Friction is a Drag

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Physics 211 Fall Project

The origins of the game we refer to as Ice Hockey today are somewhat uncertain. Although there are conflicting theories on how and where the game came about, it is generally considered by most accounts to have evolved from the game “Hurley,” which was played year-round in Ireland with a ball and a stick during the early 1800’s. When the game jumped across the pond to Nova Scotia, the lords capitalized on this game considered too difficult and frankly too painful to play during the cold of winter by the Irish. The game attained its contemporary name of ice hockey from “Hurley on Ice,” during the middle 19th century. Since that time, sports enthusiasts and athletes alike have attempted to maximize performance while maintaining the integrity of the game. From the invention of the Zamboni in 1949, to the regular usage of face masks for goalies and helmets by the wingers and defensivemen in the early 1970’s, the distinguished pioneers of the game have molded it into what it is today, but as we will discover, there is always room for improvement at all levels, even the microscopic. Ice hockey pucks can be very challenging to control when it is moving over a rough surface, even for the professionals. Our study delves into the complexities and interactions between the hockey puck and the ice, in order to determine more efficient ice-treatment options and hopefully contribute to the existing literature evaluating the coefficient of friction between the two surfaces.

Friction is a force between two touching surfaces which opposes their motion if they are moving relative to each other and opposes any force which acts horizontally on either one if they are stationary. Friction is a passive force, which means it does not initiate motion it merely opposes it. During our analysis of kinetic friction factors in the classroom, we discovered that surface area and speed will not affect friction; yet, we determined the friction force is proportional to how hard the two objects or surfaces are pressed against each other. Stated more formally, friction force is proportional to the normal force. At the molecular level, it has been consistently demonstrated that any surface is full of inconsistencies or asperities; there is no such thing as a perfectly smooth or flat surface (Kennedy, Jones, Schulson, 2000; Stuart, 2003). It is a common misconception that smooth surfaces will experience less friction than rough ones, but as we discovered in our Physics 211 laboratory-based class, a block moving over a smooth glass surface experiences more sliding friction than it does over the relatively rough surface of a wooden board. This fact led researchers to examine different factors that may play a role in friction. As Stuart (2003) noted, friction has been examined at the molecular levels and some different theories have been formulated, which are quite interesting and counter intuitive, such as: “rough surfaces may be more slippery than smooth surfaces, coefficient of friction may be dependent on speed, and dry surfaces may be more slippery than wet surfaces.” Smooth surfaces sometimes have more sliding friction associated with them than rough surfaces; therefore, other factors must be considered when studying friction, such as adhesion, which is the attraction between molecules on sliding surfaces (Laws, 2004).

Ice is generally considered as a material which exhibits very low friction in sliding. The Coefficient of Friction is a unit less number which represents the resistance to sliding of two surfaces in contact with each other. The coefficient of friction is calculated by the ratio of the frictional force to the normal force. For example, rubber on ice (i.e. hockey puck to ice) has a coefficient of static friction ~0.06 (Ableman, 2004).

The coefficient of friction for rubber on asphalt is approximately 0.6; therefore, rubber on ice is about 10 times “more slippery” than rubber on asphalt. There are several different factors that influence the coefficient of friction for ice, but before we examine them, let us look a little further into the current research regarding what actually occurs at the microscopic level between the hockey puck and the ice surface.

In part of our experiment, we are examining the differences between the coefficient of friction for ice that is smooth, and ice that has been extensively skated on, consequently resulting in a hypothetically rougher surface. The common terminology used to differentiate between the two variants is “fast ice,” and “slow ice.” So, how exactly does an object such as a puck move over ice? According to Kennedy *et al*. (2000), objects experience very low friction in sliding due to a lubricating layer of water resulting from transferred thermal energy; however, Somorjai (2004) states that ice has a “quasi-fluid layer” that coats the surface of ice and makes it slippery, even ice that is 129-degrees below centigrade! Braun, Glebov, Graham & Menzel (1998) studied the structural arrangement of water molecules on the ice surface to attain direct information on their vibrational motion, and concluded that molecules are surprisingly mobile, which explains many peculiarities in the interactions of ice with its environment. They also claim this “vibrational disorder” at the ice surface explains why two pieces of ice fuse when pressed together.

Somorjai (2004) further mentioned, “…skates and pucks do not generate enough pressure to instantly liquefy ice.” This “quasi-fluid” layer can be thicker or thinner depending on temperature. As temperature increases, so does the actual amount of the "quasi-fluid layers," which Somorjai (2004) states accounts for the differences between slow ice and fast ice. Slow ice has more of these quasi-layers which appeals to the figure skaters, because they will experience softer landings, while hockey players experience more friction, as they must skate through more of these water-like layers. Conversely, hockey players enjoy the fast ice, because it allows them to skate faster requiring less work as a result of less friction; however, the figure skaters avoid fast ice because it is much harder and hurts more when you fall on it; hence the need for "full battle-gear" for the hockey players, while the figure skaters wear mini-skirts.

So, what are these imperfections on a surface (also called asperities) and how do they affect the motion of a puck over the ice surface? If you talk to any seasoned hockey player, he/she will tell you there is a major difference between good ice and bad ice (It is important to note these are different terms than the previously examined terms of slow and fast ice). According to Brendan Lenko, P.E., who is an engineer and "The President of Energy Ice" (2004), there are five main qualities of ice, which can have an effect on motion of a hockey puck. They are: chippiness, smoothness of ice, friction of the ice, hardness, and quality and accumulation of ice shavings. He noted an ice skate will move thru ice in a different manner than a hockey puck, and thus will be subject to different qualities of the ice surface. For example, a small asperity may have little or no effect on the ice skater because he has much more mass and less ice contact area than a puck. When referring to ice surfaces, the evident ice shavings are the premise for periodic resurfacing. The shavings will either stick to the ice surface, which is called sintering, or it will not adhere, subsequently posing much less of a problem for the movement of the hockey puck. Sintering is an undesirable quality of ice and is related to surrounding temperature and humidity (Lenko, 2004). As snow sticks to ice (sinters), the actual ice surface gains more asperities and consequently results in a greater coefficient of friction because there is more adverse interaction between the two surfaces.

