low in order to allow riders to accelerate downhill. The average COF for snow tubes on snow was in the range of other snow sports equipment on snow; see Table 2. The effective COF of the snow tubes on the deceleration mats was similar to or less than ski suit fabrics on snow, footwear on snow, rubber on ice, or tires on ice.

Table 2. Coefficients of friction for snow tubes on deceleration mats compared to other snow sports equipment, and footwear material, and tires on snow and ice. If the mean and standard deviation were not provided, the range is presented.

	Coefficient of Friction Mean (±std dev) or Range	Reference
Snow Tubes		
No mat	0.08 ± 0.03	*Current study*
Flat mat	0.11 ± 0.07	*Current study*
Folded mat	0.26 ± 0.14	*Current study*
Skis and Snowboards on Snow		
Skis—alpine	0.03–0.07	*Nachbauer* et al., *2016* [3]
	0.02–0.14	*Wolfsperger* et al., *2021* [4]
Skis—Nordic (cross-country)	0.02–0.22	*Budde* et al., *2021* [5]
Snowboards	0.03–0.14	*Wolfsperger* et al., *2021* [4]
Snowboards—boarder-cross	0.04–0.05	*Hasler* et al., *2016* [6]
Ski Suit Fabrics on Snow		
Racing suit, smooth	0.19–0.33	*Nachbauer* et al., *2016* [7]
Racing suit, dimpled	0.35–0.48	*Nachbauer* et al., *2016* [7]
Ski overall	0.26–0.31	*Nachbauer* et al., *2016* [7]
Footwear on Ice		
Natural rubber (tread)	0.27 ± 0.02	*Gao* et al., *2004* [8]
Polyurethane (smooth)	0.22 ± 0.03	*Gao* et al., *2004* [8]
Synthetic rubber (tread)	0.28 ± 0.03	*Gao* et al., *2004* [8]
Rubber on Ice, Snow, and Sand		
On snow covered ice	0.02–0.15	*Klein-Paste* et al., *2010* [9]
On sand-snow on ice	0.29–0.40	*Klein-Paste* et al., *2010* [9]
Tires on snow	0.32–0.62	*Ella* et al., *2013* [10]

There was improved stopping ability with the *folded* mats compared to the *flat* mats. Unlike folding the mats, there was no trend produced when changing the geometric protuberance on the mat surface (*ribs* vs. *projections*) presenting to the snow tube in our tests. Because we flipped or exchanged the mats before each test and presented a clean mat surface for the snow tube to contact, our study provided the best-case scenario for deceleration and for observing differences produced by the surface protuberances. In many tests, snow was pushed onto the deceleration mat by the snow tube and rider. Though we did not quantify the snow remaining on the mats after each test, the snow pushed onto the mat was unaffected qualitatively by the surface protuberances. Interestingly, the *folded* mats often shed naturally most of the snow that was pushed onto the mats in the tests. This occurred when either the mat unfolded after the snow tube moved fully past or during the decompression of the folded section. This "self-cleaning" ability of the *folded* mats may be useful for busy snow tubing operations or when it is actively snowing and may help produce more repeatable rider deceleration.

The kinematic data prior to the run-out area showed low frequency vibrations at the pelvis (near the COM), not unlike those found in other snow sports [11]. In the *folded* mat tests, the snow tube riders bounced slightly in the vertical direction after they passed the fold, producing a small vertical component of acceleration. This vertical component of acceleration was within the range observed prior to the run-out area during natural vibrations. The vertical component of acceleration could be attributed to the slight drop (on the order of 5 cm) from the double layer of mat at the fold. Despite this bounce, there was no significant increase in the pitch angle of the riders as they traversed the deceleration mats when compared to the *flat* mat condition. We hypothesize that the pitching motions of the rider were related to the compression of the snow tube as the rider weight shifted during deceleration and that inflation pressure of the tubes could influence this motion.