The average mass of a standard NHL hockey puck is 160g. It is an ideal object for the game because its mass minimizes erratic bounces, and the black opaque color allows for it to be seen clearly against the ice surface. A hockey puck is made of an elastomeric rubber polymer, which has a published coefficient of static friction with ice of 0.06 (Kurtus, 2003). The ice-on-ice coefficient is 0.01 (Kennedy *et al.* 1999). Interestingly enough, NHL referees freeze official game hockey pucks before each game in an attempt to reduce the coefficient of friction between the hockey puck and the ice surface.

There are several factors which influence the coefficient of friction between ice and a hockey puck. Although we discovered contradictory evidence in our Physics 211 laboratory-based class, Barnes *et al*. (1971) noted at low sliding speeds, the friction coefficient of ice can be considerably higher and may be influenced significantly by velocity. Kennedy *et al.* (2000) replicated these findings and noted adhesion and its subsequent elimination through frictional heating is probably responsible for the general decrease in the friction coefficient with increases in sliding velocity. It should be noted their experiments were conducted using ice-on-ice examinations. Kennedy *et al*. (1999) went on to mention, "…these results confirm that the combination of frictional heating and melting temperature depression (from contact pressure) can cause contacting asperities to melt, producing a thick meltwater layer which lubricates the contact and limits adhesion."

In our experiment we analyzed how various ice surface conditions affected the coefficient of friction between a hockey puck and the ice. We had three surface conditions: ice with few asperities, ice with many asperities, and ice covered with a thick layer of water. In our first testing situation of examining puck movement over a smooth ice surface, we hypothesize the puck will continue moving at an affectively constant velocity, due to minimal friction. In our second testing situation using ice with many asperities, we theorize the coefficient of friction will be significantly greater in comparison to smooth ice, resulting in a constantly decreasing speed as a function of time. This would be consistent with most of the mainstream literature on the subject, which states the irregularities of the ice surface will result in a greater coefficient of friction; however, it should be reiterated there is conflicting research on the subject. In our final situation, a water covered ice surface, we predict the coefficient of friction will decrease, subsequently resulting in the puck losing less speed compared to the smooth ice testing situation.

Methods

Procedures

Before we actually started to collect our data, it was necessary to contact an ice rink that would enable us to run a series of experiments on their ice surface. Upon investigation, we ran into a common liability issue with many facilities concerned about objects being present on the ice surface. We finally were able to contact the Olympic Ice Oval in West Valley, Utah, which, in the name of science, was graciously willing to allocate a block of ice time to our experiment at no charge. Once this set back was overcome we were able to begin the experimental process. The Olympic Ice Oval was extremely helpful in providing ice time that immediately followed heavy use. After we had completed our first series of tests, the maintenance staff kindly resurfaced the ice using a Zamboni.

We first found an area of ice that had experienced extensive use. We cleared away large pieces of loose ice using a towel but left the asperities of the surface intact. We then placed 4 feet of measuring tape on the ice surface for scaling purposes in the digital video we would be creating. We then set up our tripod on an elevated surface using the bench and the surrounding rink wall. The angle of the video camera was adjusted to include a frame with the puck and our 4 feet of measuring tape to be transferred to the VideoPoint 2.1.2 program at a later time. The video camera was started and we placed the NHL regulation hockey puck on the ice surface. With two people sitting at either end of the measured distance, we began to perform a series of slides across the rough ice surface varying the initial speed of the puck.

After all of this data was collected using our digital video camera, the ice was resurfaced by the Zamboni provided by the Olympic Oval. Directly proceeding the resurfacing of the ice, we again measured out a distance of 4 feet on our measuring tape and placed it on the ice surface while it was still wet. We then slid the puck over the wet ice surface collecting more video footage. For this scenario we followed the same procedures as in the previous series of tests. We then waited for a few minutes until the freshly resurfaced ice had completely solidified. Upon drying we then preformed more experimental slides on a surface that had been untouched since the resurfacing. This was done so in the same manner as the slides preformed on the heavily used ice surface and the wet surface.

Once all the trials were recorded, we downloaded the video to a PC and, using video editing software, we edited the video so it only included pertinent frames. This edited video was then loaded into VideoPoint and point data was collected. The resulting time and position information was then transferred to Excel for calculations and graphing.

Apparatus

-VideoPoint software version 2.1.2

-One NHL regulation Hockey puck

1 inch high 3 inch diameter weight 164.2 grams

-Digital video camera Sony DCR TRV 50

-Tripod

-Microsoft Excel

-Microsoft Word

-Measuring tape

-Olympic Oval Ice Skating Rink that has had extensive skating use

-Olympic Oval Ice Skating Rink after resurfaced by a Zamboni

-Three pairs of Ice skates

-Towels to brush ice surface free of ice pieces

Figure 1 Depiction of experimental hockey puck with measured 4-foot scale on ice surface

Results

Since we had three separate scenarios and at least three trials per scenario, we created a great deal of raw data. Through the use of VideoPoint we generated time and x-axis position data from five trial runs on smooth ice, three trial runs on wet ice, and three trial runs on rough ice. We plotted this raw data using Excel and found a best fit 3rd degree polynomial equation for the data as illustrated in figure 2. Initially we expected the acceleration to be constant so we used a 2nd degree polynomial for the best fit lines; however, our calculated coefficients of friction had a standard deviation relatively large to the coefficient of friction itself so we considered the possibility of a dynamic coefficient of friction.

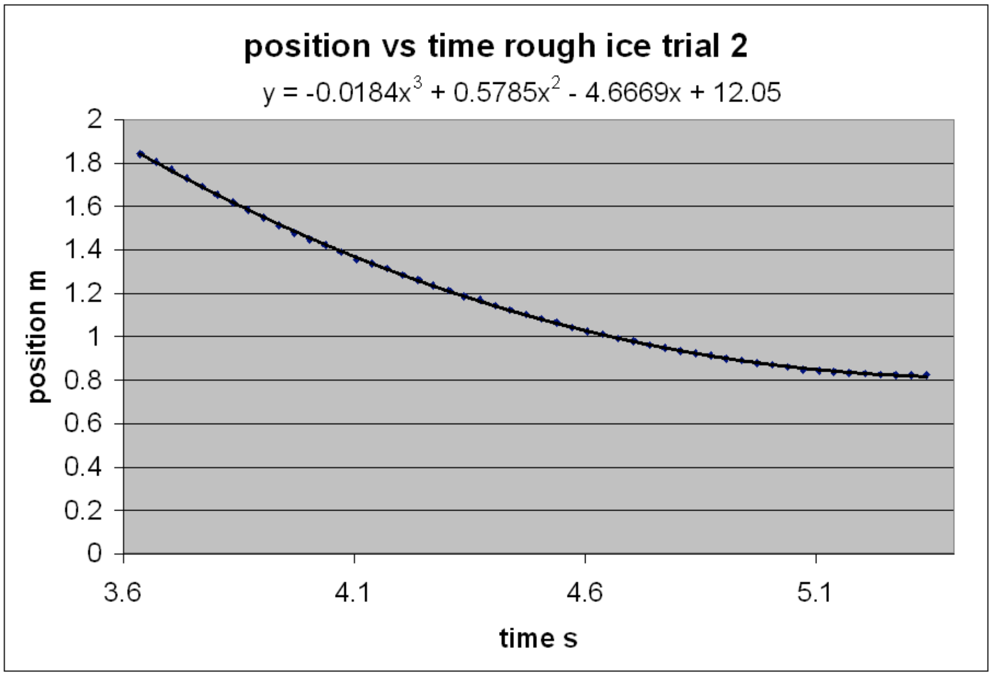

Figure 2 graph of position *vs.* time for second rough ice trial

With the resulting best fit equation calculated by Excel, we took the first and second derivatives to get equations for the velocity and the acceleration, respectively. Using these equations we calculated the instantaneous velocity and acceleration for each data set. This resulted in the data exemplified in table 1 for each data set.

smooth ice trial 2				
Time (s)	x-position (m)	x-velocity (m/s)	x-accel (m/s^2)	coefficient of friction
41.88	0.1693	2.10907648	-0.651208	0.066449796
41.91	0.2405	2.08938202	-0.661756	0.067526122
41.94	0.3082	2.06937112	-0.672304	0.068602449
41.98	0.3759	2.04219768	-0.686368	0.070037551
42.01	0.4369	2.02144842	-0.696916	0.071113878
42.04	0.5046	2.00038272	-0.707464	0.072190204
42.08	0.5724	1.97180288	-0.721528	0.073625306
42.11	0.6367	1.94999882	-0.732076	0.074701633
42.14	0.6977	1.92787832	-0.742624	0.075777959
42.18	0.7654	1.89789208	-0.756688	0.077213061
42.21	0.823	1.87503322	-0.767236	0.078289388
42.24	0.8873	1.85185792	-0.777784	0.079365714
42.28	0.9415	1.82046528	-0.791848	0.080800816

42.31	1.006	1.79655162	-0.802396	0.081877143
42.34	1.063	1.77232152	-0.812944	0.082953469
42.38	1.121	1.73952248	-0.827008	0.084388571
42.41	1.179	1.71455402	-0.837556	0.085464898
42.44	1.236	1.68926912	-0.848104	0.086541224
42.48	1.29	1.65506368	-0.862168	0.087976327
42.51	1.345	1.62904042	-0.872716	0.089052653
42.54	1.395	1.60270072	-0.883264	0.09012898
42.58	1.45	1.56708888	-0.897328	0.091564082
42.61	1.5	1.54001082	-0.907876	0.092640408
42.64	1.544	1.51261632	-0.918424	0.093716735
42.68	1.605	1.47559808	-0.932488	0.095151837
42.71	1.649	1.44746522	-0.943036	0.096228163
42.74	1.693	1.41901592	-0.953584	0.09730449
42.78	1.737	1.38059128	-0.967648	0.098739592
42.81	1.785	1.35140362	-0.978196	0.099815918
42.84	1.825	1.32189952	-0.988744	0.100892245
42.88	1.869	1.28206848	-1.002808	0.102327347
42.91	1.91	1.25182602	-1.013356	0.103403673
42.94	1.951	1.22126712	-1.023904	0.10448
42.98	1.988	1.18002968	-1.037968	0.105915102
43.01	2.029	1.14873242	-1.048516	0.106991429
43.04	2.062	1.11711872	-1.059064	0.108067755
43.08	2.1	1.07447488	-1.073128	0.109502857
43.11	2.134	1.04212282	-1.083676	0.110579184
43.14	2.167	1.00945432	-1.094224	0.11165551
43.18	2.201	0.96540408	-1.108288	0.113090612
43.21	2.228	0.93199722	-1.118836	0.114166939
43.24	2.266	0.89827392	-1.129384	0.115243265
43.28	2.289	0.85281728	-1.143448	0.116678367
43.31	2.316	0.81835562	-1.153996	0.117754694
c1 =	-0.0586			
c2 =	7.0369			
c3 =	-278.96			