In this study, we attempted to keep constant the speed of the snow tube riders entering the run-out area in order to compare the effects from the deceleration mat conditions. The results, however, exhibited a large range of speeds (5.0 to 14.1 m/s) entering the run-out area; it is unclear what caused the variation, but changes in the snow conditions on the downhill portion of the tubing run and foot drag by the riders are two likely contributing factors. The Pearson's correlation coefficient (r) between the speed entering the run-out area and peak deceleration was 0.33; there was little relationship between speed entering the run-out area and the peak deceleration. A similar result was obtained for effective COF (r = 0.12). Because speed did not influence significantly the deceleration and effective COF across our tests, it is expected that additional, consecutive mats would further slow snow tube riders and would be recommended when shorter slowing distances are desired; additional tests at lower speed would be prudent to check this hypothesis.

4.2. Safety Considerations: Reduced Run-Out Distance Needed with Deceleration Mats

The use of multiple, consecutive deceleration mats in each snow tubing lane is not uncommon. Using a constant COF for each surface (snow or deceleration mats) and the balance of linear momentum, the run-out length and number of deceleration mats necessary to bring snow tube riders to a stop can be estimated. Care must be taken when assessing snow tube lane design in general because there are several difficult to specify factors that may influence the run-out kinematics for a given rider, such as rider mass, snow condition, temperature, variables related to air resistance, the amount of snow covering the deceleration mat surface, etc. With this caveat, the value of using deceleration mats can be shown with an example.

The effect of deceleration mats on the distance traveled in the run-out of a tubing hill is assessed below. To illustrate the effects of snow tube deceleration mats, we started with the balance of linear momentum for the center-of-mass of the snow tube and rider system on a horizontal (0°) run-out:

$$ma = -\mu_X(x)\cdot mg - \frac{1}{2}\rho C_d A v^2 \tag{3}$$

where x is the position of the system along the run-out, v is the velocity, a is the acceleration of the system, m is the mass of the snow tube and rider system, g is the gravitational constant, ρ is air density, C_d is the geometric drag coefficient, A is the cross-sectional area normal to the direction of motion, and $\mu_x(x)$ is the coefficient of friction that depends on the location of the snow tube and changes whether it is on snow, a flat mat, or a folded mat. Equation (3) can be rewritten to:

$$\ddot{x} + \frac{1}{2}\frac{\rho C_d A}{m}\dot{x}^2 + \mu_X(x)g = 0 \tag{4}$$

and solved numerically.

For this example, a snow tube rider enters a 50 m long, horizontal run-out at 9.5 m/s. The rider and snow tube system have a total mass (m) of 91 kg (75 kg snow tube rider with 16 kg of equipment, including clothing and a snow tube), with a total cross-sectional area (A) of 0.59 m^2 projected along the downhill direction of travel. Further consider the case in which there is no wind, the temperature is 0 °C, the air density (ρ) is 1.18 kg/m^3, and the C_d is 1.

Three example configurations were considered: (1) *no mats*—no deceleration mats are placed in the run-out and $\mu_X(x)$ is constant at 0.08; (2) *flat mats*—1.52 m long, flat mats are placed in the run-out and separated by 0.5 m, such that μ_x = 0.11 while the snow tube is on a flat deceleration mat and μ_x = 0.08 when the snow tube is on the snow between mats; (3) *folded mats*—the mats from *flat mats* (2) configuration are folded at the downhill end (the front edges of the mats remain in the same places), such that the mats are effectively

1.02 m long and μ_x = 0.26 while the snow tube is on a folded mat and μ_x = 0.08 when the snow tube is on the snow between mats. In this example, the number of deceleration mats was the same in the *flat mats* (2) and *folded mats* (3) configurations, but there is more space (tube-on-snow distance) between mats in the *folded mats* configuration because of the mat folding. Equation (4) was solved numerically (using MATLAB R2021a, Mathworks, Natick, MA, USA) for the three configurations; the velocity of the snow tube system as a function of distance travelled in the run-out is shown in Figure 4.