Table 1 Data chart of position, velocity, acceleration, and the coefficient of friction

An Example of the velocity equation from table one is:

$$3C_1t^2 + 2C_2t + C_3 \tag{5}$$

Where C_1, C_2, C_3 are the coefficients of the t^3, t^2, and t components of the best fit 3rd degree polynomial, and t is the time. Likewise the equation for acceleration is:

$$6C_1t + 2C_2 \tag{6}$$

Finally, to calculate the coefficient of friction we realized that in our experiments the only horizontal force acting on the puck was from friction ($F_{netx} = F_f$). The ice rink was basically level, therefore any deviation from level is considered negligible ($F_N = F_g$). Then we combined equations 1 and 4 to get the equation:

$$ma = \mu F_N = \mu F_g = \mu ma_g \tag{7}$$

or simply:

$$ma = \mu ma_g \tag{8}$$

By dividing both sides by ma_g we are left with an equation for μ:

$$\mu = ma/ma_g \tag{9}$$

$$\mu = a/a_g \tag{10}$$

This is the equation we used to calculate our coefficient of friction.

Based on the fact that a dynamic μ better fit our data we considered the possibility that it varied. Since our μ is a ratio of the hockey puck's acceleration and the acceleration of gravity (equation 10), which is constant, if μ varies then the puck's acceleration must as well. To allow this we used a 3rd degree polynomial for the best fit line. Even if there were no significant changes in the acceleration, using a 3rd degree polynomial for the best fit did not introduce more possibility of calculation error because using a higher order polynomial always increases the accuracy of the best fit line. Any second order polynomial is a third order polynomial, with the leading coefficient of zero. Although a 3rd degree polynomial may introduce a physical property that does not necessarily exist, we feel it matches the data significantly better.

Data analysis

Once the data had been collected and calculated it was apparent there was a connection between velocity and the coefficient of friction. Specifically, as the speed increased the coefficient of friction decreased. The does not appear linear however as is illustrated in figure 3.

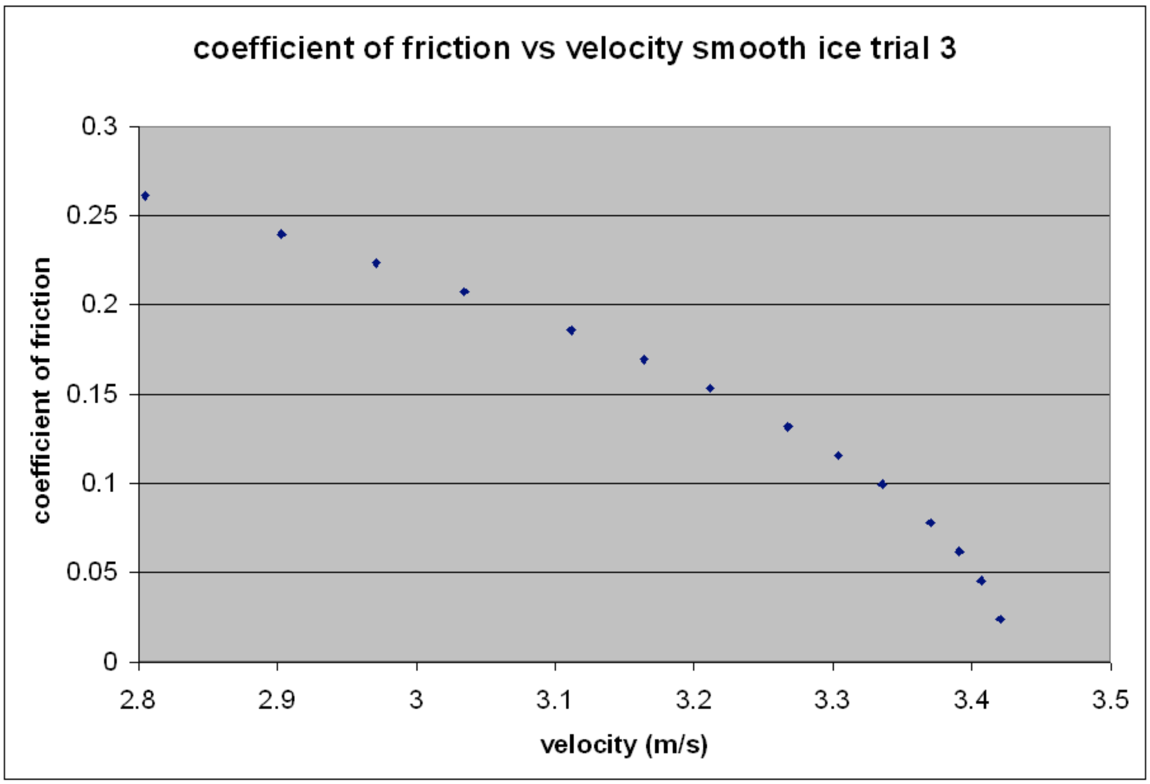

Figure 3 graph of coefficient of friction *vs.* velocity for third smooth ice trial

Every smooth ice trial has a coefficient of friction vs. velocity graph with the same shape as figure 3 but there is an inconsistency in the numerical relation. Figure 4 illustrates the coefficients of friction of all five smooth ice trials.

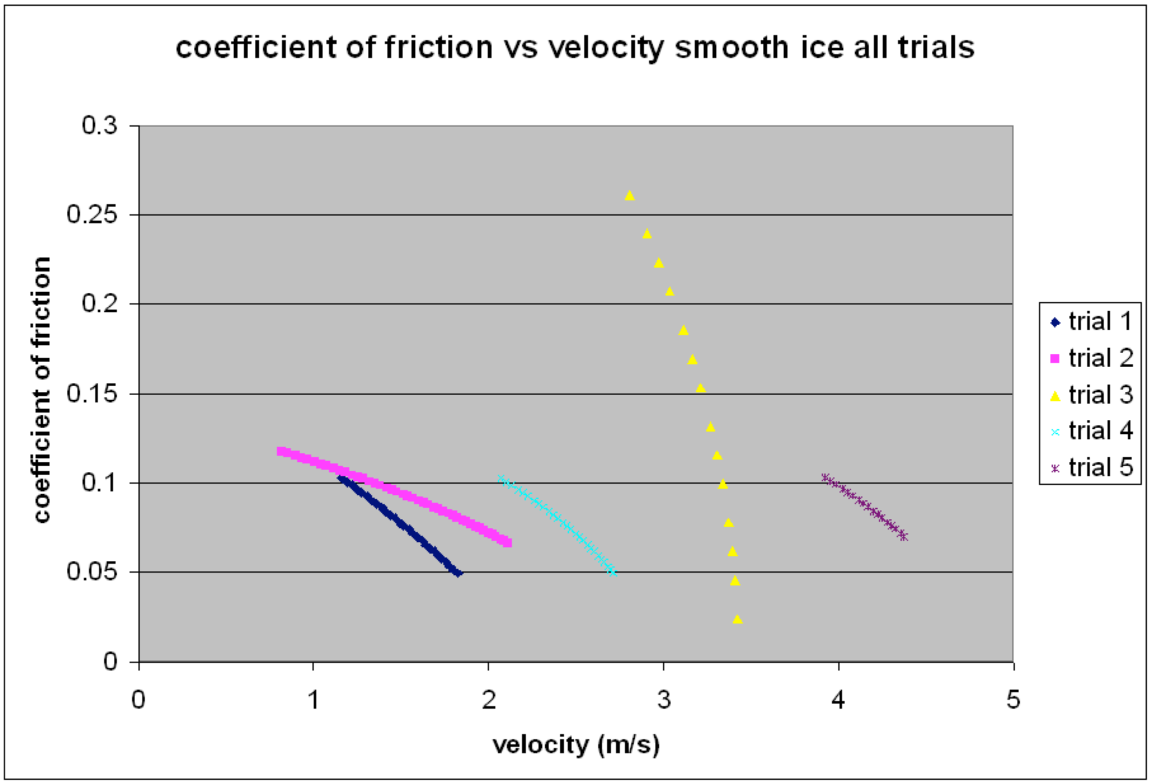

Figure 4 graph of coefficient of friction *vs.* velocity for all smooth ice trials

While figure 4 does show each trial having the same shape graph, there is no numerical consistency between trials leading us to believe that there are other factors that affect the coefficient of friction on ice. This is consistent with the findings of Kennedy *et al.* (1999) who noted the coefficient of friction is closely related to the sliding velocity, friction force, hardness of the ice (which influences contact area), and the thermal conductivity and diffusivity of the contacting materials. To further complicate the coefficient of friction on ice, both the wet ice trials and the rough ice trials have one coefficient of friction *vs*. velocity graph as shown in figure 5.