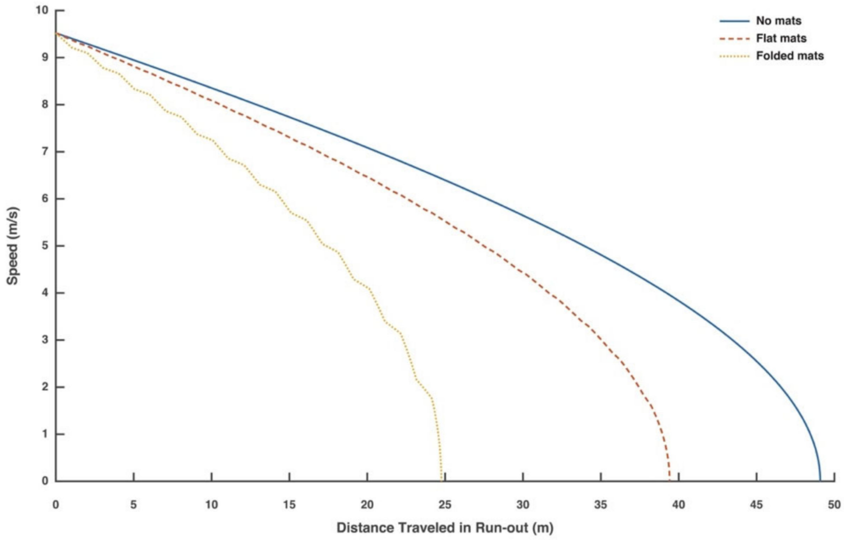


Figure 4. Example of the distance traveled by a snow tube system in a horizontal run-out when using no mats, flat deceleration mats, or folded deceleration mats.

This example shows the value of deceleration mats for a theoretical tubing hill. In the *no mats* configuration, a typical snow tube and rider would require 49.1 m to stop (approximately 10.9 s), using 98% of the run-out distance and offering very little additional space in case of an unusually fast descent or a decrease in friction in the run-out; in this example, there is only a small margin to accommodate changes in environmental factors and rider characteristics that may result in faster run-out entry speeds. In the *flat mats* configuration, the typical snow tube and rider would require 39.4 m to stop (approximately 8.6 s), using 79% of the run-out distance. Though the friction coefficient was only slightly higher than the *no mat* configuration, the flat mats stop the snow tube rider in less distance and offer more space to stop in case of an unexpectedly fast descent. Finally, in the *folded mats* configuration, the typical snow tube and rider would require 24.8 m to stop (approximately 5.2 s), using only 49.5% of the run-out distance. Using folded mats in this example would allow for the greatest protection from a snow tube traveling too far and exiting the run-out. Because it is possible that the snow-to-snow tube friction could be lower than the values measured in our study or even decrease (during the course of a day or even more quickly), it would be advisable in this example for the run-out to be longer or for the tubing hill operator to add deceleration mats to the run-out area.

4.3. Limitations

Snow tube inflation pressure could have affected the results. In our tests, we filled the tubes until they were firm but did not measure or monitor the inflation pressure throughout testing. It is possible that the snow tube air pressure changed with ambient temperature and incident solar radiation throughout testing. This is a topic that we plan to address in future work.

Other parameters were not examined in this study and could influence the effective COF, such as rider mass, riding position, foot drag, the material and wear of the bottom of the snow tube cover, and snow properties. For example, only one riding position (chest presenting to the snow tube) was examined in the current test series, but some riders use an alternate riding position wherein the rider sits in the hole of the ring torus with his or her knees bent on top of the upper surface and feet hanging outside the torus. The interaction with the deceleration mats and the effective COF may be affected by this alternate riding position. Time and resources limited the testing and further work to assess these additional parameters is planned.

5. Conclusions

In this pilot study, deceleration mats slowed snow tube riders effectively without destabilizing riders in a snow tubing run-out area. Folding the deceleration mat slowed more quickly snow tuber riders when compared to flat mats or no mats. The use of multiple mats in succession in each snow tubing lane would likely further aid in slowing snow tube riders. Deceleration mats are an additional tool to slow snow tube riders for operators to consider when designing or maintaining run-outs and mitigating faster run-out entry speeds due to uncontrollable changes in environmental conditions and snow tube rider characteristics.

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