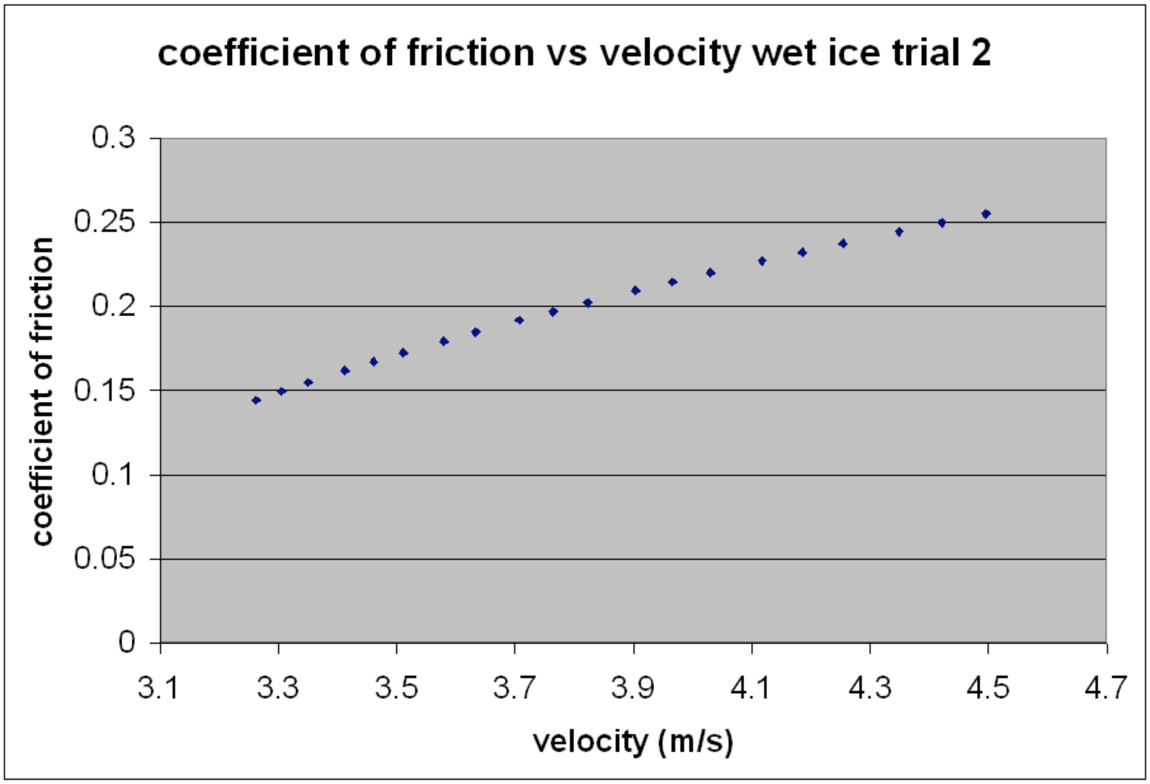

Figure 5 graph of coefficient of friction *vs.* velocity on second wet ice trial

We could not account for this inconsistency in our data nor could we resolve the obvious contradiction. Our analysis of the relative coefficient of friction between various ice surface conditions is summarized in figure 6.

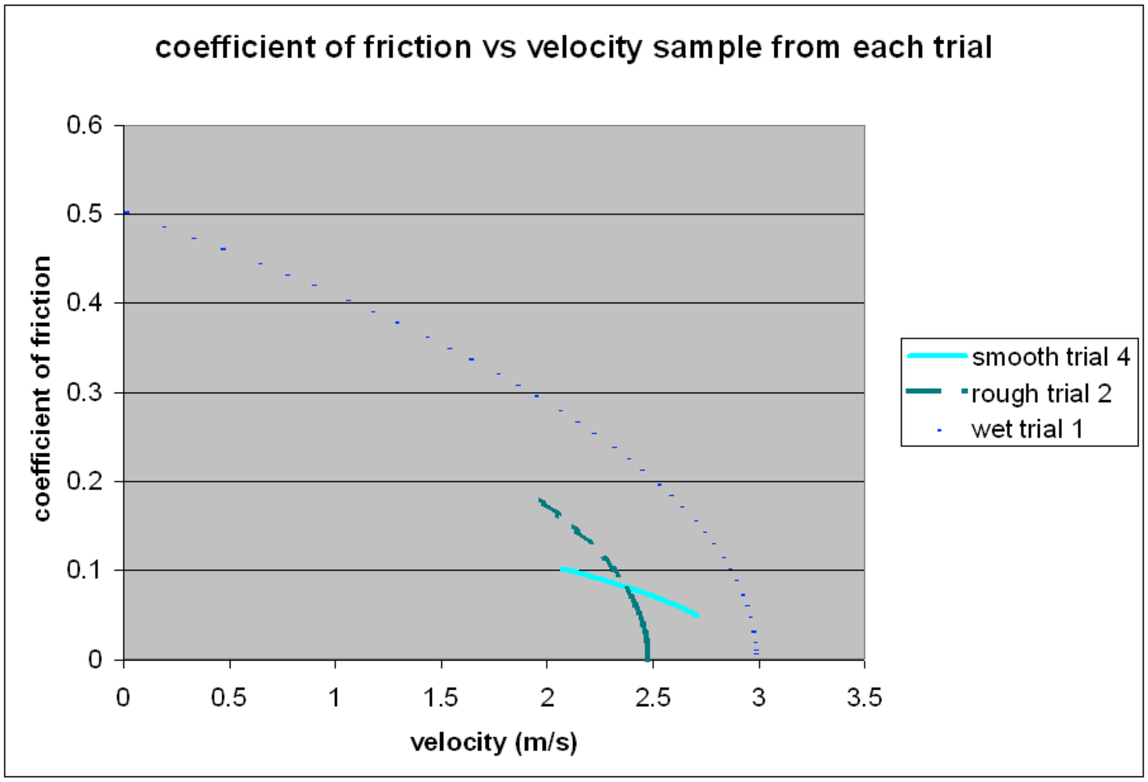

Figure 6 graph of coefficient of friction *vs.* velocity for one sample from each condition

As figure 6 illustrates, our data suggests that a rough ice surface leads to a higher initial coefficient of friction than a puck on smooth ice but the rate of change of the coefficient of friction is much higher on rough ice. The dubious data collected for the wet trials suggests the same relative increase in the initial coefficient of friction when compared to the smooth ice trials.

Discussion

We conclude there is an inverse correlation between velocity of a hockey puck under no horizontal forces other than friction, and the coefficient of friction between that puck and ice under all experimental conditions examined. More specifically according to our data, as the speed of the puck increases, the coefficient of friction decreases on ice with many asperities (figure 7), few asperities (figure 8) and a wet surface (figure 9).

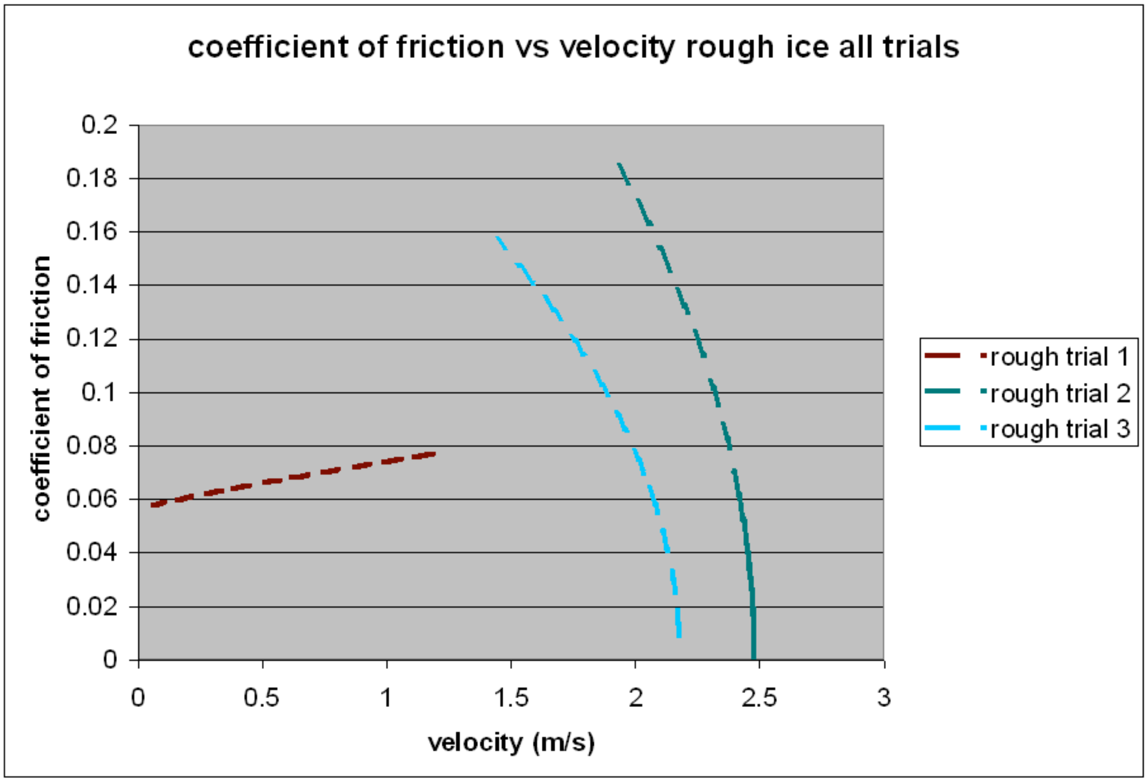

Figure 7 graph of coefficient of friction *vs.* velocity for all rough ice trials

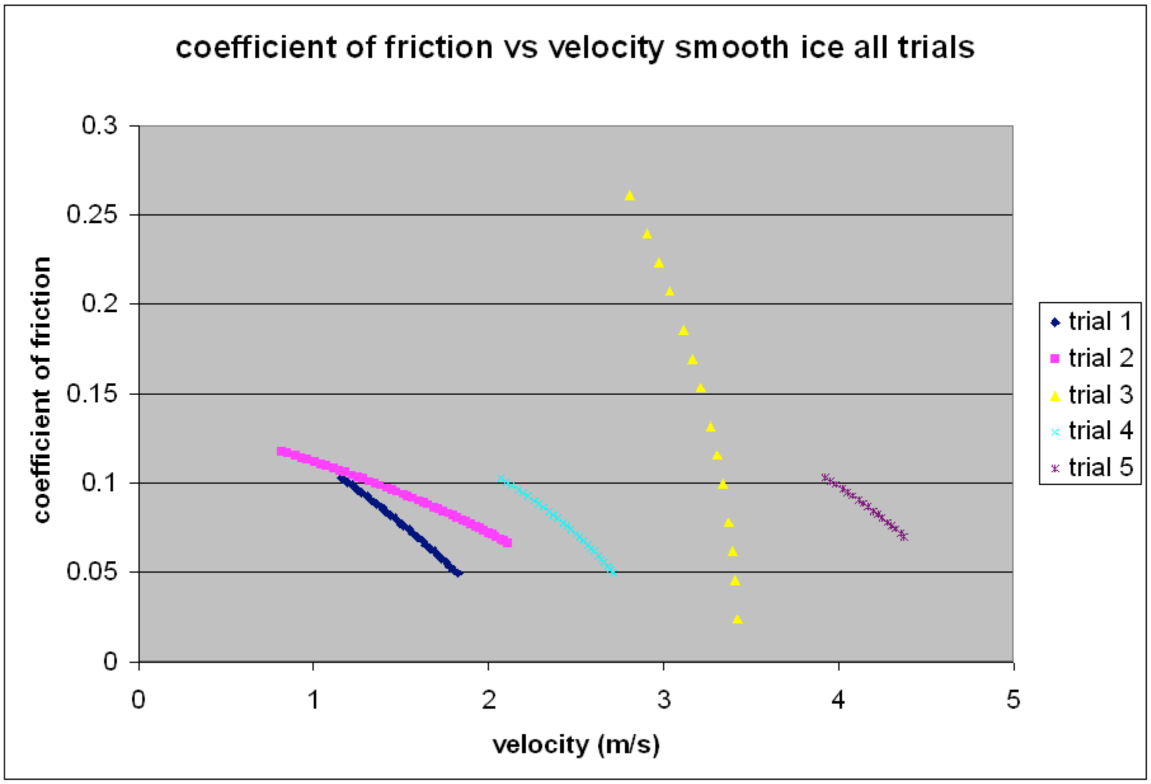

Figure 8 graph of coefficient of friction *vs.* velocity for all smooth ice trials

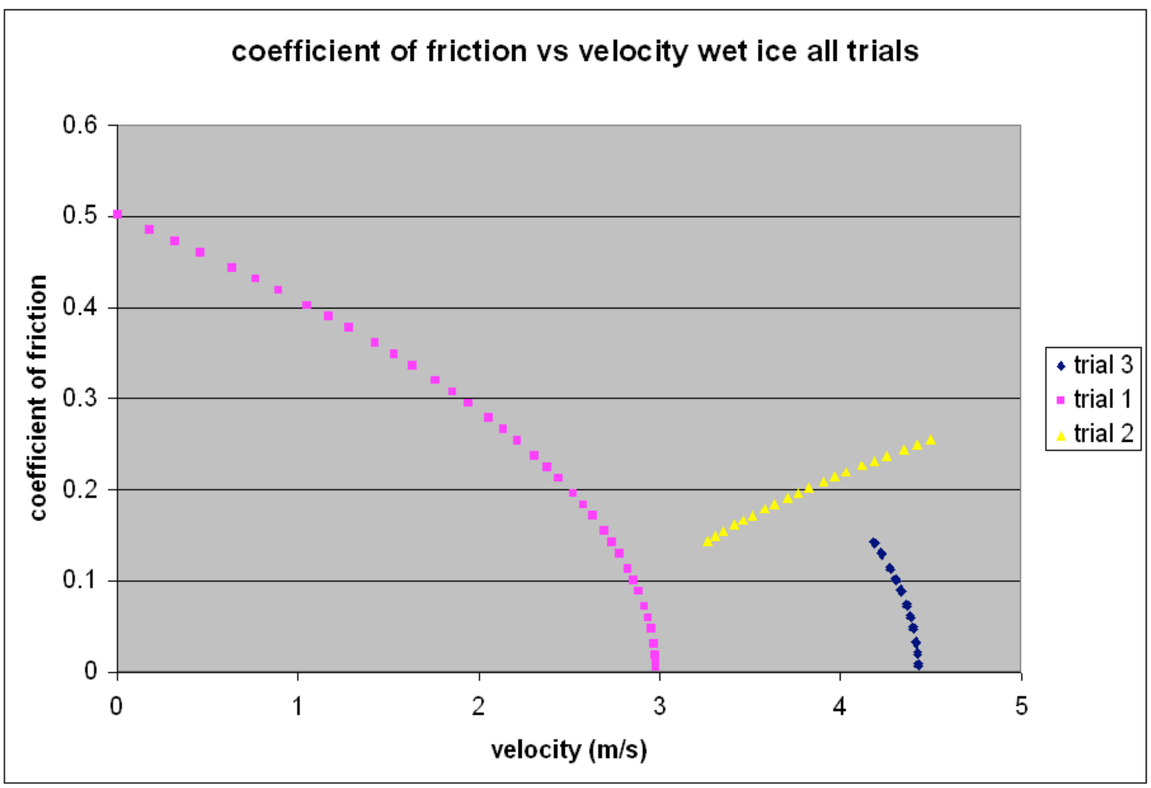

Figure 9 graph of coefficient of friction *vs.* velocity for all wet ice trials

This does not appear to be the only factor influencing coefficient of friction between a hockey puck and ice. Our data suggests asperity of the ice surface is directly related to the initial coefficient of friction and its rate of change, this is consistent with Kennedy *et al.* (1999) who stated, "… frictional heating during ice friction results in the melting of the surfaces by contacting ice asperities and that the resulting water layer acts as a lubricant." In the wet ice condition we predicated that the water onto of the ice would act as a lubricant thus decreasing the coefficient of friction. Our data indicates that our hypothesis was incorrect. It appears as though the water on the surface was deep enough to partially submerge the puck resulting in factors other than friction affecting the acceleration of the puck. We conclude that our experimental design was flawed for the water covered ice trials.

It is with great humility we acknowledge there are obvious sources of uncertainty for our data. A source of uncertainty in the acquisition of our data is in the video recorder and VideoPoint data collection routine. The frame rate of the video camera is a limitation on the number of samples we can take and fewer samples can lead to less accurate results. Additionally, exposure times are so long that the puck appears to be in two places at once thus making the selection of the proper place to add the data point in VideoPoint dubious. The problem of accurate data point selection in VideoPoint is compounded by the limited resolution of the camcorder. There is uncertainty introduced by using only the x coordinates of the points because a human is sliding the puck and cannot get the velocity perfectly horizontal. It should also be noted we have data which is inconsistent with the majority of out findings. Specifically, in two separate experimental trials (wet and rough surface conditions) we found that the coefficient of friction increased while the majority of our data as well as our preliminary research suggest it should decrease.

Fundamentally we feel inherent design flaws were the major source of uncertainty. Following the acquisition of our data we found variables that we did not record or even account for in our original design. We determined that amount of time the friction force acts on the system is a significant factor when determining the coefficient of friction. Energy transfer from kinetic to thermal energy takes a finite amount of time which we did not consider in our experiment. This flaw could be corrected by taking multiple samples at the same initial speed. A potential solution is a mechanism capable of being secured to the ice which uses a spring loaded system able to shoot the puck with varying reproducible initial speeds down a straight chute. This improvement also reduces uncertainty resulting from our inability to slide the puck at a consistent angle. After our experiment we also realized the temperature of the ice and the temperature of the puck are factors needing consideration. Our data may have been skewed because both the temperature of the part of the puck touching the ice and the ice itself may have changed from trial to trial, thereby changing the coefficient of friction. This variation in temperature may have affected the time needed to melt the surface of the ice. It has also been documented that the surrounding humidity of the ice environment is influential in ice shaving's ability to sinter to the ice surface (Lenko, 2004). This means the higher the relative humidity, the more likely we are to see sintering, and subsequently a high coefficient of friction between the hockey puck and the ice will theoretically result. Determining the relative humidity would provide us with important information when considering the asperity value between the two respective surfaces. Our failure to consider temperature and relative humidity could be corrected by using a laser thermometer to measure the temperature of the immediate surrounding microenvironment and a hygrometer to determine the relative humidity before each trial. The puck's temperature should be regulated by placing it in an ice bath that has reached equilibrium. To further reduce the uncertainty in this experiment, we would need to have a way to quantify the asperity of the ice and to ensure the asperity is consistent over the entire path the puck will take.

Relevant Equations

$$F_f = \mu F_N \tag{1}$$

$$W = Fd \tag{2}$$

$$K = 1/2mv^2 \tag{3}$$

$$F = ma \tag{4}$$

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